CHANGES OF CLIMATE

Proceedings of the Rome Symposium
organized by Unesco and the World Meteorological Organization

LES CHANGEMENTS DE CLIMAT

Actes du colloque de Rome
organisé par l'Unesco
et l'Organisation météorologique mondiale

U N E S C O

ARID ZONE RESEARCH — XX

CHANGES OF CLIMATE

PROCEEDINGS OF THE ROME SYMPOSIUM

ORGANIZED BY UNESCO AND WMO

RECHERCHES SUR LA ZONE ARIDE — XX

LES CHANGEMENTS DE CLIMAT

ACTES DU COLLOQUE DE ROME

ORGANISÉ PAR L'UNESCO ET L'OMM

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Compte rendu des recherches relatives à l'hydrologie de la zone aride

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The reviews of research are published with a yellow cover; the proceedings of the symposia with a grey cover.

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FOREWORD

The arid zone programme of Unesco, which was started in 1951 with the creation of an Advisory Committee on Arid Zone Research, became one of Unesco's Major Projects in 1957. With its object of promoting and stimulating research in the various scientific disciplines which have a bearing upon problems of the arid regions, the Major Project has proved an excellent example of integrated approach between many different disciplines and a successful endeavour in international scientific co-operation having wide educational and cultural implications. The ultimate aim of the programme is not only the increase of knowledge but also the improvement of the living conditions of mankind and in particular of the people living in desert or semi-desert regions. A co-ordinated scientific effort has commenced in most of these countries not only with an intensification of existing research programmes but with the establishment and development of special Desert Research Institutes or Arid Zone Research Centres whose function it is to provide the basic scientific information needed for any development plans.

The abundance of information available in some branches of scientific research has become a problem to research workers, and one of Unesco's tasks has been to publish in this Arid Zone Research *collection a series of* Reviews of Research *which have summarized the state of knowledge in a given discipline of science related to arid zone problems.*

With a view to maintaining adequate liaison between the scientists engaged in arid zone research all over the world and to giving them an opportunity to present and discuss the results of their work on specific projects, Unesco has also organized a number of symposia. Within this framework, and at the suggestion of the World Meteorological Organization (WMO), the Advisory Committee on Arid Zone Research recommended at its fifteenth session that a symposium on changes of climate with special reference to the arid zones be organized in 1961 jointly with WMO.

The problem of climatic fluctuations is one of extreme complexity and one which relates to many disciplines. At the same time it is of particularly great importance in the arid zone, where minor variations may have considerable consequences. The purpose of the symposium was to bring together scientists who have contributed to the subject from such fields as meteorology, oceanography, geomorphology, geography, hydrology, botany, geology and even archaeology, so as to obtain a coherent and comprehensive picture of present knowledge, theories and implications of climatic change.

At the invitation of the Italian Government, the symposium took place in Rome from 2 to 7 October 1961. The opening ceremony was held in the main hall of the Italian National Research Council under the chairmanship of Professor G. Polvani, president of the Council, and speeches were also delivered by Madame Maria Badaloni, Under-Secretary, Ministry of Education, Professor A. Fantoli, representing the Ministry of Foreign Affairs, and General F. Giansanti, head of the Meteorological Service. Dr. Luna B. Leopold, chief hydraulic engineer of the United States Geological Survey and member of Unesco's Advisory Committee for Arid Zone Research, gave an opening address on the importance of the problem of changes of climate, particularly in the arid zones, and proposed that an international programme of observation of drainage basins should be organized within the next few years.

Some 115 scientists from 36 countries took part in the symposium, and the working sessions were held in the conference room of the Food and Agriculture Organization.

Forty-five papers describing original research were presented and discussed during the nine working sessions, and the present volume contains the text of these papers together with a brief summary of the discussions to which they gave rise. As in previous proceedings, the papers have been reproduced in their original language (English or French). They are followed by a summary in the other language. The papers have been grouped into four sections :

I. Changes during the period of meteorological records ;

II. Changes during the late geological and early historical records ;

III. *Theories of changes of climate;*

IV. *Significance of changes of climate;*

V. *Conclusions of the symposium. The final session consisted of the presentation and discussion of a paper by Dr. C. C. Wallén (Sweden) on the conclusions to be drawn from all the papers presented.*

In accordance with proposals made by the Commission for Climatology the WMO secretariat prepared two documents for the symposium. The first—the Bibliography on Climatic Fluctuations—*was compiled from information received from 28 countries about published and unpublished meteorological studies on climatic fluctuations carried out in their countries during the past 10 years. The second document is a list of climatological stations for which observational series extend over 80 years or more. Information was received from 49 countries; 17 of these have no such stations; in the 32 countries, however, there are no less than 791 stations with records for 80 years or more. These two documents have been reproduced by the WMO secretariat and distributed to the participants in the symposium.*

The assistance given by the Italian authorities, in particular by the Meteorological Service, in the organization of the symposium greatly contributed to its success. Special credit is due in this connexion to Colonel Luccardi, secretary of the Italian organizing committee, and to all his staff.

AVANT-PROPOS

Le programme de l'Unesco relatif aux terres arides, dont la mise en œuvre remonte à la création en 1951 d'un Comité consultatif de recherches sur la zone aride, est devenu en 1957 l'un des projets majeurs de l'Unesco. Ce projet, qui vise à promouvoir et à stimuler la recherche dans les diverses disciplines scientifiques dont dépend la solution des problèmes des régions arides, constitue un excellent exemple d'un effort concerté de la part de nombreuses disciplines différentes et représente l'heureuse issue d'une tentative de collaboration scientifique internationale dont les effets, dans le domaine de l'éducation et de la culture, seront considérables. L'entreprise a pour ultime objet, non seulement de servir la science, mais encore d'améliorer les conditions de vie de l'homme et en particulier des populations qui vivent dans les régions désertiques ou semi-désertiques. On a commencé à se livrer à des travaux scientifiques concertés dans la plupart de ces pays ; non seulement les programmes de recherches se poursuivent avec une activité accrue, mais encore on voit se créer ou se développer des instituts de recherches sur les déserts ou des centres de recherches sur la zone aride, dont le rôle est de fournir les données scientifiques sans lesquelles il serait impossible d'établir des plans de mise en valeur.

*L'abondance des informations dont on dispose dans certaines branches de la recherche scientifique crée pour les chercheurs un véritable problème ; c'est pourquoi l'Unesco s'est chargée de publier, dans cette collection (*Recherches sur la zone aride*) une série de comptes rendus de recherches dont chacune résume l'état des connaissances actuelles dans un domaine scientifique en rapport avec les problèmes de la zone aride.*

En vue de maintenir le contact entre les hommes de science qui, dans le monde entier, se consacrent à des recherches sur la zone aride, et afin de leur donner l'occasion de présenter et de discuter les résultats de leurs travaux sur des sujets particuliers, l'Unesco a en outre organisé un certain nombre de colloques. C'est dans cette intention que, sur la proposition de l'Organisation météorologique mondiale (OMM), le Comité consultatif de recherches sur la zone aride a recommandé lors de sa 15e session qu'un colloque sur les changements de climat, notamment dans la zone aride, soit organisé en 1961 conjointement avec l'OMM.

Les variations climatiques sont une question d'une complexité extrême qui touche à un grand nombre de disciplines et qui, en même temps, présente une importance toute particulière dans les régions arides, où des changements minimes peuvent avoir des conséquences considérables. L'objet de ce colloque était de réunir des hommes de science dont les travaux ont contribué à la connaissance de cette question dans des domaines tels que la météorologie, l'océanographie, la géomorphologie, la géographie, l'hydrologie, la botanique, la géologie et même l'archéologie, de façon à pouvoir obtenir un tableau coordonné et complet des connaissances et des théories actuelles sur les changements de climat et leurs effets.

Sur l'invitation du gouvernement italien, ce colloque a eu lieu à Rome du 2 au 7 octobre 1961. La séance d'ouverture s'est tenue dans la grande salle du Conseil national de recherche italien, sous la présidence du professeur G. Polvani, président de cet organisme ; des discours ont été prononcés par Mme Maria Badaloni, sous-secrétaire au Ministère de l'éducation, par le professeur A. Fantoli, représentant le Ministère des affaires étrangères, et par le général F. Giansanti, chef du Service météorologique. Le Dr Luna B. Leopold, ingénieur hydraulicien en chef du Geological Survey des États-Unis d'Amérique et membre du Comité consultatif de recherches sur la zone aride, de l'Unesco, a fait un exposé général sur l'importance du problème des changements de climat, en particulier dans la zone aride ; il a proposé qu'un programme international d'observation de bassins versants soit établi au cours des prochaines années.

Au nombre de 115, des hommes de science venus de 36 pays se sont rencontrés pour participer à ce colloque ; les séances de travail se sont tenues dans une des salles de conférence de l'Organisation pour l'alimentation et l'agriculture.

Au cours de 9 séances de travail, 45 communications *relatives à des recherches originales ont été présentées et discutées ; le présent volume contient le texte de ces communications, ainsi qu'un bref résumé des discussions auxquelles elles ont donné lieu. Conformément aux précédents, les communications sont reproduites dans la langue originale (anglais et français) avec un résumé dans l'autre langue. Elles ont été groupées en quatre sections :*

I. Changements survenus au cours de la période couverte par les observations météorologiques.

II. Changements survenus à la fin des temps géologiques et au début des temps historiques.

III. Théories des changements de climat.

IV. Portée des changements de climat.

V. Conclusions du colloque. Dernière séance consacrée à la discussion d'un rapport de synthèse sur les résultats du colloque présenté par le Dr C. C. Wallén (Suède).

Conformément à une proposition de la Commission de climatologie, le secrétariat de l'OMM avait préparé deux documents en vue de ce colloque. Le premier — Bibliography on climatic fluctuations *— avait été établi sur la base de renseignements fournis par 28 pays au sujet des études météorologiques, publiées ou inédites, effectuées sur leur territoire au cours des dix dernières années sur les fluctuations climatiques. Le deuxième document est une liste des stations climatologiques dont les séries d'observations s'étendent sur quatre-vingts années et plus. Cette publication réunit les renseignements envoyés par 49 pays ; dans 17 d'entre eux, il n'existe pas de station de ce genre ; mais dans les 32 autres, on n'en compte pas moins de 791 dont les relevés couvrent quatre-vingts années ou davantage.*

Ces deux documents ont été reproduits par le secrétariat de l'OMM et distribués aux participants du colloque.

L'organisation du colloque a été grandement facilitée par les autorités italiennes — notamment par le Service météorologique — qui ont ainsi largement contribué au succès de la réunion. Des remerciements tout particuliers sont dus au colonel Luccardi, secrétaire du comité italien d'organisation, ainsi qu'à tous ses collaborateurs.

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CHANGES DURING THE PERIOD OF METEOROLOGICAL RECORDS

CHANGEMENTS SURVENUS AU COURS DE LA PÉRIODE COUVERTE PAR LES OBSERVATIONS MÉTÉOROLOGIQUES

Chairman / Président : DR. R. G. VERYARD

A REVIEW OF STUDIES ON CLIMATIC FLUCTUATIONS DURING THE PERIOD OF THE METEOROLOGICAL RECORD

by

R. G. Veryard

Meteorological Office, Air Ministry, London

FOREWORD

During the early stages of the planning for this symposium it was proposed that the first session should be devoted mainly to a review paper covering the whole field of the symposium and that some provocative ideas should be thrown eut as a basis for the subsequent discussions. The latter requirement presents no difficulty as there is ample scope for argument regarding the methods, criteria and theories for determining and explaining climatic fluctuations. But to summarize facts —and fancies—in respect of all the aspects of climatic change to be discussed at the symposium would call for an unduly long disquisition on highly heterogeneous material in many hundreds of papers. In any case, as there is to be a review paper for each session, it is hoped that it will be sufficient if this review paper (for Session I) relates almost entirely to the period of the meteorological record. It may be mentioned that, in order to ensure the availability of comprehensive information for study before the symposium, the World Meteorological Organization (WMO) called upon each member country to supply particulars of all climatological studies carried out in the country since 1950, plus particulars of the more important studies prior to 1950 (now issued by WMO in a publication entitled *Bibliography on Climatic Fluctuations*). Although all members did not respond to the appeal, the replies received showed that a staggering number of papers had been written amounting to over 300 in North America and a comparable number in Europe, the total exceeding 700. A large number of the studies, in many different languages, related to the period of the meteorological record and it has not been possible, in the time available, to digest or even to obtain access to all the papers. So the author of this review may perhaps be forgiven if certain findings are overlooked. For the same reason, it is hoped that authors will not feel aggrieved if special mention of their work is not included in this paper. By far the greater number of papers have been of a statistical nature and, in spite of the rapid development in recent years of a dynamical approach to the study of the general circulation, only in a comparatively few climatological studies has this approach been used. Further reference to this point will be made later.

METHODS

The methods of determining the existence and magnitude of climatic fluctuations vary from the old-fashioned simple analysis for various elements of departures from "normal" (the normal being an average value based on some selected period, generally 30 years) or the use of "running means"—to the modern and more advanced "power-spectrum analysis" of a time series using electronic computers. In regard to use of a "normal" period the question arises whether any period can really be regarded as "normal". In any case, a comparison of means of different periods is of little use without an examination of the nature of the frequency distribution. Also, the use of moving averages has its limitations. So, whatever the method, there is always need for precaution and doubtless some of the more important statistical pitfalls will be mentioned during the discussion at this session.

In this connexion, it may be useful to mention that a special chapter, written by experts, on the use of statistical methods will be included in the WMO *Guide to Climatological Practices* now under publication. One important precaution which has to be taken is to ensure the representativeness and homogeneity of the basic data. A comprehensive study of the causes of instrumentally observed secular temperature trends has been carried out by Mitchell (1953). He draws attention to many factors which are not always realized; for example, the effect of urbanization in causing an "artificial" temperature rise at city meteorological stations, A common practice is the construction of time series from mean monthly temperatures based on mean daily temperatures calculated from $\frac{\text{max.} + \text{min.}}{2}$. It is debatable, however, whether such values are really adequate for assessing climatic change. For example, Marshall (1954) using data for Kew Observatory has shown that the mean monthly temperature is sometimes unrepresentative and occasionally misleading as a means of comparing one particular month with the same month in other years. As he suggests, the mean maximum and mean minimum temperatures may be much better criteria of the temperature characteristics of a month. Attention is also drawn to a recent paper by De Vries and Birch (1961) which indicates that, according to the irrigation rate and distance down-wind from the irrigated area, irrigation may exert an appreciable, even if mainly local, influence on the distribution of energy and thereby on the climate near the ground. The authors found that for the irrigation seasons of 1956-57 and 1957-58 in the Nanneella district east of Rochester in Victoria (Australia), the differences of temperature at screen level between a "dry-land" station and a station in the irrigation area could be as much as 1-2° C. Maybe, in addition to "urbanization", irrigation, and pollution there are several other important effects of man's activities on local, if not regional or global climate, which could lead to "fluctuations" in a time series of temperature, rainfall, etc. Again, and now the writer is riding his favourite hobby-horse, are not mean monthly values of temperature, rainfall, etc., of very limited use for the study of climatic fluctuations —because of the short-term variations (due to thunderstorms, moving highs and lows, etc.) within a month ? It has been suggested that time averages might be replaced by ensemble averages—but how does one choose the ensemble ?

In recent years, harmonic analysis appears to have become less popular—but the hunt for "cycles" still goes on. Berlage (1957) has listed all the many "cycles" which have been "discovered" by various investigators —yet it seems that not one of these has been established beyond doubt. Indeed, experience with long-period records suggests that one cannot really expect to break down fluctuations into unique periodicities of different but exact wavelengths. Often the time series shows something like a "beat" phenomenon—but with an unevenly varying wave-length. For example, a recent study of tropical stratospheric winds by Veryard and Ebdon (1961) indicates a waxing and waning fluctuation in the zonal component varying from 23 to 29 months, the average period being 26 months. Indeed, there can be no doubt that various lag effects, feed-back mechanisms, etc., operate over periods of a considerably different time scale. For dealing with this problem, power-spectrum analysis may provide the answer and a good example is the study of the rainfall at Woodstock College by Lansberg, Mitchell and Crutcher (1959). A few last words before leaving the subject of methods. It is surprising how many workers in the field of climatic fluctuation have ignored not only the variance of the element being studied but also the possibility that the distribution of the element may not be a "normal" or "circular" one and may, in fact, have two or more modes. Of course, it is not so easy to determine statistically significant time changes of variance and extreme values as of means but it will doubtless be agreed that studies of climatological fluctuations should not be based solely on mean or average values but that adequate attention should be given to frequencies and extreme values.

FINDINGS

No one can deny that the climate does change and that there are fluctuations varying from the small scale involving a century or so to the large scale involving millions of years and embracing the great Ice Ages. In the former category are the fairly well authenticated changes which have occurred in historical times in the countries bordering on the North Atlantic. Thus there is good reason to believe that following an "optimum" period of climate about 2000-4000 B.C., when temperatures were some degrees higher than today, there have been several variations. For example, according to Brooks (1954), there were several climatic phases in the last 10 centuries : a mild, relatively dry period from before A.D. 1000 to 1250 followed by a rainier, stormy period from about A.D. 1250 to 1400, then a period of colder but less stormy weather from A.D. 1400 to 1600 when sea ice increased but mountain glaciers were still relatively small, and then the "Little Ice Age" from A.D. 1600 to 1850 when glaciers oscillated about an advanced position with three main maxima, about 1650, 1750 and 1850. Finally, we come to the period of the meteorological record. It was not until the nineteenth century that the measurement of meteorological elements by means of instruments really got under way and by the end of that century, with the encouragement of the International Meteorological Organization (the predecessor to WMO), instrumental meteorological observations, based on standard procedures and practices, became fairly world-wide. Attempts have been made, e.g., by Manley (1959), to reconstruct, from all the instrumental data available, the temperature régime back to the end of the seventeenth century. But owing to site changes, breaks due to wars, etc., there are as yet very few really homogeneous long-period records. Nevertheless, such records as are available, including synoptic charts and non-meteorological evidence such as the measurement of glaciers, have made it possible to get some idea of the existence of climatic "trends" on fluctuations during the last 100-200 years—at least for a great part of the Northern Hemisphere, but only for a few areas in the Southern Hemisphere. It so happens that this period of the meteorological record has been a period of retreat of glaciers, of decreasing ice cover and of rising temperatures and it is this most recent climatic fluctuation which has been the subject of innumerable papers.

In the following paragraphs an attempt is made to extract the "meat" from these papers under the headings of "Temperature", "Precipitation" and "Pressure, pressure patterns and winds".

TEMPERATURE

Air temperature

It is now generally accepted that the most striking feature of climatic fluctuations during the period of the meteorological record has been a warming in many parts of the world since about 1850 until a decade or two ago when in some places, but not all, there appears to have been a levelling-off or a fall of temperature. Let us look at the evidence.

From a carefully compiled long-period temperature record for Delft, Zwanenburg, Utrecht and De Bilt, Labrijn (1945) has shown, by means of overlapping 30-year means, that up till 1945 there was a general rise in winter mean temperature in the Netherlands from about 1790 onwards (apart from a slight relapse at about 1890) and a slow increase in summer mean temperature from about 1800 until the end of the nineteenth century and thereafter a decrease until about 1920 followed by another rise. A decreasing difference between summer and winter temperature, especially from 1900 onwards, indicated that the warming was accompanied by decreased continentality. For Iceland, Eythorsson (1949) found a steady rise of annual temperature of about 1.1° C. from approximately 1916-25 to 1926-35, the rise starting earlier in the north than in the south of the country. From long-period temperature records for Helsinki and Oulu, Keranen (1952) concluded that the climate of Finland had become continuously milder during the seventeenth century with a peak warming in the 1930s, but some levelling-off in the 1940s. For Lapland, Blüthgen (1952) found that the mean annual temperature for the period 1935-50 showed a rise of 1° C. over that for the period 1901-30 whilst corresponding means for November and December showed a rise of 3° C. For Norway, the studies of Hesselberg and Birkeland (1956) and Hesselberg and Johannessen (1958) show that there was a rapid rise of temperature at Norwegian stations in 1917-22 especially at Spitsbergen, e.g., 7° C. in winter, 3° C. in spring, 2° C. in summer, 3° C. in autumn, and 4° C. for the whole year. The rise continued after 1922 but at a slower rate (1° C. per year) with a greater increase at Spitsbergen than farther south. The peak of the fluctuation was reached in the 1930s, having been greatest in winter and smallest in summer. In 1941-50 there was a reversal of the trend especially with the cold winters of 1940-42.

There are several other studies on temperature fluctuations in western Europe but the results are rather conflicting. For example, Glasspoole (1955) using 10-year moving averages of temperature for the British Isles found marked differences in curves for England and Wales and for Scotland although on the whole the trends were very similar with an increase of about 0.5° C. in the annual temperature from 1922-31 to 1929-38. For England and Wales he found a steady increase of over 1° C. from 1923-32 to a peak in 1943-52 in spring, a very rapid increase in summer of about 1° C. from 1922-31 to a peak in 1932-41 followed by a decrease, and a steady increase in autumn of nearly 1° C. from 1918-27 to a peak in 1942-51. Whilst the rise in temperature in autumn started earlier than in spring or summer and continued for a longer period, the curves for these three seasons were similar; but the curve for winter was more nearly a mirror image of the others. Thus the winter curve shows a general decrease of over 1° C. from a maximum in 1918-27 to a minimum in 1937-46 which was followed by a rapid increase of over 0.5° C. until 1942-51.

Steinhauser (1960) has demonstrated that during the period 1901-30 the climate of central Europe showed very strong oceanic influence. This is particularly noticeable in a curve given by Steinhauser *et al.* (1957) showing fluctuations in the variance of temperature at Vienna for which a long-period record is available; in the 1870s/80s and from the 1930s/40s onward the variance was approximately twice as much as that in the period in between. Using this long-period record for Vienna and also long-period records for Berlin, De Bilt, Basle and Milan, Steinhauser gives some interesting curves of 5-, 10-, and 30-year running means of annual temperature. Whereas the curves for Basle and Milan run almost parallel, these curves and the remaining curves show little correspondence on the whole; for some years they move together and for others they diverge or converge. It is interesting to note that decadal averages for Vienna which showed a rise in the 1930s were thrown back by the three cold years of 1940-42 but subsequently exceeded all previous values.

E. S. Rubinshtein (1956) in a detailed study of climatic changes in the U.S.S.R. during the 30-40 years up to 1950-55 found a warming trend, most noticeable in the winter months, which culminated in the thirties; but whereas there was a decline from then on over a considerable area, especially the western U.S.S.R., the warming trend continued at high latitudes of the U.S.S.R., e.g., Januaries in the Barents Sea were very warm up to 1950 and high winter temperatures persisted in the estuaries of the rivers Ob, Yenisey and on the Arctic Ocean coast. Rubinshtein also found that the peak warming periods in the eastern regions of the Asiatic territory of the U.S.S.R. were not always concurrent with those in western Siberia and European U.S.S.R. She emphasized, and this is a point made by other workers, that not all years in the period of considerable warming were warm but that there was simply a tendency for warm years to prevail. Commenting on the lack of uniformity in temperature anomalies from one region to another, Rubinshtein gives interesting figures showing isolines of the correlation coefficient between Moscow and different parts of the U.S.S.R., and she draws attention to the fact that the lines are elongated in the direction of the prevailing flow patterns, i.e., along the axis of the Asiatic anticyclone in January and nearly meridional in winter; thus the correlation between Moscow and Barnaul mean monthly temperature is +0.45 in January but —0.55 in May.

In a study of temperature trends in Canada up to 1952, Longley (1953), using 10-year running means, found that in every district with records going back to 1880 the decade of the eighties was cold with a minimum in 1879-80 and that warming occurred immediately thereafter in all districts. But he also found that the variations from about 1900 onwards were by no means the same in all districts and that there were many minor fluctuations varying in space and time. In the eastern parts of the country, the period 1903-26 was marked by a slow fall in temperature in the maritime region and in northern Ontario with only minor but parallel changes in other districts. In the periods 1926-52 there was a general rising tendency, especially from 1926 to 1939, but in many districts there was a reversal between 1939 and 1943; northern Ontario did not participate in the 1926-39 climb but was the only district for which the decade ending in 1952 was not the warmest on record. Longley found that west of Lake Superior 1946-47 saw the end of the very warm decades, and in the succeeding years there was a drop in mean temperature of over 0.5° C. In fact, in Alberta, the decade ending 1951 was the coldest since 1904. Also, stations between Lake Superior and the mountains showed no common trend during the period 1903-1940; a marked rise between 1903 and 1930 in Saskatchewan was in contrast with the apparent trend in neighbouring districts. Longley also mentions that, in addition to the regional differences, some of the changes, e.g., the cooling of northern Ontario between 1903 and 1926, were gradual, but others were abrupt, e.g., the fall in the 1950s in western Canada. A later study by Thomas (1957) of changes in the climate of the province of Ontario, whilst showing a definite and fairly general increase in temperature from the end of the last century onwards, confirms that the warming was not steady and was less common in northern Ontario than in southern Ontario. In an earlier paper Thomas (1955) discussed decadal means of temperature data for the coastal areas of Nova Scotia and Newfoundland. He found a warming trend from about 1890 onwards with the biggest increases in winter and peaks in the early 1930s. Crowe (1958) found similar results for the coast of British Columbia.

For the north-eastern United States of America, Conover (1951) showed a 3.5° F. rise in winter temperatures in the nearly-100-year series from Milton and Blue Hill, Massachusetts. Kincer (1946), using long-period temperature records for a number of stations in the United States, found a general rise with the decade ending 1892, a levelling-off between 1903 and 1920, and then a pronounced rise up to 1940, the temperature for the warmest 10 years (decade ending in late 1930s) being nearly 2° C. higher than for the coldest (decade ending 1875-76). He indicates in his paper that he obtained similar results at Paris and Cape Town up to 1930. Landsberg (1960) from his examination for the two 25-year periods 1906-30 and 1931-55 of monthly, seasonal and annual temperature means from stations in the United States with homogeneous records found that the temperature in most places, but not all, showed significant rises (at the 95 per cent probability level) with winter and summer being the main seasons of the positive trend. The area of greatest rises was found to be situated over the Great Lakes region but the general rise did not occur in the south-west of the United States, and the change was slightly negative for an area in the southern Appalachians.

In a paper on "Climatic Fluctuations in the Middle East during the Period of Instrumental Record" offered to this symposium, N. Rosenan reports that annual temperatures in the Middle East show a minimum in the decades 1890-1910, a rise of 0.5° C. to 1.0° C. in 1900-30 with a maximum in the 1930s, followed by a drop everywhere in the 1940s and a rise at many stations during the 1950s; he mentions that no influence of summer temperature on the trend of annual temperature could be found.

Many papers on climatic fluctuations in the Far East have been written by Japanese workers, especially H. Arakawa, but most of them are based on historical evidence. In studies of the secular change of climate in Japan, Yamamoto (1950, 1951, 1957) found different trends in different seasons in different parts of the country. He indicated, in particular, that whereas decadal means of temperature showed a general rise in summer from 1898 onwards in northern Japan, the winter values showed a reversed parallel tendency in middle and south-western Japan. Fujiwara and Ishiguro (1957) using long-period records for agricultural stations in Hokkaido found a summer and spring rise in average temperature from about 1910 onwards, mostly in July and August, and that the temperature in the 1940-50s was greater than in the previous 30 years.

For India, Pramanik and Jagannathan (1954), in a thorough study of climatic changes back to the last century, found no general tendency for an increase or decrease in maximum or minimum temperature at any station but they indicated that the data for some stations suggested a "cycle" of 30-40 years.

In a paper on changes of climate in North Africa offered to this symposium, Dubief maintains that as far as temperature is concerned there may have been a slight change in that area in the last 50 years, but this is debatable. For South Africa, also in a paper offered to this symposium, Hofmeyr and Schulze, using data going back to the last century, report a significant positive trend in temperature of about 0.03° C. per year at Cape Town and O'okiep during the period 1901-30.

For Jakarta (Indonesia), a long-period temperature record is available and De Boer and Euwe (1949) drew attention to a fluctuating but almost continuous increase in the value of the mean annual temperature from 1866 (25.9° C.) onwards (27.0° C. in 1940)—an increase which could not have been due solely to urbanization as the same trend was found at rural and high-level stations in Indonesia. At about 1921 there was a discontinuity in the temperature rise and Schmidt-Ten Hoopen and Schmidt (1951) who examined mean monthly temperatures for Jakarta showed that this discontinuity was due to a decrease in the values for January to April, beginning about 1910 and reaching a peak in 1921. In fact, these two workers showed that, although there had been an overall warming at Jakarta there was no parallelism in the curves of mean monthly maximum or minimum temperature and they concluded that variations in other elements affected the temperature in different ways.

Using a nearly-50-year series of temperature records, from 1903 to 1950, for the South Orkney Islands, Prohaska (1951) found no one-sided trend although the data indicated some long-periodic fluctuations. In regard to Antarctica, Wexler (1961) contends that in the Little America area (78° S.) there has been a warming of over 0.5° C. between 1912 and 1957 some few miles in from the edge of the ice shelf but that no significant temperature trend has occurred at McMurdo Sound.

Studied in detail, the findings of various workers in respect of temperature fluctuations do not present a simple picture by any means and it is not easy to "marry" the results. Baum and Havens (1956) attempted to do this in an excellent summary of climatic fluctuations in the North Atlantic maritime regions but what appears to be the first attempt to carry out a global study was made by Willett (1950) using records for 50 years or more for over a hundred stations (mostly in the Northern Hemisphere and mostly in temperate latitudes). Willett's aim was to establish global trends of temperature. He found that from about 1885, there was a significantly upward trend—but by no means uniformly so over all parts of the globe. He reported that the trend amounted to an average of over 1° C. in winter mean temperature and about 0.5° C. in the annual temperature; it was most pronounced in the higher middle and polar latitudes of the Northern Hemisphere, but apparently negative in the polar latitudes of the Southern Hemisphere. In particular, Willett drew attention to a winter rise of nearly 4° C. in western Greenland and about 7° C. in Svalbard in the 20-year period centred on 1930.

Lysgaard (1949) in a broad survey of variations during the period of the meteorological record up to 1940 (but also with limited and by no means world-wide coverage) showed that for January the greatest rise of temperature was from 1910 to 1940, amounting to more than 3° C. in Greenland and more than 2° C. at Spitsbergen, in the North Sea and the northern part of North America, the rise on the whole becoming smaller (or even negative) southwards in the Northern Hemisphere, with a suggestion of a fall in parts of the Southern Hemisphere, especially South-East Asia and Australia. For July he found that the greatest rise, more than 1° C., had taken place in Finland, northern Scandinavia and the central parts of Canada and the United States, and that there was an appreciable fall in central Asia and the monsoon districts of southern Asia and also north of New Zealand—but a rise in Australia and South America.

In order to illustrate the essential difference between local and regional fluctuations given by decadal averages and long-period trends over wide areas, Callendar (1958) examined the temperature records for selected stations in Europe and showed that even in a small area the size of the British Isles there was an appreciable lag between the warming in one district and another; for example, whereas 1931-40 was the warmest decade in the extreme north-west, 1943-52 was the warmest decade in the south-east. He also showed that, for 30-year averages, Stykkisholm, West Iceland, had the largest range (over 1° C.) and Vienna the least (about 0.5° C.) whilst in the British Isles the range of the fluctuation increased northwards from about 0.5° C. at Greenwich to 0.6° C. at Aberdeen. However, Callendar agreed that the 1921-50 period gave the highest 30-year average at all stations since before 1880. He also stated that the highest 30-year averages recorded in the nineteenth century at Vienna, Greenwich and Trondheim were not exceeded by a significant amount until those ending about 1930. In view of the known recession of glaciers before 1900, Callendar contended that the picture had been one of slow amelioration of climate, with some setbacks, followed by an acceleration in the three to four decades up to about 1950, but with a hint of levelling out in recent years. He also provided curves comparing decadal averages from 1910 to 1950 for Grimsey, near Iceland, and Laurie Island, South Orkneys, which show that a great oscillation occurred in the late 1920s between the far north and south of the Atlantic Ocean amounting to over 2° C. from 1927 to 1930; he put forward the view that, especially as the glaciers of south Georgia appear to have retreated less than those from the Hielo Continental (50° S.), an overall flatness shown by the Laurie curve might be due to the strongly thermostatic control of melting pack ice in southern latitudes. He went on to suggest that the "present climatic fluctuation" had so far failed to penetrate the thermal barrier of melting pack ice which protects the great southern ice cap. In regard to the question whether the warming is in fact now on the wane, Callendar (1960) has pointed out that in the three years 1957-59 warm summers in Europe have caused increasing recession of Alpine and Scandinavian glaciers which had previously showed a tendency to slow down.

He also mentions that the warm summers of 1954-57 and 1959 caused a severe recession of the glaciers in New Zealand, that in Japan the 10 years 1948-57 were warmer than any decade since before 1880, and that in the Canadian prairies and the adjacent plains of the United States mean temperatures which were down in 1945-46 were more than 0.5° C. above the 1901-30 average in 1952-58 and as much as 1° C. above in eastern Canada and north-eastern United States. Callendar therefore contends that temperatures have still been increasing in many regions although there has been a tendency since 1948 in the sub-Artic for some temperatures to fall. In yet another paper, Callendar (1961) using a debatable method of combining on a regional basis the annual temperature deviations for a number of stations to give integrated values over large areas and zones, expresses the view that the rising trend in recent decades is significant from the Arctic to about 45° S. but quite small in most regions below 35° N. and "is not yet apparent in some".

Although Mitchell (1961) who followed up, and on the same lines, the work of Willett (1950), used a rather different selection of data and a different method of analysis from those used by Callendar (1961), their findings are in fairly good agreement, except for the south temperate zone, as will be seen in Table 1 prepared by Landsberg and Mitchell (1961).

TABLE 1. Thirty-year change of annual mean temperature

Callendar [1]		Willett-Mitchell [2]	
Latitude limits	°C.	Latitude limits	°C.
60° N.-25° N.	0.39	60° N.-20° N.	0.32
25° N.-25° S.	0.17	30° N.-30° S.	0.19
25° N.-50° S.	0.14	20° N.-50° S. 20° N.-60° S.	0.06
60° N.-50° S.	0.23	60° N.-60° S. 80° N.-60° S.	0.21 0.27

1. 1921-50 minus 1891-1920.
2. 1920-49 minus 1890-1919.

In regard to the discrepancy for the south temperate zone (which is not surprising in view of the poor network of stations and the few long-period records in that zone) Callendar considers that for 25-50° S. a better figure would be 0.10 based on the period 1921-50 minus 1901-30, a value which is in closer agreement with that obtained by Mitchell. Landsberg and Mitchell also agree with Callendar that urbanization has probably had little effect on the computed global trends. In a more recent global study on secular change to be given in a paper by Mitchell at this symposium there is some confirmation that the "world-wide" warming trend of earlier decades was apparently reversed in the 1940s although temperatures have continued to rise in some places. Mitchell suggests that the temperatures, when averaged for Northern and Southern Hemispheres, have apparently varied in parallel but he also points out that world average trends are not representative of most geographical regions. In particular, he mentions that regions of most rapid warming prior to 1940 tend to coincide with regions of most rapid cooling since 1940.

In trying to fit all the many bits of evidence together, one can hardly avoid the conclusion that during the period of the instrumental record there has in fact been a fairly general if not an overall warming—at least up to the 1940s. It would appear that this was slow and irregular at first but became more rapid later reaching a peak somewhere in the 1930s-40s. There can be no doubt that the rise has not been uniform or symmetrical in respect to the Pole; it has been least or nil in middle latitudes of the Southern Hemisphere and greatest in high latitudes of the Northern Hemisphere, especially in areas bordering the Atlantic Ocean. It also appears that the rise of temperature in some areas has lagged behind the rise in others; in fact, for a time at any rate, the fluctuations in some places have been opposed to those in others. Moreover, the warming has embraced short-period variations, and might only be part of a much larger period fluctuation covering perhaps some hundred years.

It may be useful to mention that in an unpublished paper, Knud Frydendahl, after a critical study of the threshold values from two comprehensive networks of different types of sunshine recorders, finds world-wide long-range variations in solar intensity, including an abrupt rise in the years close to 1920.

Sea temperature and ice cover

As climatic changes must be linked to variations in the heat balance of the sea-land-air system as a whole, there can be little doubt that fluctuations in the atmosphere must be associated with fluctuations in the oceans. Indeed, as a secular heat reservoir the sea may play an important role and Rossby (1959) has suggested that anomalies in heat can probably be stored and temporarily isolated in the deep sea and, after periods of the order of a few decades to a few centuries (the time required for a whole thermo-haline cycle), may again influence the heat and water-vapour exchange with the atmosphere. It is appropriate therefore to include in this review some mention of ocean climatological studies.

In the now famous paper of Ahlmann (1948), evidence of all kinds, meteorological, glaciological, oceanographical and biological, is produced to support the finding of a climatic amelioration during the previous 100-150 years. In particular, Ahlmann found that the temperature of the northernmost Atlantic had increased since the beginning of the century, perhaps to a considerable depth, and that the salinity of the water had also increased indicating a more southerly origin of the water. He also drew attention to a decrease of over

100 cm. in the thickness of the ice forming annually in the Polar Sea and in the extent of drift ice in Arctic waters (e.g., a reduction of 1 million square kilometres in the Russian sector between 1924 and 1944) enabling coal to be shifted from Spitsbergen for seven months per year as against three at the beginning of the century and the north coast of Europe and Asia to be quite free of ice at times. Ahlmann's findings in regard to ice-cover were amplified in a comprehensive study by Maksimov (1954) which confirmed a marked decrease in ice-cover in the northern North Atlantic from about 1890 to the 1940s. Also, Lamb and Johnson (1959) from their examination of all the available data on Arctic ice reported a long period of minimum amount in the north Atlantic from about 1920 to the late 1940s followed by increases in the 1950s. However, it may be noted here that, according to a footnote in a paper by Schell (1956) on the interrelations of Arctic ice with the atmosphere and ocean, for long period variations there is a tendency for ice in the North Pacific Arctic to vary in an opposite sense to that in the North Atlantic Arctic : in the latter area the average ice limit decreased by 18 per cent from 1910 to 1939 but apparently increased by 22 per cent in the former area in the same period.

Brown (1953), compared ships' observations of air and sea temperature in the area between latitudes 60° and 70° N. and longitudes 25° W. to 15° E. (i.e., between Iceland and Norway) for the decades 1910-19 and 1940-49. He found that, whereas the air temperature data showed a general rise of 1°-2° C. in all months, the sea-surface temperature data showed a more complicated picture ; there was a rise of about 2° C. southward of Iceland, about 1° C. along the Norwegian coast but only about 0.3° C. between 0° and 5° W.

Later, Bjerknes (1959), using more extensive information [including the analysis by Riehl (1956) of ships' reports received by the United States Weather Bureau and the historical data as summarized by Smed (1952)], showed that a maximum rate of rise of sea-surface temperature was to be found from the 1890s to the present along the Gulf Stream from Cape Hatteras to the edges of the Newfoundland Banks ; a belt from Ireland to the edge of Labrador was not warmed up during the same period but north of that belt there was a warming concurrent with the climatic amelioration in Greenland, Iceland and Scandinavia. Bjerknes put forward the view that most of the observed secular changes in ocean temperature south of 50° N. could have been caused in part by increasing wind drag which had speeded up the Antilles current and the Gulf Stream and possibly also by an increasing thickness of the warm surface layer in the areas of increasing anticyclonic wind drag. He also suggested that between 50° N. and 57° N. a corresponding surface cooling, connected with the thinning out of the surface layer by increasing cyclonic wind drag, assisted partly by increasing cold winds from North America, must have been strong enough to overcompensate the advective warming in the belt from Ireland to the edge of the Labrador current. Bjerknes added that the sea-surface temperature data which have become available after the break due to the second world war indicate a culmination in the warming near Greenland in the early 1930s, whilst from Iceland to the British Isles the maximum seemed to have occurred in the early 1940s. (See also reference to another paper by Bjerknes (1960), in the section dealing with pressure patterns and winds.)

Riehl (1956) in a search for correlations between sea-surface temperature anomalies and the incidence of hurricanes did not obtain as fruitful results as might be expected from his contention that these storms depend greatly for their maintenance on local heat transfer from ocean to atmosphere. However, he did find fairly good correlation between sea temperature and hurricane tracks and produced diagrams to show how the location of the tracks had changed since the beginning of the century ; in 1909-20 during an alleged cooling in tropical sea temperatures the tracks migrated westwards of 80° W. but in a subsequent, warming period, especially after 1925, the tracks returned to the eastward of 80° W. There was also a change in the recurvature longitude and Riehl suggested that the displacements reflected displacements of the Azores-Bermuda high and could therefore be interpreted as due to changes in the general circulations.

Several studies on the variation of sea-surface temperatures, as observed by ocean weather ships, have been published by Rodewald. In his 1956 paper he provided a map which showed that the warming of the waters of the Gulf Stream at weather ship D had reached +1.5° C. but that little warming had taken place just north of 50° N. at weather ships C and J. (The map also suggested a system of anomalies in the North Pacific analogous to those in the North Atlantic.) In a paper offered to this symposium Rodewald reports the results of a more recent examination of the ocean weather ship observations and some supplementary data. Whilst he finds that the decade 1951-60 was, relatively, a rather warm one, he indicates that the trend within the decade was that of a distinct cooling. He also shows that the decadal trend from 1951 to 1960 was by no means uniform—the trend in the north-eastern North Atlantic being opposite to that in the west and south. In another paper offered to this symposium, the results of studies of long-term variation in sea-surface temperature (and other elements) in the Bay of Bengal and the Arabian Sea were reported by Rao and Jagannathan ; they state that there does not seem to have been any significant systematic increase or decrease during the past 60 years although there is a suggestion of long-period oscillations.

Perhaps all that need be said in concluding this section is that by and large it would seem that changes in the wind régimes could account for the changes in sea-surface temperature.

PRECIPITATION

It is much more difficult to obtain a coherent picture of rainfall fluctuations on a global or even a regional basis than it is for temperature fluctuations. Long-term trends are lost in short-term variations and the consistently greater predominance of year-to-year variability over much smaller climatic fluctuations makes it imperative to test the reality of any alleged fluctuation—and many workers fail to do this. However the method of plotting cumulative deviations from the mean [as used by Kraus (1955) and others] seems to yield valuable results and power-spectrum analysis [e.g., as used by Landsberg *et al.* (1959)] may prove to be most helpful now that electronic computers can be used. Some of the studies of long-period rainfall records (rarely homogeneous) are discussed in the following paragraphs.

In his study of recent climatic fluctuations, Lysgaard (1949) reported that the rainfall variation during the period 1910-40 showed positive anomalies for the Arctic and the north temperate zone, in Mexico, at La Plata, in southern India and south-west Asia (with a maximum in the Philippines) but negative anomalies over the greater part of the United States, the north of South America, Africa (with a maximum in west Africa), Malaya and Australia. However, he pointed out that overlapping curves of 30-year annual means showed little resemblance. For Greenland, Diamond (1958) found that there had been a decreasing trend since 1920 with the biggest negative anomaly from 1932 onwards. No comprehensive study of secular variations appears to be available for the whole of Canada but the studies of Thomas (1955) for the Atlantic coast and of Kendal and Thomas (1956) for the prairie provinces indicate that there was a trend towards small annual amounts in some areas, e.g., southern Ontario, in the last few decades, but that, taking into account the variations in precipitation from year to year, there had been no significant tendency as in the case of temperature. However, according to Kimble (1950) there have been changes in the precipitation régime in North America. He says that there was a decline in the first half of this century and gives, as an example, a fall from 22.12 inches in the 1900s to 19.80 inches in the 1940s in the winter rainfall amount at Montreal and a decrease in the expectation of snowfall to 80 inches from 130 inches or so in the 1880s. Dingle (1955) in a study of the change of precipitation patterns over the United States in the past 60 years did not find any noticeable one-sided trend in any part of the country and Landsberg (1960) also found no significant rainfall changes in the United States.

For Europe the evidence is conflicting. The continental studies of Steinhauser (1960), Péczely (1953) and Russian workers, the regional study of Carapiperis (1960) for the Mediterranean region and the many local studies such as those by Dammann (e.g., 1957 and 1959) for Germany, Lysgaard (1954) for Denmark, Glasspoole (1957) for the British Isles, etc., all indicate different trends in different months and seasons and in different areas. For example, Glasspoole (1957) found some striking difference between curves of 10-year moving averages of rainfall in (*a*) England and Wales and (*b*) in Scotland, although the trends were rather similar. The curves for England and Wales showed maxima in 1874-83 and 1923-32 and a minimum in 1893-1902 whilst those for Scotland showed maxima in 1871-80 and 1923-32 with a minimum in 1885-94. As in the case of temperature fluctuations over the British Isles, the winter trends were found to be quite different from those of other seasons. One interesting finding of Glasspoole (1957) from a study of the variation in the number of rain days (which he found to be largely similar to the variation of rainfall amount) was that curves of 10-year running average of the mean amount of rain per rain day showed a remarkable increase in spring over England and Wales from 1921-30 onwards and in Scotland from 1934-45 onwards. The curve for spring corresponded closely with the corresponding temperature curve. In a paper by Berg (1943) it is indicated that during the first half of the century there was a sharp fall in the level of the Caspian Sea due to a decrease of precipitation and similar falls in the basins of the Danube, Don and Dnieper. In fact, most of the European studies on rainfall fluctuations indicate discontinuities around 1885-95.

Neumann (1960), using a "homotopic" series of annual rainfall amounts for Jerusalem ingeniously devised by Rosenan (1955) plus records and historical evidence of Dead Sea levels, came to the conclusion that there is a close parallelism between rainfall fluctuations in Palestine and the middle latitudes of the Northern Hemisphere. In a list of climatic fluctuations in Palestine since 1750, Neumann indicates a marked rise in rainfall from 1870 to a high level in 1890, then a rather sharp fall until about 1920 and finally, in 1920-50, a fall of 10 per cent below the average for 1846-1958, i.e., about 20 per cent below the level of the closing decades of the nineteenth century. Rosenan, in his paper for this symposium, states that the precipitation trends in Palestine were opposite to those of temperature. He mentions that there was a maximum of precipitation at most places in the Middle East during the 1890s, a minimum during the 1920s and 1930s followed by a rise almost everywhere in the 1940s and then a fall (with record minima at some stations) in the 1950s. Rosenan adds that, with the exception of the last decade, Middle East trends of rainfall (and temperature) were similar to those in Athens and Rome.

Arakawa (1956*a*, *b*) found that in Japan the average annual amount of precipitation decreased at about the turn of the century and again at about 1940; as river gauge readings at Hankow (China) and rainfall data for Seoul (Korea), showed a similar minimum at the turn of the century, he concluded that the variation in rainfall in Japan was paralleled in the Far East.

In a paper offered to this symposium by K. N. Rao relating to trends in rainfall of the arid and semi-arid zones of India, the main conclusion is that there has been no statistically significant change in either the annual or the seasonal rainfall of these areas during the past 80 years. This confirms the findings of Pramanik and Jagannathan (1954) but these workers did suggest a tendency for deficient rainfall near the hills in north and north-east India to become more frequent and also a general tendency for rainfall in excess of the mean to be more frequent in the case of south-west monsoon rainfall (altough some places have shown a tendency for rainfall to decrease). In a study of 100 years' rainfall data for Karachi Naqvi (1958) suggested that a line drawn through "normal" values for the periods ending 1886, 1890, 1900, 1910, 1920 and 1940 indicated a rising trend—but he did not claim that this was significant. He did maintain, however, that the data revealed a 50-year cycle (with an amplitude of about 1 ½ inches) and that there was no reason to doubt its validity.

In the paper by Dubief, referred to earlier, the author indicates that there is no evidence that rainfall at Algiers has been subject to a secular variation during the last 120 years but he mentions that precipitation data for stations in the northern Sahara (and also Tripoli, Benghazi and Alexandria) suggest a maximum about 1884-96 which has not been reproduced since. He also points out that there appears to be an inverse relationship between rainfall in the littoral and rainfall in the driest areas of North Africa.

Schwerdtfeger and Vasino (1954) in a study of rainfall changes in Argentina indicated that the annual precipitation in the north-eastern part of the country was 35 per cent greater in 1941-50 than in 1902-11 but Prohaska (1951) found no well-defined trend in the rainfall in the South Orkney Islands.

In the paper by Hofmeyr and Schulze referred to earlier, it is stated that there was a significant negative trend in rainfall at Cape Town during the period 1901-30. For the Indonesian Archipelago, F. H. Schmidt (1951) states that available data indicate opposed variations in the rainfall amounts occurring in the north and south of the area—a minimum at the southern stations and a maximum at the northern stations occurring in or about 1925. Schmidt attributes the anomalies to anomalous oscillations in the intertropical convergence zone.

Some of the most interesting studies of rainfall fluctuations, chiefly for tropical regions, have been made by Kraus (1954, 1955*a*, 1955*b*, 1958). In his 1954 paper he reports on a study of secular changes in the rainfall régime of south-west Australia. He shows from an analysis of a long series of rainfall observations from Victoria and New South Wales that there was a decrease of summer rainfall to a maximum about the turn of the century and then a gradual increase for 50 years; winter rainfall trends were opposite. Kraus found that fluctuations of a much larger amplitude affected the rainfall régime of autumn and spring, suggesting the possibility of a discontinuous change of climatic development about the turn of the century. In his paper on secular changes of tropical rainfall régimes (1955*a*) he again reports that tropical rainfall decreased abruptly at the end of the nineteenth century and suggests this was largely due to a contraction of the rainy belt and a shortening of the wet seasons. Kraus (1955*b*) also found that the Australian and North American east coasts, up to a latitude of about 45°, exhibited the same pattern of change in the precipitation régime as in the tropics and he indicated that, in the terms of seasons, the change was largest in autumn and summer for North America and in autumn and spring for Australia. Kraus contends that there is little evidence of any world-wide fluctuations in the rainfall régime north of 40° N. and points out that the recent return to somewhat wetter conditions in the tropics has been associated in eastern Australia and in eastern North America with an increased incidence of tropical cyclones. For the Australian coast this has been demonstrated by Brunt and Hogan (1956) who found a noticeable increase in the last 15 years and for the American coast by Rodewald (1958).

In an interesting summary of his work on climatic changes (as revealed by meteorological records), Kraus (1958) contends that such changes have been most apparent along the shifting boundaries of climatic zones. He points out that during the past few hundred years, the boundaries of the Alpine and sub-Arctic regions have experienced some striking changes in glaciation and that there have been considerable variations in extent and seasonal duration of sea ice; and he contends that, from the analysis of rainfall and stream-flow records, it has now been established that fluctuations of corresponding or even larger amplitude occurred in the sub-tropics at the boundaries of the arid zone. His findings indicate that precipitation in the sub-tropics was generally above the 1881-1940 mean during the recorded part of the nineteenth century and that the dry period (involving changes of long-term means amounting to some 30 per cent more) which set in rather abruptly at the end of the century was accompanied by a widening of the arid belts. He quotes as an example a difference of 84 per cent in the rainfall at Aden before and after 1894. Kraus points out that in climatologically corresponding locations the changes occurred simultaneously north and south of the Equator but adds that during the same time, the climates of the Antarctic ice cap, the central Sahara and the Amazon rain forest do not appear to have altered a great deal.

Certainly, as far as global fluctuations of rainfall are concerned, there is little to add to the findings of Kraus. From his studies and the various papers referred to above, it does seem that something happened about the end of the last century to affect not only the temperature régime but the rainfall régime also, i.e., the rainfall evidence supports the temperature evidence for the existence of a fluctuation within the last hundred years or so which now appears to be on the wane or reversing.

PRESSURE, PRESSURE PATTERNS AND WINDS

In the Foreword of this paper, reference was made to the need for using the dynamic approach to the study of climatic fluctuations, i.e., for interpreting variations in temperature, rainfall, etc., in terms of air motion. Many workers have in fact attempted this but largely with the aid of wind and pressure data for the surface only. This is understandable inasmuch as reliable and adequate long-period upper-air observations are not yet available. However, findings based on surface data only may be misleading. Considerable progress has already been made in determining the climatology of the upper air and although comparatively little is yet known about the middle or upper stratosphere there is now no doubt that there are varying flow patterns and "preferred" types of circulation in the upper layers of the atmosphere as well as in the lower layers. Moreover, there is an increasing belief that winds in the higher atmosphere and in the lower atmosphere may be inter-linked. Already there is some evidence of secular variations and "trends" or "fluctuations" in the upper air as indicated in the papers by Veryard and Ebdon (1960, 1961) and others. As more upper-air data become available it may be possible to identify the "upper-air aspects" of climatic fluctuations and to present a three-dimensional picture of such fluctuations—in terms of variations in the so-called general circulation. The writer uses the expression "so-called" deliberately because the same difficulty in defining a "normal" or average circulation applies in respect of the general circulation as in respect of temperature, rainfall, etc.; still more so, in fact, because information regarding the three-dimensional behaviour of the general circulation is available for a much shorter period and is less complete. Meanwhile, we can survey the various findings in respect of pressure pattern and wind variations during the period of the meteorological record.

In an early study, Scherhag (1936) examined the changes of pressure patterns during the preceding 25 years and came to the conclusion that there had been an intensification of the well-known "centres of action", both highs and lows. Shortly afterwards, Ångström (1939) attributed the warming and smaller annual temperature variations in high latitudes to an "increased circulation".

Ahlmann (1948) and other earlier workers were quite convinced that the shrinkage of the glaciers in Scandinavia during the warming period referred to earlier was mainly due to increased advection of warm air and he produced data to show that there had been a strengthening of west to south-west winds. Later, Hesselberg and Johannessen (1958) demonstrated that Spitsbergen, where the recorded temperature rise was greatest (7° C. in the winter, from 1917 to 1922) and which formerly was generally north of the depression track, had been visited more frequently by depressions bringing more west to south-west winds; they pointed out that the cyclonic winds swept away the cold-surface layers that are produced by outgoing radiation in cold calm weather.

Brier (1947), from an examination of the *Historical Northern Hemisphere Daily Weather Maps*, considered that between 1899 and 1939 there had been an appreciable decrease in the total mass of air over the Northern Hemisphere, especially in high latitudes. Incidentally, he pointed out that the relation between "zonal index" and temperature trend is not a linear one.

Lysgaard (1949) found that in the period 1910-40 the pressure in January had become lower over the northern part of the North Atlantic but higher in the southern part (where the Azores anticyclone had become noticeably more intense and more extended) and that the Siberian anticyclone had also intensified. He also indicated that, in winter, pressure had become higher overland but lower over the oceans in the north temperate zone but vice versa in south temperate and subtropical zones. For summer, Lysgaard found a considerable decrease of pressure over western Europe, central Asia and southern Australia but an increase over the Atlantic Ocean between west Africa and North America, over the Rocky Mountains, La Plata, New Zealand and Japan. From a consideration of pressure gradients he deduced that in January there had been an increase of south-easterly air flow over the area around the North Sea and the Baltic plus a strengthening westerly wind over western Europe and south Scandinavia from the turn of the century up to about 1935 (when there was an abrupt decrease) and also a strong north-easterly trade wind up to about 1939. Lysgaard postulated a significant increase in the winter transport of Atlantic air masses to Europe during the warming period.

Pettersen (1949) pointed out that any systematic increase of air from more southerly latitudes in one area must be compensated by advection in an opposite direction elsewhere (unless an accumulation of air is to result in the Arctic) but that, as winter temperature had increased in regions where the winds were predominantly northerly as well as southerly, the changes in the general circulation accompanying the warming must have been complex. Using the *Historical Daily Weather Maps*, he determined values for net, zonal, total and meridional transport, and meridional exchange, and concluded that the recent climatic variation must have been due to changes in intensity of heat sources and sinks which had led to: (*a*) some reduction of zonal circulation and an intensification of meridional circulation; (*b*) an increase in cyclonic activity and in meridional exchange in the Newfoundland-western North Atlantic area and also in the Mediterranean-Balkan area; and (*c*) an increase in the northward transport of air from eastern Central Europe towards Scandinavia and from eastern North Atlantic towards Iceland and the Norwegian Sea, together with an overweight of net northerly advection within the Atlantic sector compensated by southward transport from the Arctic in other longitudes.

Petterssen put forward the argument that, if the warming had been associated with an increased supply of heat to the atmosphere as a whole, one would expect an increase in the temperature gradient from the Equator to the Poles—but at the surface the reverse had been the case. Hence an opposite change in upper layers was to be expected. He added that an analysis of rainfall in Scandinavia suggested a general increase during the warming period and therefore an increase in the vertical temperature gradient.

In a paper following up his earlier work, Scherhag (1950) suggested that the increase which had been found in the general circulation reached a peak in 1921-30 and had fallen off in 1931-40 but that, in spite of this, the temperature rise was apparently still going on in many areas.

In a study of the variability of summer temperatures in Sweden, Wallén (1953) by calculating moving standard deviations and by examining the frequency fluctuations of different pressure patterns over southern Scandinavia, found that the rise of summer temperature had been connected with a definite decrease in the frequency of north meridional situations and an increase of south and warm meridional cases as well as of zonal situations; high variability appeared to be connected with meridional circulations and low variability with zonal circulations. Wallén also put forward the view that strong zonal flow and meridional flow can exist simultaneously and that, as it appeared that atmospheric circulation had definitely increased in the preceding years, blocking action must be a manifestation of this increased general circulation causing an intensified exchange of air between low and high latitudes. He suggests that blocking action is favoured by very strong westerly flow upstream.

Mather (1954) compared the positions of the Northern Hemisphere pressure systems during 1901-30 with those in 1931-40 and found that the latter period showed quite a different pattern from that for the earlier one. He pointed out that the Icelandic and Aleutian lows moved 5°-10° in longitude to the east whilst the Siberian high moved a similar distance to the west and that fluctuations of opposite sign occurred in temperature and precipitation in various segments of the hemisphere concurrent with changes in "blocking". Mather thus showed that there could be synchronous interdependent climatic changes but with different signs in different areas.

Fay (1958) in a study of long-period temperature records at Edinburgh, Copenhagen, Berlin, Wilno and Vienna produced curves which showed appreciable differences between one month and another and between one station and another and he attempted to depict the mean circulation patterns associated with the observed temperature fluctuations. He concluded that during the period under study there had been an increasing gradient together with a southerly shift of the mean Azores-European ridge and a shift of the westerlies to the north.

In an interesting study by Bjerknes (1958) estimates are given of the relative importance of variations in different "limbs" of the general circulation in relation to climatic fluctuations. In particular, he examined ships' wind observations for the two periods 1906-13 and 1922-27 for latitudes 1°, 7°, 19° and 25°, and computed values of the meridional and zonal components of the trade winds for each period. From these data and from an analysis of the implications for meridional heat flux represented by a time change in the trade winds, Bjerknes concluded that there was an intensification of meridional eddy flux of heat in middle latitudes concurrently with an intensification of the Hadley circulation. He contended that only if the eddy flux of heat increased could one understand the warming which had taken place in northern climates with a maximum amplitude in the Arctic.

Another interesting paper on climatic variation and observed changes in the general circulation is by Lamb and Johnson (1959). Using every bit of data they could get hold of they were able to amplify the findings in previous pressure pattern studies by constructing monthly mean m.s.l. pressure maps for January and July covering as much of the world as possible back to the earliest years for which data could be found. The discussion in their paper relates mainly to the January charts from 1760 onwards. Their findings showed that the air motion at the surface waxes and wanes from time to time and from one area to another. In particular, they found that the circulation intensity in January increased over many areas of the world from about 1800 to a maximum around the 1920s and 1930s. This trend was most apparent over the North Atlantic where the intensification was most pronounced from the 1880s to 1920s. No relationship could be found between the prevailing intensity of the air motion and the latitudes of the main pressure systems and much variety was noted in the forms taken by both strong and weak "circulations" in different years and decades.

In a more recent paper, Bjerknes (1960) draws attention to the fact that by far the greater part of the solar energy for the maintenance of the atmospheric circulation is received by way of the oceans. He examined ships' reports of sea temperature for the two eight-year periods 1890-97 and 1926-33 and found the salient long-trend feature to be a warming along the jet-stream part of the Gulf Stream near North America with a maximum value of +2° C. or so south of Newfoundland. Comparing this trend with the corresponding trend in atmospheric pressure he was able to show that an intensification of the subtropical high meant increasing trade winds, increasing westerlies as far as 55° N., and also some increase of the southerly wind component off the coast of North America—all leading to a strengthening of the Gulf Stream. A zone roughly between 50° and 60° N. showed a net temperature fall, with a maximum intensity east of 30° W.—yet the water advection there comes directly from the Gulf Stream. But the pressure change for the same area showed a net increase in cyclonic wind stress and Bjerknes suggested this may have caused increasing upwelling and hence a cooling of the sea surface. Bjerknes went on to discuss the nature and annual heat cycle of the oceanic Iceland "cyclone" with its upper cold core vortex, which is in direct heat exchange with the atmosphere. From an examination of the historical sea temperature record for the eastern North Atlantic, and using the pressure values at Vestmannaeyjar off the south-west coast of Iceland to give an indication of the year-by-year fluctuations in vorticity of wind stress of the Iceland low, he found that the sea temperature and the vorticity had a long-range trend in common—a slow decrease from the 1890s to about 1920 and a joint, relatively quick upward trend until the early 1930s. Bjerknes concluded that a deepening Iceland cyclone (increasing cyclonic wind stress) is associated with a cooling of the ocean surface and vice versa, with the ocean changes a couple of years behind the smoothed atmospheric changes. This assigned the primary role to the atmosphere with the ocean following the lead. Bjerknes concluded with a discussion of the mechanism of the long-range trends operating in both atmosphere and ocean (with, apparently, a two to three years lag of the latter) and pointed to the need for studying the feed-back effects.

A considerable number of papers on the relationship between climatic fluctuation and changes in the general circulation have been published by Russian workers and because of translation difficulties the writer may have overlooked some of the more important contributions. An interesting paper by A. A. Girs was read at a conference in New York, in January 1961, on Solar Variations, Climatic Change and Related Geophysical Problems, organized by the New York Academy of Science and the American Meteorological Society. Using the Russian system of classifying pressure patterns into three main types (westerly, easterly and meridional, as applied to Eurasia) he gave figures to show a predominance of the westerly régime in 1900-29, of the easterly régime in 1930-39 and 1949-57, and of the meridional régime in 1940-48—with a combined westerly and meridional régime in 1891-99. Girs pointed out that the easterly régime is associated with considerable southerly advection towards Spitsbergen and probably led in the 1930s to the remarkable warming of the European sector of the Arctic. He also expressed the view that the warming in the Arctic had now been replaced by a cooling trend. Belinsky (1957), in a paper which discusses the use of some properties of atmospheric processes in long-range forecasting, suggested that the warming since 1910 had been accompanied by an increased circulation leading not only to greater cyclonic activity over the oceans, but also greater anticyclonic activity over the continents. He also considered that there had been a marked decrease in the quantity of air over the Northern Hemisphere in recent decades, especially in 1930-39, and that after 1930 there was less exchange of air between the two hemispheres and that this was linked with a decrease in rainfall during 1930-40 in the equatorial zone and the Indian and Pacific Oceans.

In an earlier paper Vitels (1948) showed that cyclonic activity north of the Arctic Circle over an area from the Kola peninsula to 100° E. was generally 40-55 per cent higher during the period 1920-39 than from 1900 to 1919. This increase in cyclonic activity (from December to February) amounted to 50-70 per cent east of the Ob river and to 70 per cent or more over Taymyr.

Tsuchiya (1959) examined changes in the surface pressure pattern over the Northern Hemisphere during 1901-40 with special reference to the Far East and concluded that whilst the winter anticyclone over Eurasia had intensified the monsoon low had deepened. Yamamoto (1958) attempted to relate the secular variations in Europe, America and the Far East with variations of the Pacific anticyclone and suggested some relationship with the subtropical jet stream. His line of argument is not easy to follow but his plea for a study of secular changes of the jet stream is certainly justified.

Few studies of fluctuations in pressure patterns are available for the Southern Hemisphere. Loewe *et al.* (1952) compared an early series of wind observations taken between 1856 and 1859 on Heard Island with data collected in 1949-51 and found a change in the mean vector wind from 310° to 258°; a similar change was found by comparing older with more recent ships' observations taken between latitudes 40°-50° S. and longitudes 60°-100° E. Deacon (1953) in a study of fluctuations in temperature, pressure and rainfall in Australia for the period 1880-1950 suggested that the mean track of anticyclones in that area tended to be more southerly in the latter half of the period than in the former. Lamb and Johnson (1959) found that the axis of the subtropical high in the Southern Hemisphere was well south before 1895 and consistently well north in 1922-40. But de Lisle (1947) in a study of seasonal pressure patterns in and near New Zealand reported an irregular southward movement of the mean subtropical high and of the mean westerly belt from about 1918 to the mid-1930s.

In his several studies of climatic fluctuations Kraus (1954, 1955*a*, *b*, 1956) made a special effort to interpret the findings in respect of rainfall and temperature in terms of atmospheric motion. For example, he found that the winter rainfall of southern New South Wales is positively correlated with the mean strength of the westerlies at 300 mb. and that the correlation in summer is negative. From this he concluded that changes of the rainfall régime in south-east Australia (see earlier under "Precipitation") were associated with an increase of intensity of the upper westerlies to a maximum at about 1900 and a following decrease. He pointed out that during the period of maximum mean westerly flow the formation of east coast cyclones in autumn and spring may have been inhibited and the monsoon rains of tropical Queensland were below normal. Kraus also found that a secular decrease of mean summer pressure in northern India was associated with an increase of winter pressure and that similar pressure changes, with an even larger seasonal amplitude, occurred throughout eastern Europe, Siberia and eastern Asia. He also suggested that a secular increase in the seasonal pressure oscillation over the interior of Eurasia may have been associated with variations in the wind field leading to colder winters in the Far East and warmer and shorter winters in Europe—with an opposite tendency in summer. In fact, Kraus reached the conclusion that it was an intensification of the "standing" circulation of the Northern Hemisphere which caused an increased transport of air into the Arctic and thus contributed to the retreat of the Arctic ice, and that the absence of large-scale "standing" oscillations in the Southern Hemisphere probably accounts for the apparent absence of marked climatic change in the Antarctic; also, as the strength of the standing monsoon-type circulations appears to be in roughly inverse relation to the strength of the zonal circulation, the resulting interaction could cause a large amplification of small disturbances in the climatic equilibrium. In a later paper Kraus (1958) gives a summary of his ideas and puts forward a theoretical explanation for the causes of the climatic fluctuations which long-period records have revealed but this will doubtless be discussed in Session III of this symposium.

To sum up, it appears that since the turn of the century until recently there has been an increase in atmospheric activity, greater exchange of air between Equator and Poles and greater turbulence; in other words, an increase in the circulation of the atmosphere accompanied by some strengthening of the zonal circulation and an increase, or perhaps a shift in the preferred location, of blocking action leading to increased cyclonic activity over the oceans and a rise in anticyclonic activity over the continent plus, perhaps, some modification or shift in the exchange of air between the two hemispheres. The change has been irregular in its progress, apparently with phase-lags in different regions, and it has been more effective (at least as far as temperature is concerned) in high latitudes than in low and in the Northern than in the Southern Hemisphere.

COMMENTS

In spite of the fact that the many studies of climatic fluctuation during the period of the meteorological record are based on different material (some of doubtful value), different periods and different methods, it is possible to draw certain tentative conclusions. There seems little doubt that, from the end of the last century to date, there have been significant changes in temperature, rainfall and flow patterns as summed up at the end of each of the relevant paragraphs. It certainly seems reasonable to argue that the retreat of the glaciers and decrease of ice in the Arctic can be attributed to higher air temperatures and stronger penetration of warm Atlantic waters into high latitudes associated with increased trade winds. Indeed, it is possible to account for the whole geographic distribution of temperature and rainfall changes (apart, of course, from small-scale and local changes due to urbanization, afforestation, overcropping, irrigation, etc.) in terms of changes in the general circulation. But the findings indicate that the primary effect of causative factor(s) may be hidden or quite distorted by the resulting effects brought about by the modifications of the general circulation and through the distribution of land and sea. But what were the causative factors leading to these changes (which seem to have occurred at other times in the historical period) ? Maybe the atmosphere has had the inherent ability (or instability) with its non-linear processes to bring about such changes itself—perhaps, let us say, on account of the oceans' capacity to store heat, or albedo effects. It could certainly be argued that the thermal damping influence of the vast mass of water in high southern latitudes may partly explain the minimum rise of temperature in the south temperate zone. Or were the changes due to some fluctuation in solar activity, to an increase of carbon dioxide, or due to a fall-out of volcanic dust ? Perhaps they were part of a bigger rhythm or the result of several short-period or long-period fluctuations operating by chance in the same direction ? These are questions which will doubtless be discussed in Session III of the symposium.

Even relatively small-scale fluctuations may have important effects, especially in "fringe" areas (and the 0° C. threshold is a vital one for human activities). In view, therefore, of the economic significance of changes of climate (a matter which is to be discussed in Session IV of the symposium) it is highly desirable that every effort and every care should be taken in the future to study such fluctuations in detail—especially with a view to such studies yielding, perhaps, the means to make long-period forecasts. It is hoped that this symposium will help to point the way.

APERÇU DES ÉTUDES RELATIVES AUX VARIATIONS CLIMATIQUES INTÉRESSANT LA PÉRIODE POUR LAQUELLE ON DISPOSE D'OBSERVATIONS MÉTÉOROLOGIQUES

par

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AVANT-PROPOS

Au moment où l'on a commencé à organiser le présent colloque, il avait été proposé que la première séance fût essentiellement consacrée à l'examen d'un document qui aurait donné un aperçu de toutes les questions à étudier et à la présentation d'un certain nombre d'idées stimulantes sur lesquelles auraient pu s'axer les échanges de vues ultérieurs. Cette dernière partie de la proposition ne soulève pas de difficultés, les méthodes, critères ou théories sur lesquels on s'appuie pour déterminer ou expliquer les fluctuations climatiques offrant évidemment matière à discussion. Mais, pour exposer, même sommairement, les constatations — ou hypothèses fantaisistes — qui ont été faites à propos de tous les aspects de l'évolution climatique dont nous aurons à nous occuper au cours du colloque, il nous faudrait passer en revue, ce qui demanderait beaucoup trop de temps, toutes sortes de matériaux hétéroclites répartis dans des centaines et des centaines de documents. De toute façon, étant donné qu'un document général doit être présenté à chaque séance, il n'y aura pas, espérons-nous, d'inconvénient à ce que celui-ci (destiné à la première séance) ne se rapporte guère qu'à la période pour laquelle on dispose d'observations météorologiques. Nous pouvons rappeler ici que, pour être sûre de pouvoir mettre à la disposition du colloque une documentation abondante, l'Organisation météorologique mondiale avait demandé à chacun de ses États membres de lui faire parvenir des renseignements portant, non seulement sur toutes les études climatologiques publiées sur son territoire depuis 1950, mais aussi sur les plus importantes de celles qui avaient paru avant cette date. Bien que les États membres de l'OMM n'aient pas tous réagi à cet appel, les réponses reçues (que l'OMM a maintenant fait paraître dans une publication intitulée *Bibliography on climatic fluctuations*) montrent qu'il a été produit un nombre impressionnant de telles études ; plus de 300 en Amérique du Nord et à peu près autant en Europe, le chiffre total dépassant 700. Beaucoup d'entre elles, rédigées en des langues très diverses, se rapportent à la période pour laquelle on dispose d'observations météorologiques et il nous a été impossible, dans le temps dont nous disposions, d'accéder à tous ces documents et, à plus forte raison, d'en faire la synthèse. Nous espérons donc qu'on nous pardonnera de passer ici sous silence certaines découvertes et que les auteurs dont nous n'aurons pas spécialement mentionné les travaux n'en seront pas offensés. Les documents en question sont, dans leur très grande majorité, de caractère statistique et, en dépit du développement qu'ont pris depuis quelques années les méthodes dynamiques applicables aux recherches sur la circulation générale, les études climatologiques menées selon ces méthodes demeurent relativement rares. Nous reviendrons ultérieurement sur ce point.

MÉTHODES

Pour déterminer l'existence et l'ampleur des fluctuations climatiques, on a recours tantôt à des procédés traditionnels allant de la simple analyse des écarts à la « normale » de certains éléments (la « normale » étant une valeur moyenne calculée pour une période déterminée s'étendant, en général, sur trente ans) ou de l'emploi de moyennes chevauchantes, jusqu'à la méthode beaucoup plus moderne et plus élaborée de l'analyse spectrale d'une série chronologique au moyen de calculatrices électroniques. Dans le premier cas, la question se pose de savoir s'il existe vraiment une période qui puisse être considérée comme « normale ». De toute façon, la comparaison des moyennes obtenues pour différentes périodes n'a que peu d'intérêt si elle n'est pas complétée par un examen de la nature de la distribution des fréquences. L'emploi des moyennes mobiles a, lui aussi, ses inconvénients. Donc, quelle que soit la méthode utilisée, il y a toujours des précautions à prendre, et il sera certainement question au cours de la présente séance de certains des principaux pièges à éviter en matière de statistique. Sans doute n'est-il pas inutile de signaler à ce propos qu'un chapitre spécial sur l'emploi des méthodes statistiques a été rédigé par des experts pour être inclus dans le guide de l'OMM qui est sur le point de paraître (*Guide des pratiques climatologiques*). Il importe notamment de prendre toutes précautions utiles pour assurer la représentativité et l'homogénéité des données de base. Une étude détaillée des causes des variations séculaires de températures résultant d'observations instrumentales a été effectuée par Mitchell (1953). Cet auteur attire l'attention sur de nombreux facteurs qui ne sont pas toujours perçus et montre, par exemple, que l'urbanisation peut provoquer une hausse « artificielle » des températures relevées par les stations météorologiques situées dans les villes. On se fonde couramment, pour l'élaboration de séries chronologiques, sur des moyennes mensuelles de température qui dérivent elles-mêmes de moyennes quotidiennes calculées d'après la formule $\frac{\text{max.} + \text{min.}}{2}$. Mais on est en droit de se demander si les valeurs ainsi obtenues peuvent vraiment servir de base à une appréciation de l'évolution du climat. Marshall (1954) a, par exemple, montré dans une étude fondée sur des données recueillies à l'observatoire de Kew que la température moyenne mensuelle est parfois « représentative » et que l'on risque d'aboutir à des erreurs lorsqu'on s'appuie sur elle pour comparer tel ou tel mois d'une année donnée au même mois d'une autre année. Comme il le fait observer, les moyennes des températures maximales et des températures minimales peuvent constituer, pour l'appréciation des caractéristiques de température d'un mois déterminé, de bien meilleurs critères. Une récente étude de De Vries et Birch (1961) montre d'autre part que le taux d'irrigation et la distance sous le vent de la zone irriguée peuvent exercer une influence — qui, pour être essentiellement locale, n'en est pas moins appréciable — sur la répartition de l'énergie, donc sur le climat, au voisinage du sol. Les auteurs en question ont constaté que, pendant les périodes d'irrigation de 1956-1957 et de 1957-1958, les températures relevées sous abri dans le district de Nanneella, à l'est de Rochester (État de Victoria, Australie), par les stations respectivement situées dans les zones non irriguées et dans les zones irriguées présentaient entre elles des écarts pouvant atteindre 1 à 2 °C. Indépendamment de l'urbanisation, de l'irrigation et de la pollution, plusieurs autres facteurs dus à l'activité humaine peuvent avoir, sinon sur le climat régional ou mondial, du moins sur le climat local, d'importants effets qui se traduiront par des « fluctuations » dans telle ou telle série chronologique d'observations relatives à la température, à la pluviosité, etc. Là encore on peut se demander — c'est d'ailleurs un de mes chevaux de bataille — si les moyennes mensuelles de température, de pluviosité, etc., ne doivent pas, en raison des variations à courte période intervenant au cours d'un mois donné (par suite d'orages, du déplacement des anticyclones et dépressions, etc.), être considérées comme ne présentant qu'un intérêt très limité pour l'étude des fluctuations climatiques. Il a d'ailleurs été suggéré que les moyennes chronologiques soient remplacées par des « moyennes d'ensemble », mais comment choisir l' « ensemble » ?

Depuis quelques années, l'analyse harmonique paraît être devenue moins populaire, mais la chasse aux « cycles » continue. Berlage (1957) a dressé la liste de tous les « cycles » qui ont été « découverts » par de multiples chercheurs ; mais il n'a jamais, semble-t-il, été trouvé de « cycle » dont l'existence puisse être tenue pour incontestable. En fait, les essais auxquels on s'est livré indiquent qu'on ne peut pas réellement espérer décomposer les fluctuations climatiques en un spectre unique d'ondes de longueurs différentes sinon exactes. Souvent les séries chronologiques révèlent une sorte de phénomène de « battement », mais avec une longueur d'onde non constante. La récente étude de Veryard et Ebdon (1961) sur les vents stratosphériques tropicaux montre, par exemple, que la composante zonale de ces vents subit une fluctuation croissante et décroissante avec une période variant de vingt-trois à vingt-neuf mois, la moyenne étant de vingt-six mois. Il n'est pas douteux que des phénomènes d'hystérésis, des mécanismes de réaction, etc., interviennent à des échelles de temps très différentes. Il y a là un problème à la solution duquel l'analyse spectrale peut efficacement contribuer et l'on peut à cet égard citer en exemple l'étude de Landsberg, Mitchell et Crutcher (1959) sur la pluviométrie à Woodstock College. Quelques mots encore avant d'abandonner la question des méthodes. Il est surprenant de constater combien de chercheurs spécialisés dans les fluctuations climatiques omettent de tenir compte, lorsqu'ils étudient telle ou telle grandeur, non seulement des limites entre lesquelles peut varier cette grandeur, mais aussi du fait que la distribution de ses valeurs successives n'est pas nécessairement « normale » ou « circulaire », mais peut comporter deux ou plusieurs modes différents. Les changements statistiquement importants que subissent au cours du temps les variances et les valeurs extrêmes sont évidemment moins faciles à déterminer que ceux qui affectent les moyennes, mais on reconnaîtra certainement que l'étude des fluctuations climatiques ne peut pas reposer uniquement sur l'examen des valeurs moyennes et qu'elle exige également un examen attentif des fréquences et des valeurs extrêmes.

CONSTATATIONS

On ne saurait nier qu'il existe des modifications du climat ; certaines, à petite échelle, sont de l'ordre du siècle, tandis que d'autres, beaucoup plus importantes, ont demandé des millions d'années, englobant les grandes périodes glaciaires. Dans la première catégorie se rangent, par exemple, les modifications nettement identifiées qu'a subi, au cours des temps historiques, le climat des pays qui bordent l'Atlantique Nord. On a ainsi de bonnes raisons de penser qu'après une période optimum (4000 à 2000 av. J.-C.) caractérisée par des températures de quelques degrés plus élevées que celles d'aujourd'hui, différents changements se sont produits. Par exemple, on peut, selon Brooks (1954), distinguer dans les dix derniers siècles plusieurs phases climatiques : à une période douce et relativement sèche (de 1000 à 1250 apr. J.-C.) a fait suite (de 1250 à 1400) une période perturbée pendant laquelle les pluies ont été plus abondantes ; puis est venue (de 1400 à 1600) une période plus froide, mais moins perturbée, au cours de laquelle les banquises se sont développées tandis que les glaciers de montagne conservaient encore des dimensions assez modestes ; le monde a ensuite traversé de 1600 à 1850 une « petite période glaciaire » pendant laquelle les glaciers ont progressé vers les plaines tout en marquant à certains moments des reculs par rapport aux points extrêmes de leur avance, ceux qui ont correspondu aux années 1650, 1750 et 1850. Nous en arrivons finalement à la période pour laquelle on dispose d'observations météorologiques. Ce n'est qu'au XIXe siècle que les mesures météorologiques instrumentales commencèrent à devenir chose courante ; mais à la fin du siècle, grâce aux efforts de l'Organisation météorologique internationale (ancêtre de l'Organisation météorologique mondiale), de telles mesures s'effectuaient déjà dans le monde entier selon des procédés normalisés. Différentes tentatives ont été faites, notamment par Manley (1959) pour reconstituer, d'après les données instrumentales disponibles, le régime des températures depuis la fin du XVIIe siècle. Mais, par suite des changements de sites, des interruptions dues aux guerres, etc., on ne dispose que très rarement de très longues séries d'observations vraiment homogènes. Il existe cependant de telles séries dont certaines se présentent sous forme de cartes synoptiques et, avec l'aide de données « non météorologiques » comme celles qui ont trait à l'observation des glaciers, il a été possible de se faire une idée des tendances ou fluctuations du climat depuis un siècle ou deux, au moins sur une grande partie de l'hémisphère boréal et quelques zones de l'hémisphère austral. Il se trouve que la période pour laquelle on dispose d'observations météorologiques a été marquée par un retrait des glaciers, par une diminution de la surface des étendues glacées et par une élévation des températures ; ce sont ces fluctuations climatiques tout à fait récentes qui ont surtout fait l'objet de nombreux articles.

Nous allons, dans les paragraphes qui suivent, nous efforcer d'analyser la substance de ces articles, de façon à en dégager successivement ce qui se rapporte aux températures, aux précipitations, à la pression atmosphérique et aux divers aspects de champ de pression.

TEMPÉRATURE

Température de l'air

Il est maintenant généralement reconnu que, pendant la période pour laquelle on dispose d'observations météorologiques, la caractéristique la plus frappante des fluctuations climatiques a été le réchauffement qui s'est produit dans de nombreuses régions du globe au cours du laps de temps approximativement compris entre 1850 et 1940 ou 1950, années à partir desquelles il semble qu'il y ait eu en certains endroits, mais non pas partout, une stabilisation ou une diminution des températures. Examinons les faits.

En s'appuyant sur un relevé soigneusement préparé des températures enregistrées au cours d'une longue période à Delft, Zwanenburg, Utrecht et De Bilt, Labrijn (1945) a montré, à l'aide de moyennes chevauchantes calculées sur des périodes de trente ans, qu'en 1945 la température hivernale moyenne des Pays-Bas n'avait jamais depuis 1790 (mise à part une légère régression vers 1890) cessé de croître, tandis que la température estivale moyenne avait augmenté entre 1800 et la fin du XIXe siècle, puis diminué jusque vers 1920 environ, et recommencé ensuite à augmenter. La diminution qu'avait subie, surtout à partir de 1900, l'écart entre la température estivale et la température hivernale indiquait en outre que le climat était, tandis que se produisait ce réchauffement, devenu moins continental. En ce qui concerne l'Islande, Eythorsson (1949) a constaté que la température annuelle s'était élevée de façon continue d'environ 1,1 °C entre 1916-1925 et 1926-1935 et que cette élévation de la température avait commencé plus tôt dans le nord du pays que dans le sud. D'après les températures relevées au cours d'une longue période à Helsinki et à Oulu, Keranen (1952) est arrivé à la conclusion que le climat de la Finlande était devenu de plus en plus doux au cours du XXe siècle, avec un maximum de réchauffement entre 1930 et 1940 et un palier à partir de 1940.

En ce qui concerne la Laponie, Blüthgen (1952) a constaté que la température annuelle moyenne avait atteint pour la période 1935-1950 un chiffre supérieur de 1 °C à celui de la période 1901-1930 tandis que les moyennes correspondant aux mois de novembre et décembre avaient subi entre ces deux périodes un accroissement de 3 °C. Pour la Norvège, les études d'Hesselberg et Birkeland (1956) et d'Hesselberg et Johannessen (1958) montrent qu'un rapide accroissement des températures s'est produit en 1917-1922 dans les stations norvégiennes et notamment au Spitzberg, accroissement se chiffrant, par exemple, par 7 °C en hiver, 3 °C au printemps, 2 °C en été, 3 °C en automne, et 4 °C pour l'ensemble de l'année. Après 1922 cet accroissement s'est poursuivi mais est devenu plus modéré (1 °C par an) et il a été plus marqué au Spitzberg que plus au sud. La fluctuation, dont les maxima et les minima se plaçaient respectivement en hiver et en été, a atteint sa pointe peu après 1930. En 1941-1950, la tendance s'est inversée, à cause, notamment, des rudes hivers 1940-1942.

Il existe différentes autres études concernant les fluctuations de la température en Europe occidentale, mais leurs résultats sont assez contradictoires. En ce qui concerne les îles Britanniques, par exemple, Glasspoole (1955) a, en tirant parti de moyennes mobiles décennales, pour l'ensemble Angleterre-pays de Galles, d'une part, et pour l'Écosse, d'autre part, obtenu des courbes qui présentent des différences assez marquées, bien que leur allure générale soit à peu près la même, la température annuelle augmentant dans les deux cas d'environ 0,5 °C entre 1922-1931 et 1929-1938. Pour l'Angleterre et le pays de Galles, Glasspoole a constaté que les températures de printemps avaient subi à partir de 1923-1932 un accroissement continu de plus de 1 °C (avec maximum en 1943-1952) ; de leur côté, les températures d'été avaient, de 1922-1931 à 1932-1941, augmenté très rapidement (d'environ 1 °C) pour redescendre ensuite ; quant aux températures d'automne, elles avaient, à partir de 1918-1927, subi un accroissement continu de près de 1 °C (avec maximum en 1942-1951). Bien que les températures d'automne aient commencé à s'élever plus tôt que celles de printemps ou d'été, et aient continué à augmenter pendant une période plus longue, les courbes correspondant à ces trois saisons étaient très semblables, tandis que les courbes correspondant à l'hiver étaient plus ou moins symétriques des précédentes. Elles faisaient en effet apparaître une diminution générale de plus de 1 °C entre 1918-1927 et 1937-1946, diminution à laquelle faisait suite jusqu'en 1942-1951 un rapide accroissement de plus de 0,5 °C.

Steinhauser (1960) a démontré que, pendant la période 1901-1930, le climat de l'Europe centrale avait subi de très fortes influences océaniques. Ces influences apparaissent de manière particulièrement nette dans la courbe établie par Steinhauser et ses collaborateurs (1957), qui révèle des fluctuations dans la variance de la température à Vienne, station pour laquelle on dispose d'une longue série d'observations; pour les périodes 1870-1889 et 1930-1949 et suivantes, la variance était à peu près le double de celle de la période intermédiaire. En utilisant cette longue série d'observations de Vienne et également de longues séries de Berlin, De Bilt, Bâle et Milan, Steinhauser a tracé des courbes intéressantes correspondant aux moyennes mobiles — quinquennales, décennales et trentenaires — des températures annuelles. Alors que les courbes de Bâle et de Milan sont presque parallèles, il n'y a que peu de ressemblances dans l'ensemble entre ces courbes et les autres. Pour certaines années, toutes ont la même marche ; mais pour d'autres, elles divergent ou convergent. Il est intéressant de constater que, pour Vienne, les moyennes décennales, en voie d'augmentation entre 1930 et 1939, ont marqué un recul peu après à cause des années froides 1940-1942, pour s'élever ensuite jusqu'à des valeurs qu'elles n'avaient encore jamais atteintes.

Dans une étude détaillée portant sur les changements climatiques en URSS au cours des trente ou quarante années qui ont précédé la période 1950-1955, M^{me} E. S. Rubinshtein (1956) constate, surtout pour les mois d'hiver, un réchauffement qui a atteint son point culminant entre 1930 et 1939 ; mais, si les températures ont ensuite décliné dans une zone très étendue, et notamment dans l'ouest de l'URSS, la tendance au réchauffement a continué à se manifester aux hautes latitudes de l'URSS ; c'est ainsi que, dans la mer de Barents, les températures de janvier sont demeurées très élevées jusqu'en 1950 et que des températures hivernales relativement hautes ont continué à régner dans les estuaires de l'Ob et de l'Iénisséi, ainsi que sur les côtes de l'océan Glacial artique. M^{me} Rubinshtein a également constaté que les périodes de réchauffement maximum n'étaient pas toujours simultanées dans les territoires asiatiques orientaux de l'URSS et en Sibérie occidentale ou en Europe. Elle a souligné — et c'est là un point sur lequel d'autres chercheurs ont également attiré l'attention — que les années de la période de grand réchauffement n'ont pas toutes été chaudes et que c'est simplement par une tendance à la prédominance des années chaudes qu'a été caractérisée cette période. Commentant le manque d'uniformité des anomalies de température d'une région à l'autre, elle a tracé d'intéressantes figures donnant les isolignes du coefficient de corrélation entre Moscou et les différentes parties de l'URSS et elle a attiré l'attention sur le fait que ces isolignes s'étirent dans la direction des courants de circulation dominants, c'est-à-dire le long de l'axe de l'anticyclone asiatique en janvier quasi nord-sud en hiver ; ainsi la corrélation entre les températures mensuelles moyennes de Moscou et de Barnaoul est de +0,45 en janvier, mais de —0,55 en mai.

Dans une étude sur l'évolution des températures au Canada, jusqu'en 1952, Longley (1953) constate, en utilisant des moyennes mobiles décennales, que dans toutes les régions pour lesquelles on dispose de relevés remontant à 1880, la décennie 1880-1889 a été froide (avec un minimum en 1879-1880) et qu'un réchauffement général s'est ensuite immédiatement produit. Mais il constate également qu'à partir de 1900 environ, les variations n'ont pas été semblables dans toutes les régions susmentionnées et qu'il s'est produit à divers moments et en divers endroits de nombreuses fluctuations mineures. Dans les parties orientales du pays, la période 1903-1926 a été marquée par un lent abaissement de la température dans la région maritime et dans le nord de l'Ontario et par des modifications parallèles, bien que moins importantes, dans les autres régions. Au cours de la période 1926-1952 s'est fait sentir — surtout de 1926 à 1939 — une tendance générale au réchauffement, tendance qui, dans de nombreux districts, s'est cependant inversée entre 1939 et 1943 ; l'Ontario septentrional n'a pas connu le réchauffement de 1926-1939 et c'est le seul district du Canada oriental où la décennie qui s'est terminée en 1952 n'ait pas été la plus chaude de toutes celles pour lesquelles on disposait de données. Toujours d'après Longley, les années 1946-1947 ont marqué à l'ouest du lac Supérieur la fin des décennies très chaudes, la température moyenne s'étant ensuite abaissée de plus de 0,5 °C. Dans l'Alberta la décennie se terminant en 1951 a même été la plus froide de toutes celles qui s'étaient succédées depuis 1904. Pour la période 1903-1940, l'examen des données recueillies par les stations situées entre le lac Supérieur et les montagnes ne permet d'autre part de déceler aucune tendance générale; c'est ainsi que le réchauffement marqué que l'on constate pour la période 1903 à 1930 dans le Saskatchewan fait contraste avec les tendances qui apparaissent pour cette même période dans les districts voisins. Longley signale également que, non seulement la température n'a pas évolué de la même façon dans toutes les régions du Canada, mais que certains des changements signalés, et par exemple le refroidissement du nord de l'Ontario entre 1903 et 1926, ont été progressifs alors que d'autres, comme l'abaissement des températures dans le Canada occidental à partir de 1950, ont été brusques.

Dans l'étude qu'il a ultérieurement faite des changements de climat dans la province de l'Ontario, Thomas (1957) montre bien que, si un accroissement général de la température s'est sans aucun doute produit dans cette province depuis la fin du siècle dernier, ce réchauffement n'a pas été continu et qu'il a été moins uniforme dans le nord que dans le sud. Dans un document plus ancien, Thomas (1955) avait examiné une série de moyennes décennales de températures pour les régions côtières de la Nouvelle-Écosse et de Terre-Neuve. Il avait constaté l'existence à partir de 1890 d'une tendance au réchauffement qui, surtout marquée en hiver, avait atteint son maximum au début de la décennie 1930-1939. Crowe (1958) est arrivé à des résultats analogues en ce qui concerne la côte de la Colombie britannique.

Pour le nord-est des États-Unis d'Amérique, Conover (1951) a mis en évidence, d'après des séries d'observations faites à Milton et Blue Hill (Massachusetts) et portant sur près d'un siècle, un accroissement de 3,5 °F dans les températures hivernales. En se fondant sur une longue série d'observations de températures dans un certain nombre de stations des États-Unis d'Amérique, Kincer (1946) a constaté qu'il y avait eu un réchauffement général pendant la décennie qui s'était terminée en 1892, que les températures étaient demeurées relativement stables de 1903 à 1920 et qu'elles avaient ensuite augmenté de façon marquée jusqu'en 1940, les valeurs obtenues pour la décennie la plus chaude (celle qui a pris fin vers 1938-1939) étant de 2 °C plus élevée que celles de la décennie la plus froide (celle qui s'était terminée en 1875-1876). Il indiquait dans son article qu'il avait, pour toute la période d'avant 1930, relevé à Paris et au Cap des résultats analogues. Landsberg (1960) a comparé entre elles, telles qu'elles ressortent de relevés suffisamment homogènes émanant de différentes stations des États-Unis, les moyennes des températures mensuelles, saisonnières et annuelles correspondant aux deux périodes de vingt-cinq ans qui vont de 1906 à 1930 et 1931 à 1955 ; il a ainsi constaté que dans la plupart des stations, mais non dans toutes, il y avait eu une élévation significative — avec une probabilité de 95 % — des températures, les accroissements les plus importants étant ceux qui correspondaient à la saison d'hiver et à la saison d'été. Il a montré que la zone où le réchauffement en question avait été le plus marqué était celle des Grands Lacs, que ce réchauffement n'avait pas affecté le sud-ouest des États-Unis et qu'il avait coïncidé avec un léger refroidissement dans le sud des Appalaches.

Dans son article concernant les fluctuations climatiques qui se sont produites au Moyen-Orient depuis le début de la période pour laquelle on dispose d'observations instrumentales (document préparé en vue du présent colloque), N. Rosenan indique que, dans cette région du monde, les températures annuelles sont passées par un minimum au cours des décennies 1890-1910, qu'elles ont augmenté de 0,5 à 1 °C, au cours de la période 1900-1930, ont atteint leur maximum entre 1930 et 1939, ont partout décru de 1940 à 1949 et se sont, dans bien des stations, relevées entre 1950 et 1959 ; il déclare n'avoir pu découvrir aucune influence des températures d'été sur l'évolution des températures annuelles.

De nombreux articles concernant les fluctuations climatiques en Extrême-Orient sont dus à des chercheurs japonais, et notamment à H. Arakawa, mais ils sont pour la plupart fondés sur des données « historiques ». Dans ses études sur l'évolution séculaire du climat au Japon, Yamamoto (1950, 1951, 1957) a relevé des tendances qui ne sont pas les mêmes pour les différentes saisons et pour les différentes parties du pays. Il indique en particulier que, si la moyenne décennale des températures d'été a, à partir de 1898, presque partout augmenté dans le nord du Japon, les températures d'hiver ont évolué selon une courbe parallèle, mais inversée, dans les parties centrales et sud-occidentales du pays. Fujiwara et Ishiguro (1957) ont — en utilisant de longues séries d'observations relatives aux stations agricoles d'Hokkaïdo — constaté que, dans cette île, les températures moyennes d'été et de printemps — et surtout celles de juillet et août — s'étaient élevées à partir de 1910 et avaient atteint entre 1940 et 1959 des valeurs plus fortes que pendant les trente années précédentes.

Pramanik et Jagannathan (1954) se sont livrés, en remontant au siècle dernier, à une étude très complète des changements climatiques dans l'Inde, mais ils n'ont constaté nulle part d'augmentation ou diminution régulière des températures maximales ou minimales ; ils ont simplement signalé que les données relevées par certaines stations faisaient penser à un « cycle » de trente à quarante ans.

Dans un article relatif aux changements de climat en Afrique du Nord qu'il a établi pour le présent colloque, Dubief fait observer que, s'il se peut que les températures aient depuis cinquante ans subi dans la région considérée de légères modifications, la chose est cependant discutable. En ce qui concerne l'Afrique du Sud, Hofmeyr et Schulze ont élaboré — également pour le présent colloque — un document qui est fondé sur des données dont certaines remontent au siècle dernier et dans lequel ils signalent, pour la période 1901-1930, une élévation significative de la température (de 0,03 °C par an environ) au Cap et à O'okiep.

Pour Djakarta (Indonésie) on dispose de relevés de températures intéressant une longue période et De Boer et Euwe (1949) ont attiré l'attention sur une élévation plus ou moins rapide, mais à peu près continue, de la température annuelle moyenne entre 1866 (25,9 °C) et 1940 (27 °C), élévation qui ne peut pas avoir été uniquement due à l'urbanisation, puisque la même tendance a été observée en Indonésie dans des stations rurales ou de haute altitude. Vers 1921, il y a eu une discontinuité dans le réchauffement et les travaux de Schmidt-Ten Hoopen et Schmidt (1951), qui ont examiné les températures mensuelles moyennes relevées à Djakarta, ont montré que cette discontinuité avait été due au fait que les températures moyennes des mois de janvier à avril avaient subi depuis 1910 une diminution qui atteignit son maximum en 1921. Ces deux chercheurs ont en fait montré que, malgré un réchauffement d'ensemble à Djakarta, les courbes de températures moyennes mensuelles maximales et minimales avaient été affectées par les variations d'autres éléments.

Prohaska (1951), utilisant une série d'observations de cinquante années — de 1903 à 1950 — dans les Orcades du Sud, n'a constaté l'existence d'aucune tendance à sens unique, mais seulement des signes de fluctuations à longues périodes. En ce qui concerne l'Antarctique, Wexler (1961) soutient que, dans la région de la « Little America » (78° de latitude S.), il y a eu, de 1912 à 1957, une élévation de température de plus de 0,5 °C, à quelques kilomètres de la bordure du plateau glaciaire, mais qu'aucune variation importante de la température ne s'est produite à Mac Murdo Sound.

Examinées dans le détail, les différentes études qui ont porté sur les fluctuations de la température n'offrent pas un tableau simple et il n'est pas facile d'en accorder les résultats. Sans doute, Baum et Havens (1956) ont-ils réussi à donner à leurs lecteurs une excellente vue d'ensemble des fluctuations climatiques intéressant les régions maritimes de l'Atlantique Nord, mais il semble que la première tentative de synthèse qui ait été faite à l'échelle mondiale soit celle de Willett (1950), lequel a utilisé pour cela des données recueillies au cours d'une période s'étendant sur cinquante ans ou davantage par plus de 100 stations (situées pour la plupart aux latitudes moyennes de l'hémisphère nord). Le but de Willett était de déterminer les tendances mondiales de l'évolution de la température. Il a constaté que, s'il y avait eu à partir de 1885 une nette tendance au réchauffement, cette tendance était loin de s'être manifestée de la même manière dans toutes les régions du globe. Dans l'ensemble, les températures moyennes hivernales avaient augmenté de plus de 1 °C, et les températures moyennes annuelles d'environ 0,5 °C ; mais ce réchauffement avait été particulièrement sensible aux hautes et très hautes latitudes de l'hémisphère nord, alors qu'il semblait y avoir eu, au contraire, un certain refroidissement aux latitudes polaires de l'hémisphère sud. Willett signalait en particulier que, de 1920 à 1940, les températures hivernales s'étaient élevées de près de 4 °C dans le Groenland occidental et d'environ 7 °C dans le Svalbard.

Examinant de façon générale — dans une étude qui ne s'étend cependant pas à l'ensemble du globe — les modifications subies par le climat depuis le début de la période pour laquelle on dispose d'observations météorologiques jusqu'en 1940, Lysgaard (1949) a montré que, pour le mois de janvier, c'était de 1910 à 1940 que s'était produit le plus grand accroissement de température ; cet accroissement avait été de plus de 3 °C dans le Groenland et de plus de 2 °C au Spitzberg, dans la mer du Nord et dans la partie septentrionale de l'Amérique du Nord ; il avait été moindre (et parfois même remplacé par une diminution) dans les parties plus méridionales de l'hémisphère boréal et semblait également avoir fait place à une diminution dans certaines régions de l'hémisphère austral et, notamment, en Asie du Sud-Est et en Australie. Pour le mois de juillet — toujours selon Lysgaard — l'accroissement de température avait atteint son maximum (plus de 1 °C) en Finlande, en Scandinavie du Nord et dans les parties centrales du Canada et des États-Unis ; la température de juillet avait au contraire sensiblement diminué en Asie centrale, dans les régions de l'Asie du Sud soumises à la mousson et au nord de la Nouvelle-Zélande ; mais elle avait augmenté en Australie et en Amérique du Sud.

Pour faire mieux comprendre ce qui distingue les fluctuations purement locales ou régionales — telles qu'elles ressortent des moyennes décennales — des fluctuations à longue période intéressant des zones étendues, Callendar (1958) a montré, en se fondant sur les températures relevées dans un choix de stations d'Europe, que, même dans une zone de faible étendue comme celle des îles Britanniques, il y avait un déphasage appréciable entre le réchauffement sur un district donné et sur un district voisin : c'est ainsi que la décennie 1931-1940 a été plus chaude que toute autre dans le nord-ouest des îles Britanniques, alors que c'est la décennie 1943-1952 qui a été la plus chaude dans le sud-est.

Callendar a également montré que c'est à Stykkisholm (Islande occidentale) que l'écart extrême entre moyennes trentenaires avait été le plus grand (plus de 1 °C) et à Vienne qu'il avait été le plus petit (environ 0,5 °C) ; dans les îles Britanniques, la valeur de cet écart avait augmenté du sud au nord, passant de 0,5 °C à Greenwich à 0,6 °C à Aberdeen. Callendar a en même temps constaté que c'est à la période 1921-1950 que correspondait dans toutes les stations considérées la plus haute moyenne trentenaire obtenue depuis la période antérieure à 1880. Il a également fait observer que les moyennes trentenaires les plus élevées enregistrées au cours du

XIX[e] siècle à Vienne, Greenwich et Trondhjem n'avaient pas été dépassées de manière significative par celles qui correspondent aux périodes dont la dernière s'est terminée vers 1930. Arguant de la régression bien connue des glaciers avant 1900, Callendar a admis que le climat s'était — en dépit de quelques retours en arrière — lentement amélioré et que cette amélioration s'était accélérée au cours des trois ou quatre décennies qui se sont terminées vers 1950, les années récentes ayant, quant à elles, été marquées par une certaine tendance à la stabilisation. Il a également tracé des courbes qui montrent, pour la période 1910-1950, l'évolution des moyennes décennales de température à Grimsey (près de l'Islande) et à l'île Laurie (Orcades du Sud), courbes qui permettent de constater qu'un important écart s'est manifesté à la fin de la décennie 1920-1930 entre l'extrême nord et l'extrême sud de l'océan Atlantique, atteignant plus de 2 °C entre 1927 et 1930. Étant donné que les glaciers de la Géorgie du Sud semblent avoir moins reculé que ceux du *hielo continental* (à 50° de latitude S.), Callendar a émis l'hypothèse que la relative horizontalité de la courbe obtenue pour l'île Laurie pourrait être due à la forte influence thermostatique de la fonte du *pack* (glaces flottantes) aux hautes latitudes australes. Il est même allé jusqu'à insinuer que la « fluctuation climatique actuelle » n'avait pas encore réussi à se faire sentir au-delà de la « barrière thermique » que constitue la zone de fusion du *pack* qui ceinture la grande calotte glaciaire australe. Pour répondre à la question de ceux qui se demandent si la tendance au réchauffement est actuellement en train de de s'affaiblir, Callendar (1960) a fait observer qu'en Europe les étés chauds des trois années 1957, 1958 et 1959 avaient provoqué une régression croissante des glaciers alpins et scandinaves alors que cette régression avait eu auparavant tendance à se ralentir. Il a également signalé que les étés chauds des années 1954-1957 et 1959 avaient provoqué en Nouvelle-Zélande une sérieuse régression des glaciers, qu'au Japon la décennie 1948-1957 avait été, depuis la période antérieure à 1880, la plus chaude de toutes et que, dans la Prairie canadienne comme dans les plaines adjacentes des États-Unis, les températures moyennes (relativement basses en 1945-1946) avaient, pendant la période 1952-1958, dépassé de plus de 0,5 °C, la moyenne de 1901-1930, l'écart se chiffrant même par plus de 1 °C dans le Canada oriental et le nord-est des États-Unis. Callendar estime donc que le réchauffement se poursuit encore dans bien des régions en dépit du fait qu'aux latitudes subarctiques, les températures ont eu depuis 1948 une certaine tendance à décliner. Dans un autre document (1961), Callendar soutient (en s'appuyant sur la méthode contestable qui consiste à combiner sur une base régionale les écarts à la moyenne de la température annuelle dans un certain nombre de stations en vue d'obtenir des valeurs caractéristiques pour de vastes zones ou régions) que la tendance au réchauffement a continué à se faire sentir au cours des dernières décennies entre l'Arctique et le parallèle 45° S. environ, mais qu'elle a été très faible, voire « imperceptible », dans la plupart des régions situées au-dessous du 35[e] degré de latitude N.

Bien que, dans leurs propres études, Mitchell (1961) et Willett (1950) soient partis de données et de méthodes d'analyse différentes de celles de Callendar (1961), leurs conclusions s'accordent assez bien, sauf en ce qui concerne la zone tempérée australe, avec celles de ce dernier auteur ; c'est ce que montre, tel qu'il a été préparé par Landsberg et Mitchell (1961), le tableau ci-dessous :

Variation de la température annuelle moyenne entre deux périodes consécutives de trente ans

Callendar [1]		Willett-Mitchell [2]	
Limites de latitude	°C	Limites de latitude	°C
60° N.-25° N.	0,39	60° N.-20° N.	0,32
25° N.-25° S.	0,17	30° N.-30° S.	0,19
25° N.-50° S.	0,14	20° N.-50° S.	0,06
		20° N.-60° S.	0,10
60° N.-50° S.	0,23	60° N.-60° S.	0,21
		80° N.-60° S.	0,27

1. Différence entre le chiffre de 1921-1950 et celui de 1891-1920.
2. Différence entre le chiffre de 1920-1949 et celui de 1890-1919.

A propos des divergences qui se manifestent en ce qui concerne la zone tempérée australe dans le tableau ci-dessus (divergences qui n'ont rien d'étonnant si l'on songe au faible nombre de relevés portant sur de longues périodes qui ont pu être établis par les trop rares stations situées dans cette zone), Callendar a fait observer que, pour la région comprise entre les 25[e] et 50[e] degrés de latitude S., la valeur qu'il obtiendrait en prenant la différence entre le chiffre de la période 1921-1950 et celui de la période 1901-1930 — soit 0,10 — coïnciderait mieux avec les résultats de Mitchell. Landsberg et Mitchell admettent d'autre part, comme Callendar, que l'urbanisation n'a vraisemblablement eu que peu d'influence sur l'évolution des températures dans l'ensemble du monde. Dans la toute récente étude d'ensemble que Mitchell a préparée pour le présent colloque sur l'évolution séculaire du climat, on trouve une certaine confirmation de la thèse selon laquelle la tendance au réchauffement qui s'est manifestée dans le monde au cours des décennies antérieures à 1940 aurait eu tendance à s'inverser, au cours de la décennie 1940-1949, bien que les températures aient, en certains endroits, continué à s'élever. Mitchell indique que les moyennes de températures pour l'hémisphère nord et pour l'hémisphère sud semblent avoir varié de façon parallèle, mais il attire en même temps l'attention sur le fait que les tendances moyennes à l'échelle mondiale ne sont pas représentatives pour la plupart des régions. Il signale en particulier que les régions qui se sont le plus rapidement réchauffées avant 1940 coïncident souvent avec celles qui se sont depuis lors le plus rapidement refroidies.

Quand on essaye de raccorder toutes les données rassemblées, on arrive à peu près nécessairement à la conclusion que la période pour laquelle on dispose d'observations instrumentales a bien été marquée, jusqu'en 1940 tout au moins, par un réchauffement assez général, sinon absolument universel, du climat. Il semble que ce réchauffement ait d'abord été lent et irrégulier et qu'il se soit ensuite accéléré pour atteindre son maximum entre 1930 et 1949. Mais il est évident que cette élévation de la température n'a été ni uniforme ni symétrique par rapport au pôle ; infime ou nulle aux latitudes moyennes de l'hémisphère austral, elle a atteint son maximum aux latitudes élevées de l'hémisphère boréal, dans les régions situées en bordure de l'océan Atlantique notamment. Il apparaît également que le réchauffement a commencé plus tardivement dans certaines régions que dans d'autres ; en fait, pendant un certain temps tout au moins, il y a eu simultanément dans différentes régions des fluctuations de sens contraires. De plus, le réchauffement a présenté des variations à courte période et pourrait fort bien n'être lui-même que l'un des éléments d'une fluctuation à bien plus longue période couvrant peut-être plusieurs centaines d'années.

Il n'est pas inutile de signaler ici que, dans un document inédit, Knud Frydendahl, après avoir procédé à une étude critique du seuil d'enregistrement de différents types d'héliographes répartis en deux vastes réseaux, constate qu'il y a eu à l'échelle mondiale des variations à longue période de l'insolation, avec un brusque accroissement dans les années voisines de 1920.

Température de la mer et revêtement glaciaire

Étant donné que les changements climatiques sont vraisemblablement liés à des variations du bilan thermique du système mer-terre-air considéré dans son ensemble, il faut, semble-t-il, admettre que les fluctuations qui se produisent dans l'atmosphère sont associées à des fluctuations intervenant dans les océans. A la vérité, en tant que réservoir séculaire de chaleur, la mer peut jouer un rôle important, et Rossby (1959) a émis l'idée que les anomalies thermiques peuvent sans doute être emmagasinées et temporairement isolées dans les profondeurs des mers, pour venir à nouveau, au bout de quelques décennies ou de quelques siècles (durée correspondant à la totalité d'un cycle thermohalin), influer sur les échanges de chaleur et de vapeur d'eau entre la mer et l'atmosphère. Nous croyons donc devoir signaler rapidement ici un certain nombre d'études de climatologie maritime.

Dans la célèbre étude d'Ahlmann (1948), des données de toutes sortes — météorologiques, glaciologiques, océanographiques et biologiques — avaient été réunies pour prouver qu'une amélioration climatique s'était produite au cours des cent ou cent cinquante années précédentes. Ahlmann constatait en particulier que, dans l'extrême nord de l'Atlantique, l'eau était — jusqu'à une profondeur sans doute considérable — devenue plus chaude qu'au début du siècle et que sa salinité avait également augmenté, ce qui indiquait qu'elle devait provenir de régions plus méridionales. Il faisait également observer que l'épaisseur des glaces qui se forment chaque année dans la mer Polaire avait diminué de plus de 100 cm, et que la superficie des glaces dérivantes dans les eaux de l'Arctique avait nettement décru (subissant entre 1924 et 1944 une réduction de 1 million de kilomètres carrés dans la seule zone russe), en sorte que les expéditions de charbon à partir du Spitzberg pouvaient se poursuivre pendant sept mois de l'année (au lieu de trois au début du siècle) et que les côtes septentrionales de l'Europe et de l'Asie se trouvaient par moments complètement libres de glace. Les travaux d'Ahlmann concernant les glaces des mers polaires ont été complétés par la vaste étude de Maksimov (1954), qui confirme que l'épaisseur de la couche de glace a, dans les parties septentrionales de l'Atlantique-Nord, sensiblement diminué entre 1890 et 1940-1949. En se fondant sur un ensemble très complet de données relatives aux glaces arctiques, Lamb et Johnson (1959) indiquent de leur côté que, dans l'Atlantique-Nord, les glaces ont été, de 1920 à 1945-1949, moins abondantes que jamais et qu'elles ont eu, à partir de 1950, tendance à redevenir plus abondantes. Il convient toutefois de remarquer que, selon une note qui figure au bas d'une des pages de l'article de Schell (1956) sur les interrelations entre les glaces arctiques et les phénomènes atmosphériques et océaniques, les quantités de glace présenteraient des variations à longue période qui auraient tendance à être opposées dans les zones arctiques de l'Atlantique-Nord et du Pacifique-Nord : c'est ainsi que, dans la première de ces zones, la surface moyenne des glaces a, entre 1910 et 1939, diminué de 18 %, alors que, dans la seconde, elle a, semble-t-il, augmenté de 22 % pendant la même période.

Brown (1953) a fait des études comparatives intéressant les décennies 1910-1919 et 1940-1949 en utilisant les observations effectuées à partir de navires et portant sur la température de l'air et de la mer dans la région comprise entre les latitudes 60 et 70° N. et entre les longitudes 25° O. et 15° E. (donc entre l'Islande et la Norvège). Il a constaté que, si, entre les deux décennies susmentionnées, la température de l'air semblait avoir subi, pour tous les mois de l'année, une élévation générale de 1 à 2° C, les données relatives à la température de la surface de la mer offraient un tableau nettement plus compliqué : elles faisaient apparaître des augmentations d'environ 2° C au sud de l'Islande, d'environ 1° C le long de la côte norvégienne, mais de 0,3° C seulement entre les méridiens 0 et 5° O.

Exploitant une documentation plus complète — et, notamment, l'analyse par L. Riehl (1956) des observations de navires reçues par le U. S. Weather Bureau et les données historiques rassemblées par Smed (1952) — Bjerknes (1959) a montré que le taux d'accroissement de la température superficielle de la mer avait, entre 1890 et l'époque présente, atteint ses valeurs maximales le long du Gulf Stream, entre le cap Hatteras et la bordure des bancs de Terre-Neuve ; aucun réchauffement ne s'est produit au cours de la même période dans la zone qui va de l'Irlande aux rives du Labrador, mais, au nord de cette zone, la mer a subi un réchauffement qui a coïncidé avec l'amélioration climatique que l'on a pu constater au Groenland, en Islande et en Scandinavie. Bjerknes a émis l'idée qu'au sud du 50e degré de latitude N. la plupart des variations séculaires de la température de l'océan peuvent avoir été partiellement dues à un accroissement des vents qui, par entraînement, s'est traduit par une amélioration du courant des Caraïbes et du Gulf Stream et peut-être aussi à une augmentation de l'épaisseur des couches superficielles chaudes de l'océan dans les régions soumises à une augmentation des vents anticycloniques. Il a également pensé qu'entre 50 et 57° N., il s'était au contraire produit, par suite du refroidissement des vents cycloniques, un amincissement et un refroidissement des couches d'eau superficielles relativement chaudes, phénomène qui, joint au renforcement des vents froids soufflant de l'Amérique du Nord, peut avoir suffi à compenser et au-delà le réchauffement par advection de la zone qui va de l'Irlande au courant du Labrador. Il a enfin indiqué que, d'après les observations de la température superficielle de la mer qui ont pu être recueillies depuis l'interruption due à la seconde guerre mondiale, le maximum du réchauffement semble avoir été atteint au début de la décennie 1930-1939 au voisinage du Groenland, mais vers 1940 seulement entre l'Islande et les îles Britanniques. (Voir ce qui est dit d'une autre étude de Bjerknes (1960) à la section qui traite des situations barométriques et des vents.)

Riehl (1956), recherchant l'existence de corrélations entre les anomalies de la température superficielle de la mer et la formation des cyclones tropicaux, n'a pas obtenu des résultats aussi probants que pouvait le laisser espérer son hypothèse selon laquelle le développement de ces perturbations dépendait essentiellement du transfert local de chaleur entre l'océan et l'atmosphère. Il a cependant trouvé une assez bonne corrélation entre la température des mers et les trajectoires des cyclones tropicaux et il a établi des diagrammes qui montrent comment ces trajectoires se sont déplacées depuis le début du siècle ; pendant la période 1909-1920 au cours de laquelle les mers tropicales sont censées s'être refroidies, ces trajectoires sont passées à l'ouest du méridien 80° O. pour revenir à l'est de ce méridien, au cours de la période de réchauffement ultérieure (à partir de 1925 surtout). Une modification est également intervenue dans la longitude du méridien où la trajectoire des cyclones s'incurve vers l'est et Riehl a émis l'idée que ce déplacement était lié au déplacement de l'anticyclone des Açores-Bermudes, et pouvait par conséquent être interprété comme la conséquence de modifications de la circulation générale.

Rodewald a publié plusieurs études sur les variations des températures superficielles de la mer observées par les navires-stations océaniques. Dans celle de 1956 figure une carte qui montre que la température des eaux du Gulf Stream avait augmenté de 1,5 °C au point D, alors qu'il n'y avait eu qu'un très faible réchauffement juste au nord du 50° N. aux points C et J. (L'examen de cette carte suggérait également l'idée qu'il existait dans le Pacifique-Nord un système d'anomalies analogues à celui de l'Atlantique-Nord.) Dans un document destiné au présent colloque, Rodewald donne les résultats d'un examen plus récent des observations des navires-stations océaniques et de quelques données complémentaires. Il constate que, bien que la décennie 1951-1960 ait été relativement chaude, il y a eu au cours même de cette décennie une nette tendance au refroidissement. Mais cette tendance ne s'est pas manifestée partout de façon uniforme ; les variations qui se sont produites dans l'ouest et le sud de l'Atlantique-Nord ont été de sens contraire à celles que l'on a observées dans sa partie nord-orientale. Dans un autre document destiné au présent colloque, Rao et Jagannathan donnent les résultats d'études effectuées sur les variations à long terme de la température superficielle de la mer (et de divers autres éléments) dans le golfe du Bengale et la mer Rouge. Ils indiquent qu'il ne semble y avoir eu depuis soixante ans aucune tendance significative à l'élévation ou à la diminution de cette température, mais seulement des oscillations à longue période.

Peut-être pouvons-nous nous contenter d'indiquer, pour conclure cette section, que les variations de la température superficielle de la mer paraissent pouvoir s'expliquer par des modifications du régime des vents.

PRÉCIPITATIONS

Que l'on se place sur le plan mondial ou sur le plan régional, les données relatives aux variations de la pluviosité, sont beaucoup plus difficiles à rassembler en un tableau cohérent que celles qui ont trait à la température. Les tendances à long terme de la pluviosité sont en effet masquées par les variations à plus courte période et, comme la variabilité interannuelle a tendance à masquer les fluctuations climatiques d'amplitude plus faible, la réalité de toute prétendue fluctuation doit faire l'objet d'un contrôle minutieux, auquel omettent de se livrer bien des chercheurs. Toutefois la méthode des écarts accumulés — méthode utilisée par exemple par Kraus (1955) — semble donner des résultats valables : l'« analyse spectrale » — employée, notamment, par Landsberg et ses collaborateurs (1959) — peut de son côté se révéler fort utile maintenant que l'on dispose de calculatrices électroniques. Nous traiterons dans les paragraphes qui suivent de différents documents dans lesquels sont étudiées les variations de la pluviosité sur la base de longues séries d'observations par malheur rarement homogènes.

Dans son étude des fluctuations climatiques récentes, Lysgaard (1949) a indiqué que, pour la période 1910-1940, la pluviosité avait présenté des anomalies positives dans l'Arctique et dans la zone tempérée de l'hémisphère nord, au Mexique, à La Plata, en Inde méridionale et dans le sud-ouest de l'Asie (avec un maximum aux Philippines), alors qu'elle avait au contraire présenté des anomalies négatives sur la plus grande partie des États-Unis d'Amérique (mises à part quelques régions), dans le nord de l'Amérique du Sud, en Afrique (avec un maximum en Afrique occidentale), en Malaisie et en Australie. Il a toutefois fait observer que les courbes des moyennes trentenaires chevauchantes des hauteurs de pluie annuelles présentaient peu de ressemblances. Au Groenland, la pluviosité aurait eu, selon Diamond (1958), tendance à décroître depuis 1920, la plus grande anomalie négative se manifestant à partir de 1932. Aucune étude sur les variations séculaires de la pluviosité dans l'ensemble du Canada ne semble avoir encore été faite ; mais l'étude de Thomas (1955) concernant la côte atlantique et celle de Kendal et Thomas (1956) concernant la Prairie indiquent que, dans certaines régions du Canada (et, par exemple, dans le sud de l'Ontario), les hauteurs annuelles de pluie ont été, au cours des toutes dernières décennies, plutôt faibles ; les auteurs de ces deux études considèrent cependant que, compte tenu de la variabilité de la pluviosité d'une année à l'autre, on ne saurait en l'occurrence parler, comme dans le cas des températures, d'une tendance réellement significative. Kimble (1950) estime, quant à lui, qu'il y a eu en Amérique du Nord une modification du régime des précipitations. Celles-ci ont, selon lui, décliné pendant la première moitié du XX^e^ siècle. Il indique qu'à Montréal, par exemple, la « hauteur des pluies hivernales » est passée de 562 mm (22,12 pouces) pour les années 1900-1909 à 503 mm (19,80 pouces) pour les années 1940-1949, la hauteur probable des précipitations neigeuses s'abaissant de son côté à 2 m (80 pouces), au lieu de 3,30 m (130 pouces) en 1880-1889. Dingle (1955) s'est intéressé aux changements qu'avaient pu subir, au cours des soixante années précédentes, les régimes de précipitations que connaissaient les États-Unis, et il n'a constaté dans aucune partie du pays l'existence de tendances bien déterminées. Landsberg (1960) n'a lui non plus relevé aucune modification significative du régime des pluies aux États-Unis.

Les études relatives aux précipitations intéressant l'Europe font apparaître bien des contrastes. Qu'elles portent sur l'ensemble du continent européen — comme celles de Steinhauser (1960), de Péczely (1953) et de divers auteurs russes — ou sur certaines régions seulement — comme celle de Carapiperis (1960) concernant la zone méditerranéenne, celles de Dammann (par exemple, 1957 et 1959) concernant l'Allemagne, celle de Lysgaard (1954) pour le Danemark ou celle de Glasspoole (1957) pour les îles Britanniques — toutes ces études font état de tendances différentes pour les différents mois, les différentes saisons et les différentes régions. C'est ainsi que Glasspoole (1957) a constaté l'existence de différences frappantes entre les courbes qu'il avait établies, d'après les moyennes mobiles décennales des hauteurs de pluie en Angleterre et au pays de Galles d'une part, et en Écosse d'autre part. Ces courbes reflétaient, il est vrai, des tendances assez analogues ; mais celles de l'Angleterre et du pays de Galles passaient par des maxima en 1874-1883 et en 1923-1932 et par des minima en 1893-1902, tandis que celles de l'Écosse passaient par des maxima en 1871-1880 et en 1923-1932 et avaient leurs minima en 1885-1894. En matière de précipitations comme en matière de températures, on constate que, dans les îles Britanniques, les tendances d'hiver sont très différentes de celles des autres saisons. Glasspoole (1957) a étudié entre autres choses la variation du nombre de jours de pluie (variation qui, d'après ses constatations, est très analogue à celle de la quantité même de pluie) et il a ainsi découvert que, pour le printemps, les moyennes mobiles décennales des quantités moyennes de pluie par jour de pluie s'étaient considérablement élevées à partir de 1920-1930 en Angleterre et au pays de Galles et à partir de 1934-1945 en Écosse. Ces courbes pour le printemps correspondaient étroitement aux courbes de température. Selon un document de Berg (1943), il y aurait eu, pendant la première moitié du siècle, et par suite de la diminution des précipitations, un net abaissement du niveau des eaux dans la mer Caspienne et dans les bassins du Danube, du Don et du Dnieper. Il est à remarquer que la plupart des études concernant les fluctuations de la pluviosité en Europe font apparaître des discontinuités vers 1885-1895.

En utilisant, telle qu'elle a été ingénieusement élaborée par Rosenan (1955) une série « homotopique » des quantités annuelles de pluie à Jérusalem et en tirant également parti de données (historiques et autres) concernant le niveau de la mer Morte, Neumann (1960) a conclu à un parallélisme étroit entre les fluctuations de la pluviosité en Palestine et aux latitudes moyennes de l'hémisphère boréal. A propos des fluctuations climatiques qui se sont produites en Palestine depuis 1750, Neumann indique que la pluviosité a augmenté de façon marquée à partir de 1870 pour atteindre une valeur élevée en 1890, qu'elle a ensuite diminué rapidement jusqu'en 1920 et a finalement pris, au cours des années 1920-1950, une valeur inférieure de 10 % au chiffre moyen de la période 1846-1958 (autrement dit, inférieure d'environ 20 % au chiffre des dernières décennies du XIX^e^ siècle. Dans le document qu'il a préparé pour le présent colloque, Rosenan fait observer que les chiffres relatifs aux précipitations et aux températures ont subi en Palestine des fluctuations de sens contraires. Il indique qu'en presque tous les points du Moyen-Orient, le volume des précipitations a atteint un maximum entre 1890 et 1899, est passé par un minimum au cours des décennies 1920-1929 ou 1930-1939, et a presque partout augmenté entre 1940 et 1949 pour diminuer de nouveau entre 1950 et 1959 (atteignant alors dans certaines stations des valeurs minimales). Rosenan ajoute que, sauf en ce qui concerne la dernière décennie, les tendances qui se sont manifestées au Moyen-Orient quant à la pluviosité (et à la température) ont été analogues à celles qui ont été constatées à Athènes et à Rome.

Arakawa (1956*a*, *b*) a constaté qu'au Japon la quantité annuelle moyenne des précipitations avait diminué vers la fin du siècle dernier, puis, de nouveau, vers 1940. Étant donné qu'il ressort des variations du niveau du fleuve à Hankéou (Chine) et des observations pluviométriques à Séoul (Corée) que ces villes ont également connu un minimum analogue vers la fin du siècle dernier, Arakawa admet que la variation de pluviosité a été, dans tout l'Extrême-Orient, analogue à celle du Japon.

Dans un document qu'il a préparé pour le présent colloque, K. M. Rao traite des tendances de la pluviosité dans les zones arides et semi-arides de l'Inde, et il arrive à la conclusion qu'il n'y a pas eu depuis quatre-vingts ans, dans ces régions, de modification statistiquement significative de la pluviosité annuelle ou saisonnière. Ainsi se trouvent confirmés les résultats auxquels étaient déjà arrivés Pramanik et Jagannathan (1954), mais ces derniers auteurs indiquaient une tendance de plus en plus marquée à un déficit pluviométrique près des collines du nord et du nord-est de l'Inde, alors que le volume des pluies de mousson du sud-ouest tendait au contraire à prendre de plus en plus fréquemment des valeurs supérieures à la moyenne (la pluviosité ayant cependant, en certains endroits bien déterminés, tendance à décroître). Dans une étude portant sur cent années d'observations pluviométriques à Karachi, Naqvi (1958) a indiqué qu'en joignant les points correspondant aux « normales » des périodes prenant fin en 1886, 1890, 1900, 1910, 1920 et 1940, on obtient une courbe ascendante. Il ne voit rien là de très significatif. Mais il soutient que les données qu'il a étudiées font apparaître, en ce qui concerne les variations des hauteurs de pluie, un cycle de cinquante ans (amplitude : 38 mm environ) dont il n'avait pas de raison de mettre en doute l'existence.

Dans l'étude déjà mentionnée, Dubief déclare qu'à Alger la pluviosité ne paraît avoir subi au cours des cent vingt dernières années aucune variation séculaire ; mais il indique que les observations de pluie des stations du Nord saharien (et des stations de Tripoli, Benghazi et Alexandrie) semblent présenter de 1884 à 1896 un maximum de pluie qui ne s'est pas reproduit depuis. Il signale également qu'il semble y avoir une relation inverse entre la pluviosité sur le littoral et sur les zones les plus arides de l'Afrique du Nord.

Dans leur étude sur l'évolution de la pluviosité en Argentine, Schwertdfeger et Vasino (1954) ont indiqué que, pour la période 1941-1950, le chiffre correspondant à la hauteur annuelle des précipitations dans le nord-est du pays était de 35 % supérieur à celui de 1902-1911. Prohaska (1951) n'a pour sa part réussi à mettre en évidence, en ce qui concerne l'évolution de la pluviosité dans les Orcades du Sud, aucune tendance bien définie.

Dans le document d'Hofmeyer et Schulze qui a déjà été mentionné, il a été indiqué qu'au Cap la pluviosité a eu nettement tendance à diminuer au cours de la période 1901-1930. En ce qui concerne l'Indonésie, F. H. Schmidt indique que, d'après les données disponibles, les variations de la pluviosité semblent avoir été de sens opposé dans le nord et dans le sud de l'archipel, passant vers 1925 par un minimum dans les stations méridionales et par un maximum dans les stations septentrionales. Schmidt attribue ces anomalies à des variations anormales dans la zone de convergence intertropicale.

Kraus a fait sur les fluctuations de la pluviosité, notamment dans les régions tropicales, des études particulièrement intéressantes (1954, 1955*a*, *b*, 1958). Son étude de 1954 porte sur les variations séculaires du régime des pluies dans le sud-ouest de l'Australie. Il y montre, en analysant une longue série d'observations recueillies dans les États de Victoria et de Nouvelle-Galles du Sud, que la pluviosité estivale est passée par un minimum vers la fin du siècle dernier et a ensuite progressivement augmenté pendant cinquante ans, tandis que la « pluviosité hivernale » évoluait en sens contraire. Kraus a constaté que les pluies printanières et automnales avaient été affectées par des fluctuations d'une amplitude beaucoup plus grande, marquant la possibilité d'une discontinuité dans l'évolution du climat vers la fin du siècle dernier. Dans son document relatif aux variations séculaires des régimes pluviométriques tropicaux, Kraus (1955*a*) constate encore que la hauteur des pluies tropicales a brusquement diminué à la fin du XIX[e] siècle, ce qui pourrait, selon lui, avoir été en grande partie dû à un rétrécissement de la zone tropicale pluvieuse et à un raccourcissement de la saison des pluies. Dans un autre document, Kraus (1955*b*) indique que, le long des côtes orientales de l'Australie et de l'Amérique du Nord, les précipitations ont subi aux latitudes moyennes (inférieures à 45° environ) à peu près les mêmes changements de régime qu'aux latitudes tropicales, les variations les plus importantes se plaçant en automne et en été pour l'Amérique du Nord, en automne et au printemps pour l'Australie. Kraus considère qu'il n'y a aucune raison sérieuse de penser que des fluctuations mondiales se soient produites dans le régime des pluies au nord du 40[e] degré de latitude boréale et il fait observer qu'au voisinage des tropiques le récent retour à des conditions un peu plus humides a coïncidé, dans l'est de l'Australie et de l'Amérique du Nord, avec un accroissement de la fréquence des cyclones tropicaux. Brunt et Hogan ont, en 1956, constaté que ces cyclones étaient devenus, au cours des quinze années précédentes, plus fréquents qu'auparavant sur la côte australienne ; et, en ce qui concerne la côte américaine, le phénomène a été mis en lumière par Rodewald (1958).

Dans un intéressant résumé de ses travaux sur les changements climatiques (tels qu'ils ressortent des observations météorologiques), Kraus (1958) soutient que ces changements ont été particulièrement apparents le long des frontières mouvantes des zones climatiques.

Il fait observer que, depuis quelques centaines d'années, des changements frappants se sont produits dans les glaciations aux frontières des régions alpines et subarctiques et que la superficie et la durée saisonnière des glaces de mer ont considérablement varié ; l'analyse des données relatives à la pluviosité et au débit des cours d'eau montre d'ailleurs, soutient-il, que des fluctuations d'une amplitude au moins égale se sont produites en bordure des zones arides subtropicales. Les études de Kraus montrent que, pendant la partie du siècle dernier pour laquelle on dispose de relevés précis, la hauteur des précipitations est, en général, demeurée, dans les régions subtropicales, supérieure au chiffre moyen de la période 1881-1940 ; elles indiquent également que la période de sécheresse qui s'est instaurée assez brusquement à la fin du siècle dernier (les moyennes à long terme subissant des variations de plus de 30 %) a été marquée par une extension des zones arides. Kraus signale, par exemple, en ce qui concerne la pluviosité à Aden, avant et après 1894, l'existence d'une différence de 84 %. Il indique que, dans des zones climatiques correspondantes de part et d'autre de l'équateur, les changements observés se sont produits simultanément, mais il ajoute que les climats régnant sur la calotte glaciaire antarctique, sur le Sahara central et sur la forêt pluvieuse du bassin de l'Amazone ne paraissent pas avoir, dans le même temps, baeucoup varié. Il ne semble pas que l'on puisse, en ce qui concerne les fluctuations mondiales de la pluviosité, ajouter grand-chose aux constatations de Kraus. Les études de ce dernier et les divers documents susmentionnés donnent bien l'impression qu'il s'est produit à la fin du siècle dernier des phénomènes qui ont affecté non seulement le régime des températures, mais aussi le régime des pluies ; autrement dit, les données dont on dispose — qu'elles aient trait à la pluviosité ou à la température — donnent à penser qu'il a dû se produire depuis cent ans une fluctuation qui serait actuellement sur le point de s'annuler ou de s'inverser.

LA PRESSION ATMOSPHÉRIQUE, LES SITUATIONS ISOBARIQUES ET LES VENTS

Il a été question dans l' « Avant-propos » de la nécessité d'étudier les fluctuations climatiques du point de vue dynamique, autrement dit d'interpréter les variations de température, de pluviosité, etc., en fonction du déplacement des masses d'air. De nombreux chercheurs l'ont effectivement tenté, mais généralement à l'aide des observations de pression et de vent en surface. Cette attitude se comprend dans la mesure où l'on ne dispose pas encore d'une suffisamment longue période d'observations en altitude sûres. Les conclusions auxquelles on arrive en se fondant uniquement sur les observations en surface n'en risquent pas moins d'être fausses. Des progrès considérables ont été déjà accomplis dans le domaine de la climatologie en altitude et, bien que mes connaissances sur la stratosphère moyenne ou supérieure soient encore assez limitées, on ne peut plus douter qu'il existe, dans la haute aussi bien que dans la basse atmosphère, des systèmes de circulation bien déterminés dont certains prédominent sur les autres. On est en outre de plus en plus persuadé qu'il peut y avoir une certaine interdépendance entre les vents à haute et à basse altitude. D'après les travaux de Veryard et Ebdon (1960, 1961) et de divers autres chercheurs il semble que la haute atmosphère soit le siège de variations séculaires et de fluctuations à plus courte période. Au fur et à mesure que l'on dispose d'un ensemble plus complet d'observations en altitude, il devient possible de déterminer les incidences des fluctuations climatiques sur l'atmosphère supérieure et d'établir un tableau à trois dimensions de ces fluctuations permettant de mettre en évidence les modifications de la « prétendue » circulation générale. Si nous mettons le mot « prétendue » entre guillemets, c'est parce qu'il est aussi difficile de définir une normale ou une moyenne relative à la circulation qu'une normale ou une moyenne de température, de pluviosité, etc., il est même plus difficile de définir une circulation générale « normale » par suite de la courte période pendant laquelle on dispose de renseignements sur le comportement de la circulation atmosphérique dans la troisième dimension. Pour le moment, nous ne pouvons que passer en revue les différentes études qui traitent de la façon dont ont varié, au cours de la période pour laquelle on dispose d'observations météorologiques, le champ de pression et les vents.

Dans une première étude, Scherhag (1936), après avoir examiné l'évolution du champ de pression au cours des vingt-cinq années précédentes, en arrivait à conclure à un renforcement des « centres d'action » positifs et négatifs. Peu après, Ångström (1959) attribuait à une « amélioration de la circulation » le réchauffement constaté aux hautes latitudes et l'affaiblissement correspondant des variations annuelles de la température.

Ahlmann (1948), suivi par d'autres chercheurs, a exprimé l'opinion que le retrait des glaciers scandinaves au cours de la période de réchauffement mentionnée plus haut, avait été essentiellement dû à une advection accrue d'air chaud et il a publié des données en montrant qu'il y avait eu un renforcement des vents d'ouest à sud-ouest. Par la suite, Hesselberg et Johannessen (1958) ont démontré que le Spitzberg, lieu des plus forts accroissements de température (7 °C en hiver de 1917 à 1922), s'était, depuis le début du réchauffement, trouvé placé plus souvent que jadis sur la trajectoire des dépressions — qui, auparavant, passaient en général plus au sud — et avait en conséquence été plus fréquemment soumis à des vents d'ouest à sud-ouest ; ils ont fait observer que les vents cycloniques balayent l'air froid des basses couches qui se forment par suite du rayonnement par temps froid et vent calme.

D'après l'examen des *Historical Northern Hemisphere Daily Weather Maps*, Brier (1947) considère qu'il y a eu, de 1899 à 1939, une diminution appréciable de la masse totale de l'air sur l'hémisphère nord — particulièrement marquée aux hautes altitudes. Il a incidemment fait observer que la relation entre l'indice zonal de circulation et les variations de la température n'est pas linéaire.

Lysgaard (1949) a trouvé que, pendant la période 1910-1940, les pressions de janvier avaient baissé au-dessus de la partie septentrionale de l'Atlantique-Nord, tandis qu'elles augmentaient dans sa partie méridionale (où l'anticyclone des Açores s'était sensiblement étendu et renforcé), et que l'anticyclone sibérien s'était également renforcé. Il a également indiqué que les pressions auraient, en hiver, augmenté pendant ladite période au-dessus des terres, et diminué au-dessus des océans, dans la zone tempérée boréale, tandis que le contraire se serait produit dans la zone tempérée et la zone subtropicale de l'hémisphère sud. Pour l'été, Lysgaard a constaté une baisse considérable de pression sur l'Europe occidentale, l'Asie centrale et l'Australie méridionale, mais une hausse nette sur l'Atlantique entre l'Afrique occidentale et l'Amérique du Nord ainsi qu'à La Plata, sur la Nouvelle-Zélande et le Japon. Lysgaard a déduit de l'examen des gradients de pression que le mois de janvier avait été marqué, depuis la fin du siècle dernier jusqu'en 1935 (année à partir de laquelle se serait produit un brusque renversement), par un accroissement des vents de sud-est autour de la mer du Nord et de la Baltique et par un renforcement des vents d'ouest sur l'Europe occidentale et la Scandinavie méridionale ; il estimait également que les alizés de nord-est devaient avoir été particulièrement forts jusque vers 1939. Il admettait qu'il y avait eu, pendant la période de réchauffement, une importante intensification en hiver du transport des masses d'air atlantique vers l'Europe.

Petterssen (1949) a fait observer que tout accroissement systématique, dans une région donnée, de l'apport de masses d'air venant du sud doit être compensé ailleurs par une advertion du nord (à moins qu'il ne se produise une accumulation d'air dans l'Arctique) ; mais il a en même temps souligné que, puisqu'un accroissement des températures hivernales avait été constaté dans des régions où les vents prédominants pouvaient aussi bien souffler du nord que du sud, les changements qui s'étaient produits dans la circulation générale pendant la période de réchauffement devaient avoir été fort complexes. Après avoir déterminé, d'après les *Historical Daily Weather Maps*, les valeurs du bilan du transport total, du transport zonal et du transport méridien ainsi que l'importance des échanges méridiens, il est parvenu à la conclusion que les fluctuations climatiques récentes avaient sans doute été dues à des changements d'intensité des sources et puits de chaleur conduisant à : *a*) une certaine réduction de la circulation zonale et à une intensification de la circulation méridienne ; *b*) un accroissement de l'activité cyclonique et des échanges méridiens dans la région « Terre-Neuve - Atlantique-Nord-Ouest » et dans la région « Méditerranée-Balkans » ; *c*) un accroissement du transport d'air s'effectuant de l'est de l'Europe centrale vers la Scandinavie et de l'est de l'Atlantique-Nord vers l'Islande et la mer de Norvège, avec, dans le secteur atlantique, une prépondérance du bilan d'advertion vers le nord compensée, à d'autres longitudes, par un transport d'air de l'Arctique vers le sud.

Petterssen a fait observer que, si le réchauffement avait correspondu à un apport plus important de chaleur à l'atmosphère dans son ensemble, il y aurait eu lieu de s'attendre à une augmentation du gradient de température entre l'Equateur et les pôles — mais à la surface du globe c'est l'inverse qui a été observé. En conséquence, il fallait s'attendre à un changement de signe contraire en altitude. Petterssen ajoutait que l'analyse de la pluviosité en Scandinavie semblait indiquer que les pluies avaient, de façon générale, augmenté dans cette région pendant la période de réchauffement, ce qui permettait de supposer qu'il y avait eu un accroissement du gradient de température vertical.

Dans l'une de ses plus récentes études, Scherhag (1950) a indiqué que la circulation générale avait sans doute atteint son maximum d'intensité entre 1921 et 1930 pour diminuer entre 1931 et 1940, mais que, en dépit de ces modifications, l'élévation de température paraissait se poursuivre dans certaines régions.

Dans une étude sur la variabilité des températures d'été en Suède, Wallén (1953) a calculé les écarts types mobiles et étudié les fluctuations de fréquence de diverses situations isobariques sur la Scandinavie méridionale ; il a constaté que l'élévation des températures d'été avait été liée à une diminution de fréquence des situations méridiennes du nord et à une augmentation de fréquence des situations méridiennes du sud ainsi que des situations zonales ; une forte variabilité est associée aux circulations méridiennes et une faible variabilité aux circulations zonales. Il a également émis l'idée qu'un fort flux méridien pouvaient coexister et que, puisqu'il apparaissait que la circulation générale s'était nettement intensifiée au cours des années passées, les « blocages » pouvaient constituer une manifestation de cette amélioration de la circulation générale provoquant une augmentation des échanges d'air entre les hautes et les basses latitudes. Les blocages, selon lui, sont favorisés par l'existence d'un fort courant d'ouest, en amont du lieu où ils se produisent.

Mather (1954) a constaté, au moyen d'une étude comparative, que les périodes 1900-1930 et 1931-1940 avaient, en ce qui concerne les positions des figures isobariques dans l'hémisphère nord, différé considérablement l'une de l'autre. Il a fait observer que les dépressions d'Islande et des îles Aléoutiennes s'étaient déplacées de 5 à 10° de longitude vers l'est, tandis que l'anticyclone sibérien s'était déplacé d'une distance analogue vers l'ouest, et que des fluctuations de signe opposé pour les températures et les précipitations s'étaient produites dans divers segments de l'hémisphère nord en même temps que des changements dans les phénomènes de blocage. Il a ainsi montré qu'il pouvait y avoir dans des zones distinctes des changements climatiques synchrones liés les uns aux autres, bien que de signes différents.

Dans une étude de longues séries d'observations de température à Édimbourg, Copenhague, Berlin, Wilno et Vienne, Fay (1958) a publié des courbes qui font apparaître des différences appréciables d'un mois à l'autre et d'une station à l'autre; il s'est également efforcé de déterminer les systèmes moyens de circulation associés aux fluctuations de température observées. Il est arrivé à la conclusion que, pendant la période étudiée, il y avait eu un accroissement du gradient de pression lié à un déplacement vers le sud des dorsales moyennes Açores-Europe et à un déplacement du lit des vents d'ouest vers le nord.

Dans une intéressante étude, Bjerknes (1958) s'efforce d'apprécier, par rapport aux fluctuations climatiques, l'importance relative des variations qui se sont produites dans les différentes branches de la circulation générale. Il étudie en particulier les observations des vents de navires pour les périodes 1906-1913 et 1922-1937 pour les parallèles 1°, 7°, 19° et 25° et il calcule, pour chacune de ces deux périodes, la valeur de la composante méridienne et de la composante zonale des alizés. A partir de ces données et d'une analyse de leurs effets probables sur le flux de chaleur méridien se traduisant par une modification, dans le temps, des alizés, il arrive à la conclusion qu'il y a eu à la fois intensification aux latitudes moyennes du flux de chaleur méridien dû aux tourbillons atmosphériques et accroissement de la circulation de Hadley. Il soutient que c'est seulement en s'appuyant sur l'hypothèse d'un accroissement du flux de chaleur résultant de la turbulence à grande échelle que l'on peut comprendre le réchauffement qui s'est produit dans les climats septentrionaux avec une amplitude maximale dans l'Arctique.

Lamb et Johnson (1959) sont les auteurs d'un autre document digne d'intérêt concernant les variations climatiques et les changements observés dans la circulation générale. Ils ont tiré parti de toutes les données qu'ils avaient pu recueillir et ont ainsi réussi à compléter les études qui avaient antérieurement été effectuées sur les configurations du champ de pression. Ils ont notamment élaboré, pour les mois de janvier et de juillet, des cartes moyennes mensuelles de pression au niveau de la mer, couvrant une aussi grande partie du globe que possible et remontant dans le passé jusqu'aux premières années pour lesquelles il a été possible de trouver des observations. Les commentaires qui figurent dans leur étude ont essentiellement trait aux cartes concernant le mois de janvier (depuis 1760). Ils ont constaté que les mouvements atmosphériques à la surface du globe ont varié avec les époques et les régions et ils ont en particulier observé que, pour janvier, la circulation avait, depuis 1800 environ, augmenté d'intensité dans de nombreuses régions, avec un maximum dans les années 1920-1940. Cette évolution a été particulièrement nette sur l'Atlantique-Nord, où l'intensification de la circulation a été particulièrement marquée entre la période 1880-1889 et la période 1920-1929. Aucun rapport n'a pu être découvert entre l'intensité des mouvements de l'air et la latitude des principaux centres d'action; les configurations du champ de pression par « circulation » rapide et par « circulation » lente se sont, d'autre part, révélées très diverses selon les années et décennies.

Dans un document plus récent, Bjerknes (1960) attire l'attention sur le fait que l'énergie solaire nécessaire à l'entretien de la circulation atmosphérique est reçue en majeure partie par l'intermédiaire des océans. Il a examiné pour deux périodes de huit ans (1890-1897 et 1926-1933) les observations de navires concernant la température de la mer et il a ainsi constaté que la plus importante des variations à long terme avait été un réchauffement le long de la partie du Gulf Stream qui affecte, au voisinage de l'Amérique du Nord, l'allure d'un courant-jet; ce réchauffement aurait atteint son maximum (+2 °C environ) au sud de Terre-Neuve. En rapprochant cette variation de la variation correspondante des pressions atmosphériques, il est parvenu à montrer qu'une intensification des hautes pressions subtropicales avait entraîné un renforcement des alizés, un renforcement des vents d'ouest jusqu'au 55e degré de latitude N. et une augmentation modérée de la composante sud-nord des vents soufflant au large de l'Amérique du Nord, l'ensemble de ces modifications entraînant un renforcement du Gulf Stream. Dans une zone comprise entre le 50e et le 60e degré de latitude N., il y avait eu, surtout à l'est du 30e degré de longitude O., un net abaissement de la température. Cette région reçoit cependant directement les eaux du Gulf Stream, mais, étant donné que les changements de pression qui y ont été observés impliquent un net accroissement de l'entraînement des eaux superficielles par les vents cycloniques, Bjerknes a émis l'idée qu'il avait pu en résulter un accroissement du phénomène de pompage des eaux profondes et, par conséquent, un refroidissement de la surface de la mer. Bjerknes étudie ensuite la nature de la dépression d'Islande et son cycle thermique annuel; cette dépression, avec son tourbillon à centre froid en altitude, est en rapport d'échanges thermiques directs avec l'atmosphère. En s'appuyant à la fois sur des renseignements historiques concernant la température de la mer dans le nord-est de l'Atlantique et sur les valeurs barométriques à Vestmanaeyjar, au sud-ouest de l'Islande (valeurs qui permettaient de se faire une idée des variations qui s'étaient produites d'une année à l'autre dans la valeur du tourbillon de la dépression d'Islande), il constatait que la température de l'océan et le tourbillon présentaient une variation à longue période analogue : diminution lente de 1890 à 1920 environ suivie d'une remontée rapide entre 1920 et 1935. Bjerknes en déduisait que tout creusement de la dépression d'Islande (correspondant à un accroissement de la force d'entraînement des eaux superficielles par les vents cycloniques) est associé à un refroidissement avec les variations affectant l'océan deux ans après les modifications de l'atmosphère.

Selon cette hypothèse, le rôle essentiel reviendrait à l'atmosphère, à l'influence de laquelle l'océan ne ferait que réagir. L'étude de Bjerknes se terminait par un examen du mécanisme des fluctuations à long terme qui se font sentir dans l'atmosphère et dans l'océan (les dernières retardant apparemment de deux ou trois ans sur les premières) et l'auteur insistait sur la nécessité d'étudier les effets de réaction.

De nombreux documents concernant les rapports entre les fluctuations climatiques et les modifications de la circulation générale ont été publiés par les chercheurs russes, et peut-être certains de ceux que nous avons dû, en raison des difficultés de traduction, passer ici sous silence, comptent-ils parmi les plus importants. Il a été donné lecture d'une intéressante étude d'A. A. Girs à l'occasion de la conférence que l'Académie new-yorkaise des sciences et la Société américaine de météorologie ont organisée en janvier 1961 à New York sur les variations solaires, les changements climatiques et les problèmes géophysiques connexes. Recourant au système russe de classification des situations isobariques en trois types essentiels — situation d'ouest, situation d'est et type méridien, sur l'Eurasie — Girs cite des chiffres qui témoignent de la prédominance du régime d'ouest en 1900-1929, du régime d'est en 1930-1939 et en 1949-1957, et du régime méridien en 1940-1948, avec un système mixte d'ouest et méridien en 1891-1899. Il fait remarquer que le régime d'est est associé à une importante advection sud-nord vers le Spitzberg, ce qui explique qu'on ait pu constater de 1930 à 1939 un remarquable réchauffement du secteur européen de l'Arctique. Il exprime également l'opinion que l'Arctique a maintenant cessé de se réchauffer et tend au contraire à se refroidir. Belinsky (1957) a publié un document dans lequel il traite de l'utilité que peut présenter, pour les prévisions météorologiques à longue échéance, l'étude de certains processus atmosphériques et où il indique qu'il se peut que le réchauffement qui s'est produit depuis 1910 ait été associé à une intensification de la circulation entraînant, non seulement une plus grande activité cyclonique au-dessus des océans, mais aussi une plus grande activité anticyclonique au-dessus des continents. Il estime également que la quantité d'air accumulée au-dessus de l'hémisphère nord a dû diminuer au cours des récentes décennies, et en particulier de 1930 à 1939, et que les échanges d'air entre les deux hémisphères ont dû s'atténuer après 1930, phénomène auquel a correspondu la diminution de pluviosité observée de 1930 à 1940 dans la zone équatoriale et sur les océans Indien et Pacifique.

Dans un document plus ancien, Vitels (1948) avait montré que, dans la zone comprise, au nord du cercle arctique, entre la presqu'île de Kola et le 100e degré de longitude E., l'activité cyclonique avait été, en général, de 40 à 55 % plus élevée de 1920 à 1939 que de 1900 à 1919. Pour la période de décembre à février, cet accroissement de l'activité cyclonique s'était même chiffré par 50 à 70 % à l'est de l'Ob et par 70 % ou davantage au-dessus du Taïmyr.

Tsuchiya (1959) a étudié les changements qu'avaient subis, de 1901 à 1940, sur l'hémisphère nord et plus particulièrement en Extrême-Orient, les situations isobariques en surface. Il est arrivé à la conclusion que l'anticyclone d'hiver eurasien était intensifié et que la dépression de mousson s'était creusée. Yamamoto (1958) s'est efforcé de relier les variations séculaires qui se sont produites en Europe, en Amérique et en Extrême-Orient aux variations de l'anticyclone du Pacifique et il a pensé que c'est par l'étude du courant-jet subtropical qu'il pourrait y arriver. Ses arguments ne sont pas faciles à suivre, mais il a parfaitement raison d'insister pour que les variations séculaires du courant-jet fassent l'objet d'un examen approfondi.

On ne possède que peu d'études sur les fluctuations du champ de pression dans l'hémisphère austral. Loewe et ses collaborateurs (1952) ont examiné des données relatives aux vents recueillies à l'île de Heard, d'une part entre 1856 et 1859, et d'autre part au cours des années 1949-1951, et ils ont constaté que le vecteur vent moyen avait tourné et était passé de 310° à 258°; des variations du même ordre ont d'ailleurs été mises en lumière par la comparaison d'observations de navires effectuées, à des époques lointaines et à des époques beaucoup plus récentes, dans la zone comprise entre 40 et 50° S. et entre 60 et 100° E. Dans une étude portant sur la façon dont ont varié en Australie, de 1880 à 1950, les températures, les pressions et les pluies, Deacon (1953) émet l'opinion que, dans cette région, la trajectoire moyenne des anticyclones a eu tendance, pendant la seconde moitié de la période considérée, à passer plus au sud qu'auparavant. Lamb et Johnson (1959) ont constaté que, dans l'hémisphère austral, l'axe de l'anticyclone subtropical était nettement plus au sud qu'en moyenne, avant 1895, et en conséquence nettement plus au nord entre 1922 et 1940. Mais, dans son étude sur l'évolution saisonnière des situations isobariques dans la région de la Nouvelle-Zélande, de Lisle (1947) considère qu'il y aurait eu un déplacement irrégulier vers le sud de l'anticyclone subtropical moyen et de la zone des vents d'ouest des latitudes tempérées.

Dans ses différentes études sur les fluctuations climatiques, Kraus (1954, 1955*a*, *b*, 1956) s'est efforcé d'interpréter les résultats concernant les variations de la pluviosité et les variations de température en fonction de modifications de la circulation atmosphérique. Il a, par exemple, constaté que, dans la partie méridionale de la Nouvelle-Galles du Sud, il existe entre la pluviosité et la force moyenne des vents d'ouest à 30 mb, une corrélation qui est positive en hiver et négative en été. Il en a conclu que les variations du régime pluviométrique dans le sud-est de l'Australie (voir plus haut) devaient avoir été liées à une intensification des vents d'ouest en altitude présentant aux environs de 1900 un maximum suivi d'une atténuation de ces vents. Il a également fait observer que, pendant la période de maximum du flux moyen d'ouest, la formation des cyclones sur la côte orientale de l'Australie pouvait avoir été entravée et que, durant cette période, l'abondance des pluies de mousson, avait été, dans le Queensland tropical, inférieure à la normale. Kraus a également constaté que, dans le nord de l'Inde, la pression moyenne d'été présentait une variation séculaire en baisse et la pression moyenne d'hiver une variation séculaire en hausse, des variations de pression analogues s'étant d'ailleurs produites, avec une intensité saisonnière encore plus grande, sur l'Europe orientale, la Sibérie et l'Asie orientale. Il a émis l'idée qu'à un lent accroissement des oscillations saisonnières de la pression sur l'intérieur de l'Eurasie pouvaient avoir correspondu des modifications du régime des vents conduisant, en Extrême-Orient, à des hivers plus froids, et, en Europe, à des hivers plus courts et plus chauds (l'évolution se faisant en sens inverse en ce qui concerne les étés). Kraus en est arrivé à conclure que c'était une intensification de la circulation générale permanente dans l'hémisphère nord qui avait entraîné un accroissement du transport des masses d'air en direction de l'Arctique et contribué de ce fait au retrait des glaces arctiques, alors que l'absence, dans l'hémisphère austral, de variations à grande échelle de la circulation générale expliquait probablement qu'il ne se soit, selon toute apparence, produit dans l'Antarctique aucun changement climatique très net. En outre, étant donné que la force des courants périodiques de mousson semble être inversement proportionnelle à celle des courants zonaux, l'interaction qui en résulte peut, selon Kraus, donner lieu à un développement considérable de petites perturbations de l'équilibre climatique. Dans une étude plus récente (1958), Kraus résume ses idées et présente une explication théorique des causes des fluctuations climatiques, telles qu'elles peuvent être décelées d'après de longues séries d'observations. Mais c'est là un document qui sera sans aucun doute discuté lors de la troisième séance du présent colloque.

En somme, il semble que, depuis la fin du siècle dernier jusqu'à une époque récente, il y ait eu un accroissement de l'activité atmosphérique, une intensification des échanges d'air entre l'équateur et les pôles, et une augmentation de la turbulence ; autrement dit, l'intensification de la circulation atmosphérique a été accompagnée d'un certain renforcement de la circulation zonale et d'un renforcement des phénomènes de blocage (ou peut-être d'un simple déplacement de la région où ils se produisent de préférence), ce qui a conduit à une intensification de l'activité cyclonique au-dessus des océans, à un développement de l'activité anticyclonique au-dessus des continents et, peut-être aussi, à une certaine modification de l'ampleur des échanges de masses d'air entre les deux hémisphères, ou à une translation des courants correspondants. Tous ces changements se sont produits de façon irrégulière — avec des retards dans certaines régions — et (en ce qui concerne tout au moins la température) ils ont été plus sensibles dans l'hémisphère nord que dans l'hémisphère sud et plus marqués aux hautes altitudes qu'aux latitudes plus basses.

COMMENTAIRES

Bien que les nombreuses études qui traitent des fluctuations climatiques au cours de la période pour laquelle on dispose d'observations météorologiques soient fondées sur des matériaux très divers — dont certains sont de valeur douteuse — ne se rapportent pas toutes aux mêmes périodes et n'aient pas toutes été réalisées selon les mêmes méthodes, on peut essayer d'en tirer certaines conclusions générales. Il semble peu douteux que, depuis la fin du siècle dernier jusqu'à l'époque actuelle, il se soit produit dans les températures, la pluviosité et les types de circulation d'importants changements dont nous avons déjà souligné, à la fin de chacune des sections appropriées, les principaux traits. Il semble évidemment raisonnable de soutenir que le retrait des glaciers et la fonte des glaces de l'Arctique peuvent être attribués à un réchauffement de l'air et à une pénétration plus profonde des eaux atlantiques chaudes dans les mers polaires, avec renforcement corrélatif des alizés. Considérée dans son ensemble, la répartition géographique des changements de température et de pluviosité (mis à part, bien entendu, les petits changements locaux dus à l'urbanisation, à l'afforestation, à la culture intensive, à l'irrigation, etc.) peut tout entière s'expliquer par des modifications de la circulation générale. Mais les résultats auxquels on est parvenu montrent que l'effet primaire de tel ou tel facteur causatif peut se trouver masqué ou totalement déformé par les effets secondaires introduits par les modifications de la circulation générale ou par la répartition des mers et des terres. Mais quels ont été les facteurs causatifs des changements dont nous avons ici à nous occuper (et qui semblent parfois ne faire que reproduire ceux qui ont déjà eu lieu au cours de l'histoire) ? L'atmosphère est-elle apte, avec ses processus non linéaires, à enfanter spontanément de tels changements — disons, par suite de la capacité thermique des océans ou par suite de modifications de l'albedo ? On pourrait sans doute soutenir que, si l'accroissement de température a été, dans la zone tempérée australe, moins marqué qu'ailleurs, cela a tenu à l'influence modératrice des importantes masses d'eau que l'on rencontre aux hautes latitudes de l'hémisphère austral. Les changements observés ont-ils été provoqués par quelque fluctuation de l'activité solaire, par un accroissement du gaz carbonique ou par une émission de poussières volcaniques ? Ne constituent-ils qu'un élément d'une fluctuation à plus grande échelle, sont-ils la résultante de variations à courte période et de variations à longue période conjuguant leurs actions sous l'effet du hasard ? Toutes ces questions seront sans aucun doute discutées au cours de la troisième séance du présent colloque.

Les fluctuations climatiques, même à petite échelle, peuvent avoir, surtout au voisinage de certains « seuils » (et celui du 0 °C est particulièrement important pour les activités humaines), des effets considérables. Il y a donc lieu, compte tenu de leurs conséquences économiques (dont il sera question lors de la quatrième séance), d'étudier de la façon la plus détaillée ces fluctuations climatiques, sans perdre de vue, en particulier, que de telles études sont peut-être susceptibles de conduire à des méthodes de prévision à longue échéance. Le présent colloque nous aidera, espérons-le, à trouver la bonne voie.

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SUR LA DÉTERMINATION DE LA STABILITÉ DES SÉRIES CLIMATOLOGIQUES

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INTRODUCTION

D'après l'édition provisoire du *Vocabulaire météorologique international* publié en 1959 par l'Organisation météorologique mondiale (OMM), le climat est « l'ensemble fluctuant des conditions atmosphériques caractérisé par les états et les évolutions du temps au cours d'une période suffisamment longue dans un domaine spatial déterminé ».

L'intérêt de cette définition réside pour nous dans le fait qu'elle reconnaît aux conditions atmosphériques un caractère à la fois évolutif et fluctuant, le premier de ces deux aspects étant concrétisé par des variations systématiques des éléments météorologiques lors, par exemple, du passage d'une perturbation, ou en liaison avec la succession des saisons au cours de l'année, et le second se traduisant par les propriétés aléatoires que possèdent les séries chronologiques habituellement tirées des observations météorologiques, soit sous la forme de valeurs moyennes ou, encore, de valeurs extrêmes.

Dans ce qui suit, nous nous occupons uniquement de la description du climat au moyen de ces séries chronologiques et, plus particulièrement, des changements de climat que l'analyse de ces séries permet de mettre en évidence.

Il est clair qu'en raison de l'existence reconnue de composantes aléatoires dans ces séries, les méthodes statistiques seront les mieux appropriées pour résoudre ce problème d'une manière objective.

GÉNÉRALITÉS

Si on désigne par x_i, avec $i = 1, 2, \ldots, n$, les termes d'une série chronologique, le fait de reconnaître dans cette série l'existence d'une composante aléatoire revient à admettre qu'à chaque terme x_i, se trouvent associées une variable aléatoire X_i et une fonction de distribution $f_i\ (X_i)$ telles que $f_i(x_i)$ fournit la probabilité d'avoir $X_i \leqslant x_i$.

Le cas le plus simple est celui d'une série aléatoire pure dans laquelle tous les termes sont distribués d'une manière indépendante suivant la même loi de probabilité, c'est-à-dire que les fonctions $f_i(X_i)$ se confondent toutes avec une seule et même fonction $f(X)$. Par contre, on peut considérer que le cas le plus général compatible avec l'hypothèse d'un climat invariable est celui d'une série aléatoire stationnaire dans laquelle un nombre fini de m termes consécutifs sont liés en probabilité par une loi de dépendance qui reste la même quels que soient les m termes consécutifs choisis dans la série.

L'analyse statistique d'une série a pour but de faire ressortir les hypothèses que l'on peut adopter pour les $f_i(X_i)$. Elle s'effectue au moyen de tests qui permettent de conclure soit au caractère aléatoire pur de la série, soit à une organisation particulière incompatible avec ce caractère.

Ces tests consistent généralement dans le calcul d'une fonction de l'ensemble des termes de la série pris dans leur ordre naturel, qui est appelée le statistique du test et dont la distribution est parfaitement connue dans l'éventualité où la série est effectivement aléatoire pure, et cette dernière éventualité est acceptée ou rejetée selon que la valeur trouvée pour le statistique est à l'intérieur ou à l'extérieur d'un intervalle d'acceptation correspondant à une probabilité donnée d'avance. La région extérieure de l'intervalle d'acceptation est la région critique et la probabilité correspondant à cette région est le niveau de signification. Celui-ci est toujours choisi suffisamment petit.

Notons aussi que chaque test est ordinairement construit de telle sorte qu'il permet de confronter l'hypothèse de travail avec une hypothèse alternative. Aussi, comme il existe, en principe, une infinité d'hypothèses alternatives [elles correspondent à toutes les possibilités de particulariser les $f_i(X_i)$], on ne peut généralement conclure au caractère aléatoire pur de la série qu'après l'avoir soumise à un ensemble de tests complémentaires.

De ce point de vue, il nous semble que les alternatives complémentaires qu'il suffit de vérifier sont respectivement la stabilité d'une valeur centrale telle que la moyenne ou la médiane, celle de la dispersion des termes de la série autour de cette valeur centrale et, enfin, l'absence de liaison entre termes consécutifs de la série. Il s'ensuit que le problème de l'établissement du caractère aléatoire pur d'une série se ramène à la recherche de tests spécifiques de chacune de ces alternatives et au choix, parmi ces tests, des plus sensibles aux alternatives considérées, c'est-à-dire de ceux ayant la puissance la plus élevée, sachant que (Mood, 1950) la puissance d'un test est la probabilité de rejeter l'hypothèse de travail lorsque l'alternative est vraie.

A ce propos, il est utile de rappeler qu'il existe deux sortes de tests d'hypothèses : ceux dans lesquels la loi $f(X)$ possède une forme analytique bien déterminée, qui est généralement celle de la loi normale (Laplace-Gauss), et ceux qui ne comportent aucune supposition particulière sur $f(X)$, sauf quelques propriétés analytiques très générales indispensables. Les premiers, que l'on nomme les tests paramétriques, présentent dans les cas les plus usuels l'avantage de posséder des propriétés optimales en ce qui concerne la sensibilité aux alternatives et de permettre la poursuite des calculs jusqu'à l'estimation des paramètres inconnus. La supériorité des seconds, qui sont les tests non paramétriques, réside, par contre, dans la grande généralité que l'absence de toute exigence relativement à $f(X)$ confère à leurs conclusions.

Aussi la marche à suivre qui nous paraît la plus rationnelle consiste à procéder tout d'abord à une analyse qualitative de la série au moyen de tests non paramétriques et à effectuer ensuite des estimations plus précises en s'appuyant sur des tests paramétriques. Dans ce dernier cas, et de toutes façons, il faudra toujours s'assurer au préalable de la validité des suppositions faites sur $f(X)$.

Cela étant, on peut se demander dans quelle mesure la méthode des tests telle qu'elle vient d'être esquissée, convient à l'étude des variations du climat puisque, on l'a vu plus haut, la série aléatoire pure ne constitue pas le schéma le plus général compatible avec la notion de climat stable.

En réalité, s'il est bien vrai qu'à l'échelle des valeurs diurnes il existe de fortes corrélations entre les valeurs consécutives des variables météorologiques, on sait aussi que l'effet de ces corrélations s'atténue de plus en plus lorsqu'on adopte des échéances de plus en plus éloignées et qu'en particulier, à l'échelle de l'année, la composante aléatoire devient largement prépondérante.

D'ailleurs, même si l'analyse d'une série stationnaire ne permet pas de conclure à son caractère aléatoire pur, il sera toujours intéressant de chercher à préciser la forme de l'organisation qui la régit.

Cette attitude est d'autant plus justifiée que si l'on voulait s'en tenir à la notion plus générale de stabilité du climat, il conviendrait de préciser à quelle échelle il convient de l'envisager.

CLASSIFICATION DES TESTS D'INDÉPENDANCE

CAS NON PARAMÉTRIQUE

Stabilité de la valeur centrale

Test de tendance (Mann, 1945). Ce test consiste dans le calcul, pour chaque terme de la série, du nombre de termes précédents qui lui sont inférieurs (ou supérieurs) et le statistique du test est la somme des nombres ainsi trouvés. Le nombre total de termes de la série étant n, la valeur moyenne du statistique est

$$\frac{n\,(n-1)}{4}$$

et pour $n \geqslant 10$ sa distribution devient très voisine d'une loi normale de variance

$$\frac{2n^3 + 3n^2 - 5n}{72}$$

Pour $n < 10$, Mann a donné une table des probabilités exactes du statistique.

Ce test peut être utilisé pour faire apparaître l'existence d'un nombre anormalement élevé de grandes valeurs au début ou à la fin de la série et, de ce fait, celle d'une augmentation ou d'une diminution systématique de la moyenne.

Par contre, il est évident qu'il ne fournit aucune indication lorsque la moyenne est oscillante. On peut toutefois remédier à cet inconvénient en appliquant le test sous une forme séquentielle, c'est-à-dire en calculant le statistique pour la série arrêtée au j^e terme, puis au $(j+1)^e$ terme et ainsi de suite jusqu'au dernier terme. En raison des propriétés du statistique qui viennent d'être rappelées on peut commencer avec $j = 10$.

Comme il s'agit d'un test non paramétrique, il est certain qu'il ne faut pas s'attendre que sa puissance soit optimale vis-à-vis de toutes les formes de tendances possibles; on retiendra cependant à ce propos que le statistique de ce test est fortement apparenté à celui du test de Mann Witney (voir Siegel, 1956, p. 126) et que, par conséquent, il possède vraisemblablement le même degré d'efficience.

Test de la stabilité de la médiane. Après avoir associé à chaque terme de la série un signe + ou un signe — selon qu'il est ou qu'il n'est pas supérieur à la médiane, on partage la série en un ensemble de k groupes d'éléments consécutifs. On forme ensuite la table de contingence à 2 lignes et k colonnes au moyen des nombres de signe + et de signe — contenus dans chaque groupe et le statistique du test est le χ^2 tiré de la manière habituelle de la table ainsi obtenue.

Si l'on note que, dans le cas où $k = 2$, la puissance du test est la plus élevée pour les séries les plus courtes (voir Siegel, 1956, p. 115), on en déduit que les meilleurs résultats seront obtenus en partageant la série dans le plus grand nombre de groupes possibles. Cela suggère l'emploi de groupes de 10 éléments consécutifs, afin de conserver aux fréquences théoriques dans la table de contingence une valeur minimale d'environ 5 nécessaire à la validité du test en χ^2.

Il est clair que ce test est moins sensible que le test précédent; on remarquera cependant que, dans le cas d'une série stationnaire, il pourra mettre des oscillations de la médiane en évidence, pour autant que ces oscillations soient suffisamment amples.

Test du signe de l'écart par rapport à une valeur centrale (Wald-Wolfowitz, 1940). Le statistique est ici le nombre de séquences homogènes (formées par la succession d'écarts de même signe) contenues dans la série. Sa valeur moyenne est

$$\left(\frac{2n_1 n_2}{n} + 1\right)$$

n_1 et n_2 étant respectivement les nombres d'écarts positifs et négatifs $(n_1 + n_2 = n)$ dans la série entière, et pour n_1 ou $n_2 > 20$, sa distribution autour de cette moyenne est approximativement normale avec une variance égale à

$$\frac{2n_1 n_2 (2n_1 n_2 - n)}{n^2 (n - 1)}$$

Pour n_1 et $n_2 < 20$, des valeurs critiques ont été calculées par Swed et Eisenhart (1943).

Ce test est également capable de mettre en évidence l'instabilité de la valeur centrale par rapport à laquelle les écarts ont été calculés. Bien qu'il ne soit pas très puissant, sa grande simplicité peut devenir très utile lors de l'examen de séries très longues.

Stabilité de la dispersion

Comme la stabilité de la dispersion des termes de la série entraîne celle des écarts par rapport à une valeur centrale déterminée, on peut se ramener au cas précédent en considérant la série des valeurs absolues de ces écarts.

Existence d'une corrélation interne

Test de la corrélation sériale (Wald-Wolfowitz, 1943). L'existence d'une corrélation interne, c'est-à-dire d'une corrélation entre termes consécutifs d'une série, est une forme particulière d'instabilité de la moyenne, puisque la distribution du prochain terme dépend, dans ce cas, d'un nombre fini de termes précédents; toutefois, en raison du nombre limité de termes consécutifs liés dans une telle série, l'effet de cette corrélation interne sur des termes très éloignés devient négligeable. Aussi, les tests de tendance ne sont-ils, en général, pas indiqués pour faire ressortir ces variations de la moyenne, et il convient de faire appel à des tests mieux appropriés.

Le test de Wald-Wolfowitz, qui est spécifique de la corrélation d'un terme de la série avec le suivant (corrélation sériale d'ordre 1), est basé sur le calcul du statistique :

$$R = \sum_{i=1}^{n} x_i x_{i+1}, \quad \text{où} \quad x_{n+1} = x_1$$

qui est approximativement distribué suivant une loi normale pour les grandes valeurs de n.

Malheureusement, comme la moyenne et la variance de R font intervenir les sommes des puissances des termes de la série jusqu'à l'ordre 4, l'application de ce test dans sa forme originale est, en général, très laborieuse.

On peut cependant simplifier le calcul en remarquant que la généralité du test n'est pas affectée si l'on remplace les termes de la série par d'autres qui conservent les relations d'inégalités existantes; en particulier, ces relations seront inchangées si l'on substitue à chaque terme de la série le nombre qui exprime le rang qu'il occupe dans la série des termes rangés par ordre de grandeur. Dans ce cas, les termes dans la série nouvelle sont les nombres entiers de 1 à n et leurs sommes sont des fonctions connues de n.

Si l'on considère alors le statistique :

$$R' = \frac{R}{S_2} \quad \text{avec} \quad S_2 = \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6}$$

on trouve après quelques calculs que ce statistique a pour moyenne et pour variante respectivement :

$$E(R') = \frac{3n+2}{4n+2} \quad \text{et} \quad \sigma^2(R') = \frac{5n^2 - 9n - 18}{20(n+1)(2n+1)^2}$$

ou encore, pour écart type :

$$\sigma(R') \cong \frac{\sqrt{n - 2{,}8}}{4n + 2}$$

L'emploi de tests plus simples peut naturellement se justifier, notamment lorsque les corrélations internes sont assez fortes et que la série est relativement longue et on notera à cet égard qu'en plus du « Test du signe de l'écart par rapport à une valeur centrale » mentionné ci-dessus, on peut également utiliser le test suivant.

Test des phases (Wallis et Moore, 1941). On détermine dans la série les sommets et les creux, c'est-à-dire les termes qui sont supérieurs ou inférieurs à la fois au terme précédent et au terme suivant, et on désigne sous le nom de phase d'ordre $d = 1, 2, 3, \ldots, i$, les séquences s'étendant d'un sommet à un creux ou d'un creux à un sommet et contenant $0, 1, 2, \ldots, (i - 1)$, termes intermédiaires.

Le statistique du test est le χ^2 déduit de la comparaison du nombre de phases d'ordre 1, 2 et $\geqslant 3$ avec leur fréquence théorique sachant que la probabilité d'une phase d'ordre d est égale à

$$\frac{6(d^2 + 3d + 1)(n - d - 2)}{(d + 3)!\,(2n - 7)}$$

Si $\chi^2 \geqslant 6{,}3$, la valeur critique de χ^2 est calculée pour $\nu = 2\frac{1}{2}$, sinon, on compare $6/7\,\chi^2$ à la valeur critique correspondant à $\nu = 2$.

Par ailleurs, on se souviendra que le nombre total de sommets et de creux est lui-même un statistique distribué approximativement suivant une loi normale de moyenne

$$\frac{2(n-2)}{3}$$

et de variance

$$\frac{16n-29}{90}$$

(voir Kendall, 1948, vol. 2, p. 125), ou encore que l'on peut effectuer l'analyse statistique complète de la série du point de vue des phases en utilisant la méthode de Kiveliovitch-Vialar (voir Vialar, 1956).

Il reste à signaler que pour mettre en évidence une corrélation sériale d'ordre 2, on pourra appliquer les tests précédents à la série obtenue en écrivant tout d'abord les termes de rang impair et en les faisant suivre par les termes de rang pair. Pour la corrélation d'ordre supérieur à 2, la généralisation du procédé est immédiate.

CAS PARAMÉTRIQUE

Ainsi que nous l'avons vu plus haut, en plus de l'hypothèse d'indépendance entre les termes de la série, on admet également ici que ces termes sont distribués suivant une loi normale. Bien que restrictive, cette dernière condition reste cependant très générale, puisque, en vertu du théorème central limite, elle est remplie par toute moyenne calculée sur un nombre suffisamment grand d'éléments aléatoires, ce qui est le cas de nombreuses variables météorologiques.

De toutes façons, on pourra toujours s'assurer de la normalité de la distribution des termes de la série en effectuant, au moyen de la méthode de Gumbel (1958), une représentation de cette série sur un graphique à échelle de probabilité normale.

Comme les tests paramétriques sont destinés à apporter les précisions qui complètent l'analyse non paramétrique précédente, nous les avons classés de la même manière.

La moyenne n'est pas stable

La série se partage en deux ou plusieurs séries parallèles stationnaires indépendantes. L'estimation de la variation de la moyenne se fera au moyen d'un t de Student avec un nombre de degrés de liberté différent selon que les variances sont les mêmes dans les séries partielles ou non (voir Hald, 1955, p. 394-398). Cette dernière condition sera vérifiée soit au moyen du test en F (en v^2) de Snedecor (voir Hald, p. 374) soit à l'aide du test de Bartlett sur l'homogénéité des variances (voir Hald, p. 291), suivant qu'il y a deux ou plusieurs séries partielles.

La moyenne est instable sans être stationnaire à aucun moment. Dans l'éventualité la plus simple, qui est celle d'une croissance ou d'une décroissance linéaire, on fera une estimation du taux de variation de la moyenne par une analyse de la régression linéaire (voir Hald, p. 528).

Par contre, si la variation de la moyenne n'est pas linéaire, il faudra ajuster des courbes fonctionnelles plus complexes ou utiliser les moyennes glissantes pour faire apparaître cette variation. Dans le dernier cas, on se souviendra, lors de l'interprétation des résultats, que ceux-ci sont altérés par les propriétés algébriques du procédé (voir Lelouchier, 1961).

La dispersion n'est pas stable

Si la série se partage en séries partielles à dispersion constante, des estimations de la variation de la variance pourront être obtenues en utilisant les propriétés du rapport F de Snedecor.

La série présente une corrélation interne

Lorsqu'une telle corrélation existe, le problème de la représentation de la série au moyen d'un schéma aléatoire est rendu délicat par le fait que l'estimation des paramètres doit être complétée par l'examen de la compatibilité du schéma avec la série. Le cas du schéma autorégressif d'ordre 1, c'est-à-dire celui où les termes de la série vérifient une relation de la forme : $x_i = \rho x_{i-1} + \varepsilon_i$, où $|\rho| < 1$ et où ε_i est une variable normale indépendante de moyenne nulle, est toutefois relativement simple.

On vérifie, en effet, sans peine, que dans ce cas la valeur de ρ et celle de ses limites de confiance seront fournies par la racine de module <1 de l'équation :

$$\rho - \beta\rho + 1 = 0 \quad \text{avec} \quad \beta = \frac{1 + r_2 - 2\alpha r_1}{r_1 - \alpha}$$

où

$$r_1 = \frac{\Sigma x_i\, x_{i+1}}{\Sigma x_i^2} \quad \text{et} \quad r_2 = \frac{\Sigma x_i\, x_{i+2}}{\Sigma x_i^2}$$

sachant que $x_{n+i} = x_i$, et où on a attribué à α successivement la valeur moyenne

$$\left(-\frac{1}{n-1}\right)$$

et les valeurs critiques du statistique ${}_1R_n$ de R. L. Anderson (1942).

La compatibilité du schéma pourra ensuite être vérifiée en comparant avec leurs valeurs critiques les valeurs des coefficients de corrélation sériale d'ordre j :

$$\frac{\Sigma \varepsilon_i\, \varepsilon_{i+j}}{\Sigma \varepsilon_i^2}$$

déduites de la valeur adoptée pour ρ.

APPLICATIONS

NUMÉROS SORTIS A LA ROULETTE DE MONTE-CARLO (d'après Vialar, 1956, p. 2)

Cette série de numéros a été choisie comme premier exemple en raison du caractère aléatoire pur qu'on doit pouvoir lui attribuer. Elle a été représentée à la figure 1 en même temps que le résultat de l'application du « Test de tendance » mentionné plus haut sous sa forme séquentielle. Le statistique y a été réduit de telle sorte qu'il soit distribué autour d'une moyenne nulle avec un écart type égal à 1 et les deux traits pointillés délimitent l'intervalle d'acceptation pour le niveau de signification de 5 %.

Il apparaît ainsi que le statistique prend des valeurs généralement comprises entre —1 et +1, exception faite des premières valeurs qui sont influencées par la présence de numéros relativement élevés au début de la série.

Par ailleurs, le « Test de la corrélation sériale » cité plus haut conduit à la valeur de $R' = 0{,}725$, soit un écart par rapport à la moyenne de 0,027 pour un écart type de 0,029. On peut donc bien conclure au caractère aléatoire pur de la série.

LES CONDITIONS THERMIQUES EN JUILLET A BRUXELLES-UCCLE DE 1833 A 1960

Pour caractériser ces conditions, nous avons choisi les moyennes mensuelles du maximum diurne M et du minimum diurne m relevés à midi, ainsi que celles de leur demi-somme T (température moyenne) et de leur différence Δ (amplitude de la variation diurne) et ce, en raison des propriétés climatologiques particulières qui leur sont attachées.

Ces moyennes ont été représentées à la figure 2 et on retiendra que l'hétérogénéité qui affectait la série à la suite du transfert du lieu des observations de Bruxelles à Uccle a été éliminée au moyen des corrections déduites des observations simultanées effectuées aux deux endroits (voir Sneyers, 1956, p. 9 et 10).

LA SÉRIE DE TEMPÉRATURES MOYENNES $\overline{T}$

Cette série a été analysée au moyen du « Test de tendance » cité plus haut, sous sa forme séquentielle et ce, en considérant d'une part les séries qui se terminent en 1960 et débutent d'année en année et, d'autre part, celles qui débutent en 1833 et se terminent d'année en année. Les valeurs correspondantes t_1 et t_2 du statistique, réduit de la même manière que ci-dessus, ont été représentées à la figure 3. On voit apparaître ainsi les valeurs significatives au niveau de 5 % pour t_1, de 1833 à 1891, et pour t_2, de 1947 à 1960 ; de plus, on constate que les courbes décrites par t_1 et t_2 se coupent entre 1928 et 1930 pour des valeurs de t assez voisines de zéro. On en déduit que l'année 1928 partage la série entière

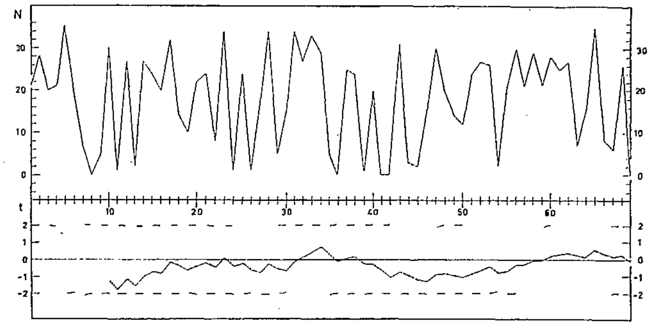

FIG. 1. Numéros sortis à la roulette de Monte Carlo (d'après Vialar). Valeurs réduites du statistique du test de tendance A_1 pour les séries partielles débutant au premier terme et arrêtées au 10^e terme, au 11^e terme et ainsi de suite jusqu'au dernier terme. Les traits ponctués délimitent l'intervalle d'acceptation pour le niveau de signification de 5 %.

en deux séries partielles stationnaires et se place au début d'une série de mois de juillet régulièrement plus chauds.

Il est toutefois évident que cette année 1928 ne fixe l'époque du changement climatique que d'une manière approximative.

La stabilité de la dispersion des valeurs de $\overline{T}$ autour de la moyenne a également été vérifiée dans les séries 1833-1928 et 1929-1960, d'une manière séquentielle au moyen du « Test de tendance ». Enfin l'absence de corrélation interne a encore été établie pour chacune des séries partielles à l'aide du « Test de la corrélation sériale » ; on trouve, en effet, pour R' respectivement : 0,7525 et 0,7120, soit des valeurs assez voisines des moyennes 0,7512 et 0,7538 (les écarts types correspondants sont 0,025 et 0,041).

Pour permettre la comparaison, on a appliqué le « Test de la stabilité de la médiane » et le « Test du signe de l'écart par rapport à une valeur centrale »,

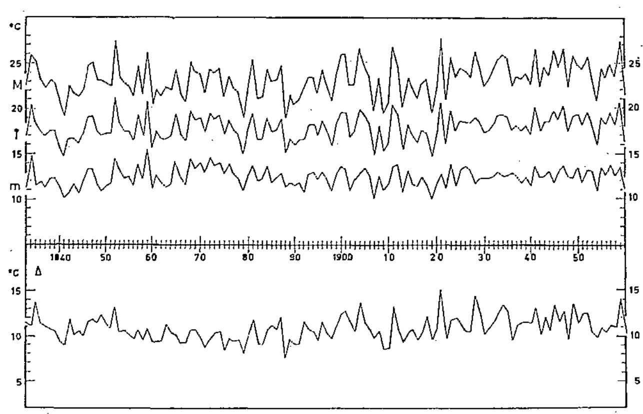

FIG. 2. — Moyennes mensuelles de la température moyenne $\overline{T}$, du maximum diurne M, du minimum diurne m et de l'amplitude de la variation diurne Δ en juillet à Bruxelles-Uccle de 1833 à 1960.

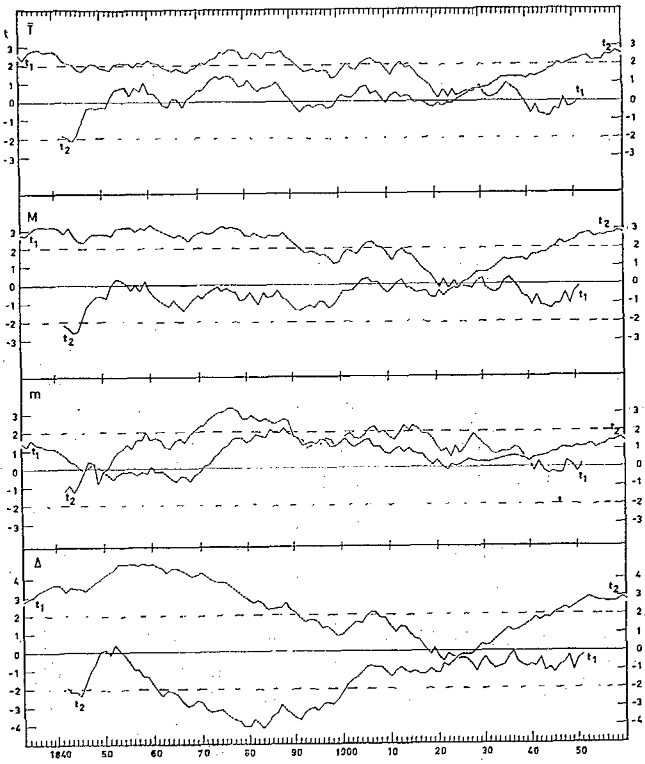

FIG. 3. — Valeurs réduites des statistiques t_1 et t_2 du test de tendance A_1 appliqué sous forme doublement séquentielle aux séries T, M, m et Δ. Les traits ponctués délimitent l'intervalle d'acceptation pour le niveau de signification de 5 %.

cités plus haut, à la série $\overline{T}$ après y avoir associé le signe + aux termes supérieurs à la médiane de la série entière (qui est 17,7) et le signe — aux autres termes.

Pour le « Test de la stabilité de la médiane », on a partagé la série en 12 groupes de 10 termes et un treizième groupe de 8 termes, et on en a déduit la table de contingence indiquée ci-dessous.

Fréquences des températures moyennes supérieures (+) et inférieures ou égales (—) à la médiane, par décennies, de 1833 à 1960

+	2	3	2	5	5	3	6	6	2	7	6	9	6	62
—	8	7	8	5	5	7	4	4	8	3	4	1	2	66

On en tire un χ^2 égal à 25,13 avec $\nu = 12$, qui est significatif pour un niveau de 5 % et confirme l'existence d'un réchauffement postérieur à 1923.

En ce qui concerne le « Test du signe de l'écart par rapport à une valeur centrale », on notera que le statistique déduit des séquences de signe + et de signe — ainsi obtenues prend effectivement une valeur inférieure à la moyenne, mais avec un écart environ égal à l'écart type. Il ne permet donc pas de conclure à l'instabilité de la médiane. Il est clair, cependant, que c'est la puissance trop faible du test qui est ici la cause d'une apparente contradiction.

Il reste maintenant à fournir des estimations de l'ampleur du réchauffement observé en faisant appel à des tests paramétriques et plus particulièrement au test de Student.

L'hypothèse de normalité ayant été vérifiée par la méthode de Gumbel, la compatibilité des variances de chacune des séries a été testée au moyen de leur rapport. Comme on trouve $F = 1{,}78$ avec $\nu_1 = 95$ et $\nu_2 = 31$, c'est-à-dire une valeur significative pour le niveau de 5 %, le test de Student n'a pu être utilisé dans sa forme ordinaire. Toutefois, comme les séries partielles comportent toutes deux plus de 30 éléments, on a pu employer l'approximation normale de ce test. On en déduit que l'accroissement de T, dont la valeur moyenne est de 0,7 °C, a une valeur réelle comprise entre 0,2 °C et 1,2 °C, avec un coefficient de confiance de 95 %.

LES SÉRIES DE M, m ET Δ

L'analyse de la série de M conduit à des résultats analogues à ceux obtenus pour $\overline{T}$. En particulier, on constate un réchauffement à partir de 1926 qui s'est traduit par une hausse moyenne de 1,3 ° et dont la valeur réelle est comprise entre 0,65° et 1,95 ° avec un coefficient de confiance de 95 %.

Cette hausse mérite d'être rapprochée de celle subie par le maximum annuel de la température de l'air, qui atteint également 1,3 ° (voir Sneyers, 1960).

L'examen des séries de m et Δ révèle un comportement plus complexe, quoique semblable pour les deux séries.

En réalité, nous avons procédé ici à des analyses successives au moyen du « Test de tendance » en retranchant de la série totale la série des dernières années formant une série stationnaire. Il est apparu de la sorte que les séries totales se partageaient d'une manière significative en quatre séries partielles stationnaires soient successivement : 1833-1854, 1855-1878, 1879-1921 et 1922-1960 pour m et 1833-1857, 1858-1879, 1880-1916 et 1917-1960 pour Δ, ce qui laisse supposer que d'autres variations climatiques ont affecté m et Δ.

En réalité, seule la variation qui s'est produite au cours de ce siècle doit vraisemblablement être prise en considération, les années 1854 et 1878 ayant coïncidé à Bruxelles l'une avec un premier changement de thermomètre et l'autre avec un second changement de thermomètre et une modification du type d'abri utilisé [1].

Il est cependant intéressant de noter que les accroissements de M et m au cours de ce siècle ont été apparemment associés à une augmentation de Δ et, par conséquent, des durées d'insolation, puisque celles-ci présentent une forte corrélation avec Δ.

1. Voir les « Notes » dans les *Annales de l'Observatoire royal de Bruxelles.*

CONCLUSIONS

En résumé, nous avons présenté un ensemble de tests susceptibles de fournir une analyse complète des séries chronologiques en vue de la détection des variations du climat et nous avons suggéré, en particulier, de procéder tout d'abord à une analyse qualitative au moyen de tests non paramétriques et de faire ensuite les estimations nécessaires en s'appuyant sur des tests paramétriques.

A titre d'exemple, cette méthode a été appliquée aux variables thermiques de juillet à Uccle. On a pu montrer ainsi que le réchauffement récent qui affecte l'été depuis 1930 environ (voir Sneyers, 1958) semble s'étendre uniformément à toute la saison et faire ressortir, pour le minimum moyen, l'existence d'hétérogénéités, vraisemblablement d'origine instrumentale, dont l'effet était ignoré jusqu'à présent.

Ce double résultat souligne suffisamment, croyons-nous, l'efficacité de la méthode préconisée.

SUMMARY

Determination of the stability of chronological series
(R. Sneyers)

Any change in climate is shown by alterations in the statistical properties of the chronological observation series; it follows, therefore, that such changes can only be revealed in these series by means of a statistical analysis.

The method of analysis proposed consists in verifying successively, for a given series, the stability of a central value (mean or median), the stability of dispersion of the variations in relation to this central value, and the lack of correlation between the consecutive terms.

It consists, furthermore, in using non-parametric tests for checking these hypotheses and in keeping parametric tests for such estimations as may be necessary.

A set of appropriate tests is given, using as an example thermic conditions in July at Bruxelles-Uccle from 1833 to 1960.

These reveal climatic variations which took place in this century, and others which relate to the past century; the latter, however, are doubtful because they coincide with changes in the methods of observations.

DISCUSSION

J. M. MITCHELL. I was very happy to hear this valuable paper by Dr. Sneyers and especially gratified that he has drawn attention to the application of good statistical tests not only to evaluate the statistical significance of climatic changes but also to evaluate the homogeneity of climatological records used in climatic change studies. I am sure that the second application is at least as important as the first. Especially in long series, non-randomness may often be found, but only a part of this may be due to real climatic change. The rest may result from inhomogeneities which in long series of data have many opportunities to creep in.

My only misgiving in these applications of statistics is to use formulae for serial correlation—such as Wald-Wolfowitz's—which are computed according to circular definitions. In cases where the null hypothesis of stationarity is tested against alternative hypotheses, such as trend, in which the expected value of the last term of the series is markedly different from the expected value of the first term, this circular definition of the serial correlation materially weakens the power of the test based on it. In other words, it is inappropriate to apply circularly defined statistics in physically non-circular universes. Would Dr. Sneyers please comment on this?

R. SNEYERS. Il est exact que la forme cyclique du statistique du « Test des phases » réduit la sensibilité du test vis-à-vis de l'alternative d'une corrélation sériale réelle. Cet inconvénient devient toutefois négligeable lorsque la série chronologique est suffisamment longue. De plus, les conditions d'utilisation d'un statistique non cyclique données par G. E. Noether paraissent plaider définitivement en faveur de l'emploi du statistique R tel que nous l'avons défini. »[1]

V. M. YEVDJEVICH. The other statistical tools for studying the climatic time series are: (*a*) the power spectrum analysis; (*b*) the range distributions (range defined as the difference of previous maximum and minimum values on the summation curve of departures of members of time series from their mean value); and (*c*) the runs, and their distribution (run of a time series may be defined in several ways).

When the random component in a time series is very large and predominates in the fluctuations of series, it seems that the use of the power spectrum analysis does not have a parti-

1. G. E. Noether, Asymptomatic properties of the Wald-Wolfowitz Test of Randomness, *Ann. Math. Stat.*, vol. 21, 1950, p. 233.

cular advantage in comparison with the classical tools of analysing the time series (i.e., correlograms), as the advantages are quite clear in the case of sea ways, tides, and similar movement with the superimposed periodic oscillations.

The contemporaneous development in the studies of sequence of random variables, and especially the theory of stochastic processes give powerful tools for the analysis of climatic time series.

The use of the theoretical results from the circular time series for the cases of open time series seems adequate when the time series are long enough, at least of 40-50 members.

R. Sneyers and E. Rosini.

1. *Power spectrum analysis* est un des ajustements analytiques auxquels on peut songer lorsque la série n'est pas aléatoire pure.
2. Le test qu'on pourrait baser sur le *range* est un test *permétrique*; de plus, il ne nous paraît pas très intéressant du fait qu'il néglige une partie de l'information statistique.
3. L'emploi des *runs* a été indiqué sous le titre « Test du signe de l'écart par rapport à une valeur centrale ».
4. L'emploi d'un schéma stochastique linéaire a également été suggéré dans le groupe des méthodes permétriques (série avec corrélation sériale).

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A QUANTITATIVE DEFINITION OF THE MEANING OF CONSTANCY AND STEADINESS OF CLIMATE

by

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The question of climatic change is considered here from the viewpoint of the definition in order to reach a criterion that can be applied to the individual elements of climate over the period in which regular observations are made. More precisely, the question now to be examined and for which a particular solution is offered, is as follows : " . . . given a long series of observations, i.e., measurement of a meteorological element, what quantitative significance must be given the statement that 'during the period covered by such observations climate has shown changes or remained stable'?"

When research is limited to the last two centuries, for which meteorological observations exist, would it not be better to use the more indicative and less technical language of assumptions and indirect systems, the only one available for the examination of longer periods ? There is a vast amount of literature and a large number of original and valuable works on long series of meteorological observations. However, I feel that the present symposium is the most suitable place to attempt an introduction of uniform criteria, chosen from among those that are statistically significant and which, at least, permit reference and comparison and the limits and range of which are well known. A series of simple considerations dictated by statistical methodology follow.

The first criterion to be established, in my opinion, concerns the meaning of the words. Considering meteorological observations as parts of an organic whole of which the existing series of data is a sample, we can initially give a conventional definition to the conceptions of constancy and steadiness. Let us say that climate is "constant" (in relation to all years in general) when the changes noted for years that are close together, even if they are not contiguous, are but small; that is, when the annual values relative to a limited number of years tend to be grouped together in a short period. Such a conception, obviously, may be applied to each annual quantity and also, for example, to thermal range. The range between summer and winter may be very pronounced but if this is repeated from one year to another with but small variations, we may say that climate, in relation to the annual range, is constant. In other words, the uniformity of climate indicates the possibility of planning over a certain number of future years.

On the other hand, we may say that climate is "steady" when, over a lengthy period of years, the standard climatic pattern remains unchanged or, more accurately, the parameters of the theoretical curve of distribution of the frequencies maintain their values. According to this definition, therefore, climatic changes are directly related to the meaning of steadiness; when steadiness is defined quantitatively, it is clear that a climatic change takes place when steadiness is lost.

The meanings of constancy and steadiness, defined as above, show substantial differences. Constancy, in fact, possesses a limit (which, in practice, cannot be reached) whereby the climatic element considered remains completely unaltered from one year to another. In reality, there will be a fairly well marked shift from such a limit and this may therefore be defined as "an index of inconstancy" with an essentially continuous nature. Steadiness, on the other hand, once defined, permits only two alternatives—it remains or it does not. In the latter case climatic change may be said to occur. Therefore, steadiness does not involve an "index" but a "criterion of control" and this criterion will be of an essentially discontinuous and exclusive nature.

Definitions of constancy and steadiness give rise to a rider that is very important from an operational viewpoint. Constancy, in order to meet practical requirements, must refer to groups of years composed of but a few units, otherwise it would lose its characteristic values and interest. On the other hand, steadiness, by virtue of its nature must refer to long periods of time and no useful information can be obtained from examination of the behaviour of single years.

In view of all this, I consider it reasonable to choose a group of five consecutive years as the basic element of reference and, at the same time, to distinguish between constancy and steadiness, to use certain ideas concerning the analysis of variability. For example, in the case of constancy, once the period for which data are available has been divided into groups of five years, it is possible to calculate the mean square deviation. This mean square deviation may be considered as the index of inconstancy. In the case of certain data (e.g., all kinds of temperature, such as the annual mean for the winter months) one may have an "effective" value; for others, such as precipitation, the "relative" value may appear more useful, i.e., the mean square deviation divided by the mean for the whole period. For example, general means have been recorded for Turin, Milan and Rome over the past 100 years, from 1861 to 1960, divided into 20 five-year periods, as shown in Table 1.

TABLE 1.

	General mean	Mean square deviation	Relative index of inconstancy
	cm.	cm.	%
Turin	85.7	18.6	22
Milan	99.8	18.1	18
Rome	83.0	15.0	18

I will omit the deductions which can be made from these figures as they can be derived from well known methods of elementary statistics. From this point onwards we will no longer concern ourselves with constancy but will turn our attention to climatic steadiness which is of more interest to this symposium.

For the analysis of steadiness, it is suggested that the five-year mean be accepted as a unit of observation. This appears to be appropriate to research requirements. In fact, there would be no sense in talking about climate and climatic change over a period of five years, or less, and for such a short period of time a more systematic analysis would have no meaning. But, we cannot run the risk of hiding some important phenomena by employing a period that is too long. As is known, analytical or statistical deductions from a series of data become of importance only when they refer to a period in which many observations have been carried out. In my opinion, a period of 15 years is necessary and sufficient to identify symptoms of a climatic change.

We have reached the point of defining the data which are adequate to the matter we are examining; it is a series of five-year values that refer to any climatic element and which we will call "observed series". As we have said, this series can be considered "steady" if its statistical parameters do not reveal a significant variation and, in particular, if its arithmetical mean can be considered as representative of the theoretical mean value for the whole series.

The analysis of steadiness consists, as statistical methodology teaches us, of two operations. The first relates to a conventional definition, that is, the definition of the "margins". In actual fact an element is considered unchangeable when its variations do not exceed a limit that is established on the basis of objective and useful considerations.

Let us assume, therefore, as a definition, that climate is steady when the most likely value of its theoretical mean value over the whole series diverges from the general mean M by less than the predetermined quantity.

This is a quantity to be fixed according to various theoretical or applied criteria (namely, medical, agricultural, economical). For instance, given a prevailing pluviometric system with a mean value M, let us consider a second system with a mean value M_1 that is markedly different (being drier or rainier) even though the means do not differ by more than the standard deviation, σ, of the individual observations (the individual mean(s) of five years). Then σ could be the pre-determined quantity referred to above. This convention could, perhaps, be substituted by another more complex and satisfactory, but it is adequate for our present purpose. Such a convention enables us to simplify the treatment (our handling), since, without any appreciable distortion, it replaces the continuous changeability of average M by a discreet changeability, embracing a rise or fall equal to the standard deviation.

Indeed, in a historical series, of which we do not know whether the "true" mean has kept steady, the convention enables us to give a quantitative specification for each of the two alternatives: a steadiness of the climate (called hypothesis H_0) and a climatic change (called hypothesis H_1).

Let us consider two cases, i.e., a drier and rainier climate, beginning with the first. We can then treat the situation in the following simple way: either the climate keeps steady at a mean value M (hypothesis H_0), or it changes to the mean value A, where $A_1 = M - \sigma$ (hypothesis H_1); all changes towards rainier climates are assigned to the H_0 hypothesis and to the H_1 hypothesis are assigned all changes towards régimes drier than the A_1 value.

For a sequential processing, a progressive number, n, of five-year groups is considered. Corresponding to every value of n there are three eventualities: either the steadiness (H_0) hypothesis or the changes (H_1) hypothesis is proved, or the outcome is uncertain and we have to proceed with case $n + 1$.

At this point, it is as well to decide what constitutes proof that an important event has occurred. Since changeability and statistical indetermination are part of the universe and absolutely certain proof is clearly unattainable, we must always be satisfied with "practical certainty"—e.g., an event having more than a 95 or 99 per cent probability of happening can be considered as certain. Yet in fixing even this limit of reliability we must realise that the possibility of a mistake can never be excluded.

Moreover, errors may be of two kinds. If the H_0

hypothesis is true, casual changeability can so distort the n observations which have been carried out as to lead us to reject the hypothesis on the basis of the adopted criterion—let us call the probability of this happening α. Alternatively, if the hypothesis is false (and H_1 is consequently true), the observations may well lead us to consider it true; let us call β the probability of this happening. The probabilities α and β must, then, be fixed according to different considerations, and it may be advisable to assume different values for these. All considerations relating to drier climates can be repeated for rainier ones if the value $B_1 = M + \sigma$ is introduced in the place of the A_1 value. It follows that the climate during a particular phase of the series became drier if we can show that the relevant true mean must have decreased to at least A_1 cm. (and similarly for an increase in raininess).

In other words, we can say that the climate did not become drier during a time period if there were only the probability (let us say of 10 per cent) that the climate had kept steady, although the mean for the period may have remained consistent with the value A_1; and similarly if there were a 5 per cent of the mean for the period being more in line with the value A_1 although the climate has changed and become noticeably drier, i.e., had reached the A_1 value. As can be seen, in this example we have accepted $\alpha = 0.10$ and $\beta = 0.05$; the choice of significant levels depends on the type of research and on those features whose existence there is a particular desire to prove.

Our reasoning can proceed as fellows. In a period when analysis shows that climate has become drier, we can, with the same criteria, decide whether it must be equated with the value A_1 or with A_2 where

$$A_2 = A_1 - \sigma = M - 2\sigma$$

or, if necessary, with the sequential values $A_3, A_4 \ldots = M - 3\sigma,\ M - 4\sigma \ldots$ Similarly, for the definition of moister climates, with $B_2, B_3, B_4 \ldots$

The following analysis, cited merely as an example, shows that, starting with any particular year of the series, two values are associated with every number n of successive five-year groups of observations and with the related mean raininess M_n

$$a'_1(n) = \frac{A_1 + M}{2} + \frac{\sigma^2}{n(A' - M)} \log \frac{1-\beta}{\alpha} = \left(M - \frac{\sigma}{2}\right) - \frac{K\sigma}{n}$$

$$a''_1(n) = \frac{A_1 + M}{2} + \frac{\sigma^2}{n(A_1 - M)} \log \frac{\beta}{1-\alpha} = \left(M - \frac{\sigma}{2}\right) + \frac{K\sigma}{n}$$

With these values we can reach an opinion on the interpretation to be given to value M_n: if $M_n < a'_1$ we must conclude that the climate has turned drier, at least during the course of the n five-year groups; if $M_n < a''_1$, we must exclude such a hypothesis; and finally, if M_n is between a'_1 and a''_1, judgement remains uncertain, and it is necessary to proceed by examining the $n + 1$ period. Assuming that the climate gets markedly drier, i.e., for comparison between A_1 and A_2, the following analysis is relevant:

$$a'_2(n) = \frac{A_2 - A_1}{2} + \frac{K\sigma^2}{n(A_2 - A_1)} = \left(M - \frac{3\sigma}{2}\right) - \frac{K\sigma}{n}$$

$$a''_2(n) = \frac{A_2 + B_1}{2} + \frac{-k\sigma^2}{n(A_2 - A_1)} = M - \frac{3\sigma}{2} + \frac{K\sigma}{n}$$

and so on.

The above considerations also hold good if the climate should turn rainier, that is, the "true" mean may go above B_1; and we thus have the following:

$$b'_1(n) = \frac{B_1 + M}{2} + \frac{\sigma^2}{n(B_1 - M)} \log \frac{1-\beta}{\alpha} = \left(M + \frac{\sigma}{2}\right) + \frac{K\sigma}{n}$$

$$b''_1(n) = \frac{B_1 + M}{2} + \frac{\sigma^2}{n(B_1 - M)} \log \frac{\beta}{1-\alpha} = \left(M + \frac{\sigma}{2}\right) - \frac{K\sigma}{n}$$

and if necessary

$$b'_2(n) = \frac{B_2 - B_1}{2} + \frac{-K\sigma^2}{n(B_2 - B_1)} = \left(M + \frac{3\sigma}{2}\right) - \frac{K\sigma}{n}$$

$$b''_2(n) = \frac{B_2 + B_1}{2} + \frac{-K\sigma^2}{n(B_2 - B_1)} = M + \frac{3\sigma}{2} + \frac{K\sigma}{n}$$

and so on.

The various regions of the (n, M) plane are indicated in Fig. 1; the different findings are based on the values specified above for the various parameters. The two curves for a'_1 and b'_1 taken together provide the following interpretation of the whole: if, starting from a certain group, we consider the series of Mi running means relating to $i = 1, 3, 5 \ldots$ five-year groups with

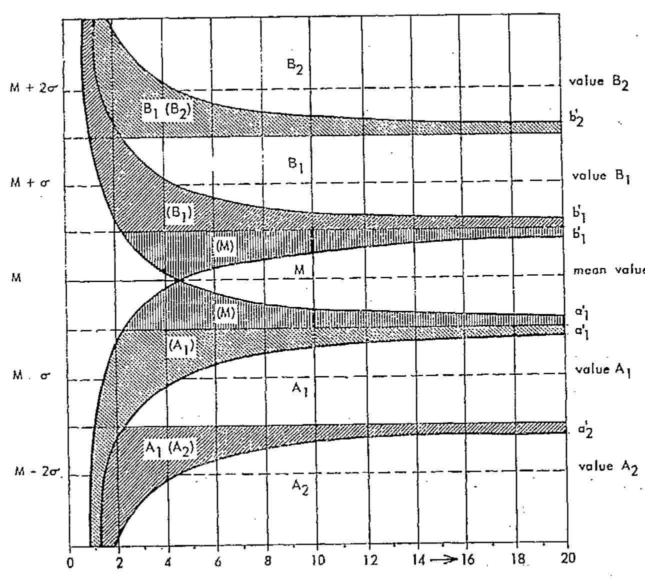

FIG. 1. Analysis of meteorological series.

each group as a medium point, and we find that corresponding to a certain period n_0 the point M_{n_0}, n_0 enters a region above the a'_1 line or under the b'_1 line, we can then state that, in relation to the specified time period, the climate must be considered to have changed either in one sense or the other, and the more surely and decisively so the smaller n_0 is.

If, in running gradually over the considered time period, we see that the historical series of n_{0s} shows consistent behaviour, then climatic change must be further acknowledged and the behaviour will indicate the direction and nature of this change.

A long series of observations have been made on the amount of precipitation in certain localities of Italy. As is known, the longest series applies to Padua, with 235 years, followed by Milan with 200 years and Rome with 180 years. The series for Turin and Palermo, 155 years each, are quoted for purposes of comparison.

Fig. 2, relating to some general studies for Italy, gives an analysis of mean precipitation, for groups of five years, obtained for a group of 20 Italian stations over a period of 120 years and, below, an analysis for 6 stations in the central Po Valley. As the figures show, the situation in the Po Valley is substantially different from that generally prevailing in Italy.

Sequential analysis, for example, shows that in the five-year groups 1950-55, three groups only are sufficient to make the mean at Rome below a'_1 statistically significant.

There would probably be only 1 chance in 20 of obtaining at random the series of 15 yearly precipitations from 1945 to 1960 if the climate had really kept steady at 81.5 cm. But here, a special point arises: the Bernoulli scheme based on the independence of successive yearly values possibly may not apply in this case since there might be a bond among the sequential yearly values, even if of a periodical type.

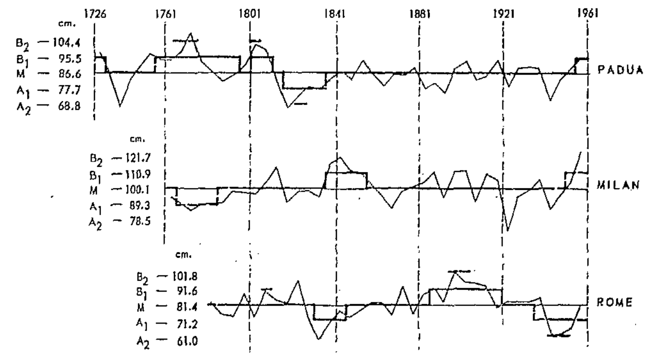

FIG. 2. Sequential analysis of precipitations.

We can reply that, in the first place, sequential analysis appears to be the most suitable method for indicating, through a statistical, rational criterion, the possible presence of some periodicity and, generally, any climatic changes. Secondly, the presence of periodicity warns us that climate, in reality, fluctuates and may not, therefore, be represented by a simple mean value, even as a first approximation.

RÉSUMÉ

Une définition quantitative de constance et de stabilité d'un climat (E. Rosini)

Le but de cette étude est de contribuer à la définition d'un critérium pour juger d'une façon générale s'il y a un changement de climat ou non dans le courant d'une série régulière d'observations météorologiques. Il est proposé de baser ce critérium sur les notions d' « index d'inconstance » et de « stabilité » dont les définitions sont données par l'auteur dans sa communication.

DISCUSSION

R. SNEYERS. L'analyse séquentielle proposée est une méthode paramétrique. On suppose que les variables sont distribuées suivant la loi de Laplace Gauss ; de plus on suppose connue la variance théorique (ce qui n'est pas le cas).

Il y a donc l'inconvénient d'un manque de généralité. Ce qui n'empêche évidemment pas que la méthode puisse rendre de grands services.

E. ROSINI. Je suis complètement d'accord sur ce qu'a observé M. Sneyers. En ce qui concerne la variance, je crois qu'on peut améliorer la situation, comme je me propose de le montrer dans de prochains travaux.

CLIMATIC CHANGES IN INDIA

I. METHODS FOR THE STUDY OF CLIMATIC CHANGES AND TRENDS IN MADRAS RAINFALL

by

K. N. Rao

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METHODS FOR THE STUDY OF CLIMATIC CHANGES

In examining the data of a meteorological element for climatic changes and fluctuations, the method to be followed is of considerable importance. A number of questions arise in this connexion. Should conclusions about climatic changes be based on a comparison of the averages for two or more periods (decades, 20 years, 30 years, etc.)? What should be the basis of comparison? Should one consider the monthly, seasonal or annual values of the element? Or should data for periods of less than a month be also examined? Again, would it be enough to study the data of individual stations or has the study to be extended to regional values and over wider areas? The whole problem poses several controversial issues and great care is therefore necessary in drawing conclusions. A brief reference is made in this paper to the main methods usually followed in the study of climatic changes. This is followed by a section on trends in Madras rainfall. Trends in the rainfall of India with particular reference to arid zones are discussed in the second part of this article.

MOVING AVERAGES

The use of moving averages is one of the very popular methods and although it is simple and straightforward, the results based on such analysis need to be accepted with very great caution. Whether we work on the basis of averages for 10, 15, 20 years (or more), the procedure is one of smoothing which removes the minor year-to-year variations. The process of smoothing, however, generates a spurious effect which is known as the Slutzky-Yule effect. Moreover, no satisfactory statistical test of significance is available to assess even those deviations which, as revealed by moving averages, are prominent. As has been remarked in the WMO *Guide to Climatological Practices* (1960), the practice of using over-lapping means requires considerable discrimination. Whilst this might be useful for a preliminary study, for statistical reasons it is not satisfactory.

COMPARISON OF MEANS OF DIFFERENT PERIODS

This is one of the well-recognized methods and the statistical t test of significance can be employed. It may be mentioned that one can also test whether the mean of a sub-period is significantly different from the mean for a long period. Let $\bar{x}_k$ be the mean of the first k years, then

$$\bar{x}_k = \frac{1}{k}\sum_{1}^{k} x_r$$

and

$$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_r$$

where $\bar{x}$ is the mean for the entire period of n years for which data are available. Then it can be shown that

$$t = \tau_k \left\{ k\,(n-2)/n - k - k\,\tau_k^2 \right\}^{\frac{1}{2}}$$

where

$$\tau_k = \frac{\bar{x}_k - \bar{x}}{s}$$

is distributed as Student's t with $n-2$ degrees of freedom and s is the standard deviation of the entire series. Both these tests assume the normality of the series. It is essential to note this point before accepting results or drawing conclusions by this method.

POLYNOMIAL FITTING

One of the powerful methods which can be employed for testing for a trend is by means of orthogonal polynomials; statistical tests are available for determining significance. This method involves considerable labour and work but the results can be very revealing. In some of the studies on climatic changes in India (Pramanik and Jagannathan, 1953), polynomials up to the fifth degree have been employed.

PERIODOGRAM AND POWER-SPECTRUM ANALYSIS

Periodogram and power-spectrum analysis are also utilized but the number of published studies using such methods has been small. Here also, as with moving averages, there is the difficulty of devising a satisfactory statistical test for significance. Moreover, the methods are laborious and involve the use of modern computers.

TIME INTERVALS

In some studies of climatic change, time intervals between those years when events satisfying certain criteria occurred have been examined statistically, for example, considering the seasonal total rainfall over a number of years, all years with less than 80 per cent (or any other specified limit) of the seasonal rainfall are listed. The intervals between the successive years are worked out and also the largest of the time intervals; and the question whether there is any significant tendency for intervals to succeed one another in groups sometimes longer and sometimes shorter is then examined. The test for the latter is to evaluate

$$M = 2nk \left\{ \log_e \left(\frac{1}{k} \Sigma T_i \right) - \frac{1}{k} \Sigma \log_e T_i \right\}$$

where T_i is the sum of the intervals in the ith group. $\frac{M}{C}$ is distributed as χ^2 with $(k-1)$ degree of freedom.

$$C = 1 + \frac{k+1}{6nk}$$

This could be used as a supplementary test.

RESIDUAL MASS CURVES

Kraus in his studies on secular changes in rainfall régimes has investigated the fluctuations by means of residual mass curves. The quantity plotted graphically is

$$Y_n = 100 \sum_{l=1}^{n} \left(\frac{r_l}{\bar{r}} - 1 \right) - C$$

where r_l is the rainfall for the lth year of the record and the mean rainfall $\bar{r}$ is computed for the standard period. The constant $C = 100 \sum_{1}^{n} \left(\frac{r_l}{\bar{r}} - 1 \right)$; the summation extending from the beginning of the record to n. The graph of Y_n rises/falls during a period of rainfall greater/smaller than $\bar{r}$, the mean for the standard period. It will be valley-shaped or concave upwards, if precipitation is increasing and convex when it is decreasing. Using this method, Kraus has tried to show that when the annual records of Madras are broken down into seasons, the idea that there is no change in the annual average of Madras has to be modified. It is important to remark that Kraus does not apply any statistical test of significance for the variations and his conclusions depend mainly on what may be seen from the Y_n graph. As has been remarked by Professor Barnard (1956) in his paper "The Statistics of Rainfall Régimes—Some Comments on Mr. Reynold's Note", while cumulative residuals are undoubtedly valuable, they need to be used with proper caution. He has further stated that "it may be true that changes in a time series are often immediately apparent on such a graph, but it is equally true that many such immediately apparent changes will turn out not to be real ones". These remarks are valuable not only with regard to the use of residual mass curves but all similar tests. It is absolutely essential that the results or conclusions must be qualified by a clear statement of the assumptions made and a definition of "significance". The deductions of Kraus with regard to Madras rainfall are commented upon in the next section on "Trends in Madras Rainfall".

The above methods are those mainly employed in the studies on climatic fluctuations; the first three methods are most extensively used.

TRENDS IN MADRAS RAINFALL

In his valuable paper on "Secular Changes of Tropical Rainfall Régimes" Kraus (1955) discussed the changing seasons of south-east India and particularly based some of his conclusions on an analysis of the rainfall of Madras. He remarked that whilst the annual rainfall of Madras during the period examined never fluctuated significantly the picture changes when the annual records are broken down. Kraus considered residual mass curves for the months of "early rain" i.e., May-July and for the main rainy period October-December. The change revealed in the mean rainfall is much larger in May-July during the south-west monsoon and the curves (Figs. 4 and 5 of his paper) for the two periods show opposing trends. Kraus therefore suggested the possibility that the same influence which caused the south-west monsoon rain to decrease may have caused the north-east monsoon rains to increase.

Rainfall data are available for Madras from 1813 (Fig. 1). Recently, a detailed statistical study of the monthly and annual rainfall of Madras has been completed (see Fig. 1). One of the items examined was the fluctuation in annual/seasonal rainfall during the last 140 years. The method used for the study of trends was different from that employed by Kraus.

May has been treated by Kraus as a month of the south-west monsoon, but the normal date of onset of the south-west monsoon in Madras is about June. Whatever the amount of rainfall in the month of May (it is only about 4 per cent of the annual rainfall), it cannot really be regarded as a month of the south-west monsoon. May is a "pre-monsoon" month and storms from the Bay of Bengal give rainfall in this area. Table 1 gives the averages, extremes, etc., for May to July. The period of the data considered is 1813 to 1955.

TABLE 1. May to July

	May	June	July	May-July
Mean (in.)	1.92	1.89	3.69	7.50
Mean as % of annual	3.9	3.8	7.5	15.2
Median (in.)	0.2	1.53	3.25	5.94
$\frac{\text{(Mean — Median)}}{\text{Mean}} \times 100$	90	19	11	21
Highest (% of mean)	1,214	457	313	416
Lowest (% of mean)	0	0	7	10
Coefficient of variation (%)	221	83	59	68

The frequency distributions of rainfall in each of the months May to July and in the season May-July are highly skew (see Table 2).

TABLE 2. Normality of Madras rainfall[1]

Month	$\frac{\mu_3}{\mu_2^{3/2}}$	$\frac{\mu_4}{\mu_2^2} - 3$
March	5.429	36.1727
April	2.869	8.3005
May	3.236	—2.7938
June	1.780	4.0938
July	0.918	0.6239
August	0.655	0.1218
September	0.727	0.1549
October	1.130	—0.2113
November	0.667	—3.2912
December	1.571	2.2220
Season	g_1	g_2
June to September	0.0411	0.1622
October to December	0.3748	—0.4423
May to July	1.8426	4.3949
Annual	0.5316	—0.1167

1. μ_3, μ_2 and μ_1 are the second, third and fourth moments respectively. g_1 and g_2 are Fisher's Statistics for testing normality; S.E. $g_1 = 0.2027$ and S.E. $g_2 = 0.4028$.

The wide variations in extremes and the very high coefficient if variation, particularly in May, are of interest. A comparison of the 14 decadal means from 1813 to 1952 is shown in Table 3.

TABLE 3. Comparison of 14 decadal means from 1813 to 1952

	May to July	June to July
Highest decadal average (in.)	11.38	5.95
% of mean	152	142
Lowest decadal average (in.)	4.86	4.30
% of mean	65	70

June plus July has less variation than May-July. Moreover, June and July are only two of the south-west monsoon months (which comprise June to September).

The period from October to November is regarded as the north-east monsoon season. The average, extremes, etc., of rainfall are given in Table 4.

The frequency distribution of October-December seasonal rainfall is not significantly different from normal. The decadal averages for this season have been compared with the mean for the entire period 1813 to 1955. None of the 14 decadal means is significantly different from the mean for the entire period. Fitting of polynomials up to the third degree shows no trend in the series. The variations of the decadal averages are from 77 per cent to 13 per cent of the mean. The variations are much smaller than in May-July and the rainfall of May-July is only about 25 per cent of that of October-December.

In Table 1 above, the rainfall of June and July has been given. Averages and extremes for the remaining months and for the south-west monsoon season are given in Table 5.

A comparison of Tables 4 and 5 is of interest. The variations in the south-west monsoon period are much smaller than during October to December. The coefficient of variation for the south-west monsoon season (June-September) is only 75 per cent of that for October-December although in the latter period the rainfall is nearly double that in the former. The combined rainfall for May-July and October-December accounts for only 75 per cent of the annual amount. These points are mentioned in order to emphasize that it would be more appropriate, for detecting trends, to consider the two

TABLE 4. October to December

	October	November	December	October-December
Mean (in.)	11.28	13.22	5.35	29.85
Mean as % annual	23	27	11	60
Median (in.)	9.20	11.99	3.90	28.73
$\frac{\text{(Mean — median)}}{\text{Mean}} \times 100$	18	9	27	4
Highest (as % of mean)	334	324	520	210
Lowest (as % of mean)	4	2	0	17
Coefficient of variation (%)	65	65	102	44

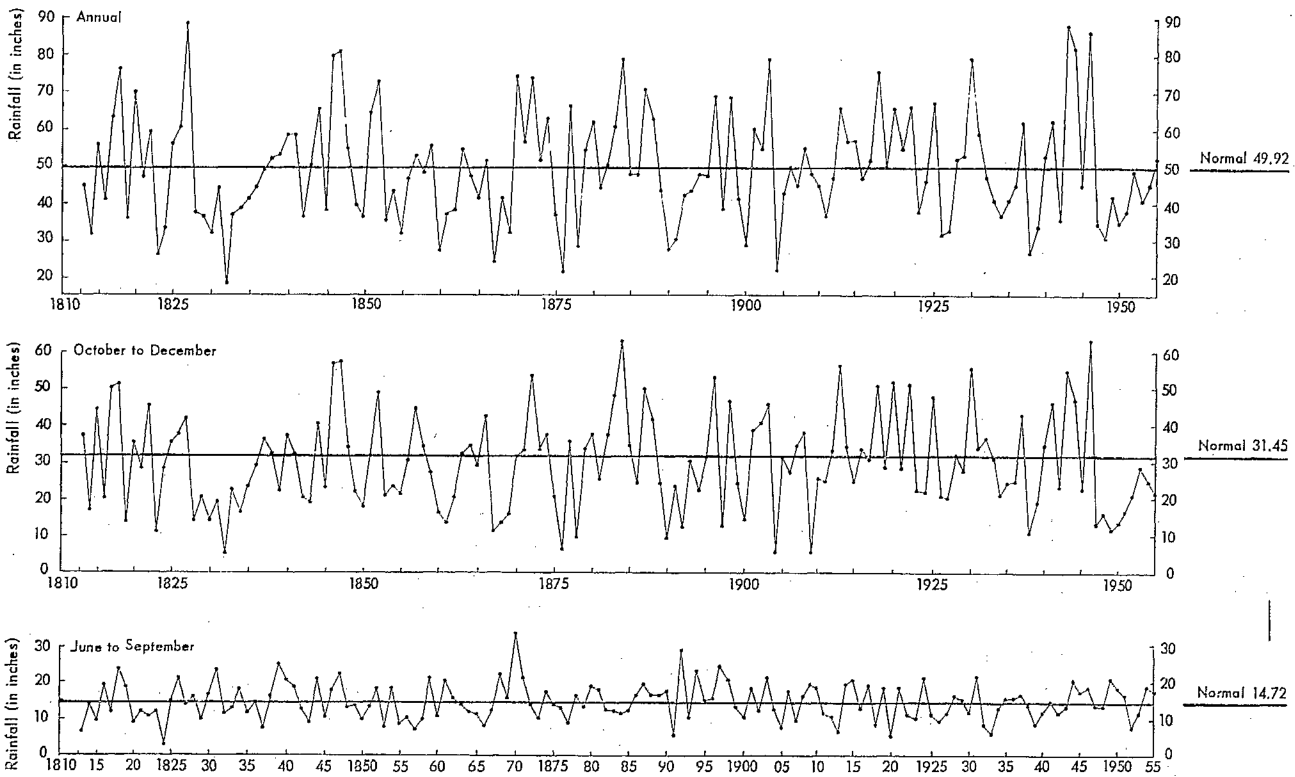


FIG. 1. Rainfall of Madras, 1813-1955.

TABLE 5. June to September

	August	September	June-September
Mean (in.)	4.65	4.74	14.98
Mean as % of annual	9.4	9.6	30.3
$\frac{(\text{Mean} - \text{median})}{\text{Mean}} \times 100$	9	15	5
Highest (as % of mean)	285	314	226
Lowest (as % of mean)	15	10	26
Coefficient of variation (%)	53	51	33

important seasons, the south-west monsoon (June-September) and the north-east monsoon season (October-December), separately and together rather than to compare a period like May-July with October-December.

This study of trends and of changes in the rainfall of Madras does not support the conclusions of Kraus regarding the significance of the variations in May-July and October-December. It shows the difficulty of formulating tests for highly skew series. In view of the above the residual mass curve as a tool for the study of secular variations of rainfall becomes of doubtful utility and, remembering Professor Barnard's comments, it should be used with the greatest caution. A detailed paper on Madras rainfall is being published separately. The annual and seasonal rainfall of Madras are shown in Fig. 1.

The above study also raised the question whether each of the monthly values of rainfall should be individually examined for trends and changes in a country like India where rainfall is so characteristically seasonal. Many of the months receive hardly any rainfall. The following is further illustrative of the very highly variable character of monthly rainfall in the less rainy months of the year.

Great care is therefore necessary in drawing conclusions about changes and trends in rainfall, when only monthly values, particularly for non-monsoon months, are considered.

TABLE 6. Coefficient of variation (%)

	January	February	March	April	May	June	July	August	September	October	November	December
Assam	87	52	59	30	30	19	18	18	24	41	80	105
Gujarat	271	250	250	150	226	62	47	59	74	155	150	200
Madras Deccan	207	241	221	81	61	41	52	63	45	56	83	172

II. RAINFALL

by

K. N. RAO and P. JAGANNATHAN

INTRODUCTION

In Part I, a brief review was made of the different methods which are most generally employed in studies on climatic changes and trends. The results obtained by Kraus (1955) for Madras rainfall by using the method of residual mass curves were compared with those obtained by other methods and some of the limitations of the former method were referred to. In this part, the results of studies on climatic changes in Indian rainfall with particular reference to the arid zones of the country are presented.

India is a vast country and is fortunate in having more than 900 stations with rainfall records for 80 years or more. The series of seasonal and annual rainfall from these stations can be considered to be broadly homogeneous. The total number of rain gauges in the country exceeds 3,000. A very large proportion of these have records for more than 50 years. It is possible therefore to present a seasonally reliable picture of the

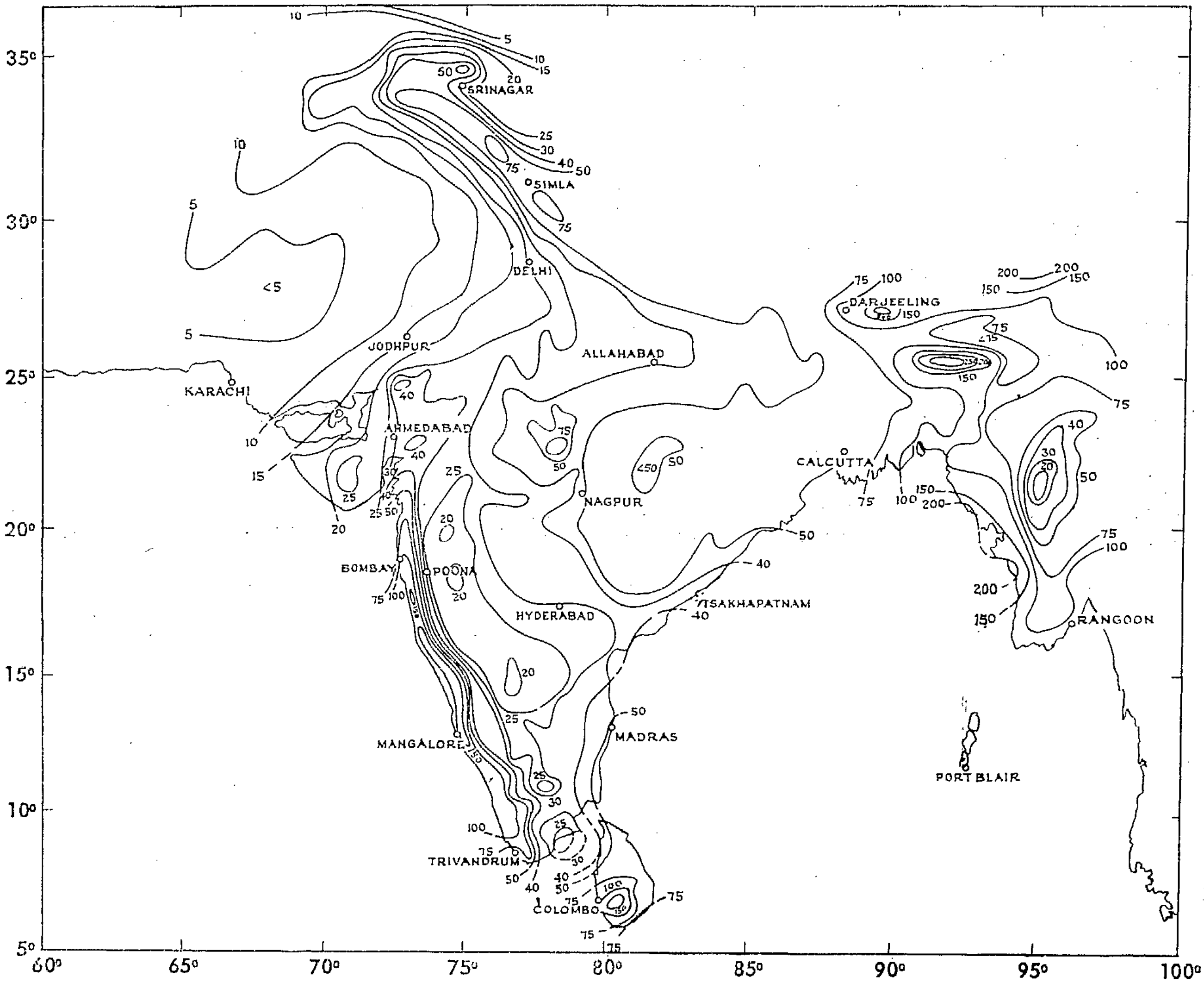


FIG. 1. Mean annual rainfall (in inches) of India.

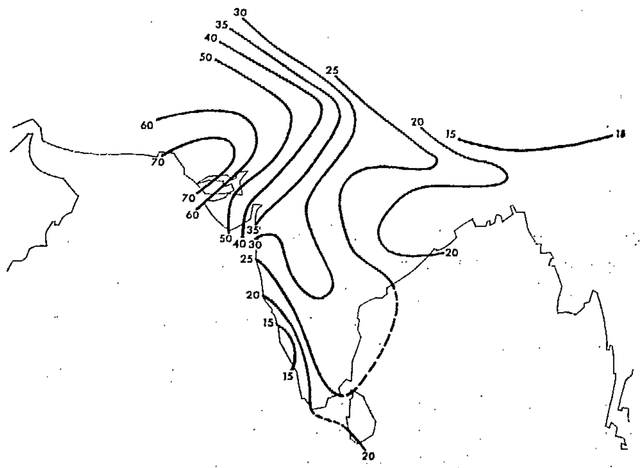


FIG. 2. Coefficient of variation of annual rainfall $\frac{\text{Standard deviation}}{\text{Mean}} \times 100$

distribution of rainfall in the country in space and time.

The average or mean annual rainfall varies from less than 5 in. in parts of western Rajasthan to over 400 in. in the Khasi and Jaintia Hills, Cherrapunji in the latter having an average of 423 in. The Western Ghats, the source of many south Indian rivers, receives the full force of the south-west monsoon and has an average of 200-300 in. Considering stations with elevations less than 3,000 ft. above sea level, the annual average rainfall for the country is about 42 in. Not only is Indian rainfall characterized by wide variations in spatial distribution but the variations from year to year are also very large and can be most marked over large tracts of the country. Taking the coefficient of variation as a measure of variability $\left(\frac{\text{Standard deviation}}{\text{Mean}} \times 100\right)$, it exceeds 30 per cent over large parts of the country. Its value exceeds 50 to 60 per cent in parts of Saurashtra and Kutch and West Rajasthan. It may be interesting to remark that many of these areas get very heavy falls of rain of 15 in. or more in 24 hours. Dharampur, a plain station in Surat district of Gujarat recorded 39 in. in 24 hours, probably a record for a plain station anywhere in the world. The principal features of the rainfall of India are shown in Figs. 1, 2 and 3.

Except over certain southern areas, most of the country receives more than 70 per cent of the annual rainfall during the south-west monsoon season (reckoned from June to September). The west coasts north of latitude 15° N., Gujarat and Rajasthan, get 80 to 90 per cent of the annual rainfall during the south-west monsoon season.

West Rajasthan, Kutch and the western half of Saurashtra get less than 20 in. rainfall annually. These

FIG. 3 (*a*). Rainfall during south-west monsoon (June to September) in each of the sub-divisions and its variability.

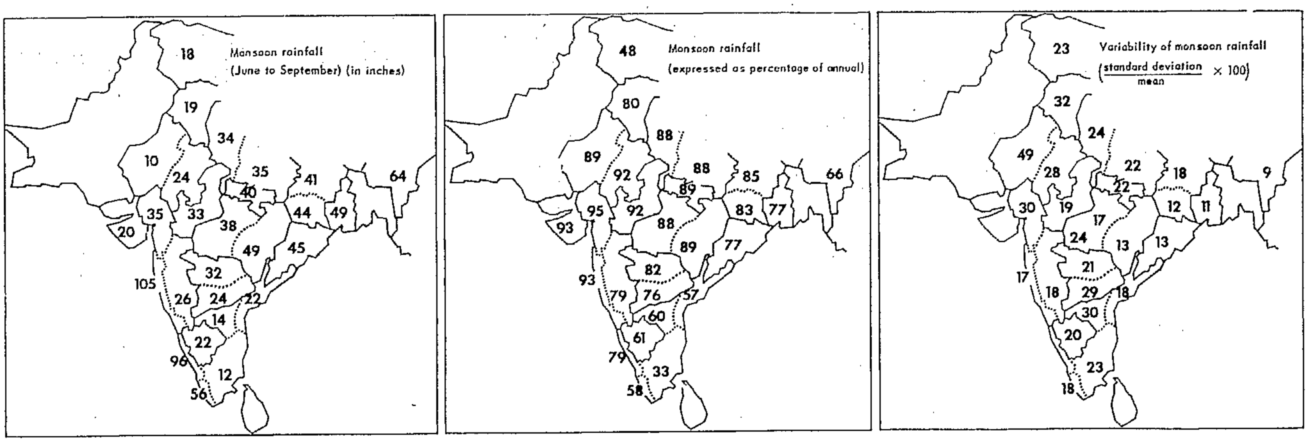
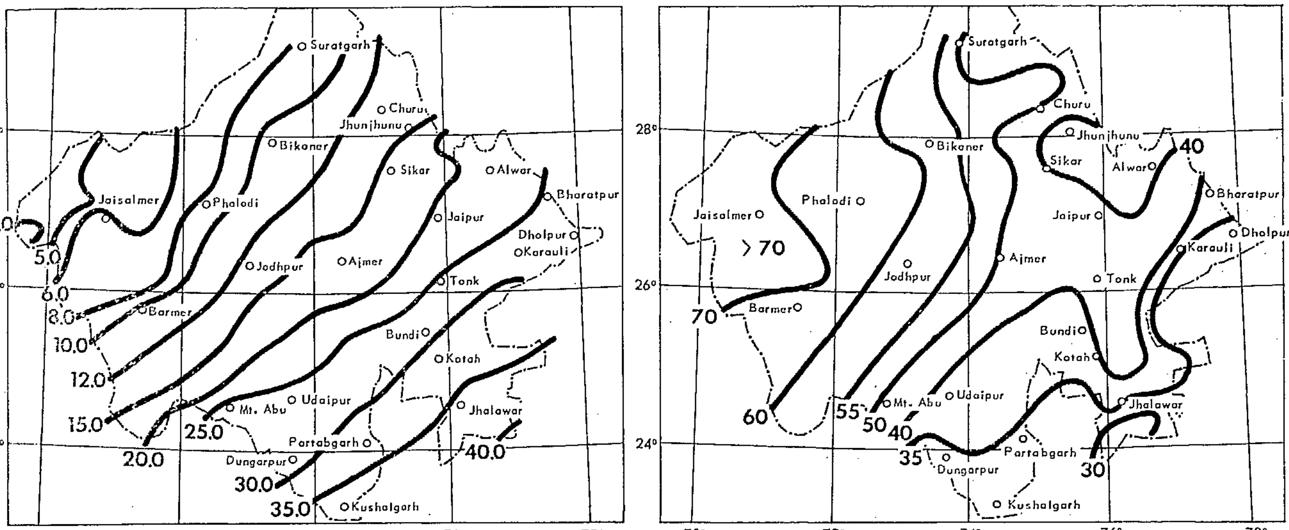


FIG. 3 (*b*). South-west monsoon (June to September) rainfall as percentage of annual.



a *b*

Fig. 4. Rainfall in Rajasthan. (*a*) Normal annual rainfall. (*b*) Coefficient of variation (%).

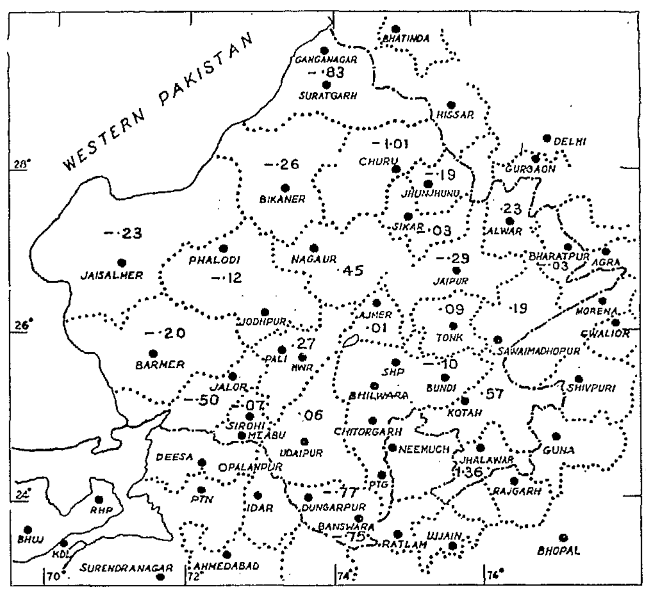
areas may be regarded as the main arid zones of the country. There are small pockets in the Deccan Plateau which have an annual rainfall of 18-20 in. In fact, a good portion of the Deccan Plateau gets less than 25 in. annually. These areas could be classed as semi-arid.

With this very brief introduction of Indian rainfall, we will now present the main results of studies on climatic changes (rainfall) in Rajasthan, Gujarat and other areas of the country.

RAINFALL OF RAJASTHAN

The area of Rajasthan is 130,000 square miles. The average annual rainfall is 21 in.; East Rajasthan has an average of 27 in. and West Rajasthan has 11 in. Over 90 per cent of the annual rainfall is received in the four months, June to September and varies from less than 5 in. in the extreme west of Rajasthan to more than 30 in. in the east. The highest values of the coefficient of variation are in Rajasthan; it varies from 30 per cent in the extreme south-east to over 70 per cent in Jaisalmer district. Both the rainfall and its variability are shown in Fig. 4. For a few stations the standard deviation is as high as the average rainfall itself. The coefficient of variation of south-west monsoon rainfall is 28 per cent for East Rajasthan and 49 per cent for West Rajasthan. The monthly values are given in Table 1.

The question of trends and changes of climate with reference to rainfall has been examined by a number of methods referred to below.



c

(*c*) Differences between 1940 and 1920 normals of districts (= + .0002).

COMPARISON OF DISTRICT NORMALS

This method has been used by some workers as a test for climatic change. For comparison, it is essential that the same set of stations should be used. The comparison given in Table 2 is between averages based on data up to 1920 and up to 1940.

TABLE 1. Monthly values

	January	February	March	April	May	June	July	August	September	October	November	December
West Rajasthan												
Average (in.)	0.13	0.21	0.14	0.10	0.28	1.13	3.43	3.93	1.44	0.17	0.06	0.10
Coefficient of variation(%)	223	152	157	170	182	96	59	76	147	253	333	180
East Rajasthan												
Average (in.)	0.29	0.25	0.21	0.13	0.39	3.07	8.94	8.45	4.13	0.56	0.20	0.21
Coefficient of variation(%)	107	152	162	231	139	63	38	50	78	150	145	171

TABLE 2. Comparison of 1920 and 1940 normals

Numerical difference (in.)	Frequency	Numerical difference (% of mean)	Frequency
0.01-0.10	7	0.1-1	13
0.11-0.20	4	2	4
0.21-0.30	5	3	4
0.31-0.41	0	4	2
0.41-0.50	3	5	0
0.51-0.75	2	5	2
0.76-1.00	2		
1	2		

The average difference taking sign into account is 0.002 in. whilst the average numerical value of the difference is 0.37 in. Fifty per cent of the differences are less than 0.23 in. Although the number of negative differences is 16, most of them are small. The mean difference as percentage of the normal is only 0.7 per cent. The district differences are shown in Fig. 4. The differences in rainfall normals of 1920 and 1940 can be regarded as small and negligible.

COMPARISON OF 1901 TO 1930 AVERAGES WITH THOSE FOR 1901 TO 1950

Uniform averages for the period 1901-50 were prepared for all the rain-gauge stations in Rajasthan. For each station, the difference 1901-30 minus 1901-50 was examined by the test mentioned in the section "Comparison of means of different periods" of Part I. It is interesting to observe that for only 6 of the 87 stations was the difference statistically significant. Out of these, for only one was the difference significant at the 1 per cent level of significance. Similar results were obtained for differences between averages for 1901-40 and for 1901-50. These analyses do not suggest any significant change in the annual rainfall of the stations in Rajasthan during 1901 to 1950. The results of analysis for two districts are shown in Table 3.

STUDY OF TREND

Linear regression equations have been fitted to the data of one or two stations in each district with records extending to over 45 years, the equation being $R = by + \text{Const.}$, where R is rainfall, y = year and b is the regression coefficient. Of the 50 stations for which this method was tried, only two showed significance at 5 per cent level. This method was also tried for seven stations with records for longer periods (see Table 4).

Only the regression coefficient of Partabsar was found to be significant. For Jaipur (1871-1950), orthogonal polynomials have been fitted up to the fifth degree (Pramanik and Jagannathan, 1953). The results are as follows: Mean: 24.42 in.; Regression coefficients: -2.48×10^{-2}, 1.90×10^{-4}, 0.90×10^{-5}, 3.37×10^{-6}, 0.12×10^{-7} £; square roots of variance contributed by different degrees of polynomial: 6.11, 2.54, 0.060, 5.86, 1.48 £; polynomial as a whole, 3.45, residual 9.68. None of the regression coefficients is significant.

The analysis of the data of individual stations also suggests that there is no trend in the rainfall of Rajasthan. In this connexion, the monsoon seasonal rainfall of the two sub-divisions East and West Rajasthan has also been examined. The frequency distributions of the series were tested for normality by Fisher's g_1 and g_2 statistics and the homogeneity of the decadal variances by the M statistic (see Table 5).

None of these figures indicates any statistically significant trend and the frequency distributions of seasonal rainfall of East and West Rajasthan are not significantly different from normal. The means for different decades were also compared.

For East Rajasthan, the decade with the highest mean, 115.9 per cent of normal, is 1941-50. Comparing it with the mean for 1901-50, we get $t = 1.53$ with 78 degrees of freedom. This is not significant even at 5 per cent level of significance.

For West Rajasthan, the decade with the highest mean, 116 per cent of normal, is 1926-35. The lowest decadal mean is 83 per cent of normal, for 1896-1905.

TABLE 3. Rainfall of Rajasthan

Station	No. of years	Mean (in.)	Standard deviation	Coefficient of variation (%)	Highest (in.)	% of mean	Lowest (in.)	% of mean	1901-30 minus 1901-50	τ_k	1901-40 minus 1901-50	τ_k	1940 minus 1920
Jaisalmer district													
Jaisalmer	50	7.03	4.81	68	22.77	324	0	0	+0.21	+0.04	+0.21	+0.04	—0.22
Devikot	48	6.06	4.46	74	21.00	347	0	0	—0.45	—0.10	—0.45	—0.10	—0.17
Bap	49	7.20	4.96	69	21.33	296	0.50	7	—0.67	—0.13	+0.25	+0.06	+0.34
Fategarh	21	7.27	3.95	54	17.63	243	1.97	27					
Lakhan	21	7.75	8.56	111	30.31	391	0	0					
Mayajalar	21	6.55	6.13	94	27.57	421	0	0					
Shahgarh	21	4.58	3.71	81	14.82	324	0	0					
Khuiala	21	4.54	2.87	63	10.77	237	0.60	17					
Tanot	21	4.14	4.17	101	20.00	483	0	0					
Kishengarh	22	4.87	3.76	77	14.70	302	0	0					
Buili	21	3.49	1.90	54	7.10	203	0.64	18					
Mohangarh	21	5.33	3.61	68	12.73	329	0	0					
Nokh	22	6.97	4.64	67	18.27	262	2.10	30					
Dawa	49	4.72	3.60	76	17.84	378	0	0	+0.39	+0.11	—0.03	—0.01	—0.72
Ramgarh	49	5.40	4.14	77	22.90	424	0.21	4	+0.10	+0.02	—0.01	—0.002	—0.23
Khaba	49	6.07	4.21	69	21.81	359	0	0	+0.40	+0.09	—0.13	—0.03	—0.39
Lathi	20	5.75	2.79	49	11.69	203	0.82	14					
Jaipur district													
Jaipur	50	22.94	10.85	47	51.86	226	3.79	17	—0.47	—0.04	+0.12	+0.01	+0.07
Chatsu	49	21.00	8.22	39	42.38	202	5.55	26	+0.25	+0.03	—0.15	—0.02	—1.39
Amber	34	25.16	10.78	43	57.00	227	8.96	36					
Jamwa Ramgarh	18	22.67	8.03	35	33.13	146	6.41	28					
Bairath	22	22.42	7.69	34	43.21	193	9.29	41					
Kotputli	50	20.31	7.70	38	40.68	200	4.14	20	+0.05	+0.006	—0.88	—0.11	—0.65
Dausa	50	21.83	8.81	40	51.36	235	5.31	24	+0.28	+0.03	—0.35	—0.04	+0.20
Lalsot	50	24.92	10.30	41	62.16	249	6.09	24	+0.06	+0.006	—0.09	—0.009	—0.65
Sambhar	49	19.64	7.08	36	39.82	203	5.37	27	—0.52	—0.07	—0.26	—0.04	—0.14
Mozamabad	14	17.65	7.47	42	29.40	167	6.99	40					
Pawata	14	20.12	7.99	40	39.60	197	8.47	42					
Sanganer	49	21.84	9.59	44	50.67	232	4.14	19	+0.18	+0.02	—0.32	—0.03	—0.18
Chomu	48	20.72	9.01	43	54.34	262	5.17	25					—0.17
Samodh	49	22.41	14.19	63	90.88	406	4.94	22					—0.63
Bandikui	49	24.23	10.23	42	59.52	246	6.41	26	+0.33	+0.03	—0.04	—0.004	+0.60
Baswa	19	22.78	7.94	35	37.94	167	10.04	44					

TABLE 4. Trend study of seven stations

Station	No. of years	Mean (in.)	Standard deviation (in.)	Regression coefficient	F
Phalodi	66	14.34	7.2	—0.0215	0.856
Nagpur	66	8.90	4.8	—0.0087	0.078
Madava	53	20.65	8.8	—0.0055	0.0048
Nawa	60	8.21	5.5	—0.0487	1.4502
Sikar	64	17.53	6.7	0.0223	0.2347
Jhun-jhunu	74	19.86	7.3	0.0020	0.0026
Partabsar	60	17.60	7.9	0.1447	6.561 [1]

1. Significant.

Table 5. Frequency distribution of seasonal rainfall

	East Rajasthan	West Rajasthan
g_1 with standard error	0.02 ± 0.27	0.16 ± 0.27
g_2 with standard error	0.64 ± 0.53	0.90 ± 0.53
M	9.7	11.7

Comparing these with the mean for 1875 to 1955, we get $t = 1.656$ and $t = 1.5$ which are not significant. The difference between the means for the two periods 1875-1924 and 1925-46 is 1.27 in.; $t = 1.002$ and is not significant even at 5 per cent level.

The linear regression coefficients are $b = 0.029$ and $b = 0.0007$ for East and West Rajasthan respectively. Neither of these is significant.

A brief discussion of the time intervals between years when the monsoon rainfall of East Rajasthan was less than 80 per cent of the normal is now given. There were 17 such occasions during a period of 81 years from 1875 to 1955 (see Table 6).

Table 6. Monsoon rainfall of East Rajasthan

Year	Departure from normal (negative)	Interval t_i	Year	Departure from normal (negative)	Interval t_i
1877	66		1915	53	2
1883	24	6	1918	56	3
1898	23	15	1925	24	7
1899	38	1	1928	29	3
1901	34	2	1939	30	11
1905	61	4	1949	33	10
1907	26	2	1951	44	2
1911	31	4	1953	32	2
1913	44	2			

About 50 per cent of the time intervals are 3 years or less. Three of the intervals are greater than 9 years, the highest being 15. Assuming that the intervals follow an exponential law and following the test used by Maguire and others in 1952, we find the ratio of the largest of time intervals (t_n) to $\bar{t}\left(= \frac{t_n}{nt} = 0.197\right)$ is less than the significant value at 5 per cent. The longest interval of 15 years is thus not significant.

To find out if there is any significant tendency for intervals to succeed one another in groups, the statistic $\frac{M}{C}$,

$$M = 2nk \left\{ \log_e \left(\frac{1}{K} \Sigma T_i \right) - \frac{1}{K} \Sigma \log_e T_i \right\}$$

where T_i is the sum of intervals in the ith group and $C = 1 + \frac{K+1}{6nk}$, was calculated. This is distributed as χ^2 with $(K-1)$ degrees of freedom. $\frac{M}{C} = 1.44$ with 3 degrees of freedom (as the intervals were divided into four groups) and this is less than the value for the 5 per cent and hence not significant.

Thus a critital examination of the rainfall of Rajasthan, by considering the data of districts, of individual stations and of the two divisions, East and West Rajasthan, does not show that there has been any significant change or trend in the annual/seasonal rainfall of Rajasthan during the past 80 years for which data are available. Table 7 gives the monsoon seasonal rainfall for East and West Rajasthan from 1875 to 1955.

RAINFALL OF GUJARAT STATE

Gujarat, including Saurashtra and Kutch, has an average annual rainfall of 33 in. Saurashtra and Kutch have an average annual rainfall of less than 20 in. Most of the area, especially the western half of Saurashtra and Kutch, receives less than 12 in. to 15 in., 94 per cent of the average occurs during the four monsoon months June to September. July is the rainiest month accounting for about 40 per cent of the annual rainfall. The rainfall of this area is highly variable. The standard deviation is 9.6 in. and the coefficient of variation 31 per cent. Excluding West Rajasthan and the adjoining areas of Punjab, Gujarat, including Saurashtra and Kutch, has the highest variability of rainfall in the country.

LOWEST RAINFALL

The lowest rainfall during a period of 80 years was 28 per cent of the normal in 1889 and the difference between the rainfall of 1898 and 1899 was 76 per cent of the normal (i.e., 25 in.); 1900 had 71 per cent more rainfall than 1899. A few noteworthy instances of big differences between successive years are given in Table 8.

These examples show clearly that very large variations from year to year are a characteristic feature of the rainfall of this area.

COMPARISON OF 1920 AND 1940 NORMALS

In a comparison of 1920 and 1940 normals the average rainfall for June to September, based on the data of 83 rain gauges in this area, was shown to be 30.70 in. for 1920 and 30.83 in. for 1940, a difference of 0.13 in.; a percentage mean difference of 0.4 and a standard deviation of 9.6. This difference is not regarded as significant.

A similar comparison of the average rainfall for August and September showed 12.75 in. for 1920 and 12.77 in. for 1940, a difference of 0.02 in. which is negligible.

TABLE 7. Rainfall of Rajasthan, percentage departure from normal

Year	Departure from normal		Year	Departure from normal		Year	Departure from normal	
	East Rajasthan	West Rajasthan		East Rajasthan	West Rajasthan		East Rajasthan	West Rajasthan
	%	%		%	%		%	%
1875	20	2	1902	—7	—26	1929	16	11
1876	18	93	1903	6	—13	1930	—7	—15
1877	—66	—75	1904	19	—51	1931	13	32
1878	9	45	1905	—61	—60	1932	—10	—3
1879	16	17	1906	0	—22	1933	48	32
1880	—5	—16	1907	—26	0	1934	31	30
1881	11	47	1908	54	102	1935	11	—8
1882	20	2	1909	10	35	1936	—6	—7
1883	—24	—36	1910	7	1	1937	1	5
1884	23	57	1911	—31	—66	1938	—17	—27
1885	16	—33	1912	7	—7	1939	—30	—56
1886	—5	8	1913	—44	—30	1940	—9	1
1887	36	—38	1914	10	—2	1941	—33	—17
1888	—9	—8	1915	—53	—74	1942	63	22
1889	28	—5	1916	39	34	1943	13	19
1890	—3	—15	1917	98	119	1944	21	82
1891	—15	—36	1918	—56	—78	1945	39	31
1892	48	63	1919	27	—4	1946	34	—14
1893	17	77	1920	—18	—33	1947	12	—3
1894	26	18	1921	—12	—24	1948	9	—21
1895	—18	—31	1922	8	—17	1949	—15	—18
1896	—14	—12	1923	15	—11	1950	16	13
1897	—2	19	1924	49	—6	1951	—44	—47
1898	—23	—36	1925	—24	—32	1952	14	9
1899	—38	—83	1926	26	60	1953	—32	—14
1900	22	10	1927	1	22	1954	—12	—9
1901	—34	—48	1928	—29	—1	1955	23	—

TABLE 8. Differences between successive years

Year	Percentage		Year	Percentage		Year	Percentage	
	of normal	Difference		of normal	Difference		of normal	Difference
1898	104		1910	109		1917	128	
		—76			—70			—92
1899	28		1911	39		1918	36	
1899	28		1911	39		1918	36	
		+71			+87			+65
1900	99		1912	126		1919	101	

STUDY OF TREND

The series of monsoon rainfall observations has been examined for trend by fitting linear regression equations. No significant trend was found and the variations from year to year do not appear to follow any definable law. The series shows no periodicity.

The above study shows that there has been no significant change either in the seasonal or in the annual rainfall of Gujarat. Table 9 gives the June-September seasonal rainfall expressed as percentage of normal together with variations from year to year. Fig. 5, shows the rainfall from 1875 to 1955 in the three adjoining areas, Gujarat (including Saurashtra and Kutch), Konkan and Bombay Deccan.

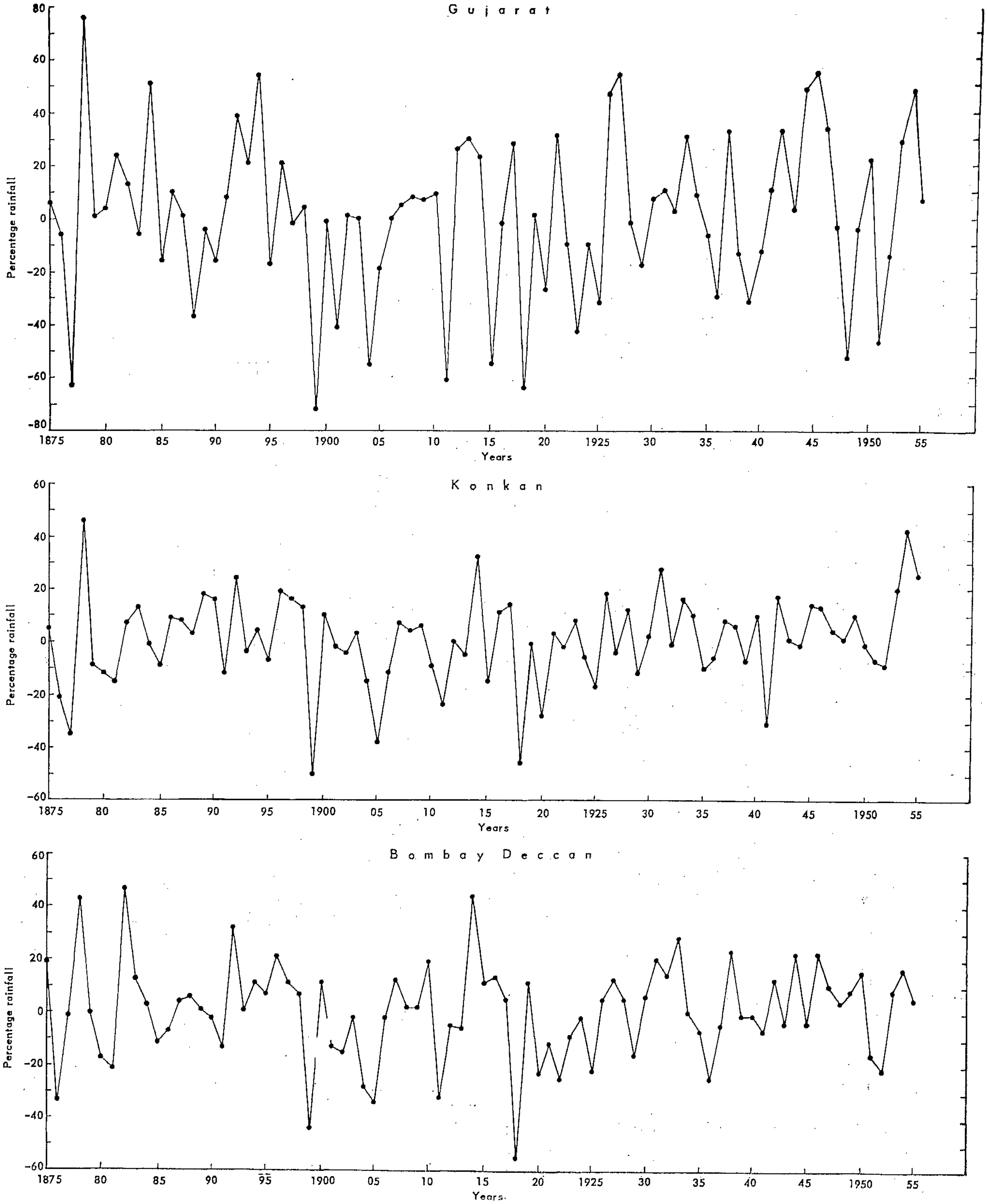


FIG. 5. June to September rainfall from 1875 to 1955 in the three adjoining areas of Gujarat (including Saurashtra and Kutch), Konkan and Bombay Deccan.

TABLE 9. Rainfall of Gujarat (including Saurashtra and Kutch), 1875-1955

Year	Rainfall expressed as percentage of normal (June to September)	Year-to-year variation	Year	Rainfall expressed as percentage of normal (June to September)	Year-to-year variation
1875	106		1915	45	—78
1876	94	—12	1916	98	53
1877	37	—57	1917	128	30
1878	176	139	1918	36	—92
1879	99	—77	1919	101	65
1880	104	5	1920	73	—28
1881	124	20	1921	131	58
1882	113	—11	1922	90	—41
1883	94	—19	1923	57	—33
1884	151	57	1924	90	33
1885	84	—67	1925	68	—22
1886	110	26	1926	147	79
1887	101	—9	1927	154	7
1888	63	—38	1928	98	—56
1889	96	33	1929	82	—16
1890	84	—12	1930	107	25
1891	108	24	1931	110	3
1892	139	31	1932	102	—8
1893	121	—18	1933	130	28
1894	154	33	1934	108	—22
1895	83	—71	1935	93	—15
1896	121	38	1936	70	—23
1897	98	—23	1937	132	62
1898	104	6	1938	86	—46
1899	28	—76	1939	68	—18
1900	99	71	1940	87	19
1901	59	—40	1941	110	23
1902	101	42	1942	132	22
1903	100	—1	1943	103	—29
1904	45	—55	1944	148	45
1905	81	36	1945	154	6
1906	100	19	1946	133	—21
1907	105	5	1947	96	—37
1908	108	3	1948	47	—49
1909	107	—1	1949	97	50
1910	109	2	1950	123	26
1911	39	—70	1951	55	—68
1912	126	87	1952	85	30
1913	120	4	1953	132	47
1914	123	—7	1954	148	16
			1955	104	—44

RAINFALL OF HYDERABAD STATE
(Pre-reorganization—Deccan)

The area of this state was 86,000 square miles with 16 rainfall stations having records for 65 to 80 years. The average annual rainfall was 36 in. and over 75 per cent of the annual rainfall occurs during the south-west monsoon (June to September).

In the first instance, the annual rainfall series of the stations and the seasonal rainfall series of the two sub-areas were tested for normality. Except for four stations, the data do not show any significant departure from normality. Probabilities for the different stations were combined and the P_λ test was found to support normality. The whole series of rainfall amounts could, therefore, be regarded as distributed normally.

Each decadal average was compared with the mean for the entire period and tested for significance. The results are given in Table 10. It will be seen that only seven out of over 100 values are significant at the 5 per cent level and one or two at the 1 per cent level. From this it can be inferred that the decadal averages do not differ significantly from the average for the entire period.

First and second degree orthogonal polynomials have been fitted to these data. The regression coefficients b_1 and b_2 are included in Table 10. The percentage of the variance accounted by the two polynomials given below the values of regression coefficients does not exceed 5 per cent. None of the coefficients is significant.

This study relates to a central area in the Deccan closely bordering a semi-arid area. It does reveal any significant change in the annual rainfall of the area.

SUB-DIVISIONAL RAINFALL

The south-west monsoon seasonal rainfall of the 25 sub-divisions of the country has been examined for trends by Rao and Jagannathan (1960). The data analysed are the percentage departures from normal of the south-west monsoon rainfall for the 80 years from 1875 to 1954. A small defect of these series should be mentioned, i.e., the number of rain gauges in each sub-division has not remained the same throughout the period. The main changes correspond to the periods when new and revised normals were introduced—1910, 1920 and 1940. A comparative study of the normals for two periods, up to 1920 and up to 1940, has shown that the effect of the variation in the number of rain gauges in the calculation of percentage departures is generally small and negligible. Orthogonal polynomials up to the third degree have been fitted. Table 11 gives the regression coefficients and the square root of the variance contributed by each of the polynomials. The residual standard error is also included.

Except in two cases, none of the regression coefficients is significant. Even in these two cases (Orissa and coastal Andhra Pradesh), only the third degree polynomial coefficients are significant. If, however, one were to consider all the divisions together and apply the test for combined probabilities, the result is not likely to be significant statistically.

TABLE 10. Rainfall of Hyderabad State

Station	$\frac{g_1}{SEg_1}$	$\frac{g_2}{SEg_2}$	Period	Mean (in.)	Standard deviation (in.)	Decadal averages and values [1] of t								b_1	b_2
						1876-85	1886-95	1896-1905	1906-15	1916-25	1926-35	1936-45	1946-55		
Asifabad	1.82	1.39	1884-1955 (67)	39.66	10.46	—	43.07	39.54	33.32	34.44	41.69	47.24	39.42		
			ex. 1887, 1922, 1925				(7)	(1892-1901)	(1902-11)	(1912-21)	0.1947	0.7247	0.0229		
Aurangabad	0.25	—0.64	1875-1955 (81)	29.14	8.56	29.98	32.83	25.58	26.84	24.29	32.05	28.74	31.72	—0.0037	0.0012
						0.0098	0.4311	0.4159	0.2687	0.5666	0.3400	0.0467	0.3014	0	4.4
Bir	1.19	—0.05	1876-1955 (79)	28.05	8.95	29.12	35.20	24.80	25.21	21.07	29.87	23.12	30.73	—0.1888	0.0028
			ex. 1892			0.1196	(9)	0.3631	0.3173	0.1095	0.2034	0.5508	0.2994	1	2.2
Karimnagar	0.44	0.88	1876-1955 (76)	34.50	9.17	32.65	36.50	31.23	—	35.47	35.74	35.34	37.35	—	
			ex. 1912-1915			0.2017	0.2290	0.3566		0.1058	0.1352	0.0916	0.3108		
Nanded	4.73[2]	7.43[2]	1876-1955 (80)	36.90	11.58	35.60	49.55	31.00	35.76	32.15	37.09	34.33	39.70	—0.0130	0.0031
						0.1123	1.0924	0.5095	0.0984	0.4102	0.0164	0.2219	0.2418	0	1.7
Nizamabad	10.48[2]	0.38	1876-1955 (80)	39.96	10.01	36.22	45.06	37.15	40.06	36.27	41.46	42.11	41.35	0.0206	—0.0001
						0.3736	0.5095	0.2807	0.0100	0.3686	0.1499	0.2148	0.1389	1	0
Osmanabad	1.27	0.59	1876-1955 (80)	33.44	8.98	36.04	39.11	28.50	32.16	30.44	34.52	30.86	35.90	—0.0135	0.0042
						0.2895	0.6314	0.5501	0.1425	0.3341	0.1203	0.2873	0.2739	0	0
Parbhani	0.65	0.35	1876-1955 (79)	32.75	10.15	33.52	35.81	26.39	35.19	30.31	33.58	33.07	34.41	0.0089	0.0022
			ex. 1894			0.0759	(9)	0.6266	0.2404	0.2404	0.0818	0.0315	0.1635		
Gulbarga	1.54	0.12	1875-1955 (80)	29.25	8.46	30.22	31.54	28.02	30.89	26.22	29.13	24.94	33.03	—0.0079	0.0015
						0.1147	0.2707	0.1454	0.1939	0.3582	0.0142	0.5095	0.4468	0	1
Janawada	3.48[2]	3.01[2]	1888-1955 (68)	30.04	8.60	—	35.29	25.52	31.35	29.37	30.17	28.97	30.69	—0.0042	0.0022
							(8)	0.5256	0.1523	0.0779	0.0151	0.1244	0.0756	0	1
Sultan Bazar	4.20[2]	2.84[2]	1869-1955(87)	30.27	9.21	34.24	33.77	27.55	32.20	32.73	28.42	27.90	27.43	—0.0048	—0.0007
						0.4311	0.3800	0.2953	0.2096	0.2671	0.2009	0.2573	0.3084	0	1.5
Bolaram	2.23	1.04	1870-1955 (84)	29.56	10.82	31.56	33.27	26.91	28.54	30.95	30.70	30.25	33.83	0.0171	0.0010
			ex. 1941, 1922			0.1848	0.3429	0.2449	0.0943	(9)	0.1054	(9)	0.3946	1	0
Mahbubnagar	1.91	0.57	1891-1955 (65)	31.64	8.68	—	—	28.13	31.20	29.29	31.25	30.00	36.64	0.0420	0.0066
								0.4044	0.0507	0.2707	0.0449	0.1889	0.5760	1	5.9
Nalgonda	2.65[2]	3.84[2]	1876-1955 (80)	28.76	8.30	26.75	29.42	24.15	30.66	31.76	28.59	28.90	29.88	0.0212	—0.0017
						0.2422	0.0795	0.5554	0.2289	0.3614	0.0205	0.0169	0.1349	1	1
Raichur	2.33	0.78	1876-1955 (80)	26.49	8.24	23.96	32.70	26.03	24.54	24.86	26.17	25.45	28.20	0.0027	0.0011
						0.3070	0.7536	0.0558	0.2367	0.1978	0.0388	0.1262	0.2075	0	0
Hanamkonda	2.02	0.91	1876-1955 (80)	35.69	10.36	31.40	37.06	31.23	36.81	38.08	37.40	35.87	37.69	0.0372	—0.0014
						0.4141	0.1322	0.4305	0.1081	0.2307	0.1651	0.0174	0.1931	3	0

1. Values of t are given below decadal means.
2. Significant at 5 % level.

TABLE 11. Trends in sub-divisional rainfall

Sub-division	Regression coefficients: First degree $\times 10^{-2}$	Second degree $\times 10^{-4}$	Third degree $\times 10^{-6}$	Square root of variance contributed by: First degree	Second degree	Third degree	Residual standard error
Assam	0.0141	0.6190	0.7963	0	0.03	6.45	8.68
Bengal	—2.2240	—16.8850	—1.8080	9.19	7.20	16.44	10.44
Orissa	—1.8940	—13.6424	—2.9830	7.82	5.71	25.76 [1]	6.56
Chota Nagpur	2.0716	3.3166	—1.2947	8.58	1.41	11.19	13.08
Bihar	0.3850	—47.5667	1.9680	1.59	20.29	5.33	17.38
Uttar Pradesh East	3.1774	—46.6580	3.1770	13.63	19.90	27.37	21.78
Uttar Pradesh West	0.1969	—4.8696	1.6500	0.85	2.07	15.71	22.93
Punjab (I)	—2.7801	4.2374	—0.1572	11.48	1.80	4.24	29.19
Kashmir	5.7270	10.4410	4.0175	23.66	4.45	10.99	35.33
Rajasthan West	—2.6695	73.9390	—6.2880	11.03	31.54	17.19	40.83
Rajasthan East	0.1324	17.4401	3.4498	0.55	7.44	8.79	31.38
Madhya Bharat	9.5458	92.7710	—1.2620	39.42	39.56	10.91	21.07
Madhya Pradesh	—4.3782	16.3917	—0.2771	18.86	6.99	2.99	22.25
Madhya Pradesh East	—1.9122	—9.1928	—1.5339	7.90	3.82	15.14	13.95
Madhya Pradesh West	3.6328	32.9259	—2.4219	15.01	14.04	20.93	17.22
Gujarat	2.9003	96.3236	—0.9871	11.98	41.09	8.59	31.07
Konkan	4.2007	53.6200	1.9612	17.35	22.87	17.47	17.00
Deccan (Desh)	0.2215	89.6645	0.2359	0.89	38.24	2.02	21.13
Hyderabad North	—4.5430	85.9824	1.0306	18.77	36.67	8.91	32.29
Hyderabad South	1.4147	6.5300	5.8780	5.85	2.78	16.72	23.81
Coastal Andhra Pradesh	3.5003	17.2280	2.5010	14.46	7.35	68.35 [1]	15.58
Rayalaseema	—3.8068	—15.9180	1.7620	15.73	6.79	15.23	28.48
Tamilnad	—4.1640	—10.7450	3.2770	17.20	4.58	8.96	22.31
Malabar-South Kanara	4.3650	—62.7924	—1.0013	18.03	26.78	8.65	18.33
Mysore	2.2400	—76.2780	3.3840	9.25	32.53	29.24	18.80

1. Significant.

RAINFALL OF INDIVIDUAL STATIONS

Pramanik and Jagannathan (1953) examined the annual rainfall data for 30 selected observatories in India and Pakistan with long records. Orthogonal polynomials up to the fifth degree were fitted to the rainfall series. In the case of some stations which appeared to show a trend, the series were further examined by means of 10-year moving averages. The decadal means for these were compared with the general mean and tested for significance. The picture which emerged from this study was that there had not been any general trend in annual rainfall.

NORTH-EAST MONSOON RAINFALL OF TAMILNAD

In Tamilnad, the principal rainy season is from October to December (north-east monsoon) accounting for about 50 per cent of the annual rainfall. In the extreme south-eastern districts, the north-east monsoon contributes 60 to 70 per cent of the annual rainfall. Krishna Rao and Jagannathan (1953) examined in detail the north-east monsoon rainfall of the different districts by means of moving averages, by the fitting of orthogonal polynomials up to the fifth degree, and by a comparison of means for different periods. No secular trend was found in the rainfall of this area.

A succession of years, from 1947 to 1961, of deficient rainfall during the north-east monsoon season in Madras State gave rise to considerable anxiety and frequent suggestions were made in the press and elsewhere that the climate had changed. A paper by Rao (1959*b*) on droughts in Madras State shows that the north-east monsoon is less dependable than the south-west monsoon. The rainfall of the two seasons is negatively correlated although the correlation coefficient for the two periods is rather small (—0.36). A result of interest is that rainfall of Madras City is highly correlated with that of Madras State. The correlation coefficient is +0.83 based on data over 75 years.

This enables one to infer from past records of rainfall of Madras City (which go back to 1813) that Madras State should have experienced deficient rainfall during the years 1828-35. Thus a sequence of five or more years of deficient rainfall, although, rare has occurred at least twice during the past 150 years. A study of time intervals between years of deficient rainfall (less than 80 per cent of the normal) has shown that the series is random.

FREQUENCY OF DEPRESSIONS IN THE BAY OF BENGAL

With a view to finding out whether there have been changes in the frequency of depressions (including cyclones) in the Bay of Bengal in recent years, a statistical study was made of the available data from 1890 by Rao and Jayaraman (1958). The annual average number is 12.6 with 13 as the median value. The standard deviation (S. D.) is 2.2 and coefficient of variation 17 per cent. The highest number during 1890 to 1950 was 17 in 1908 and the lowest 7 in 1910. The decadal mean frequencies are shown in Table 12.

TABLE 12. Decadal mean frequencies

Period	1891-1900	1901-10	1911-20	1921-30	1931-40	1941-50
June to September	7.7	6.8	6.5	7.8	6.9	7.2
October to December	2.6	3.1	3.8	3.9	3.3	3.3
Annual	11.7	12.0	11.9	14.5	12.5	13.1

The means for different periods for the seasons and for the year were compared. Orthogonal polynomials up to the fourth degree were fitted to the series and the total contribution to the variance was only 8 per cent. None of the regression coefficients was found to be significant. The series were tested for periodicity by periodogram and correlogram methods. No significant periodicity was found. The statistical analysis did not show significant differences in means or regression coefficients or periodicity.

CONCLUSION

A detailed statistical examination of the seasonal and annual rainfall of Rajasthan, the western part of which is one of the principal arid zones of the country, shows no significant change or trend in the annual and seasonal rainfall of the area.

Studies of Indian rainfall also do not show any statistically significant change or trend in the normal or seasonal rainfall of India.

Great care and caution are necessary in drawing conclusions based on analysis of rainfall series which do not follow the normal law. This applies particularly in the case of monthly rainfall of India.

RÉSUMÉ

Évolution du climat de l'Inde (K. N. Rao et P. Jagannathan)

Plus d'une douzaine d'études portant sur les changements de climat de l'Inde ont été publiées. Des données inédites sont également accessibles. La plupart de ces études traitent des précipitations et de la température. Les documents des observatoires sur les températures s'étendent sur une période de soixante ans. En ce qui concerne les précipitations, un grand nombre de stations ont des observations portant sur plus de quatre-vingts ans ; quelques-unes, sur plus d'un siècle. Les observations d'altitude sont encore peu nombreuses, mais la structure de la circulation générale sur l'Inde pour les vingt ou trente dernières années a été étudiée. Tous ces travaux se rapportent uniquement à la période de mesures instrumentales. Les auteurs font un examen critique des travaux effectués jusqu'ici.

L'auteur passe en revue les méthodes adoptées par différents chercheurs pour l'étude des changements de climat. Il indique les limitations des moyennes chevauchantes et autres méthodes de comparaison des moyennes des différentes périodes sans examen préalable de la nature de distribution des fréquences.

La méthode de la courbe de masse résiduelle a été largement utilisée par Kraus dans ses études des changements séculaires des précipitations dans les différentes parties du monde. L'application de cette méthode aux précipitations de l'État de Madras, qui dispose de la plus longue série d'observations, depuis 1813, est examinée en détail. Kraus (1955) a fait remarquer, dans la section 7 de son article sur « Les variations séculaires de régime des précipitations tropicales », que, alors que les précipitations moyennes annuelles de l'État de Madras n'ont jamais subi de fluctuations significatives, il n'en est pas de même lorsque l'on subdivise les résultats annuels. Après examen critique, il est difficile d'accepter ses résultats et ses méthodes, en raison des résultats des autres méthodes statistiques. En relation avec de telles études, la question se pose de savoir si l'analyse pour tous les mois doit être effectuée pour les précipitations de zones qui ont une saison de pluies fixe. Une question analogue se pose également dans le cas de l'étude d'événements rares comme les cyclones.

Dans l'Inde, c'est Madras (ville) qui a la plus longue série d'observations de précipitation (à partir de 1813). Au cours de la seconde guerre mondiale, la station urbaine a été déplacée pendant quatre ans (1943-1946). Les séries de la station urbaine ont été rendues homogènes à l'aide d'observations de comparaison. Novembre est le mois le plus pluvieux de l'année et 60 % de la précipitation annuelle de 49,4 inches est limitée aux trois mois de la mousson de nord-est (octobre-décembre). Les distributions de fréquence des séries annuelles et saisonnières sont presque normales, alors que les distributions mensuelles sont très asymétriques.

Les moyennes décennales pour une saison et pour l'année ont été comparées avec les moyennes correspondantes pour l'ensemble de la période. Aucune des différences n'est statistiquement significative. Ces séries ont été également analysées en utilisant des polynomes orthogonaux jusqu'au 5e degré. Il n'y a aucune indication de variation séculaire. Les séries annuelles ont été analysées pour rechercher les périodicités en utilisant le périodogramme et également les méthodes d'autorégression.

Un groupe d'années, de 1947 à 1951, de précipitations déficitaires dans l'actuel État de Madras ont donné à penser à des changements dans le régime des précipitations et cette séquence a été considérée comme exceptionnelle. La corrélation entre la précipitation de la mousson de nord-est de l'État de Madras et pour la ville de Madras atteint +0,83. Les séries de précipitations pour l'État de Madras pour les années antérieures à 1875 ont été extrapolées. Cela a suggéré qu'il devrait y avoir également eu des années déficitaires dans l'État de Madras au cours des années 1828 à 1835 comme c'était le cas pour la ville de Madras. La séquence 1947 à 1951 n'est, par conséquent, pas exceptionnelle.

Dans le présent article les données sur les précipitations du Rajasthan, du Gujurat (Saurashtra et Kutch compris), du Deccan et des régions voisines ont été examinées pour voir s'il existait une tendance à l'évolution au cours des dernières soixante à quatre-vingts années. Ces régions sont également les principales régions arides et semi-arides du pays. L'analyse porte sur les données des stations individuelles et également sur celles de zones restreintes, mais elle est limitée à la précipitation saisonnière et annuelle.

La précipitation du pays et sa variabilité dans le temps et dans l'espace est rapidement examinée. Dans le Rajasthan les données pour plus d'une centaine de stations ont été examinées, les moyennes de différentes périodes comparées. La tendance linéaire a été calculée. Les intervalles de temps entre les années de précipitation déficitaire sont brièvement discutés. Une étude analogue a été tentée pour les autres régions. Il est intéressant d'observer que le coefficient de variation de la précipitation de mousson du Deccan, dans l'État de Bombay, est pratiquement le même que pour le Konkan bien que la précipitation de cette dernière région soit quatre fois supérieure à celle de la première.

La principale conclusion de ces études est qu'il n'y a pas eu de changement statistiquement significatif de la précipitation annuelle ou saisonnière de ces régions au cours des quatre-vingts dernières années.

DISCUSSION

R. G. VERYARD. You say that there has been no significant change in precipitation but this consists of different kinds of rainfall—orographic, convectional and that associated with large-scale convergence. Re the last item is there any evidence of a fluctuation in the frequency of monsoon depressions?

K. N. RAO. A detailed paper on the frequency of depressions and cyclones in the Bay of Bengal has been published by Rao and Jayaraman (1958). There is no evidence of a fluctuation in the monsoon depressions.

C. C. WALLÉN. Looking at Table 9 of your contribution one cannot avoid feeling that there are several periods within the record where rainfall has deviated considerably from the long-term mean and although being not statistically significant on a long-term basis it must have been quite significant to, for instance, agriculture in this area. It always bothers me that there are no criteria as to how long records should be used for studies of the statistical significance of a fluctuation. A change that seems from the practical point of view highly important may be so also statistically by using a short period of record although becoming insignificant in a long period.

K. N. RAO. In the study of time series, particularly rainfall, it is desirable to have records for a long period of 80 to 100 years, otherwise results based on short-term records are likely to be misleading. Action on any fluctuations in short-term data should therefore be guarded. As an illustration I would mention the example of Madras State which experienced consecutive years of deficient rainfall from 1947 to 1951 during the north-east monsoon season. The press, the public and the government showed great anxiety. Views were freely expressed that the climate of the state had changed. Nothing damages public confidence as much as failure of rains. The data of Madras City showing records from 1813 were examined and the correlation between Madras City and Madras State rainfall was found to be +0.83. This is highly significant and the series of Madras State were extrapolated backwards.

From this we could infer that during the consecutive years 1828 to 1835 also, the state must have had deficient rainfall. The series of years 1947 to 1951 was thus not unique.

In some of the semi-arid tracts of India, two or more consecutive years of deficient rainfall are not unusual. The variability of rainfall of these areas is also high. As farmers are generally aware of such fluctuations, the pattern of cropping in such areas does not appear to have been changed.

J. Namias. It seems quite possible that the India area may not partake in very long period climatic fluctuations (of the order of 100 years) as much as other areas of the world, since the general circulation there is so strongly forced by the Indian monsoon. In other words, the physical processes creating the monsoon, once initiated, may ensure a rain-producing circulation regionally, relatively independent of fluctuations in remote centres of action. Of course, this does not mean that no shorter period climatic fluctuations are possible there—in fact, Dr. Rao's data indicates fairly high variabilities on a shorter time scale.

K. N. Rao. The series analysed generally cover data of more than 50 years. In some cases the series extend to over 100 years. In the analysis of these data, the physical processes involved in the creation of the monsoon have not been considered, nor does it appear necessary for the purpose in view. Once the series is shown to be distributed normally, there is only a 5 per cent chance that any member of the series will be outside M $\pm 2\sigma$ where M is the mean and σ the standard deviation of the series. Any short-period fluctuation which may exist will not be regarded as statistically significant if they lie in the range M $\pm 2\sigma$.

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CLIMATIC FLUCTUATIONS IN THE MIDDLE EAST DURING THE PERIOD OF INSTRUMENTAL RECORD

by

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INTRODUCTION

The length of the period of instrumental record of climatological data is a consequence of the opening-up of an area to modern scientific understanding. The Middle East may be regarded as one of the cradles of meteorological and hydrological recording, as borne out by a meteorological register kept by Claudius Ptolemæus, the geographer, at Alexandria (Egypt), in the first century A. D. (Brooks, 1949), by reports on regular observations of rainfall effectiveness in Palestine at the same time (Vogelstein, 1894; Hann, 1895), by records of the Nile gauge at Cairo for the last 1,200 years (Brooks, 1949). But modern scientific interest and the first steps to record climatological data came late to the area, and were, in most cases, due to the initiative of European and American physicians, engineers, teachers and clergymen. Thus the longest continuous series of meteorological data in the Middle East, that of Jerusalem, starts as late as 1860. As late as the first decade of this century we find records of six stations which continue until now with temperature and precipitation data. There are serious gaps in the spatial distribution of the data; whereas Cyprus, Lebanon, Israel, Egypt and Sudan are represented, there is no continuous record available from Turkey which is longer than 40 years; the Baghdad series is frequently interrupted and does not lend itself to reconstruction. Table 1 summarizes the data which were used in the preparation of this paper.

Table 1. List of stations, periods of observations, and sources

Station	Element	Period	Source[1]
Rome	Temperature	1811-1960	*World Weather Records*; Communication by United States Weather Bureau
	Precipitation	1781-1960	
Athens	Temperature	1861-1960	*World Weather Records*
Nicosia	Temperature	1901-60	*World Weather Records*; *Monthly Climatic Data of the World*
	Precipitation	1901-60	
Beirut	Temperature	1881-1960	*World Weather Records*; *Monthly Bulletins*, American University, Beirut; *Bulletin Mensuel*, Lebanon Meteorological Service
	Precipitation	1881-1960	
Haifa	Precipitation	1881-1960	Israel Meteorological Service
Tel Aviv	Precipitation	1901-60	Israel Meteorological Service; A. Bitan (1961)
Jerusalem	Temperature	1861-1960	Israel Meteorological Service; Rosenan (1955)
	Precipitation	1851-1960	Israel Meteorological Service
Alexandria	Temperature	1871-1960	*World Weather Records*
	Precipitation	1871-1960	*World Weather Records*; Sutton, (1940)
Cairo	Temperature	1871-1960	*World Weather Records*; *Monthly Climatic Data of the World*
	Precipitation	1891-1960	
Khartoum	Temperature	1901-60	*World Weather Records*; *Monthly Climatic Data of the World*
	Precipitation	1901-60	

1. See also bibliography at the end of this article.

As may be expected with series of data which in most cases were affected by changes of authorities, observing personnel, instrumentation and observation sites, a high degree of homogeneity cannot be expected. Therefore, no rigid homogeneity tests were applied. The representativeness of the data for their area was rather deduced from the similarity of trends, and from the uniformity of an increase of a change of identical sign from station to station according to their geographical position. At places where large local variations of an element, especially precipitation, are experienced, as for example at Beirut, Haifa, Tel Aviv, Jerusalem, care was taken that the dat a referred to asingle site (homotopic series). The data were taken either from original records and publications, or from compilations, among which *World Weather Records* were used whenever possible. The sources of the data are given in Table 1.

SCOPE AND METHODS OF INVESTIGATION

In order to find for the analyses of this paper, the right size of time interval, which on one hand will extinguish the year-to-year fluctuations and on the other hand not efface indications of climatic change, consecutive 10-year averages were used. Tests carried out for the 100-year rainfall series of Jerusalem showed that 5 years' averages were still too short and 20-year averages already too long. No attempt was made to smooth the curves by the use of sliding averages, or cumulative deviations. Simultaneous data from Athens and Rome were used, in order to link Middle East trends to those of southern Europe.

The elements analysed in this study are temperature and precipitation; the parameters used were annual averages (temperature) annual totals (precipitation) for 10-year periods and the standard deviation of the annual values from these. No attempt was made to analyse changes of seasonal values of these elements, as precipitation is strictly seasonal in occurence in the Middle East (generally in winter, at Khartoum in summer), and as temperature data for the summer season at Jerusalem for the last hundred years show the trend of annual data only slightly, and as the winter temperatures (December to February) exercise a major influence on the annual temperatures.

CHANGES OF TEMPERATURE

The curves of 10-year running averages of annual temperatures for six stations in the Middle East, and for Rome and Athens are shown in Fig. 1. There is a certain uniformity of trend as a minimum is found at all stations in the decades 1891-1900, 1901-10 and 1911-20. This is followed by a rise at all stations with a maximum reached in the 1930s everywhere, with the only exception of

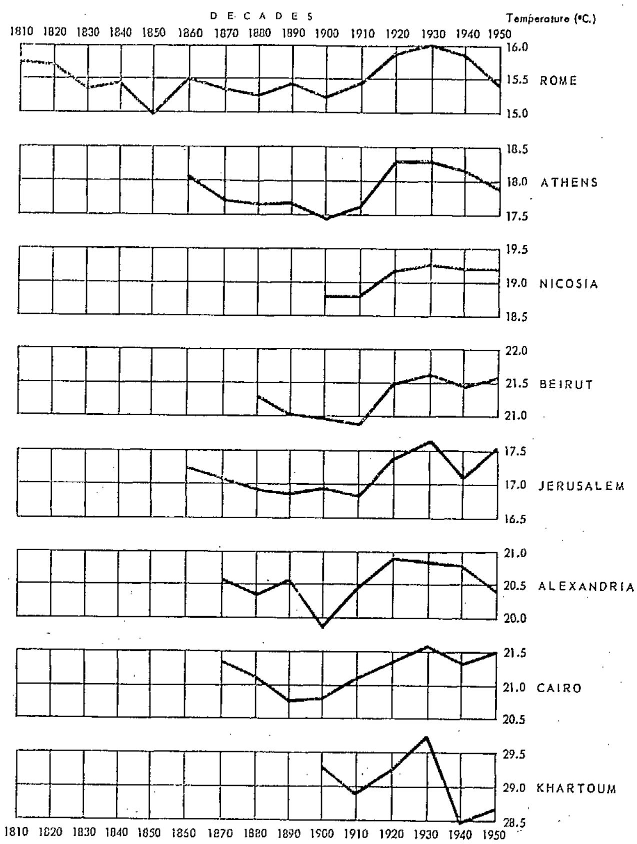

FIG. 1. Ten-year running averages of annual temperatures, six Middle East stations, Rome and Athens.

Alexandria where the 1920s showed the maximum temperatures. The 1940s showed a drop throughout, whereas the 1950s showed again a rise in temperature at most stations, with the exception of Nicosia, where the temperature remained unchanged, and Alexandria where it decreased further. Up to 1940, the changes from decade to decade at Rome and Athens are in phase with those of the Middle East stations.

The dimensions of the changes seem to increase from north to south: the rise of temperature from the 1900-10s to the 1930s amounted to 0.5° C. at Nicosia, 0.75° C. at Beirut, 0.8° C. at Jerusalem, 0.9°-1.0° C. at Alexandria, Cairo and Karthoum; this compares with rises of 0.85° C. at Athens and 0.8° C. at Rome. The changes of temperature from the 1930s to the 1940s, and to the 1950s do not show any characteristics in their dimensions.

CHANGES OF PRECIPITATION AMOUNT

Changes of amounts of precipitation were generally opposite to those of temperature in the Middle East (see Fig. 2).

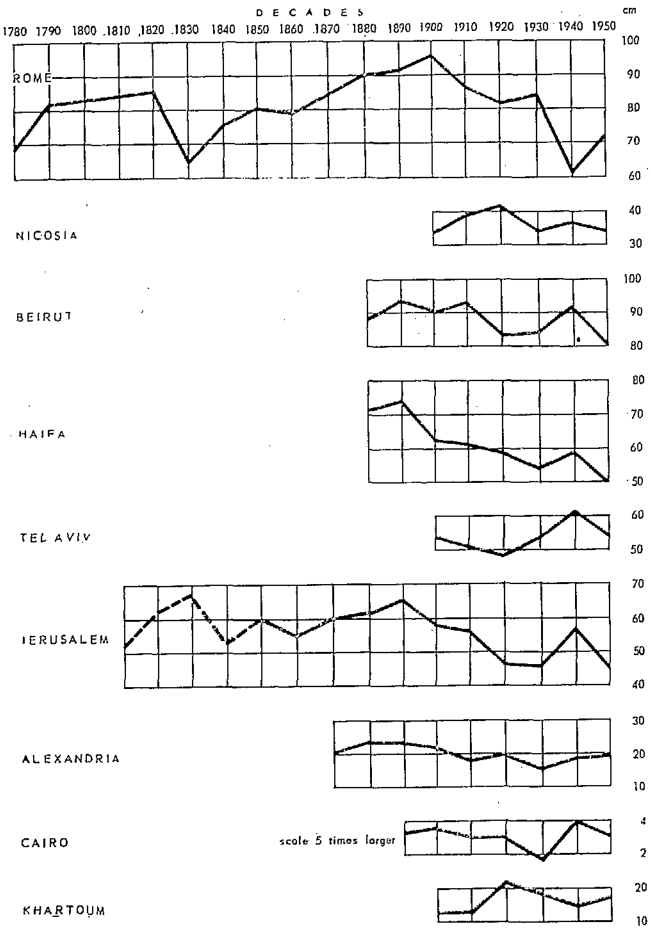

Fig. 2. *Ten-year running averages of annual precipitation* amounts, eight Middle East stations, and Rome.

There was a maximum of precipitation at most stations during the 1890-1910s and a drop towards a minimum in the 1920-30s. The 1940s showed again a rise, and the 1950s a drop. At Khartoum all trends were opposite, as the only station with summer rains, in opposition to the pronounced winter precipitation at all other stations. As Alexandria's trend was exceptional in the field of temperature, so it was also with precipitation, showing a slight rise towards the 1950s. The parallelity of precipitation changes in the Middle East and at Rome holds good only until the decade of the 1930s. At Rome a drop in the 1940s is followed by a rise in the 1950s. The decrease in precipitation from the peak at the beginning of the century to the low in the 1920-30s amounted to 12-18 per cent of the mean at Rome, Nicosia, Beirut and Tel Aviv; to 30-44 per cent at Haifa, Jerusalem, and Alexandria; and to 77 per cent at Cairo. The absolute amounts of the decrease in precipitation during the first decades of this century were 2 cm. of mean annual rainfall at Cairo, 6-11 cm. at Alexandria, Tel Aviv, Beirut, Nicosia, and Rome, and 19-20 cm. at Jerusalem and Haifa. The rise from the 1930s to the 1940s amounted to 2-3 cm. at Nicosia, Alexandria and Cairo, to 5 cm. at Haifa, and to 8-11 cm. at Beirut, Jerusalem and Tel Aviv. The drop from the 1940s to the 1950s was 1 cm. at Cairo, 3 cm. at Nicosia, 7 cm. at Tel Aviv, and 10-12 cm. at Beirut, Haifa and Jerusalem. The 1950s showed the lowest values of the whole series at Nicosia, Beirut, Haifa, and Jerusalem. As well for temperature changes as for those of precipitation it seems that the changes increase from the sea inland, from north to south, and seem to show an increase where mountains approach the coast.

CHANGES OF VARIANCE

An attempt was made to investigate the variation of the variance from decade to decade of temperature and precipitation data. The long series of Beirut, Jerusalem, Alexandria and Cairo were used, and the results are shown in Fig. 3. As well for temperature as for precipitation the highest values of variance were found in the 1870s, after which decade a sharp drop occurred. Values remained more or less uniform hereafter with minor peaks for temperature variance in the 1900-10s, and a run which is more or less opposite to the trend of temperature. No general statement can be made for the trend of variance of precipitation after the 1870s, except for the relative uniformity of data. It may be mentioned that a significant positive correlation ($r = 0.782$; $n = 10$) exists for the variance of temperature and that of precipitation at Jerusalem (and at no other place), and also for the variance of temperature at Jerusalem and at Beirut ($r = 0.941$; $n = 9$).

INTERRELATIONS BETWEEN TEMPERATURE AND PRECIPITATION

The general inverse relationship of the trends of temperature and precipitation mentioned earlier can be proven by the relatively high correlation which exists at Jerusalem ($r = -0.947$; $n = 10$). An inverse relationship per five-year intervals could be established for precipitation at Jerusalem and Khartoum ($r = -0.53$; $n = 12$). This may hint at a mechanism of the general circulation connected with the relative position of the subtropical anticyclonical belt (Rosenan, 1951).

DEVIATION OF TREND OF PRECIPITATION AMOUNTS AT TEL AVIV

It might be of interest in connexion with the specific purposes of this symposium to draw attention to the departure of the trend of precipitation amounts at Tel

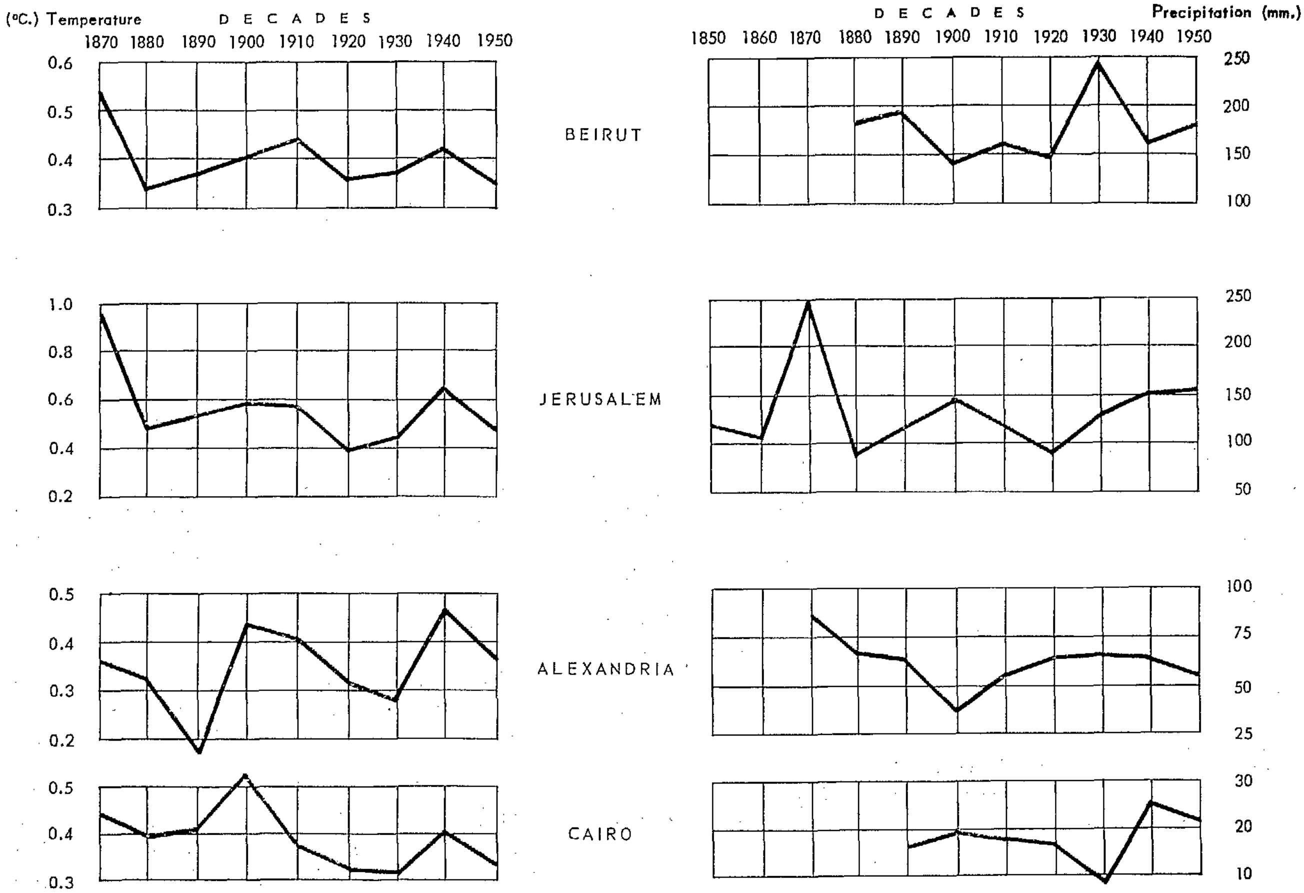

FIG. 3. Ten-year running data for standard deviations of annual average temperature and precipitation, Beirut, Jerusalem, Alexandria, Cairo.

Aviv in comparison with those of Jerusalem, Haifa and Beirut, during the six decades of this century. Whereas the sign of change of precipitation amount from decade to decade is almost always identical at Tel Aviv with that at the other stations, Tel Aviv showed a continuous relative increase in precipitation from the 1920s till now. The precipitation amount of Tel Aviv given as a ratio of that of Jerusalem, Haifa and Beirut, given equal weight to each of them, during the last six decades, is given in Table 2.

The largest deviation from the ratios of Tel Aviv to the combined stations from the ratio of Tel Aviv to a single station in any decade is 0.06, and the mean deviation is 0.028. Several explanations of this departing trend of Tel Aviv precipitation were tried, none giving a satisfactory answer. The responsibility of change of site and instrumentation is ruled out, as at all four stations records are referred to a specific site, and the data were checked by those of neighbouring stations at the same place. An increase of continentality in the course of this century would accentuate the difference of precipitation between coastal and inland stations. But

TABLE 2. Precipitation amount of Tel Aviv, as ratio of that of Jerusalem, Haifa, Beirut, by decades, 1901-10 to 1951-60 (average annual precipitation amount 1901-60 at every station = 100)

Decade	Ratio Tel Aviv to			Ratio Tel Aviv to three stations combined
	Jerusalem	Haifa	Beirut	
1901-10	0.895	0.935	0.97	0.93
1911-20	0.865	0.89	0.88	0.88
1921-30	0.97	0.865	0.93	0.92
1931-40	1.10	1.04	1.02	1.05
1941-50	1.045	1.13	1.10	1.09
1951-60	1.175	1.19	1.10	1.16

this argument would only hold for the ratio Tel Aviv : Jerusalem, as both Haifa and Beirut are coastal stations, although without a substantial coastal plain developed in their neighbourhood. Another explanation could be sought in the fact of the increasing agriculture, especially by means of irrigation in the area around Tel Aviv which had its main development in the decades following the 1920s. This would match with values greater than one of the ratio of the precipitation during the period 1921-50 as related to that of the period 1901-30 (Atlas of Israel, 1957). These large values are restricted to an area around Tel Aviv, stretching some 30 km. to the north and south and about 20 km. to the east, and to an area in the Jordan Valley to the south of Lake Tiberias; all the rest of the country shows values smaller than one of the ratio 1921-50 : 1901-30. Both areas of a positive deviation were centres of development of irrigated agriculture especially from the 1930s onward. But it is difficult to see a relation between increased irrigation which is applied mainly during the months April to September and increased precipitation during the months November to March. A possible mechanism might be the increase of relatively tall vegetation, as a major part of the irrigated areas consists of citrus groves, banana plantations and maize fields, which all have a relative large roughness parameter and thus may have caused increased turbulence and convection. However, this explanation might not stand any quantitative consideration. Nevertheless, it was thought important to point out this unique deviation from the general trend of precipitation amounts in the Middle East.

EXTENSION OF JERUSALEM PRECIPITATION SERIES BY DEAD SEA LEVEL DATA

Finally I should like to present here a possibility of extending our knowledge on precipitation data in Palestine back to the beginning of the last century. This is given by a reconstruction of the level fluctuations of the Dead Sea carried out recently by C. Klein (1960). Level changes of the Dead Sea, which as a lake without outlet reflects changes in precipitation, mainly over the catchment area, and temperature, mainly over the lake surface. Level recordings are known from 1930 to date, and for a short period at the beginning of this century. For the intermediate and the preceding periods back to 1807 travellers' reports were used which contained indications of the relative inundation of a small hillock at the north-western end of the Dead Sea, just where most pilgrims reached the shore of the lake. By way of this yardstick and others of a similar nature the curve of the level fluctuations from 1807 to date could be reconstructed[1], as shown in Fig. 4.

1. A prior attempt was made by Koppe, with the following attempt by J. Enge (1931) to explain the level fluctuations by means of variations in rainfall over the catchment.

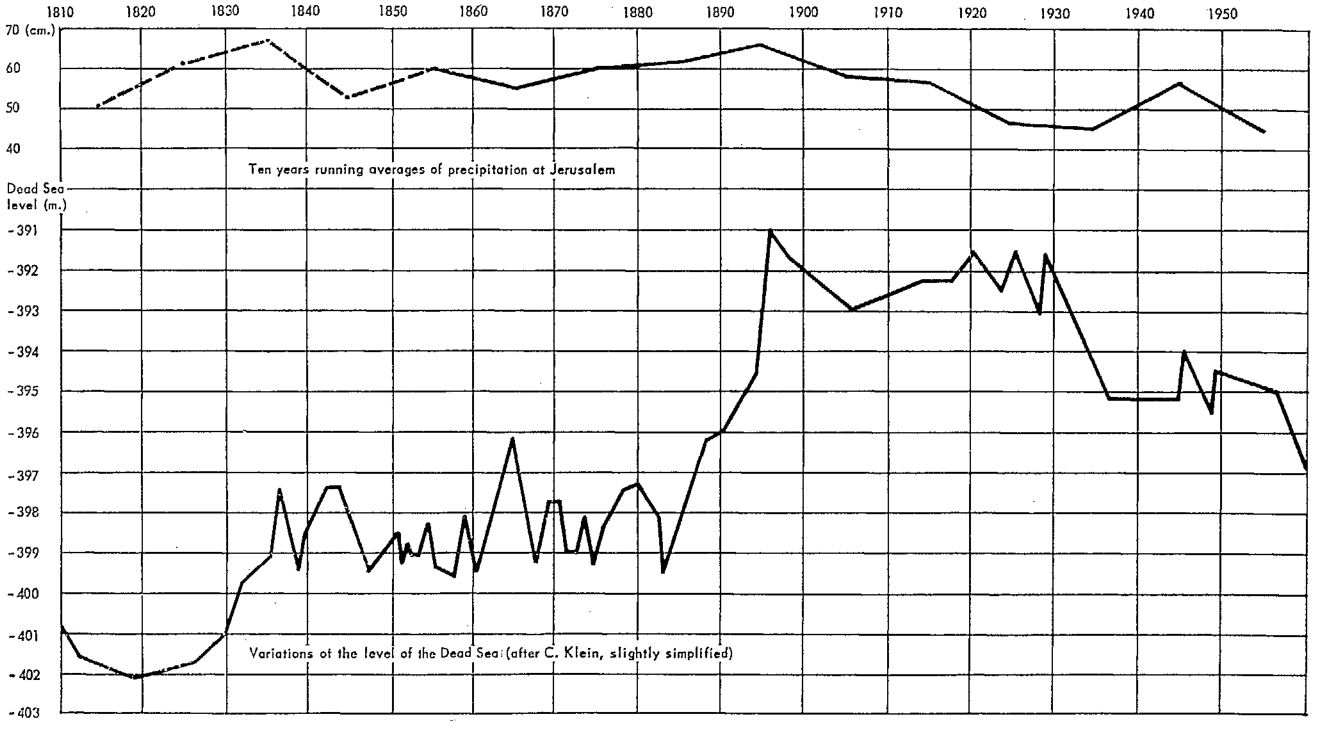

FIG. 4. Variations of the level of the Dead Sea, and ten-year running averages of precipitation at Jerusalem from the beginning of the last century to date.

Comparisons of the precipitation data of Jerusalem, at the edge of the Dead Sea catchment and about 25 km. distant, with the level changes of the Dead Sea have shown satisfactory results. The correlation coefficient shown in Table 3 were received.

TABLE 3. Correlation coefficients of Jerusalem precipitation to Dead Sea level changes

Period	Basis	Correlation Coefficient	Number of pairs
1930-58	Annual	0.77	28
1900-60	Five-yearly	0.82	12
1846-1960	Five-yearly	0.53	23

It was thought unnecessary to correlate separately temperature at Jerusalem (as being representative in its change for that at the Dead Sea) with Dead Sea level changes, as precipitation and temperature at Jerusalem showed a high negative correlation (see above). Thus it was assumed that the effects of high precipitation and low temperature, and vice versa, on the Dead Sea level were synchronous.

On the basis of the regression equations won from the correlations carried out and using the Dead Sea level curve reconstructed by C. Klein, the five-year precipitation averages for Jerusalem for the period 1810-45 were computed.

The precipitation curve for Jerusalem, thus received for the period 1810-50 is given in Figs. 2 and 4 as a dotted line. This extrapolation shows relative minima of precipitation in the 1810s and the 1940s and a maximum in the 1830s, which is as high as the maximum of the 1890s, whereas the Dead Sea level curve shows for the same period an absolute low in the 1810s, a slow rise in the 1820s, a steeper rise in the 1830s, and a more or less steady stage in the 1840s and 1850s. It may be pointed out, that these extrapolated figures of precipitation at Jerusalem for the period 1810 to 1840 are in opposition to the trend of precipitation data at Rome during the same time interval[1].

CONCLUSION

In conclusion, I should like to make some general remarks on the climatic fluctuations encountered in the Middle East during the instrument period:

1. There is a fairly wide agreement between tendencies in southern Europe and the Middle East.
2. As should be expected in arid or semi-arid regions, changes of precipitation and temperature are opposed.
3. Therefore, the main deviation of the trend in the Middle East from that in southern Europe occurs when spells of low precipitation occur in the Middle East, without being based on changes in circulation on a world-wide scale as, for example, in the 1950s.
4. There seems to be a marked difference in the size of climatic variations and in their phase between maritime and more continental stations, continental stations being more directly subject to variations in the circulation pattern of the atmosphere, whereas maritime stations seem to depend more on fluctuations of sea temperature which reflect changes in air circulation patterns more slowly.
5. When taking data of levels of deep lakes without outlet (where level changes do not affect largely the size of the evaporating surface) as indicators of climatic changes, it might be advisible not to explain a low-level stage by low precipitation and vice versa, but to be aware of the fact that periods of rise of the level correspond to high precipitation (and/or low temperatures), and similarly those of fall of the level correspond to low precipitation (and/or high temperatures), and that periods of a constant level, no matter whether high or low, correspond to an intermediate stage of precipitation and/or temperature.

ACKNOWLEDGEMENT

I should like to express my gratitude to Professor J. Neumann of the Meteorology Department of the Hebrew University of Jerusalem, for his kindness in discussing the items of this paper, and to Mr. M. Gilead, Director of the Israel Meteorological Service, for his assistance during the preparation of this paper.

1. The interpretation of the Dead Sea data for an extension of the Jerusalem precipitation series offered here is somewhat different from that given by Neumann (1960).

RÉSUMÉ

Variations climatiques observées au Moyen-Orient depuis la mise en service des appareils enregistreurs (N. Rosenan)

Des relevés nombreux et représentatifs des températures et des précipitations ont été effectués au Moyen-Orient par les stations suivantes : Nicosia, Beyrouth, Haïfa, Tel-Aviv, Jérusalem, Alexandrie, Le Caire et Khartoum.

Ces relevés s'étendent sur des périodes dont la durée va de soixante à cent ans. Les moyennes décennales des chiffres annuels ont été comparées d'une période et d'un endroit à l'autre.

Les températures ont atteint un minimum au cours de la période 1890-1910, et un maximum de 1930 à 1940. Une chute générale s'est produite après 1940, puis les températures se sont relevées dans de nombreuses stations à partir de 1950. Le réchauffement constaté de 1900 à 1930 s'établit entre 0,5 à 1 °C.

Les précipitations ont varié à l'inverse des températures. Dans la plupart des cas, le maximum a été observé vers 1890, et le minimum pendant la période 1920-1940. Une augmentation s'est produite presque partout après 1940, tandis qu'à partir de 1950 la quantité des précipitations est redevenue faible, les minimums records ayant été atteints à Nicosia, à Beyrouth, à Haïfa et à Jérusalem. Sauf durant cette dernière période, l'évolution des températures et des précipitations au Moyen-Orient a été analogue à celle qu'on enregistrait en même temps à Athènes et à Rome.

Il n'a pas été possible de mettre en lumière une influence des températures estivales sur la courbe des températures annuelles.

Des données récemment rassemblées sur les variations du niveau de la mer Morte de 1807 à nos jours ont servi à évaluer l'importance des précipitations à Jérusalem avant le début des observations, car il existe une corrélation significative entre les variations quinquennales de ces deux facteurs. Il paraît ressortir de ces recherches que les chiffres les plus bas ont été atteints de 1810 à 1820 et de 1840 à 1850, et les chiffres les plus hauts de 1830 à 1840 — ce qui représente une évolution inverse de celle qui a été constatée à Rome.

Depuis une quarantaine d'années, les précipitations enregistrées ont augmenté de 28 % de plus à Tel-Aviv que dans les stations avoisinantes. L'auteur cherche l'explication de ce phénomène dans l'évolution des méthodes agricoles et dans le caractère de plus en plus continental du climat, sans cependant formuler aucune conclusion catégorique.

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CONTRIBUTION AU PROBLÈME DES CHANGEMENTS DE CLIMAT SURVENUS AUX COURS DE LA PÉRIODE COUVERTE PAR LES OBSERVATIONS MÉTÉOROLOGIQUES FAITES DANS LE NORD DE L'AFRIQUE

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Dans l'état actuel des choses, il me paraît difficile de distinguer dans le nord de l'Afrique une évolution du climat qui soit vraiment incontestable, du moins à l'échelle du siècle. Tout ce qu'on observe, ce sont des variations plus ou moins limitées dans l'espace et de courte durée — quelques années ou dizaines d'années — tantôt dans un sens, tantôt dans un autre et dont les effets se compensent sensiblement au bout d'une centaine d'années.

Avant d'aller plus loin, je pense qu'on ne saurait trop répéter qu'il s'agit là d'un problème difficile à résoudre. A mon avis, pour l'aborder il faut, tout d'abord, disposer de données climatiques remplissant les conditions suivantes :

1. Elles doivent appartenir à des séries d'observations continues s'étendant sur plus d'un siècle. Cette période de temps me paraît nécessaire si l'on veut s'affranchir des variations de courte durée. Ces dernières, en effet, risquent de conduire à des conclusions erronées en faisant prendre pour une modification climatique séculaire ce qui n'est en réalité qu'une phase temporaire de l'évolution du climat. De telles séries de mesures sont très rares dans le nord de l'Afrique. En ce qui concerne plus précisément le Maghreb et le Sahara, je n'en connais qu'une seule, celle de la pluviosité à Alger-Port. Dans toutes les autres stations, les durées des observations sont moins étendues ou présentent des lacunes. Bien sûr, on peut essayer de combler les manques et allonger les périodes de temps que l'on veut utiliser en déterminant les correspondances qu'il peut y avoir entre les éléments climatiques de stations voisines, mais on risque alors d'introduire des erreurs qui sont du même ordre de grandeur que la faible variation séculaire que l'on recherche.
2. Il faut faire appel à des stations où le milieu environnant n'a pas subi de modifications susceptibles d'influer sur les données climatiques. Je pense ici à l'extension considérable qui s'est produite dans les grandes villes algériennes où les premières observations ont obligatoirement débuté.
3. Il est nécessaire que les mesures aient été faites en un seul emplacement, dans un même type d'abri météorologique et suivant des méthodes d'observation identiques. Ce n'est pas le cas en Algérie et au Sahara français où, pour ne parler que de ces régions, les abris ont été profondément modifiés il y a une quarantaine d'années.

Les séries d'observations ayant les qualités requises, il faut également que les variations décelées en une station donnée puissent se rencontrer dans des stations voisines pour qu'elles aient un caractère général.

La conjonction de toutes ces conditions est évidemment très rare, c'est pourquoi nous sommes encore peu renseignés dans le nord de l'Afrique sur le sujet proposé.

Cela dit, je considérerai tout d'abord la question de la pluviosité.

VARIATION DE LA PLUVIOSITÉ DU NORD DE L'AFRIQUE DEPUIS LE DÉBUT DES OBSERVATIONS

Comme je le disais précédemment, nous avons à Alger-Port une station pluviométrique dont les données possèdent les qualités énoncées plus haut. Les mesures débutèrent en 1843 et se sont poursuivies de façon rigoureusement continue au même endroit, jusqu'en 1942, soit pendant exactement cent ans[1]. Étant donné sa situation, il est vraisemblable que le milieu environnant a été peu perturbé par l'extension de la ville et des installations portuaires. De plus, les comparaisons que l'on peut établir entre les hauteurs de pluies recueillies en cette station et dans celles de l'Hôtel de ville puis de l'Université d'Alger permettent de contrôler les

1. Les observations pluviométriques ont commencé à Alger en décembre 1837 et ont été faites en de nombreux points dans les années qui ont suivi, mais, en dehors d'Alger-Port, leurs valeurs sont sujettes à caution.

mesures faites à Alger-Port dans ces dernières années et, surtout, de les prolonger jusqu'en 1960 avec une exactitude suffisante, bien que la pluviosité soit très variable d'un point à un autre de la ville[1].

De l'examen de ces cent dix-huit années d'observations, il découle que, si la hauteur annuelle de pluie a diminué notablement entre 1854 et 1862, elle n'a plus présenté, par contre, de variations de très longue durée depuis cette dernière date jusqu'à nos jours (1960). Les moyennes annuelles établies sur cinquante ans ont été, d'une part, de 695,0 mm de 1843 à 1892 et de 607,4 mm de 1893 à 1942, d'autre part, de 623,2 mm de 1860 à 1909 et de 628,7 mm de 1910 à 1959[2]. Bien entendu cela n'implique pas que la courbe de la pluviosité annuelle soit une droite depuis 1862. En fait, elle présente des oscillations, des séries d'années sèches alternant avec des séries d'années humides. Il résulte de cela que les moyennes peuvent différer assez notablement suivant les périodes de temps qui sont choisies, lorsque celles-ci ne sont pas suffisamment étendues. En voici un autre exemple plus typique. Si, avec Butzer (1957), on considère les périodes de trente ans s'étendant l'une de 1881 à 1910, l'autre de 1911 à 1940, il apparaît que la hauteur de pluie a augmenté de 1,8 % entre la première série d'années et la seconde (625,9 mm de 1881 à 1910 contre 637,3 mm de 1911 à 1940), mais si on décale de quelques années les périodes étudiées, cette croissance de la pluviosité tombe à moins de 0,2 % (605,5 mm de 1890 à 1919 et 606,6 mm de 1920 à 1949). On peut d'ailleurs dire que les écarts entre les moyennes de deux périodes successives sont d'autant plus grands que ces dernières sont plus courtes. C'est pourquoi les variations de la pluviosité que l'on peut trouver au cours de quelques dizaines d'années ne peuvent être prises en considération dans le problème qui nous intéresse.

On a pu se demander si les oscillations que l'on constate dans les hauteurs de pluie ne sont pas dues à des rythmes périodiques résultant de la superposition d'ondes de périodes différentes. En ce qui concerne les données d'Alger, ce problème a été abordé par Gauckler (1903) et surtout par Petitjean (1928). D'après ce dernier auteur, les variations de la pluie annuelle à Alger seraient sous la dépendance de deux grandes ondes, l'une d'une période de trente-cinq ans, l'autre de quinze ans. La première aurait un caractère mondial, la seconde un caractère plus local et dépendant de la latitude. De plus, d'après l'auteur, la « courbe réduite » des pluies présenterait en 1903 une remarquable symétrie. Autrement dit (je cite) « les parties de la courbe antérieures à cette date se reproduisent symétriquement par rapport à un axe passant par le point 1903 ». De ces constatations, Petitjean a déduit une prévision de la pluviosité en 1928, date de son travail, à 1978. Si cette dernière ne paraît pas tout à fait exacte d'après ce qu'on peut en juger actuellement, il faut reconnaître qu'elle s'écarte peu de la réalité, du moins si l'on ne considère pas une année particulière mais une période de quelques années. Il y a là une méthode intéressante à retenir et il est probable que l'auteur serait arrivé à de meilleurs résultats s'il avait pu tenir compte d'ondes de plus longue durée lesquelles évidemment ne peuvent être décelées tant qu'on ne disposera pas de séries continues d'observations s'étendant sur un ou deux siècles.

Tout ce que nous venons de voir ne concerne qu'Alger et ne peut être étendu à l'ensemble de l'Algérie. Bien que les mesures des hauteurs de pluie aient suivi de très près les progrès de l'occupation française[3], nous ne disposons pas actuellement de séries de données, sans lacunes et faites au même emplacement, s'étendant sur une période de temps suffisante en dehors de la station précédente. Aussi ce qui suit est-il donné à titre de simple indication. Si donc on se limite à des périodes de temps plus courtes on peut faire appel aux séries d'observations faites à Orléansville et à Laghouat. La première s'étend sans solution de continuité de 1876 à 1941, la seconde de 1874 à 1944, mais avec des lacunes en fin 1897, début 1899 et fin 1905. Si l'on considère des périodes de trente ans analogues à celles adoptées précédemment, il apparaît qu'à Orléansville la pluviosité de la période 1911-1940 (392,6 cm) a été inférieure de 6,5 % à celle de 1881-1910 (420,0 mm) et qu'il en a été sensiblement de même à Laghouat (—7 %) entre les mêmes périodes de temps (188,7 mm de 1881 à 1910 contre 169,0 mm de 1911 à 1940). On voit que la variation de la pluviosité est inversée par rapport à celle d'Alger-Port. Seltzer (1946) était arrivé à une constatation analogue en comparant les moyennes pluviométriques de 1913-1938 à celles de 1878-1938, en neuf stations algériennes. Il écrit dans son ouvrage *Le climat de l'Algérie* (p. 155) : « La pluie serait donc en augmentation dans la partie la plus arrosée de l'Algérie (le littoral), en diminution dans la partie la plus sèche; comparée à la période 1878-1938, la carte de pluie 1913-1938 présente un relief pluviométrique légèrement trop accentué. »

J'ajouterai, toujours avec beaucoup de réserves, que les graphiques de pluie de Biskra, de Ghardaïa et de Laghouat, stations du Nord saharien, semblent présenter un maximum de pluie assez net de 1884 à 1896, lequel ne s'est pas reproduit depuis avec cette ampleur. Il est curieux de constater que cette période de pluviosité maximale se rencontre également à Tripoli et à Benghazi (Fantoli, 1952) ainsi qu'à Alexandrie. Sutton (1938) écrit d'ailleurs, dans l'introduction de son ouvrage *Climatological normals for Egypt and the Sudan, Cyprus and Palestine* : « Apart from irregular fluctua-

1. La moyenne des écarts entre les hauteurs annuelles de pluie d'Alger-Port (634,9 mm) et d'Alger-Université (753,1) a été de 118,2 mm pendant les trente ans de mesures communes (de 1913 à 1942). Cet écart, bien entendu, varie d'une année à l'autre. Cependant le graphique de correspondance que l'on peut établir entre les deux couples de données, montre que les écarts croissent avec les hauteurs de pluie et cela avec une régularité telle que l'on peut calculer les hauteurs annuelles manquantes, en l'une ou l'autre des deux stations, avec une marge d'erreur qui ne dépasse certainement pas 4 % en valeur absolue. C'est ce qui nous a autorisé à prolonger la courbe de pluie d'Alger-Port jusqu'à nos jours.
2. Moyennes de cent ans : 1843-1942, 651,2 mm; 1860-1959, 626,00 mm. Moyenne de cent vingt ans : 1840-1959, 649,9 mm.
3. Les observations pluviométriques débutèrent, par exemple, en 1838 à Constantine, en 1841 à Oran, en 1845 à Biskra, en 1865 à Laghouat, en 1867 à Géryville, pour ne citer que les plus anciennes.

tions there seems to have a very slight increase in rainfall from the beginning of observations in 1869 for about thirty years, and a more pronounced decrease since then. »

Pour le moment, on ne peut pas dire grand-chose sur l'évolution des pluies sur le reste du Sahara, les premières observations pluviométriques étant de date trop récente et les chutes de pluie trop espacées dans le temps. Il semble toutefois que non seulement la concordance des distributions annuelles de pluie dans les différentes régions sahariennes soit très faible, ainsi que je l'ai montré pour le Sahara central (Dubief, 1947), mais aussi que l'évolution générale de la pluviosité de ces dernières années soit très différente d'une région à une autre. Il faut voir là — comme en Algérie — une conséquence de la diversité des origines de pluies sahariennes (dépressions du front polaire ou dépressions dérivées de celui-ci au nord, dépressions soudano-sahariennes, aux trajectoires variables dans le temps, orages des moussons estivales, soudanaise au sud, méditerranéenne au nord).

Il ressort de ce qui précède qu'en l'état actuel des choses il ne semble pas que la pluviosité ait subi une modification vraiment significative au cours des cent dernières années. Les variations que l'on rencontre sont vraisemblablement causées par la superposition d'ondes de périodes différentes qui restent encore à préciser.

Dans ce qui précède, on a considéré seulement les séries des hauteurs de pluie tombées au cours d'une année civile, c'est-à-dire l'ensemble des précipitations de douze mois consécutifs sans tenir compte de l'origine de celles-ci. Or, nous venons de le voir, ces origines peuvent être très diverses. On peut ainsi se demander si chaque courant dépressionnaire et chaque balancement annuel des grandes masses d'air n'ont pas des évolutions séculaires qui leur sont propres. Auquel cas la variation dans le temps de la pluviosité, en une région donnée, serait la résultante de toutes les variations séculaires des différentes sources de pluie qu'on peut y rencontrer.

Queney (1936, 1937) a montré qu'il en était bien ainsi en ce qui concerne l'Algérie. Sans entrer dans le détail de son étude, je dirai qu'après avoir partagé ce pays en neuf régions par une double division, l'une dans le sens ouest-est suivant les trois provinces d'Oran, d'Alger et de Constantine, l'autre dans le sens nord-sud suivant trois zones climatiques (littoral, Tell et Sud), l'auteur a constitué dans chaque région une série pluviométrique moyenne unique à partir de toutes les données des stations ayant fonctionné depuis la colonisation française. Ces séries moyennes lui ont permis d'étudier les régimes pluviométriques moyens de chaque région pour les trois périodes: septembre 1850 - août 1870, septembre 1870 - août 1900, septembre 1900 - août 1930. Des différences importantes entre ces régimes lui sont alors apparues. Il a trouvé, en particulier, qu'un maximum de pluviosité avait eu lieu en décembre et un autre en mars, pour la période 1870-1900, alors que pour celle 1900-1930 on a, en général, un maximum en novembre et un autre en janvier. La différence entre ces deux périodes consiste surtout en une diminution générale des pluies de décembre et de mars, l'écart étant le plus important dans les deux zones extrêmes de l'Oranie (littoral et sud) où il y a une diminution de plus de 20 % dans les totaux annuels moyens. La comparaison des moyennes décennales montre que le changement s'est généralement opéré vers 1900 et qu'une nouvelle augmentation des pluies de décembre se manifeste à partir de 1920. Queney a enfin montré qu'il y avait recrudescence des pluies d'avril et de mai tous les neuf ou dix ans en moyenne (exactement 9,4 ans) pour les premières, tous les cinq ans (4,8 ans) pour les secondes. La périodicité est particulièrement nette pour le Sud constantinois de 1870 à 1920 et pour les précipitations du mois de mai. Il a fait remarquer, avec raison, que ces dernières pluies sont nettement distinctes de celles qui sont habituelles dans les régions tempérées; elles se produisent lorsqu'il existe un courant dépressionnaire allant du Sahara occidental à la Tunisie, autrement dit, lorsque les dépressions soudano-sahariennes traversent cette région.

Par des méthodes assez empiriques, je l'avoue, basées sur les renseignements oraux que j'ai pu recueillir auprès des Touaregs hoggar en utilisant leurs listes de noms d'années, j'ai montré (Dubief, 1947) que le pourcentage des pluies d'hiver et de printemps a été de 1900 à 1939 nettement inférieur à ce qu'il avait été entre 1860 et 1899 (—6,9 % pour les précipitations d'hiver, —9,0 % pour celles de printemps) tandis que celui des pluies d'été a fortement augmenté pendant le même temps (+17,8 %) et que celui des pluies d'automne a peu varié (—1,9 %). Il semble ainsi qu'il y ait eu une variation très nette de la répartition annuelle de la pluviosité au Hoggar aux alentours de 1900; l'influence des pluies d'été, de faible qu'elle était avant cette date, est devenue presque prépondérante après celle-ci (35,3 % au lieu de 17,5 %). Bien entendu, cela appelle des réserves.

Je préciserai que toutes les précipitations qui apparaissent de l'automne au début de l'été en cette région sont en liaison avec des dépressions en provenance du Soudan et traversant le Sahara en direction de l'est ou du nord-est; les pluies du plein été sont liées au front intertropical (FIT), c'est-à-dire à l'invasion du pays touareg par l'air humide de la mousson soudanaise. Le Sahara central n'est jamais atteint par des dépressions appartenant, directement ou indirectement, au courant polaire. Cela n'empêche pas les pluies d'hiver du Sahara central et méridional d'avoir des caractéristiques voisines de celles que l'on rencontre en Europe en cette saison. Elles sont souvent, en effet, lentes, continues, assez persistantes et parfois abondantes. Il est bon de se souvenir de cette constatation lorsqu'on émet des hypothèses sur le paléo-climat du Sahara. Bien que sortant de notre sujet, j'ajouterai cette remarque que l'on oublie trop souvent: on peut avoir un climat typiquement méditerranéen en des régions n'appartenant pas au domaine des perturbations du front polaire.

Quoi qu'il en soit, je retiendrai de ce que nous venons de voir l'enseignement suivant: pour déceler des variations de la pluviosité dans des régions comme le nord de l'Afrique, où les précipitations ont des causes très différentes, il faut étudier séparément les divers types de pluie qui s'y présentent.

VARIATION DE LA TEMPÉRATURE DU NORD DE L'AFRIQUE DEPUIS LE DÉBUT DES OBSERVATIONS

Ainsi que je l'ai signalé au début de cette communication, les premiers abris météorologiques très ouverts, de type Montsouris, ont été remplacés progressivement en Algérie et au Sahara français, depuis 1914, par des abris de type anglais beaucoup plus fermés. Cette modification des conditions d'observation ne permet plus de comparer entre elles les valeurs de la température de l'air recueillies avant et après cette transformation. De ce fait, sur tout le territoire dépendant des observations françaises, on ne dispose pas actuellement de mesures s'étendant sur un nombre d'années suffisant pour déceler une variation séculaire éventuelle de la température qui soit incontestable. Il faut ajouter à cela les changements d'emplacements des abris, les conditions défectueuses dans lesquelles les premières observations ont été faites et les modifications du milieu dues au développement urbain. En ce qui me concerne, il ne m'a été possible d'ébaucher cette étude qu'à partir des données de Biskra et de Touggourt (Dubief, 1959, p. 297). Celle-ci m'a montré : « ... que s'il y a vraiment une variation séculaire de la température, ce qui reste discutable, celle-ci est extrêmement faible, puisqu'elle n'atteint pas un demi-degré en une cinquantaine d'années ». Les conclusions auxquelles on peut parvenir en Égypte sont un peu plus probantes, grâce à la continuité des observations qui a régné pendant cinquante-quatre ans à Abbassia, puis à Helwan, et à la simultanéité des mesures dans ces deux stations pendant un laps de temps suffisant; cependant quelques réserves doivent être faites sur les conclusions que l'on peut en tirer, étant donné le développement urbain qui s'est produit autour de ces deux stations. D'après Sutton (1938, p. VII), ces longues séries de valeurs montrent que la température a d'abord diminué graduellement de 1869, début des mesures, à 1893, puis a augmenté de façon continue depuis cette seconde date. Il semble que cette croissance se soit étendue, en s'amplifiant vers le sud, à tout le Sahara oriental, si l'on en juge d'après les données d'Assouan et d'Atbara, les moyennes de 1921-1931 étant en augmentation sur celles de 1902-1920 de 0,9 ° dans la première station, de 1,1 ° dans la seconde.

On ne peut distinguer évidemment une variation séculaire quelconque lorsqu'on considère les autres éléments du climat nord-africain. Tout ce que l'on peut dire c'est que ses caractéristiques générales n'ont pas changé depuis les premières observations européennes. En particulier la description du climat saharien faite par Schirmer (1893) reste encore très valable de nos jours. On est d'ailleurs frappé par l'exactitude des conclusions de cet auteur, lesquelles étaient pourtant basées sur des observations rares et discontinues.

SUMMARY

Contribution to the problem of climatic changes during the period covered by the meteorological observations made in northern Africa (J. Dubief)

The author first defines the requirements which must, in his opinion, be met by the series of observations utilised in such research. He then analyses at length the pluviometric data for the port of Algiers and rapidly reviews those for a few other stations in North Africa. His study leads to the conclusion that rainfall does not seem to have shown any definite secular variation in North Africa during the past 120 years. He takes the view that there have been only periodic rhythms resulting from the superposition of waves of different periods. The same is said to be true of the distribution of precipitation throughout the year.

As regards temperature changes, it is possible that there may have been a slight increase in the course of the past 50 years, or so, but this is by no means certain.

DISCUSSION

R. G. VERYARD. You have referred to the depressions which travel from south-west to north-east over North Africa and have suggested they originate from the equatorial disturbances. Could they not be associated with an extended trough in the upper westerlies of middle latitudes?

J. DUBIEF. Je ne saurais le dire actuellement, nos études sur les causes de ces dépressions étant encore trop peu poussées. Un fait paraît certain, c'est qu'on n'observe pas de ces dépressions lorsque les *upper westerlies* n'existent plus à haute altitude, au-dessus du Sahara central (cas du mois d'août, par exemple). Mais si c'est une condition nécessaire, elle n'est pas suffisante et il faut, semble-t-il, qu'il y ait aussi un renforcement de la discontinuité située sur la face orientale de l'anticyclone atlantique à la hauteur du Sahara, par descente d'air froid sur l'Atlantique ou les régions voisines.

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TEMPERATURE AND RAINFALL TRENDS IN SOUTH AFRICA DURING THE PERIOD OF METEOROLOGICAL RECORDS

by

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INTRODUCTION

Past research in climatic change has demonstrated that resulting deductions are largely dependent upon how the subject-matter is treated. Climatologists are in agreement that a long-term study of temperature and/or rainfall should give an indication of the presence or absence of climatic changes in a given locality, but no standard method exists as to how these elements should be analysed, or, more important, what reality tests, other than the usual statistical tests, should be applied in order to prove their climatic significance. Most frequently the method implies the determination of a linear trend over the whole period for which data at a station are available. More logical would be to obtain a rough preliminary idea as to whether any upward or downward tendencies do exist in the data and, if so, to derive and test the regression coefficients for picked periods.

The aim of the present paper is to present linear regression results for certain South African stations and to indicate the effect of time and space shifts on them. From these shifts, it is presumed, a conception can be formed of the climatic significance of any trend index.

With this aim in mind, four main periods were chosen: 1841-70, 1871-1900, 1901-30 and 1931-60, each covering 30 years of observations. In addition, certain auxiliary periods of the same length and multiple periods of 30 years were analysed. The auxiliary periods serve to show the effect of time shifts of 5 or 15 years and the multiple periods to indicate the smoothing effect that enters in such cases.

Periods of 30 years were chosen as basis of analysis because there is some superficial indication in South African data of general upward or downward trends lasting this length of time, and also because such periods are generally adopted for the computation of climatic "normals". Another consideration is that trend analyses over very short periods result in indices of doubtful value, whereas the choice of very long periods tends to bridge possible shorter climatic changes without indicating their presence.

Analyses were limited to seven main and seven auxiliary stations. The main stations are Cape Town, O'okiep, Port Elizabeth, Queenstown, Durban, Johannesburg and Windhoek (in order of distance from Cape Town), whilst the auxiliary stations are Caledon, Worcester, Piquetberg, Swellendam, Cape St. Blaize, Oudtshoorn and George. The latter stations serve to prove the persistence in space of a very significant regression coefficient obtained for Cape Town's rainfall for 1901-30.

RESULTS OBTAINED

For the sake of illustrating the principles involved in the method of analysis, the annual mean temperatures and annual rainfall amounts at Cape Town for periods of 100 and 120 years, respectively, are given in Tables 1 and 2. These data are presented graphically in Fig. 1.

For the sake of clarity, the statistical formulae required in linear trend analysis are summarized as follows:

If b is the regression coefficient with time, t, in a linear equation of the form $y = a + bt$, its value can be determined from

$$b = \frac{\overline{yt} - \overline{y}\,\overline{t}}{\overline{t^2} - (\overline{t})^2} = \frac{\overline{yt} - \overline{y}\,\overline{t}}{(\sigma t)^2}$$

where y is temperature or rainfall, a the intercept of the straight line on the y axis, σt the standard deviation (root mean square) of t (which is always 8.66, 17.32, 25.98 or 34.64, for $t = 30$, 60, 90 or 120 years), and bars signify arithmetic means.

Finally, the standard error of b, as given by Brooks and Carruthers (1953) is

$$\sigma b = \frac{\sigma y}{\sigma t} \sqrt{\frac{1 - r^2}{n - 2}},$$

TABLE 1. Cape Town (Royal Observatory). Annual rainfall (in mm.)

Year	1	2	3	4	5	6	7	8	9	10
1840	589	668	630	477	531	566	568	591	625	851
1850	517	595	560	513	618	557	566	617	936	740
1860	646	814	651	481	475	489	584	507	822	714
1870	511	745	605	666	653	672	907	1042	476	450
1880	650	770	815	719	709	706	586	916	787	669
1890	770	1040	595	520	588	471	511	731	681	540
1900	653	857	759	808	766	515	505	627	610	547
1910	696	560	610	636	660	538	643	569	498	685
1920	656	485	708	478	620	503	482	423	496	419
1930	485	603	461	488	557	513	714	640	492	615
1940	835	693	547	851	637	573	575	587	523	677
1950	712	617	619	836	609	735	857	489	627	427

TABLE 2. Cape Town (Royal Observatory). Annual mean temperatures (in °C.)

Year	1	2	3	4	5	6	7	8	9	10
1860	170	164	166	169	175	172	171	166	171	167
1870	171	169	174	166	167	165	169	162	161	164
1880	169	173	169	167	173	172	171	168	166	166
1890	167	159	167	168	164	171	168	164	168	170
1900	169	169	159	164	168	162	166	164	172	172
1910	172	172	172	169	172	170	172	175	173	173
1920	170	169	172	170	174	169	179	172	173	176
1930	175	177	172	180	174	173	176	172	179	174
1940	170	175	167	172	175	170	173	172	177	171
1950	169	173	175	170	167	169	171	172	173	179

where $r = b\,\dfrac{\sigma t}{\sigma y}$ is the coefficient of correlation between y and t, σy the standard deviation of y, and n is the number of terms.

In these expressions, the units of a are °C. temperature and mm. for rainfall, whilst the units for b are °C. per year and mm. per year for temperature and rainfall, respectively.

Averages, standard deviations, linear regression coefficients and, in certain cases, standard errors of the regression coefficients of annual mean temperatures and annual rainfall amounts are contained in Table 3 for the given stations and periods.

It will be noticed from this table that the results cover a wide range of values for both the analysed elements. Most important was to see whether valid conclusions regarding climatic change could be arrived at by considering the values of b for the main stations in the chosen periods. From the temperature regression coefficients in Table 3 it is noticed that the greatest value of 0.31, i.e. for Cape Town in 1901-30, is appreciably higher than twice its standard error of 0.008, which corresponds to 95 per cent significance. This increase is portrayed in the relevant straight dashed line in Fig. 1. But, as no statistical test is absolute, the question of the climatic significance of this temperature rise must also be taken into account. In order to decide this issue, use is made of two climatic principles which can be stated as follows:

Climatic changes cannot start or stop abruptly, at least not if they are caused by generally accepted long-lasting terrestrial or extra-terrestrial factors. Conse-

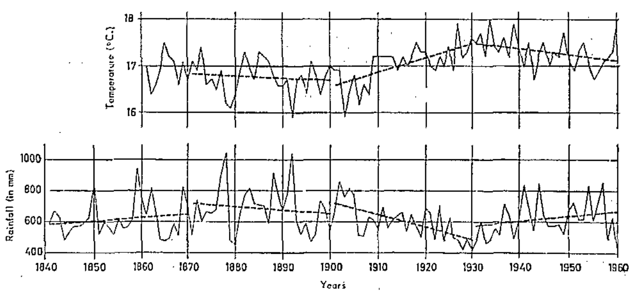

FIG. 1. Annual mean temperature $\left(\dfrac{\text{max.} + \text{min.}}{2}\right)$ and annual rainfall variation at Cape Town, and linear regression curves fitted for 30-year periods.

TABLE 3. Thirty-year averages ($\bar{y}$), standard deviations (σy), time regression coefficients (b) and regression standard errors (σb) for temperature and rainfall at chosen stations and for given periods.

Station	S. lat.	E. long.	Period in Years		Temperature (°C.)				Rainfall (mm.)			
					$\bar{y}$	σy	b	σb	$\bar{y}$	σy	b	σb
Cape Town (Royal Observatory)	33°56′	18°29′	1841-70	30	—	—	—	—	616.6	115.3	1.99	2.49
			1856-85	30	—	—	—	—	666.3	146.0	3.11	—
			1863-92	30	16.81	0.39	—0.12	0.008	686.2	156.9	9.03	2.97
			1871-1900	30	16.76	0.34	—0.005	—	683.4	152.3	—2.40	—
			1886-1915	30	—	—	—	—	664.0	130.4	—0.05	—
			1896-1925	30	16.94	0.37	0.023	—	620.8	101.5	—2.24	—
			1901-30	30	17.04	0.44	0.031	0.008	600.4	110.6	—8.11	1.80
			1906-35	30	17.20	0.36	0.029	—	558.8	81.1	—3.90	—
			1916-45	30	—	—	—	—	577.8	110.0	3.76	—
			1931-60	30	17.31	0.31	—0.013	—	619.8	116.9	3.31	—
			1841-1900	60	—	—	—	—	650.0	139.2	1.67	1.03
			1901-60	60	17.17	0.38	0.009	—	610.1	114.1	—0.12	—
			1871-1960	90	17.03	0.41	0.008	0.002	634.5	132.5	—1.21	0.53
			1841-1960	120	—	—	—	—	630.0	128.8	—0.30	—
Caledon	34°13′	19°25′	1901-30	30	—	—	—	—	555.6	88.2	—2.11	1.88
Worcester	33°39′	19°26′	1901-30	30	—	—	—	—	295.0	78.5	—4.75	—
Piquetberg	32°54′	18°45′	1901-30	30	—	—	—	—	512.0	97.2	—4.51	—
Swellendam	34°02′	20°27′	1901-30	30	—	—	—	—	760.5	184.0	—9.51	—
Cape St. Blaize	34°11′	22°09′	1901-30	30	—	—	—	—	434.1	93.7	—3.75	—
Oudtshoorn	33°35′	22°21′	1901-30	30	—	—	—	—	245.7	79.8	—1.78	—
George	33°58′	22°28′	1901-30	30	—	—	—	—	890.9	179.6	—8.64	—
O'okiep	29°36′	17°52′	1901-30	30	17.42	0.49	0.030	0.009	160.0	55.1	0.06	—
			1931-60	30	17.58	0.40	—0.005	—	155.6	60.4	1.39	1.29
Port Elizabeth (Hill Lighthouse)	33°57′	25°37′	1871-1900	30	—	—	—	—	538.4	116.4	—5.69	—
			1901-30	30	17.51	0.36	0.021	—	589.3	118.1	—1.97	—
			1931-60	30	18.07	0.37	—0.015	—	614.4	84.9	—0.36	—
Queenstown	31°54′	26°52′	1901-30	30	16.35	0.36	0.005	—	536.3	118.8	—1.44	—
			1931-60	30	16.67	0.47	—0.001	—	540.0	104.4	0.85	—
Durban (Botanical Gardens)	29°51′	31°00′	1871-1900	30	—	—	—	—	1028.0	269.1	—7.77	5.68
			1901-30	30	21.31	0.33	0.023	—	1022.0	243.1	—8.18	5.07
			1931-60	30	21.84	0.37	0.003	—	1002.5	207.1	2.97	—
Johannesburg (Union Observatory)	26°11′	28°04′	1931-60	30	15.91	0.39	0.017	—	784.2	145.6	3.13	—
Windhoek	22°34′	17°06′	1901-30	30	—	—	—	—	344.4	143.3	—0.12	—
			1931-60	30	19.16	0.64	0.030	0.013	370.0	155.2	1.32	—

quently a time shift of say five years should not materially affect a regression coefficient relating to a trend over 30 years. Another principle is that for the same reason climatic changes cannot be limited to a small region only. Due to this, a reasonable space shift within the same climatic region should not appreciably affect the regression coefficient.

In accordance with these principles, two five-year time shifts were applied on the 1901-30 temperatures for Cape Town, and, as indicated in Table 3, in both cases more than 95 per cent significance was maintained. No space shift was applied to these temperatures as the time-shift test proved to be very convincing.

Considering the rainfall results for Cape Town in Table 3, it is observed that the value of —8.11 for b in 1901-30 compares very favourably with its standard error of 1.80. However, backward and forward shifts of five years give fairly but not convincingly significant regression coefficients. Additional proof of the significance was consequently sought in the results from space shifts to stations Caledon, Worcester, etc., up to George, of which the first and the last are 90 and 370 km., respectively, distant from Cape Town. Of these no less than five have clearly significant values for b in 1901-30.

It must therefore be concluded that both annual mean temperature and annual rainfall at Cape Town experienced statistically and climatically significant changes during 1901-30. Of added importance is the fact that the trend coefficients of these two elements have opposite signs, as indicated in Table 3 and Fig. 1. This opposition is in line with the negative correlation coefficients between temperature and rainfall, which have been found to be —0.26, —0.14, —0.21, —0.49, —0.22, —0.42, —0.59, respectively, for the seven main stations in Table 3. Such an opposite relation, which must be ascribed to either the cooling effect of rain and cloud conditions or to a common atmospheric circulatory cause, does in fact prove that a significant increase (or decrease) in either of these elements must be associated with an equally significant decrease (or increase) in the other.

Only for one other analysed period, namely 1863-92, did the annual rainfall experience a pronounced change. Here b is 9.03 (with σb 2.97), but for a backward time shift of five years b drops to 1.34 and for a similar forward shift it drops to —0.83. The regression coefficient of 9.03, in a period that was chosen by sight, is therefore climatically non-significant and should warn trend analysts against possible false conclusions from seemingly statistically significant results.

Looking at the indices of the remainder of the main stations, it appears that O'okiep experienced a statistically significant increase of 0.30° C. per year in 1901-30, much like Cape Town did in the same period. On the other hand, a similar increase at Windhoek, but in 1931-60, is practically insignificant. As for rainfall, a fairly significant increase occurred at Port Elizabeth in 1871-1900. But at Durban the even greater regression coefficients of —7.77 and —8.18 in 1871-1900 and 1901-30 are statistically non-significant, due to the corresponding large standard deviations of rainfall and consequent large standard errors of the b— values. In this connexion it should be pointed out that rainfalls and their standard deviations tend to increase or decrease together, as borne out by the $\bar{y}$ and σy values in Table 3.

At this stage reference must be made to the results obtained for Cape Town in the multiple periods, namely in 60, 90 and 120 years. As can be expected a kind of average effect, as compared to the 30-year analyses, takes place in these cases. Therefore no outstandingly high regression coefficients appear in these longer term analyses. On this account the b— values for rainfall completely lose all significance, a result which conforms to that of de Loor, who analysed a 109-year series of annual rainfall at the same station. Because of this finding, some doubt must be attached to the otherwise statistically significant increase of temperature at the rate of 0.009° C. per year through 1901 to 1960 and of 0.008° C. per year through 1871 to 1960. On the other hand, these increases are in harmony with those mentioned by Callendar for different regions, which fact adds to their significance in accordance with the space-shift test mentioned above.

In conclusion it must be pointed out that no time or space-shift test were applied to stations other than Cape Town, since the aim was simply to illustrate their value. Also, the standard error significance test of regression coefficients for samples of 30 observations is admittedly not ideal. However, in view of the object to examine a specific approach to the subject of climatic change, it is believed that such tests are sufficiently reliable.

RÉSUMÉ

Les tendances de la température et de la pluviosité en Afrique du Sud pendant la période pour laquelle on possède des données météorologiques (W. L. Hofmeyr et B. R. Schulze)

Les données présentées illustrent l'évolution des températures annuelles moyennes et du volume annuel des précipitations, par périodes de trente ans ou multiples de trente ans (jusqu'en 1960) pour sept stations principales et sept stations auxiliaires d'Afrique du Sud. Celles qui proviennent de stations auxiliaires, ou qui concernent certaines périodes secondaires, servent à vérifier la signification climatique des tendances constatées. C'est ainsi qu'au Cap (la station qui recueille des données depuis le plus longtemps), on constate, aux environs de la période 1901-1930, une hausse des températures moyennes et une baisse des précipitations dans des proportions significatives tant du point de vue statistique que du point de vue climatique. Pour certains multiples de trente ans, l'augmentation de température se maintient mais la tendance correspondante des précipitations cesse d'être significative.

DISCUSSION

R. G. VERYARD. Have you any ideas regarding a physical explanation of the negative correlation between temperature and rainfall. Could it be a subsidence phenomenon?

W. L. HOFMEYR. Due to the limited time for presenting the paper, I did not refer in my talk to the explanation given in the text, namely that the negative correlation must be due to either the cooling effect of rain and cloud or, vice versa, to the heating effect of cloud absence. The latter condition is intimately connected with subsidence in the subtropical high-pressure belt and bordering regions, as mentioned by Mr. Namias in his comment.

J. NAMIAS. Regarding the question of negative correlation between rainfall and temperature—this is a common phenomenon in the interior of continents during summer. For example, in the Central Plains of the United States, these correlations for monthly values in summer run as high as —80. The physical explanation must contain the upper level anticyclones which dominate dry areas in summer. Through these, dry air from the westerlies (aloft) is flung and this air is further dried out by subsidence into the core of the upper level anticyclones. This, in turn, inhibits cloud formation and allows insolation to rapidly heat the ground and then the overlying air. Of course, the conditions are quite the reverse without the upper level anticyclone and thus frequently with convergence, ascent of air, cloud and screeing of insolation.

E. L. DEACON. The fall in rainfall at Cape Town during the earlier part of this century brings to mind a finding of S. C. Das (*Aust. J. Phys.*, no. 9, 1956, p. 394-399) that there has been a southerly shift of the high pressure belt over the period 1909-54. This he derived from the observations at a chain of stations running down the east coast of Australia and statistical tests showed it to be a significant effect. As DeLisle in New Zealand has also found evidence for such a movement, it would be interesting to consider the implications of the South African results in this connection.

W. L. HOFMEYR. No corresponding pressure analysis has been made to date in South Africa.

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SECULAR TRENDS IN THE SOIL TEMPERATURES AT COLABA, BOMBAY

by

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INTRODUCTION

The secular variation of climate is a problem of perpetual interest to the meteorologist. For inquiries of this type it is obvious that systematic and reliable observations over a long series of years are required. In his paper entitled "Is our Climate changing ? A Study of Long-Term Temperature Trends", Kincer (1933) who analysed some of the long series of air temperature data available for a few stations in the United States and elsewhere has arrived at the conclusion that "with the exception of a region in low latitudes stretching from the West Indies eastwards over northern Africa and the Mediterranean country, there is a general upward trend of temperature".

The problem of climatic changes can also be attacked from the point of view of secular variations in the temperature of the earth's crust, for here we have the additional advantage of dealing with stationary soil layers, whereas the air temperature at a place comes very much more under the influence of atmospheric circulation.

Systematic records of soil temperature for a long series of years are very rare. At the Colaba observatory at Bombay, however, the recording of soil temperatures at various depths was taken up as early as 1849, so that a uniquely long series of data is available for discussion. In the present paper we shall summarize the results of an analysis of this series of data with particular reference to the secular changes at different depths below the surface of the ground. The first indication of the pronounced secular change in the Colaba soil temperatures was given in the *Annual Report on Agricultural Meteorology in India for the Year ending* 21 *August* 1934[1].

SITUATION OF THE OBSERVATORY AND THE EXPOSURE OF THE SOIL THERMOMETERS

The following extract from the annual observatory volume for the year 1847 will give an idea of the situation of the observatory: "The island of Colaba on which the observatory is built is a narrow island with a south and north direction, bending a little to the east, towards the south in a long reef called "the Prongs" which is exposed for more than a mile at low water. The base of the lighthouse is its highest point. The observatory compound or enclosure is a little to the north and east of the lighthouse. The formation of the ground is greenstone trap which decomposes into a rusty soil. There are a few mango and corah trees within the compound but no other than the latter excepting shrubs within some distance of the observatory. The shore slopes gradually away on the western side of the island nearly two and a half miles in length. It is continued towards coral reefs and the open sea and on the east slopes for some distance until it suddenly sinks into the deep water which forms the entrance to the Bombay harbour. As a meteorological observatory it is probably free from the influence of hills, nearly so from the radiation of houses. The results may, therefore, be considered as accurately those of a small island connected with the land."

Regarding the exposure of the soil thermometers, the records state that a pit was dug out in the middle of a thatched shed, large and deep enough to accommodate all the thermometers and then was filled up with soil composed of red earth and decomposed trap gravel, the thermometers being embedded in the soil with their bulbs at the proper depths. All the thermometers were made by Messrs. Newman Co., of London; the divisions are on brass scales. The value of one division, approximate range of scale exposed above ground and length of that part and of one average degree are given in Table 1.

The 132 in. thermometer was sunk in 1879 so that we have a record of only 47 years for that depth. The early records show that for some years the thermo-

1. Government of India Press, 1934 (ICAR publication).

TABLE 1. Soil thermometers

Depth of bulb (in inches)	Divided into (°F.)	Approximate range of exposed part (°F.)	Length of range (in inches)	Average length of 1° (in inches)
1	1.0	30-145	8.19	0.07
9	0.2	30-145	5.20	0.12
20	1.0	35-160	6.23	0.05
60	1.0	35-160	6.81	0.05
132	1.0	50.140	6.44	0.07

meters were read every hour. But later it was found that no appreciable diurnal variation reached the depths of 20, 60 and 132 in. Therefore, the thermometers at these depths were read only once a day and the other thermometers were read five times a day after the year 1851. From these observations monthly means have been calculated and published in the annual volumes entitled *Meteorological Observations made at the Colaba Observatory, Bombay*. These monthly means form the data for the present analysis.

The errors of graduation of all the thermometers were determined in 1928 (after which year soil-temperature observations were not taken) when they were removed from the soil, by comparing them with a standard thermometer, in a water bath. The corrections, together with corrections determined again in April 1936, are shown in Table 2.

TABLE 2. Graduation corrections

Thermometer	Correction (°F.)	
	1928	1936
1 in.	—0.8	—0.85
9 in.	—1.0	—1.25
20 in.	—2.0	—2.32
60 in.	—2.1	—1.76
132 in.	0.9	1.00

The thermometer at the depth of 9 in. was found to be broken in the year 1912. For 1912 and 1913 observations were not taken for that depth. Therefore, values have been interpolated for them from two of the previous years and two of the succeeding years by applying Newton's formula for interpolation. It is interesting to note that in spite of the replacement of this instrument by a new one in 1914 the secular trend of temperature at this depth is similar to that at the other depths as recorded by the old instruments.

The data of soil temperatures for the depths of 1, 9, 20 and 60 in. are available for the period of 66 years (1860-1925) while those for the depth of 132 in. are available only from 1879 to 1925.

These data provide interesting material for the examination of secular changes over a series of years particularly as the same instruments were kept undisturbed throughout the period, except in the case of the 9 in. one referred to above. One method of studying variation with time is to express the temperature as a function of time such as $y = a + bt + ct^2 + dt^3$, where t represents the independent variate time (successive years). This equation suffers from the fact that the values of the constants a, b and c change with the order of the curve. This difficulty was solved by Dr. R. A. Fisher (1954) who introduced his method of curve fitting by using the properties of orthogonal polynomials. A detailed account of the method is given by him in his book on *Statistical Methods for Research Workers*.

The 12 series of the monthly means of the soil temperatures for the above period for each of the five depths were fitted with orthogonal polynomial curves. The variance contributed by each order of the curve ean be calculated from the values of X_2', X_3' . . .. The significance of secular changes can be tested by comparing the x's with their standard residual errors.

The series for the depth of 132 in. were fitted with a polynomial of the third degree only since the variation at this large depth is small. The observations for the other depths were fitted with polynomials of the fifth degree.

DISCUSSION OF THE RESULTS

It will be seen that the mean temperature varies during the year from 83° to 85.1° F. at the depth of 132 in., 82.53° to 86.89° F. at the depth of 60 in., 80.17° to 87.68° F. at the depth of 20 in., 77.24° to 85.96° F. at the depth of 9 in. and 76.11° to 86.44° F. at the depth of 1 in. The range of variation is greatest at the depth of 1 in., being equal to 10.3° F., and goes on decreasing with depth, the value of 2.1° F. being recorded at the depth of 132 in. It is interesting to observe that the lowest temperature is recorded in the months of January at the depth of 1 in. and 9 in., February at the depths of 20 in. and 60 in. and March at the depth of 132 in. Also, the highest temperature is recorded in the months of May at the depths of 1 in. and 9 in., June at the depths of 20 in. and 60 in. and July at the depth of 132 in.

As regards the secular changes which are brought out by the values of x's for the various depths, the following tendencies are observed. The variance contributed by the first degree is very significant and positive, for all the months and at all the depths showing that during the period under consideration there is a definite tendency for the soil temperature to increase. Some of the higher degree curves are also significant in certain cases, chiefly the third degree curve at the depths of 9, 20 and 60 in. and the fifth degree curve at the depth of 20 and 60 in.

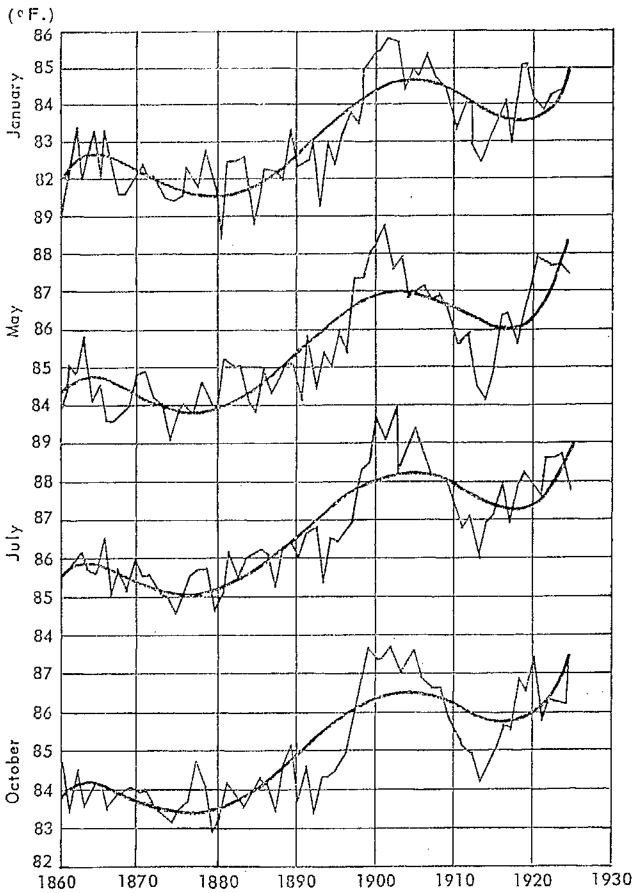

FIG. 1. Soil temperatures, Bombay (depth, 60 in.).

Fig. 1 shows, for example, the actual and smooth polynomial values of the soil temperatures for the months of January, May, July and October. The increasing tendency of soil temperature is very clearly brought out by these curves.

As a result of this investigation, the Colaba Observatory decided to reinstall these thermometers. Data are again being recorded since 1939. These show that the higher temperatures recorded in 1925 are being maintained.

We may examine the smooth polynomial curves for different depths and estimate from the maximum (X) and the minimum (N) values of the curve the range of the variation of the soil temperatures during the series of years under consideration. Table 3 gives the mean values of (X) — (N) for the year as a whole. The mean values of (X) — (N) may be compared with the corrections of the instruments as determined in 1928 which are also given in Table 3.

TABLE 3. Mean values for 1928

Depth (in inches)	Mean value of (X) — (N) for the year as a whole	Correction of thermometer (°F.)
1	3.7	—0.8
9	3.7	—1.0
20	4.7	—2.0
60	3.9	—2.1
132	2.5	0.9

The values of (X) — (N) indicate that the soil temperatures have an increasing tendency during the period as a whole and that these tendencies are large compared to the corrections of the thermometers. Even if it is argued that thermometers had a "nil" correction when they were originally installed and that the corrections found in 1928 were the result of some slow changes in the instruments, it is clear that the increasing tendency of the temperatures actually recorded is more than the instrumental corrections. It is very significant in this connexion that the records obtained from the new thermometer installed so late as 1914 (to replace the instrument broken in 1912) fit in with the trends shown earlier by the previous instrument at the same depth and by the instruments at the other depths. This appears to be against the suggestion that the changes in the instruments themselves may account for the actual trends observed. A visual examination of the actual instruments did not show any deterioration in their external surfaces.

The present investigation had been completed some time ago but the publication of the detailed results was delayed due to other preoccupations. The present symposium on climatic changes demands that their publication be no longer delayed.

In conclusion, the present writers wish to thank the successive directors of the Colaba Observatory for giving the necessary facilities for the compilation of the data and for examining the instruments which were actually used for recording them.

RÉSUMÉ

Tendances séculaires des températures du sol à Colaba (Bombay) (L. A. Ramdas et N. Rajagopalan)

Les auteurs examinent les tendances ascendantes significatives des températures du sol enregistrées à l'Observatoire de Colaba, à Bombay (Inde), de 1860 à 1925 à des profondeurs de 2,5 cm, 23 cm, 50 cm et 150 cm au-dessous de la surface du sol, et de 1879 à 1925 à une profondeur de 335 cm. Ces tendances ont été étudiées en ajustant des polynômes orthogonaux aux séries chronologiques.

Il apparaît qu'à toutes les profondeurs les températures du sol présentent pendant l'ensemble de la période considérée des tendances ascendantes très marquées eu égard aux corrections des thermomètres.

Ces observations ont pris fin en 1925 ; mais les thermomètres ont été remis en place en 1939, et les données enregistrées par la suite indiquent que les températures élevées enregistrées en 1925 se maintiennent.

DISCUSSION

V. Yevdjevich. Was there any change in the ground water level due to irrigation or otherwise?

L. A. Ramdas. The observatory is situated on a rocky island with the sub-soil water table sufficiently deep. There is heavy rainfall during the south-west monsoon, but this too has shown a secular trend.

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CLIMATIC FLUCTUATIONS IN THE ARID ZONE OF THE UKRAINE

by

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From our point of view the aridity of a climate can be reliably defined by means of "coefficients of moistening" which are given by the ratio of the rainfall to the evaporative capacity. The latter is defined as the potentially possible evaporation in a given locality under prevailing atmospheric conditions. For our purposes we use values of evaporation from an open water surface. To the northern part of the arid zone one may allocate the steppe districts of the Ukrainian Soviet Socialist Republic in the most droughty districts of which the "coefficients of moistening" are 0.4-0.5 whilst in the rest of the territory of the steppe the coefficients are 0.5-0.75. The boundary of the arid zone passes, approximately, from Krizhopol to Uman-Cherkassi-Poltava-Kharkov.

The semi-arid or forest-steppe zone with a "coefficient of moistening" of 0.75 to 1.0 reaches the line of Chernovzi-Ternopol-Zhitomir-Chernigov. The north-west part of the republic is in a zone of sufficient moistening and the mountain districts are in a zone of excessive moistening.

The first information about the plains adjoining the Black Sea and the Sea of Azov to the north dates from deep antiquity. However, particulars about climate are available from the time when Herodotus first visited the Scythian land, about 2,500 years ago.

From an examination of antique source material about the climate of the northern lands located close to the Black Sea, the analysis of Homer's poems carried out by B. P. Multanovski, and also A. A. Borisov's investigation into climatic fluctuations in the Crimea, and considering the presence of large amounts of pine pollen in peat bogs, one may conclude that in the middle of the first millennium B.C. and in the beginning of our epoch the climate of the Ukraine was somewhat colder and more humid than it is now.

The Scythia account from Roman sources stops in the fifth to sixth century and from then till the tenth century very little information about climate can be found. There is only a very little mention of a "hard frost" in 791 and of a severe winter in 794-95 when deep snow brought death to a great number of people and horses in the north-west part of the Black Sea.

Only from the time of the formation of the state of Kiev with its high original culture does information about striking meteorological phenomena appear in chronicles. Simultaneously with accounts of state events chroniclers diligently wrote down unusual natural phenomena: droughts, floods, severe and warm winters. There are also descriptions in the chronicles of northern lights and optical phenomena.

There is no doubt of the authenticity of the phenomena described in the chronicles. In his day, M. A. Bogolepov (1908) was the first to utilize the Russian annals for the study of climatic fluctuations. Supplementary to historical records about weather are the "tales of foreigners" who have visited Russia since the thirteenth century, and also the diaries of Russian travellers.

Having systematized these data we have published a summary (Buchinsky, 1954) showing the number of years with various meteorological phenomena, harmful to man's activity, in each fifty years (from 850 to 1800). The data in this summary indicate that striking meteorological phenomena were most frequent in the fifteenth century, i.e., this was a period when the climate was noticeably more disturbed as revealed by the increased number of droughts, floods, storms and thunderstorms, severe and snowy winters and, as the result, of hungry years. From the fourteenth to the fifteenth century one may deduce a deterioration of climate and then, beginning with the sixteenth century, an improvement.

The apparent discrepancy in the simultaneous increase in the number of droughts and floods in the fifteenth century reminds one of the sequence of events observed in recent years when droughts have alternated with high floods.

As we approach modern times, meteorological sources of data become more plentiful. Computations of a "drought index" have been made for each 100 years in the following way: column (*a*) of Table 1 contains the number of years having abundant rains, floods, storms and thunderstorms and column (*b*) the number of years with droughts based on direct evidence and indirect indications (mainly raids of locusts). The numbers in column (*b*) are then expressed as a percentage of the total of the numbers in columns ($a + b$), thus giving the degree of drought in each century.

TABLE 1. Drought index

Century	*a*	*b*	$a + b$	Drought index
Tenth	4	1	5	20
Eleventh	3	6	9	67
Twelfth	26	9	35	26
Thirteenth	23	2	25	8
Fourteenth	30	17	47	36
Fifteenth	62	17	79	22
Sixteenth	41	15	56	27
Seventeenth	31	17	48	35
Eighteenth	27	15	42	35

The data concerning the great drought in the eleventh century based on odd historical sources are not quite reliable but, nevertheless, it is clear that in the eleventh century the number of drought years exceeded the number of rainy years. The drought index of 67 per cent is the highest for all the nine centuries examined. In this century, a pronounced sinking of the Caspian Sea level took place.

Moreover, in one of the earlier works on the history of Kiev (Zagrevsky, 1868) we are told that in the eleventh century "Kiev district and the capital itself were suffering from great calamities. All the plants and cornfields dried up from continuous excessive heat, the wood in marshes caught fire, the work of rural inhabitants ceased". Hence, there is reason to assume a most droughty period at that time. In the twelfth century the drought index decreased and it reached a minimum of 8 per cent in the thirteenth century. In the fourteenth century the drought index increases sharply—up to 36 per cent (but it is still lower than in the eleventh century); the number of dry seasons also increases, but seasons abounding in water remain at the level of the previous century (Shvez, 1957).

It should be mentioned that after Kiev was ravaged by Tatars, a chronicle was compiled in the north where it is known that droughts were considerably rare. Thus, for the thirteenth century the drought index must be considered critically, especially as there was nothing in the literature to confirm the unusual lowering of the drought index. The fifteenth and sixteenth centuries are characterized with a lowering of the drought index which fits in with data indicating a greater wetness of the territory at that time. In the seventeenth century the degree of drought somewhat increased again.

It should be noted that the average drought index for the tenth to fourteenth century is somewhat higher than it is for the fifteenth to eighteenth century. This provides a basis for supposing that, beginning from the fifteenth century, the observed territory experienced increased wetness. Moreover, in describing droughts in the first half of the second millennium, the chronicles refer more often to burning woods, dried-up rivers, lakes and swamps than in the second half. This also suggests that in the first half of the current millennium droughts were more intensive. Thus one may imagine that, having begun in the first millennium of our age, a century-old drought cycle continued up to the middle of the current millennium but was interrupted with moist intervals in the eighth, tenth and, perhaps, the thirteenth century. In the middle of the second millennium the degree of drought decreased.

In the Middle Ages droughts in the area of the Russian plain embraced vast spaces right up to Pskov, Novgorod and Moscow, in spite of the fact the area was almost completely afforested at that time.

For many places in the Ukraine there are long meteorological observations but the wars which were going on in this territory from 1914 till 1923 and from 1939 to 1945 broke the continuity of the records. This has hampered the development of research on climatic fluctuations and much spade-work in filling the gaps must first of all be carried out for several "basic" meteorological stations.

Curves of running 10-year average temperatures at Odessa, Nikolayev and Lugansk are given Fig. 1. Each point of the curves corresponds to a 10-year average temperature for the period indicated below on the horizontal scale. The horizontal straight lines on the graphs indicate values of average temperature for the period for which the running averages were computed. The numbers on the right of the horizontal lines indicate average values based on many years. If observations were missing, the running averages were calculated from "restored" values. The decades which have a "restored" values even for a year, are shown by the figures with a dotted line.

Curves of running means provide interesting information about the character of temperature and precipitation fluctuations.

From Fig. 1 it will be seen that the course of air temperature in the arid zone of the Ukraine has a continuous character for the last 150 years, except during the middle of the last century when it was broken, apparently by the heterogeneity of the series of observations. It may be noted also that the course of air temperature in the Ukraine has a cyclic character but with recurrence periods of different duration.

The temperature curves for the neighbouring stations of Odessa and Nikolayev show a parallelism from the second half of the nineteenth century.

It should be noted that the temperature fluctuations consist of five cycles; only at Nikolayev is a sixth one observed. The curve for Lugansk differs somewhat but even here, it will be noticed, there are five cycles,

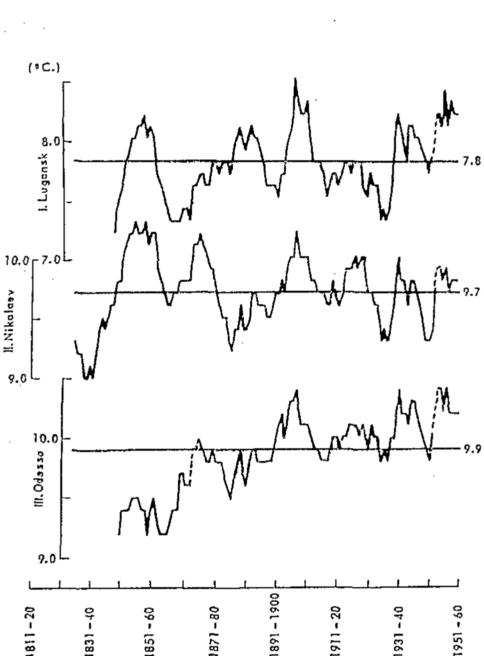

Fig. 1. Running 10-year means of annual temperature for Lugansk, Nikolaev and Odessa.

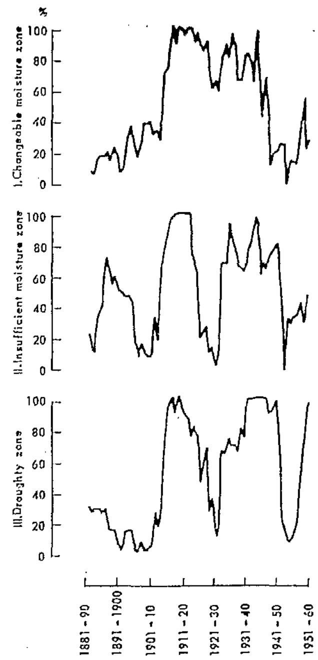

FIG. 2. Secular variation of positive anomalies of the precipitation in the zones of the U.S.S.R. (as percentage from the area of each zone): Changeable moisture zone, insufficient moisture zone and droughty zone.

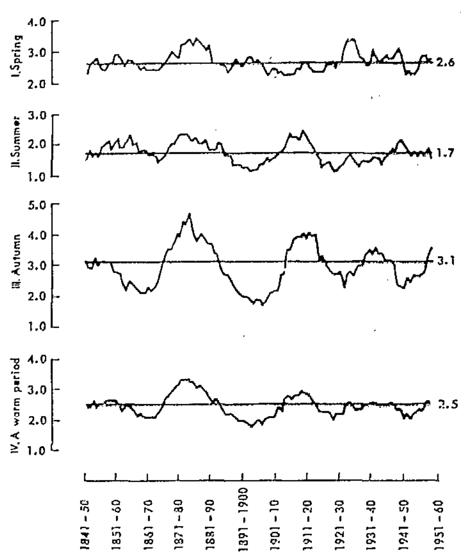

FIG. 3. Secular variation of the degree of drought at Odessa during spring, summer, autumn and warm period.

It is characteristic of the nineteenth century that the duration of the cycles is somewhat larger than in the twentieth century. Thus, the duration of the first three cycles was 20-32 years and the duration of the following fourth and fifth cycles was only 16-17 years, both occurring simultaneously at all the stations of the Ukraine. The amplitude of fluctuations in average 10-year temperatures is of the order of 1.3°.

It should be borne in mind that some other period of duration might be derived by using a different averaging period.

From Fig. 1 it will be seen that an increase of temperature began in the middle of the last century and reached a maximum in 1848-57; there was then a decrease to the next minimum, which was at a higher level than the previous one at several stations (e.g. Nikolayev).

Later, warming took place in the south of the republic: in the east there was a smoother rise of temperature followed by a decrease in the years 1890-99.

The last years of the nineteenth century were notable for a higher temperature compared with the norm. In 1897-1906, a maximum was recorded for the whole period of observations at several stations (Lugansk, Odessa). After this, there was a temperature decrease which continued till the end of the 1920s when temperature reached a normal level. Then a warming began again which continued till 1930-39, followed by a temperature fall till 1940-49 at Lugansk and Odessa and somewhat below normal at Nikolayev. In all the following decades the temperature exceeded the norm by 0.3°-0.7°.

The parallelism observed in the temperature graphs is absent in the curves of annual total precipitation. Some intersecular cycles are observed at each separate station, lasting more than a hundred years, but with different duration.

For the purpose of eliminating inaccuracies in the data of individual stations and in order to reveal precipitation fluctuations a general review of data for the whole territory of the republic has been carried out. Average values of annual total precipitation for many years (norms), computed for each station, were subtracted from average values for running 10-year periods. The resulting differences were expressed as percentages of the norm. Calculations were made for 30 stations evenly distributed throughout the territory for the period 1881-1959.

The fluctuations in each running 10-year period were plotted on a map; 10 per cent isolines were drawn for both positive and negative anomalies. Altogether

70 maps were plotted; for the early decades of observations (1881-99 and so on) the maps were based on the data for 11-14 stations but from 1885-99 till 1890-99 they were based on 15-23 stations. Only from 1896 to 1905 were data for all the stations plotted.

Plotted in such a way, the maps reveal fluctuations in the differences from normal precipitation over the territory of the U.S.S.R. and each zone separately, from decennium to decennium. By means of the planimetry of areas with identical fluctuations (within the limits of isolines having positive and negative values 0-10 per cent, 11-20 per cent, 21-30 per cent and 30 per cent) information about the zonal distribution of precipitation anomalies was obtained for each successive decennium. In Fig. 2 data are given showing the extent of areas with a positive precipitation anomaly, the relation of each area of each zone being expressed as a percentage. It should be noted that a territory with a coefficient of moistening 0.4-0.5 is chosen as a drought zone, a coefficient 0.5-0.75 applying to a zone of insufficient moistening and 0.75-1.0 to a zone of changeable moistening. The end of the last century saw considerable drought as the positive precipitation anomalies embraced a much smaller area than the negative ones.

In the beginning of the current century, the territory became wetter and by the second decade the precipitation was everywhere above normal. Thereafter the precipitation began to decrease until a minimum was reached in 1921-30, when 90 per cent of the area was enveloped in negative anomalies in the drought zone.

In 1922-31 the area with positive precipitation anomalies increased sharply; the increase continued until 1932-41, when precipitation was above normal in 98 per cent of the territory of the U.S.S.R. The increased wetness in a large zone in the centre and in the south of the territory amounted to 16-28 per cent above normal. The following five running decades were marked by an exceptionally abundant fall of precipitation in the Crimea amounting to 37 per cent above normal.

As from 1933-42 the area with positive anomalies began to decrease whilst the area with negative anomalies gradually spread to the south-east and enveloped almost the whole territory of the republic by 1942-51. In the following years the area with positive anomalies began to increase and towards the end of the period of observations these anomalies enveloped almost the whole drought zone and a considerable part of other zones. Apparently, a drought cycle had come to an end.

Thus, in the last 80 years two wet cycles with an average duration of 22 years each are observed in the south of the Ukraine. An ascending branch of a third cycle is also indicated. The recurrence of precipitation anomalies is not so evident in semi-arid zones; the minimum in the twentieth century is more feeble.

Droughts are common phenomena in the southern part of the Ukraine. To study their recurrence a pluviothermic coefficient, PTC, is used. PTC represents the relation of precipitation totals to average monthly temperature totals for a definite period or season (spring, summer, autumn).

A comparison of PTC with crop fields showed that PTC = 2.0 characterizes a territory inflicted with drought. PTC values computed for seasons for 89 years (1871-1959) were plotted on maps. Analysis of these maps made it possible to determine the distribution of areas affected by each drought separately and provided an opportunity to compute the extent of the area of the territory involved by each drought.

When the extent of the territory of the U.S.S.R. affected by a drought reached 1-10 per cent it was considered a local drought, 11-20 per cent a vast one, 21-30 per cent a more vast one, 31-50 per cent an extraordinary one and more than 50 per cent a catastrophic one.

The probability of more vast spring droughts is estimated to be 13 per cent; they occurred in 1875, 1885, 1892, 1899, 1906, 1921, 1924, 1939, 1947, 1951, 1954 and 1959.

There were extraordinary spring droughts in 1872, 1918, 1937, 1950 and 1957, and the probability of recurrence is 6 per cent; catastrophic droughts occurred in 1934 and 1946 and the probability of their recurrence is 2 per cent.

PTC values may also be used for the study of secular change in the degree of drought at any one point. In Fig. 3 such data are given for seasons at Odessa. As will be seen from this figure, PTC secular fluctuations also have a cyclic character, especially in autumn. In spring, the fluctuation of the degree of drought has a more smooth character. There are two periods of increased wetness in the eighties of the last century and in the thirties of the current century. There was an increase of drought in the fifties.

Drought cycles are most pronounced in the seventies of the last century and in the twenties of the present century.

Fluctuations in the degree of drought as examined above for separate seasons yield 3 maxima and 4 minima for the whole warm period of 117 years in Odessa. In recent years there appears to be a tendency for wetness to increase.

In recent years, interest in the problems of climatic fluctuations has increased considerably; evidence of this is the sharp increase in the number of published works. However, their application to the whole globe or even to separate countries is difficult because authors use different methods and different observation periods. It is extremely necessary to unite the efforts of research workers in this field under the direction of the World Meteorological Organization.

RÉSUMÉ

Les fluctuations climatiques dans la région aride de l'Ukraine (I. E. Buchinsky)

La région aride de l'Ukraine est limitée, au nord, par une ligne qui va de Kryjopol à Kharkov en passant par Ouman, Tcherkassy et Poltava. La région semi-aride s'étend jusqu'à une ligne qui va de Tchernovtsy à Tchermigov en passant par Ternopol et Jitomir.

Au milieu du premier millénaire av. J.-C. et au commencement de notre ère, le climat de l'Ukraine était un peu plus froid et humide qu'il ne l'est actuellement. Le cycle séculaire de la sécheresse, qui a fait son apparition pendant le premier millénaire de notre époque, s'est poursuivi jusqu'au milieu du second millénaire. Il a subi des interruptions aux VIII^e^ et X^e^ siècles et, peut-être, au XIII^e^. Au milieu du second millénaire, le climat a commencé à devenir moins sec et la température de l'air à baisser.

Telle que l'auteur a pu l'établir, la répartition géographique des 122 sécheresses observées du X^e^ au XVIII^e^ siècle montre que la sécheresse qui a sévi dans la plaine russe s'est étendue sur de très grandes distances jusqu'à Pskov, Novgorod et Moscou, bien que cette région fût alors presque complètement recouverte de forêts.

Des observations météorologiques instrumentales sont effectuées, en Ukraine, depuis cent à cent cinquante ans. L'analyse des données relatives à la température et aux précipitations a montré qu'il existait des fluctuations cycliques, mais que la durée de chaque cycle était variable.

La courbe séculaire des précipitations annuelles est irrégulière. L'absence de synchronisme dans les fluctuations des précipitations est manifeste dans le territoire de la République d'Ukraine. Le réchauffement progressif du climat a commencé vers le milieu du XIX^e^ siècle; il s'est accentué entre 1930 et 1940, s'est ensuite ralenti pendant quelques années et s'est poursuivi normalement depuis.

Les précipitations ont commencé à diminuer aux alentours de 1930. Vers 1945, l'aire géographique des anomalies négatives couvrait presque tout le territoire de la république. Puis elle a commencé à diminuer et il semble que le cycle de la sécheresse ait alors pris fin. A l'heure actuelle, le volume des précipitations annuelles suit une courbe ascendante; il atteint déjà un niveau normal et, dans certaines régions du sud de l'Ukraine, il lui arrive même de le dépasser.

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SEA-SURFACE TEMPERATURES OF THE NORTH ATLANTIC OCEAN DURING THE DECADE 1951-60 THEIR ANOMALIES AND DEVELOPMENT IN RELATION TO THE ATMOSPHERIC CIRCULATION

by

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THE RECORD WARMING OF THE CANADIAN ATLANTIC COASTAL WATERS DURING THE EARLY FIFTIES OF THIS CENTURY

When looking for the evidence of climatic change over the open sea, one should, perhaps, begin with a study of coastal waters where there are stations which have been recording surface-water temperature for a long time. In this paper I take the Canadian Atlantic Coast as a starting point, because I have obtained records from that area (including unpublished values for 1960) through the kindness of Mr. L. M. Lauzier.

Observations of sea-surface temperature are taken twice daily at several points along the Canadian Atlantic coast so one may follow the trend of temperatures from year to year. The longest continuous series of observations along the Canadian Atlantic coast is that taken at St. Andrews, New Brunswick (45°05′N., 67°04′W.) from 1921 to date.

According to Louis M. Lauzier (1958) the temperature variations at St. Andrews are generally indicative of the conditions on the whole Canadian Atlantic coast and can be used as an index of temperature variations along the coast.

L. M. Lauzier (1953), and L. M. Lauzier and J. H. Hull (1961) have published the monthly and annual means of surface-water temperatures taken at St. Andrews, and Fig. 1 showing three-year moving averages is based on these values. The general warming trend in the waters of the Bay of Fundy comes out very clearly in this figure.

But the interest here is chiefly in the most recent decade. When the three-year means are used, this decade is found to start with the warmest years ever recorded, namely 8.3° C. for the period 1951-53 which is 2.4° C. higher than the coldest period 1922-24, and 1.3° C. higher than the normal for 1921-59. In regard to the extent of this phenomenon, it may be mentioned that there was also exceptional warmth of coastal surface waters on the United States Atlantic coast during the early fifties, at Eastport, Boston, New York, Atlantic City and to a minor degree at Baltimore and Charleston (Rodewald, 1956*b*).

According to curves of 10-year moving averages provided by L. M. Lauzier (personal communication) there is a fairly strong positive correlation between water temperatures at St. Andrews and air temperatures at Halifax, Nova Scotia and at Sable Island, Nova Scotia. The warmest 10-year period in all three curves is that of 1949-58, and as the values of Halifax go back to the period 1874-83, it can be said that in the fifties of the present century surface waters along the Canadian Atlantic coast were climatically the warmest for 80 years. The Halifax 10-year averages of air temperature never surpassed 45.0° F. before 1941-50, but from then on they were constantly above, reaching 45.8° F. during the period 1949-58.

J. Bjerknes (1959), in a study of the recent warming of the North Atlantic, chose the period 1926-33 as one of outstanding warming of the Gulf Stream system, i.e., as compared with the conditions in the period 1890-97. In this connection it is worth mentioning that the surface waters at St. Andrews were 1.0° C. warmer during the period 1949-58 than during the (Bjerknes) period 1926-33, the recent decade 1951-60 being 0.8° C. warmer than the 1926-33 period.

The secular increase in the sea temperature of north-west European waters is a well-known phenomenon, discussed by various authors, e.g., Jens Smed (1949, 1951), E. Goedecke (1952), A. J. Southward (1960). Generally speaking, this increase is of the order of magnitude of 0.5° C. when the periods c. 1880-1920 and c. 1920-60 are compared. But the extreme West Atlantic warming around 1960 has no parallel in the coastal waters of the European side of the North Atlantic. The sea surface temperature at the Elbe I Light Vessel (54.0° N., 08.2° E.), in the southern part of the North Sea, shows no distinct trend at all during the last 40 years (except a lowering of the maxima from 1932-34 to

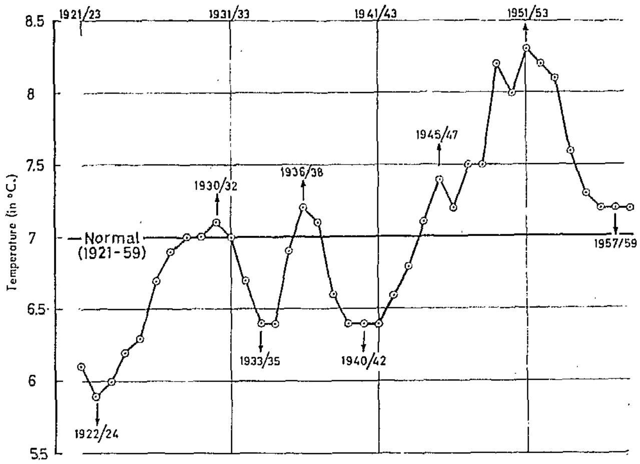

FIG. 1. Surface-water temperatures; three-year running means, St. Andrews, New Brunswick.

1957-59, see Fig. 2). Also in the western English Channel (Southward, 1960) the decadal mean 1951-59 (12.43° C.) was near "normal" with respect to the period 1922-59 (12.49° C.), though it was 0.35° C. higher than the period mean for 1903-27 (12.08° C.).

THE DECADAL COOLING TREND FROM 1951-53 TO 1958-60 IN THE WESTERN NORTH ATLANTIC

The second remarkable feature of Fig. 1 is the pronounced cooling trend in Canadian waters during the last decade. The amount of cooling—based on three-year means—is 1.1° C. which is more than any former amount of cooling during the period of record. In spite of this cooling, however, the present "minimum" of sea-surface

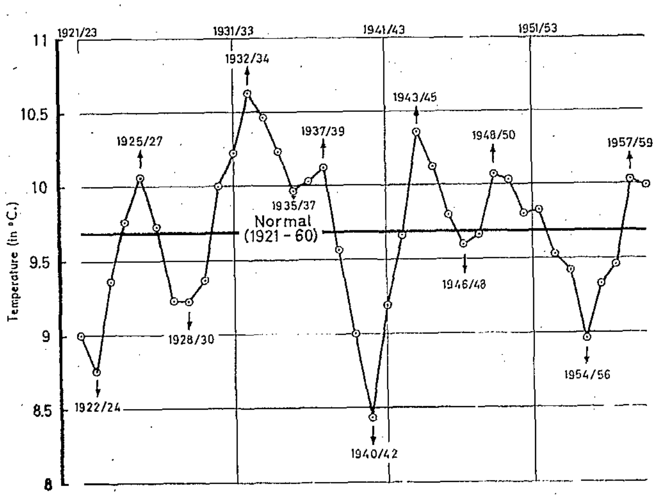

FIG. 2. Surface-water temperatures; three-year moving averages, Elbe I Light Vessel.

temperature is at the same level as the former maxima of 1930-32 and 1936-38.

Thus we are at a stage where the future development is of special interest: will there be a new warming during the sixties of this century, possibly leading to even higher water temperatures than at the beginning of the fifties—or will a further cooling take place to yield a more "normal minimum" again, as in 1933-35 and 1940-42?

Any attempt to answer such questions on the secular warming and its possible reversal cannot be made without considering the spatial extent of the phenomena. As we want to deal with the North Atlantic Ocean we must "go out to sea".

The nearest station in the open sea is the stationary weather ship called D which is located in nearly the same geographical latitude as St. Andrews. However, there is a distance of more than 1,000 nautical miles between St. Andrews and the ocean weather station D (44° N., 41° W.). Moreover, the water masses at these two locations are rather different, D bordering upon the Gulf Stream with a normal annual mean near 17° C., and St. Andrews lying on the "Cold Wall" with a normal annual mean of 7° C., or 10° lower than D.

Nevertheless, the trend of water temperatures is fairly parallel at these two locations. This may be seen from Fig. 3 which shows the curve of annual means for the last decade. Also at D the last decade starts with very high sea-surafce temperatures, but during these 10 years the retrogression there is even more pronounced than at St. Andrews. The anomaly of the decade with respect to sea-surface temperature normals is nearly the same at both locations, namely +0.7° C. at D and +0.64° C. at St. Andrews.

So we get a first impression that both the record warming of the surface waters in the western part of the ocean and the decadal cooling form part of a large-scale phenomenon.

It should be emphasized, however, that the parallelism between the "Cold Wall" region (represented by St. Andrews) and the Gulf Stream region (represented by D) is not a permanent feature. The trend of sea temperatures from 1890-97 to 1926-33 as revealed by J. Bjerknes (1959) gives a totally different picture. Whilst there was up to 2° C. warming along the stem of the Gulf Stream (to the west-south-west of ocean weather station D), there was a small cooling in the colder waters near Newfoundland and Nova Scotia. (This cooling is confirmed by L. M. Lauzier's graph of Halifax 10-year moving air temperatures, giving a respective lowering of about 0.2° C.)

J. Bjerknes (1959) was able to show (Fig. 2) that the effect of the pressure change from 1890-97 to 1926-33 was to accelerate the Gulf Stream (pressure rise in the subtropical high, pressure fall broadly north of 45° N. through the Atlantic). But the "anomaly wind", represented by the isallobars, was also from west-south-west in the "Cold Wall" region, thus exerting an offshore stress on the surface waters. By this offshore component (and by additional cold air advection) some relative cooling of the coastal waters becomes understandable.

It will be shown later that during the last decade of "parallelism between Gulf Stream and Cold Wall" the circulation conditions were largely different from those studied by J. Bjerknes.

THE "THERMAL SWING" BETWEEN THE SOUTH-WESTERN AND THE NORTH-EASTERN NORTH ATLANTIC DURING THE PERIOD 1951-60

When we look at the behaviour of the sea-surface temperature at the other Atlantic weather ships, we find as a third interesting phenomenon of the last decade a "thermal see-saw". But, before giving a broader view, we should mention the source of data. For the ocean weather stations we have made use of the radio weather reports normally transmitted at three-hourly intervals (eight per day). The data have been checked in the Seewetteramt, Deutscher Wetterdienst, and transferred on to punch-cards regularly since November 1950. Certainly some errors or omissions may have remained in the data, due to faults in telecommunication, etc., but most of these can be supposed to fade away in the statistical processing of the large quantity of data.

The average set of data for the nine ocean weather stations during the decade 1951-60 consisted of 233 observations per month and station—not much less than eight per day—giving a total of more than 250,000 observations for the decade and the collective set of data for the nine weather stations.

The advantage of using wireless reports as basic data is that the data can be processed by machine immediately month after month. Thus statistical results can be achieved in a very short time and in many ways (means and frequencies of all reported elements, wind vectors, etc.). Although the results are preliminary and subject to small errors, they are currently available, i.e., without the usual "climatological time lag".

Sea-surface temperatures have to be derived from the reported air-sea temperature differences, and the author has published monthly and annual normals for all ocean weather stations positions (Rodewald, 1952), to facilitate comparison with the actual averages (Rodewald, 1953, 1956*a*). The normals are very roughly—see Rodewald (1952)—for the period 1900-40, so that a general comparison with the normals of sea-level pressure for the period 1900-39 as published by R. Scherhag (See Inst. für Meteor. und Geophys., 1953), or intercomparison between surface anomalies can reasonably be made.

Fig. 4 gives curves of three-year moving averages of sea-surface temperature for the nine ocean weather

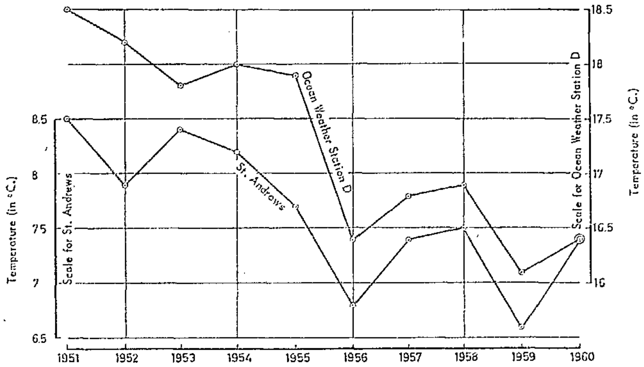

FIG. 3. Annual means of sea-surface temperatures; St. Andrews, New Brunswick, and ocean weather station D.

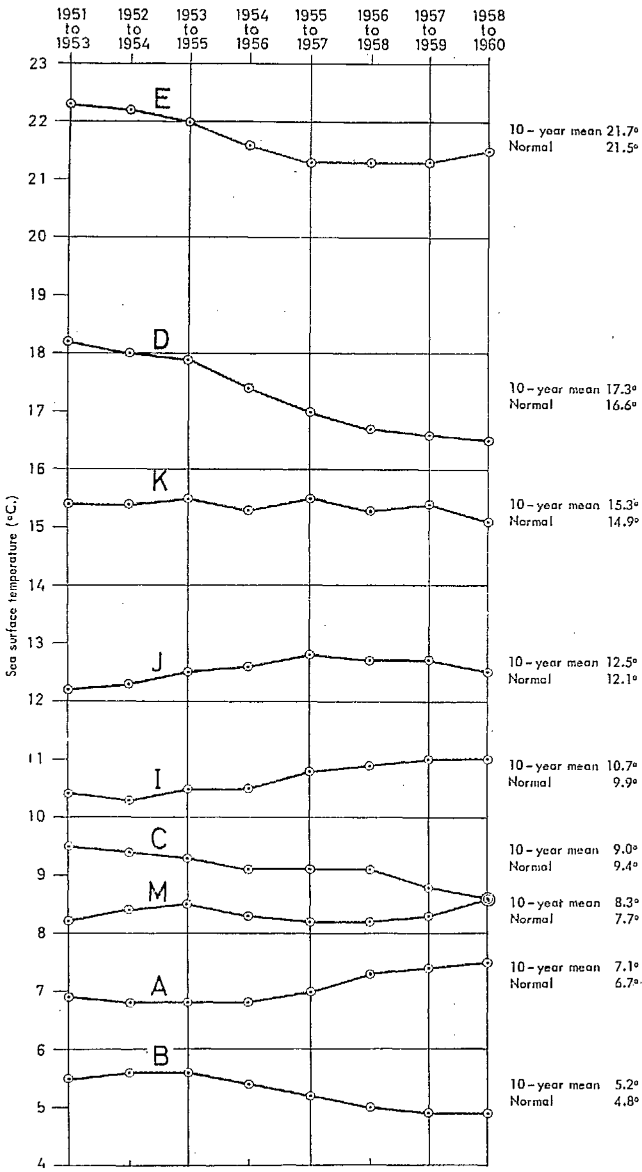

FIG. 4. Moving three-year means of sea-surface temperatures of the ocean weather stations.

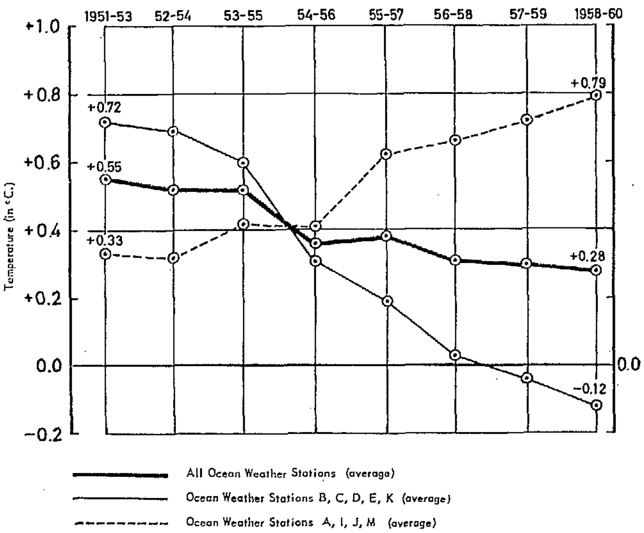

FIG. 5. The trend of surface temperature anomalies in the North Atlantic Ocean during the decade 1951-60.

stations. It will be seen, e.g., from the converging curves of C and M and the diverging curves of A and B that the trends are different.

We can distinguish generally between ocean weather stations with decadal warming and those with decadal cooling, these two forming two sub-collectives (A + I + J + M) and (B + C + D + E + K). Fig. 5 shows the respective trends for the western and southern (B to K) and for the north-eastern (A to M) ocean weather stations, and for the collective of all nine.

The "thermal see-saw" between the two sub-collectives thus becomes obvious, as demonstrated by departures from normal. The collective of all ocean weather stations shows a cooling; the positive anomaly has been reduced from +0.55° C. (1951-53) to +0.28° C. (1958-60), and with a further decadal cooling rate of this amount it would disappear.

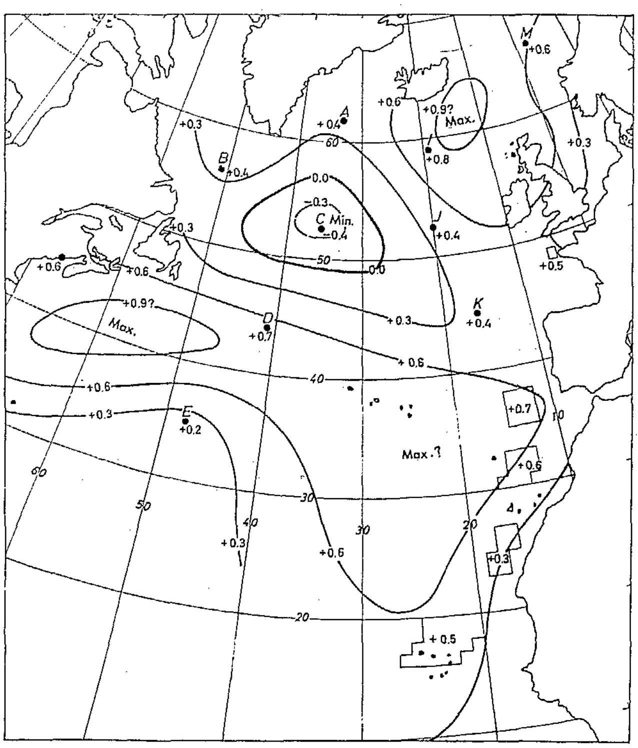

FIG. 6. Sea-surface temperature anomalies (in °C.), decade 1951-60.

THE SURFACE-TEMPERATURE ANOMALY OF THE NORTH ATLANTIC DURING THE DECADE 1951-60 AND THE CORRESPONDING ANOMALY OF ATMOSPHERIC CIRCULATION

Though 1951-60 was in itself a decade of largely changing thermal conditions, its mean conditions are of some interest, and a preliminary account is given here. In addition to the data of ocean weather stations "German ships" observations along the English Channel to Cape Verde Islands route have been used, following the selection made by H. J. Bullig (1954). For comparison, only night values (19.00-09.00 G.M.T.) have been used as by Bullig; also, the same normal period (1906-13) + (1922-38) has been chosen for deriving anomalies. As the available number of ships' observations for 1951 and 1960 are not really enough the actual period used for the tests is mostly 1952-59.

In Fig. 6 isallotherms have been drawn, tentatively, to show the pattern of anomalies. The picture resembles that given by J. Bjerknes (1959) in so far as there are two regions of strong positive anomalies, a subtropical and a subpolar one, which are separated by a negative or smaller positive anomaly north of 50° N. A similar distribution had already been found by the author (Rodewald, 1956*c*) for the early fifties. A physical interpretation of this special pattern of sea-temperature trends has been given by J. Bjerknes (1959).

Though the picture in Fig. 6 is a preliminary one, there seem to be some real differences from that of the "Bjerknes period" (1926-33). Obviously the warming formerly concentrated in the Gulf Stream has spread to the west (see earlier); but it would appear that there has also been an eastward spreading into the region of the north-east trades. As for the cooling region north of 50° N., a displacement to the west can also be noted.

The decadal anomaly of atmospheric circulation for 1951-60 is represented by Fig. 7, the computation of which was based on the *Grosswetterlagen* (Deutscher Wetterdienst, 1951-60). Generally, the departures from normal (1899-1939) have been small. There was no remarkable strengthening of the subtropical high as (relatively) in the "Bjerknes period", nor was there a pressure fall of more than 2 mb. between 50° and 60° N. as in that period.

The only noteworthy features are some deepening and south-westerly extension of the Icelandic Low, and a distinct strengthening of the Greenland high, combined with above-normal pressure to the west and east of the Icelandic low. When considering this pattern, however, it should not be overlooked that the "Bjerknes period" forms part of the normal period used in this study.

With this in mind, the cooling near ocean weather station C may be attributed to an increased cyclonic wind stress, whilst the distribution of warming in the other regions can be attributed to the respective "anomaly winds" which would tend to accelerate the warm Irminger Current along its whole length.

The mean surface-temperature anomaly for the decade 1951-60 and for the collective of nine ocean weather stations is +0.4° C., and the mean decadal anomaly for the whole North Atlantic north of 20° N. is roughly estimated to have been +0.5° C. (+0.47) in relation to the normal period 1900-40 (approx.).

THE TRIENNAL MEAN CONDITIONS AT THE BEGINNING AND AT THE END OF THE DECADE 1951-60

In itself the last decade was by no means uniform with regard to sea temperatures and circulation pattern, but it embraced a trend, as shown earlier. Thus a geographical presentation of the mean conditions of the three-year periods 1951-53 and 1958-60 may be useful.

Fig. 8 shows the outstanding West Atlantic sea-surface warming during the early fifties (1951-53) which appears, however, to extend over the Azores region into the source area of the north-east trades. The relatively cool region between 50° and 55° N. is well marked, though not by a significant negative anomaly.

The corresponding mean pressure anomaly (Fig. 9) indicates that there was no circlation anomaly in the sense of strengthening the Gulf Stream system. There was, on the contrary, an easterly "anomaly wind" within the belt along the 40th parallel, and the onshore component over the "Cold Wall" region would appear to be chiefly responsible for the exceptional warming of the American coastal waters. This effect was extremely pronounced during the winter seasons of 1952 and 1953, as shown by the author (Rodewald, 1953).

Fig. 10 for the end (1958-60) of the decade gives quite another picture of surface-temperature anomalies. The "western warming" has nearly totally disappeared, and instead the mid-Atlantic negative anomaly has intensified and spread to the south-west. The warming of the north-east Atlantic has now become a predominating feature.

For comparison the circulation anomaly for the same three-year period is given in Fig. 11. The most noteworthy feature is the extended negative pressure anomaly to the west of Ireland, this "cyclonic" anomaly

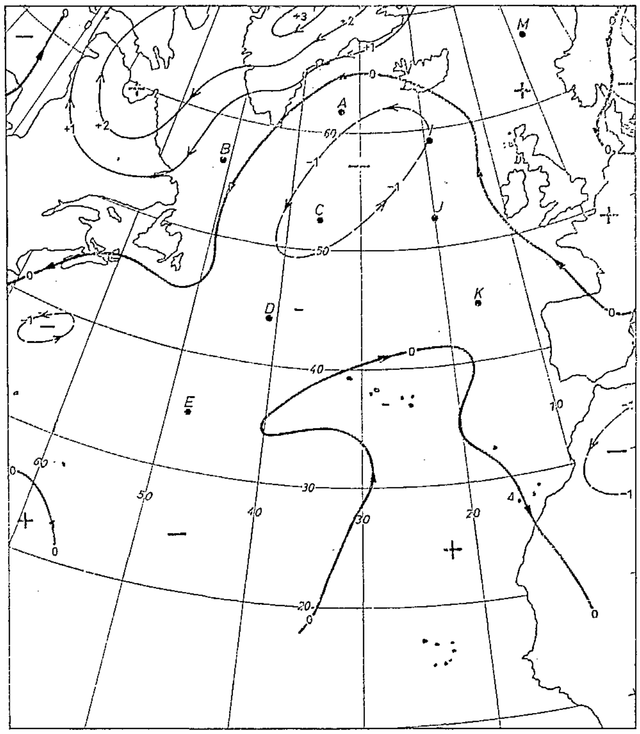

Fig. 7. Mean pressure departure (mb.) from normal (1899-1939), decade 1951-60.

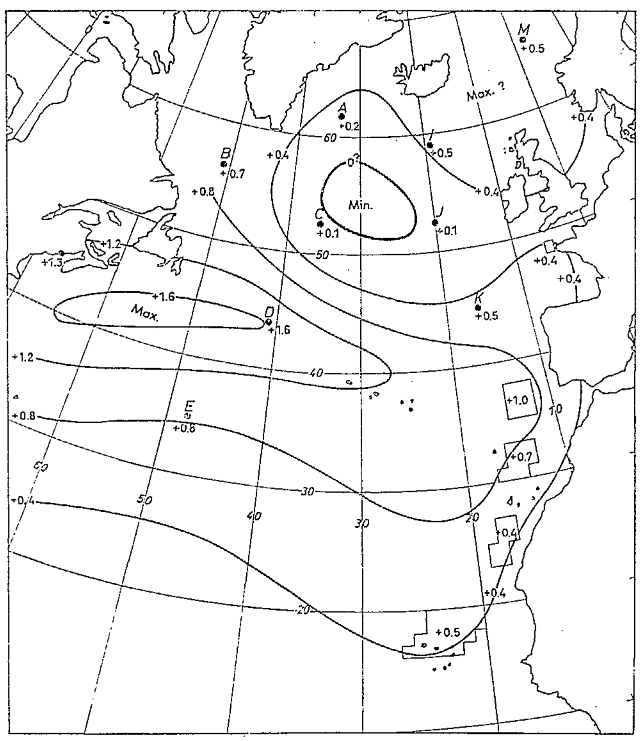

Fig. 8. Sea-surface temperature anomalies (°C.), period 1951-53.

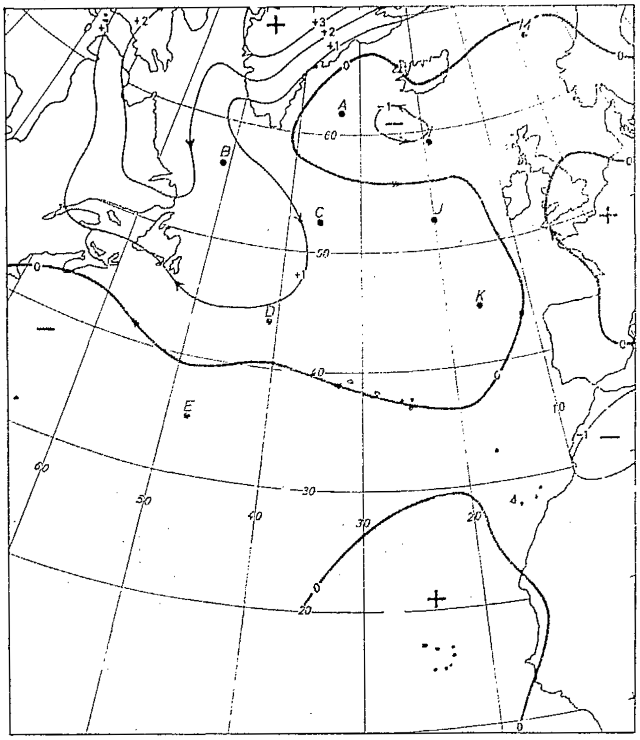

FIG. 9. Mean pressure departure (mb.) from normal (1899-1939), period 1951-53.

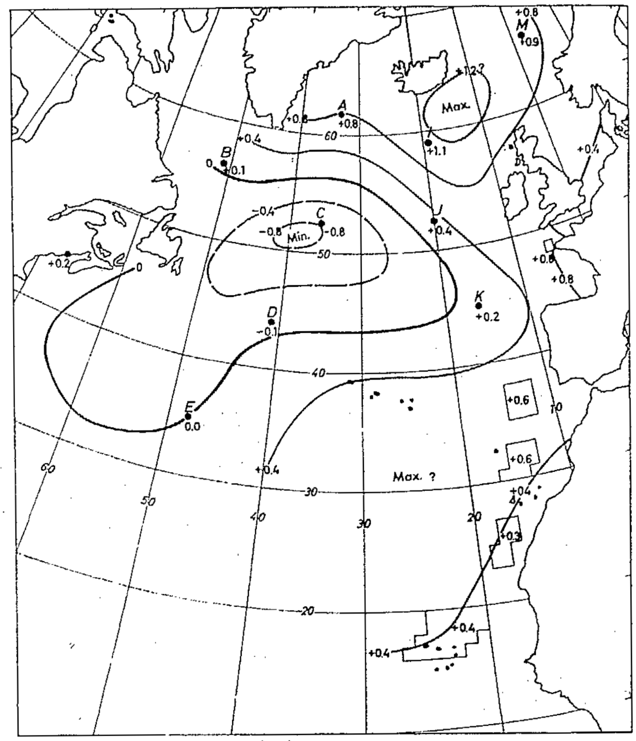

FIG. 10. Sea-surface temperature anomalies (°C.), period 1958-60.

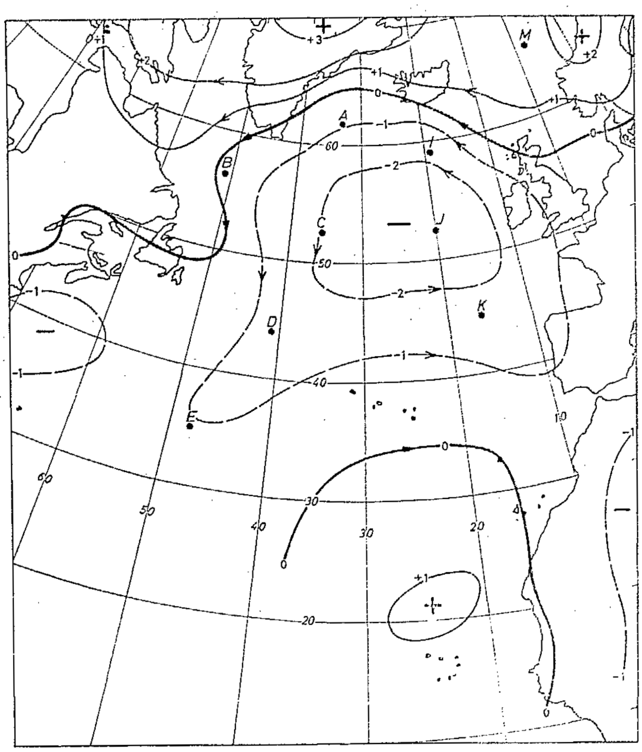

FIG. 11. Mean pressure departure (mb.) from normal (1899-1939), period 1958-60.

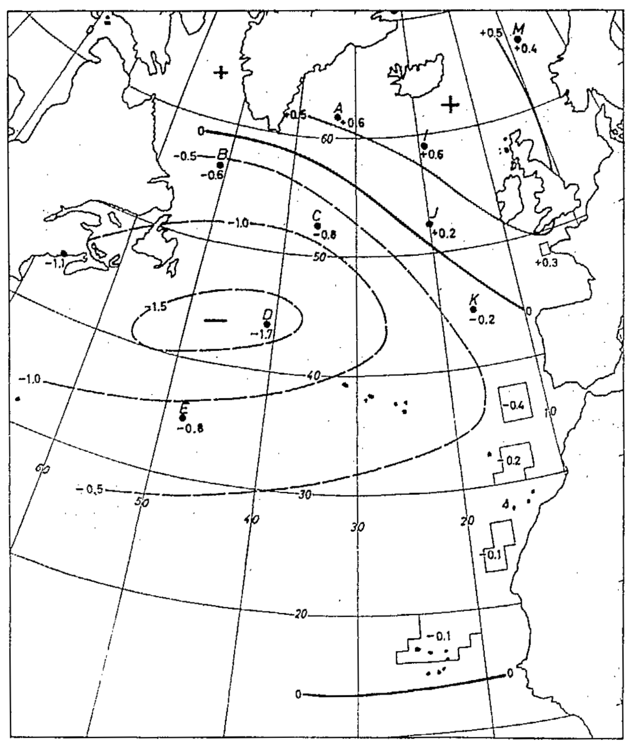

FIG. 12. Change (°C.) of sea-surface temperature from the period mean 1951-53 to the period mean 1958-60.

being surrounded by relatively high pressure especially on its northern half. The "anomaly winds" (marked by arrows) explain, to some extent at least, the distribution of relatively warm and cold sea-surface areas in that they operate in the sense of accelerating the warm Irminger Current system and of adding a northerly component to the flow in the region of the ocean weather stations B, C, D, E.

THE DEVELOPMENT OF THE NORTH ATLANTIC TEMPERATURE ANOMALIES DURING THE LAST DECADE IN RELATION TO THE CHANGE IN ATMOSPHERIC CIRCULATION

An interesting development during the decade 1951-60 is revealed by Fig. 12 for sea temperature and by Fig. 13 for the general circulation. Obviously the decadal cooling is of far greater amount and extent than the warming which is limited to the north-eastern waters. The mean rate of cooling over the whole North Atlantic (north of 20° N.) can be roughly estimated to be 0.3°-0.4° C.

Fig. 13 shows that in the same period there was a broad southward expansion of the polar vortex (Icelandic low). This example is a warning against the use of localized circulation parameters such as the pressure difference Azores-Iceland. It may be seen from Figs. 14 and 15 that the pressure change is practically zero or very small if the locations of the Azores high and of the Icelandic low are compared, whereas the mean barometric gradient for west winds had considerably increased south of the axis of pressure fall (from Labrador to Brittany).

The decadal development seems to support the idea that an expanding polar vortex over the ocean is accompanied by a cooling of the sea surface on a spatial average, especially so in middle latitudes. Though it would be premature to generalize this result, it seems to be worth further study (and similarly the contrary effect of a "contracting polar vortex").

THE INTENSIFICATION OF THE GENERAL CIRCULATION OVER THE NORTH ATLANTIC DURING THE DECADE 1951-60

It should not be overlooked that the behaviour of sea-surface temperature—which is so important in view of the fact that heat stored in the sea is fed back to the atmosphere—depends upon quite a number of different factors. The precise influence of these various factors is difficult to determine and, moreover, the effects may be different between various ocean areas (and, perhaps, not constant with time).

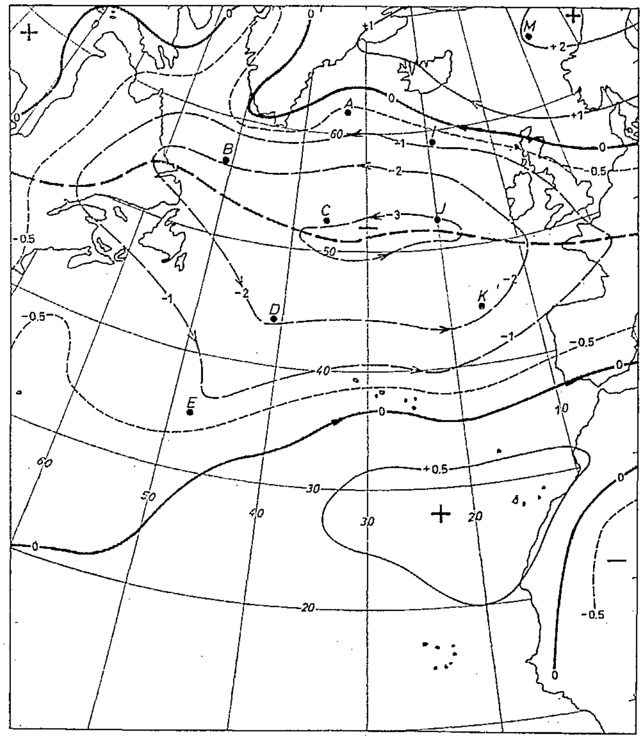

FIG. 13. Pressure change (mb.) from the period mean 1958-60.

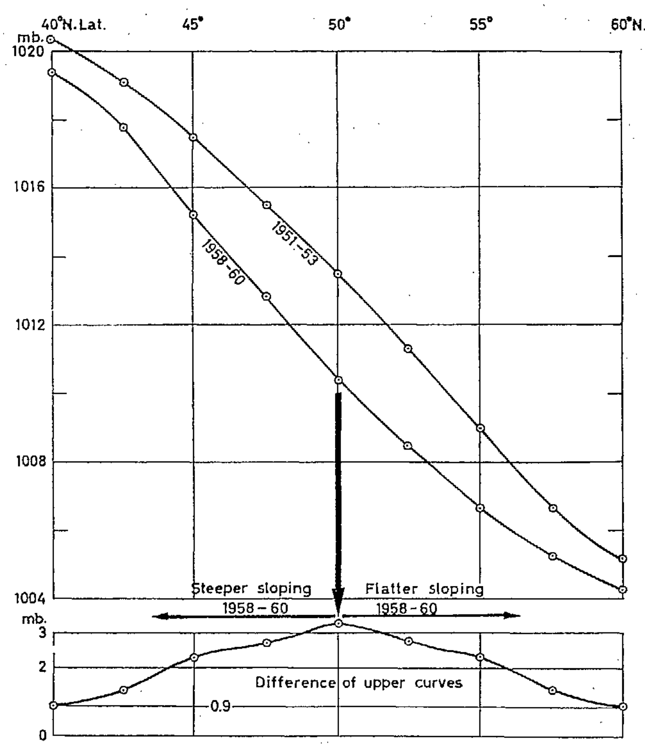

FIG. 14. Mean barometric slope along 30° W. longitude from 40° to 60° N. latitude, for the periods 1951-53 and 1958-60.

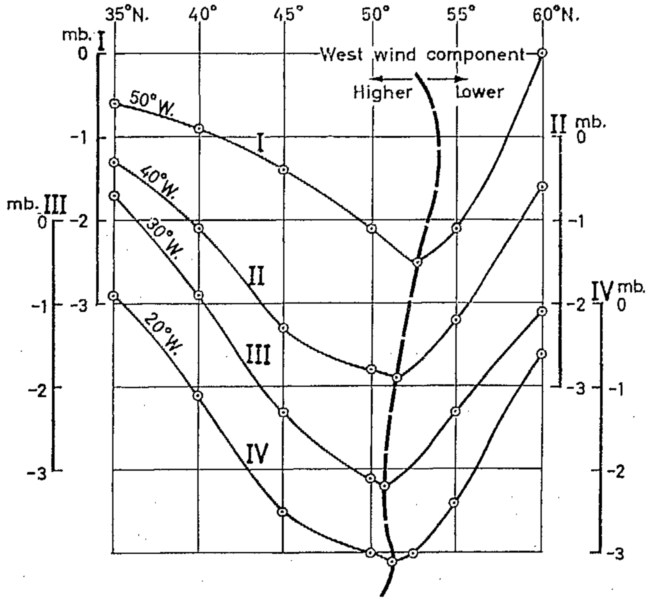

Fig. 15. Meridional profiles through the field of pressure change. Difference of the three-year averages (1958, 1959, 1960) minus (1951, 1952, 1953).

The distinct decadal trend of sea-surface temperature in 1951-60 suggests an inquiry into possible trends of other elements, and some preliminary results in this field conclude this study.

Fig. 16 reveals a clear decadal trend of increasing windiness over the North Atlantic, the "windiness" being defined as the percentage frequency of strong winds plus gales ($\geq$22 knots). For the collective of nine ocean weather stations the increase from 1951-53

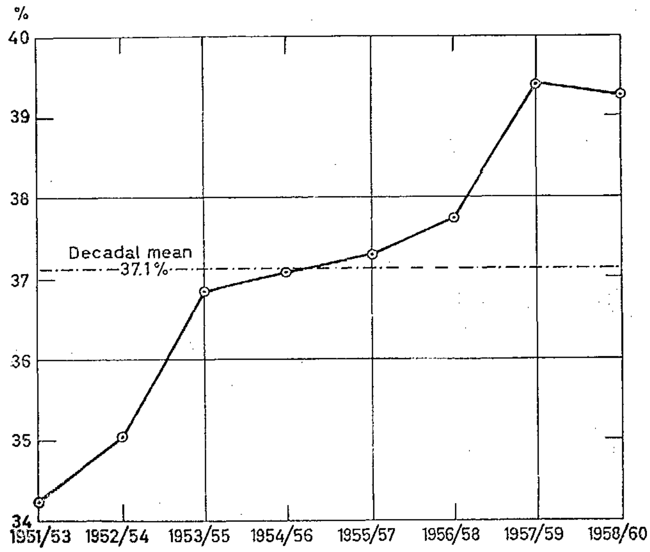

Fig. 16. Three-year running means of windiness over the North Atlantic Ocean (average of all nine ocean weather stations). Windiness = percentage frequency of winds $\geq$ 22 knots (strong winds + gales).

(34.2 per cent) to 1958-60 (39.3 per cent) is 5.1 per cent. Given an initial value of 100, the increase amounts to 14.8 per cent.

This increase in windiness was not limited to only some of the ocean weather stations but occurred, more or less, at all of them. A similar result is obtained if the mean wind velocities at the ocean weather stations are considered, and Fig. 17 gives a tentative picture of the distribution of the change (in knots) of mean wind speed from 1951-53 to 1958-60. For the collective of all nine stations the increase from 1951-53 (18.4 knots) to 1958-60 (19.8 knots) is 1.4 knots (or 7.5 per cent).

There is certainly no clear local correlation between change in sea temperature and change in wind force, but the net result of spatial integrating is that the cooling trend is related to a trend of increasing atmospheric circulation during the last decade.

At a first glance, this is a result which seems to contradict the findings in some former studies which suggested that the ocean warming could be explained by an increased atmospheric circulation. But a "sub-polar warming" has also been found in the recent decade. Undoubtedly more extended and more detailed research is necessary to find more conclusive answers to all the many questions regarding oceanic climatic change.

Finally, it may be mentioned that the decadal variation of air temperature in 1951-60 was very similar to that of sea temperature at the ocean weather stations. But though the individual signs of change at

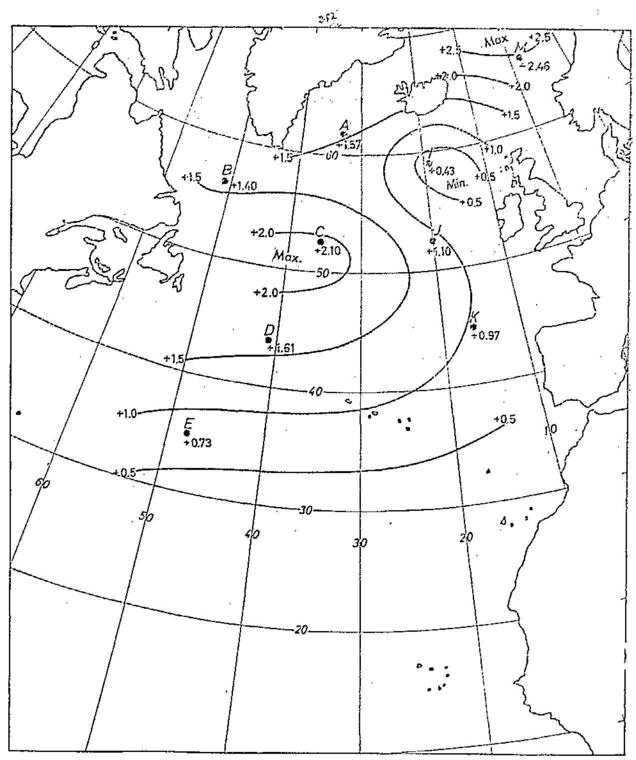

Fig. 17. Mean wind speed change (in knots) from the period 1951-53 to the period 1958-60.

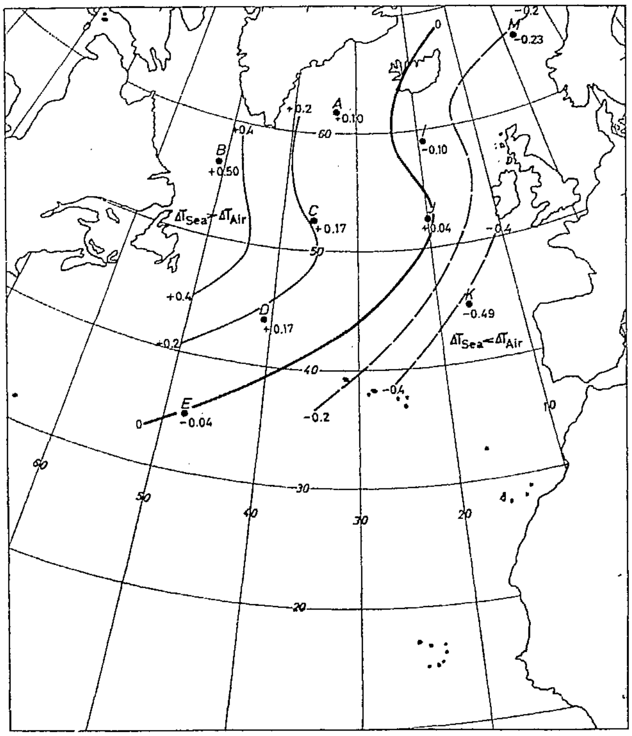

Fig. 18. Comparison of the change in air and sea-surface temperature, period 1951-53 to period 1958-60.

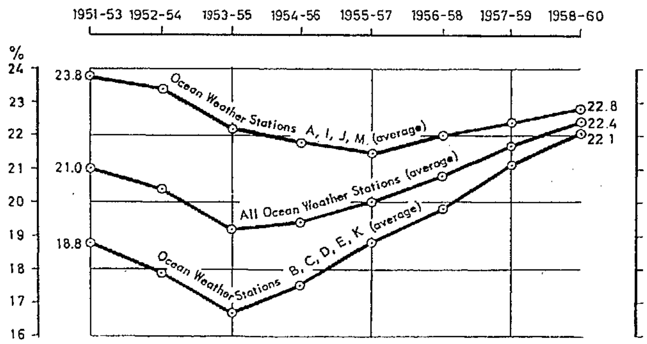

Fig. 19. Three-year moving means of precipitation frequency over the North Atlantic Ocean.

each of the stations were the same, the amounts (air-sea) were not the same. The particular distribution for air-sea differences is shown in Fig. 18. For the collective of nine ocean weather stations the sea-surface cooling from 1951-53 to 1958-60 was a little greater (—0.27°) than the air cooling (—0.21°). The final figure (Fig. 19) suggests that there was an increase in precipitation frequency during the decade.

In the field of interrelations between sea and atmosphere there are many problems. It is the author's opinion that one cannot speak yet of a definite turning point in the recent Atlantic warming, but the present decade of the sixties should be carefully watched for further development.

RÉSUMÉ

La température superficielle de l'océan Atlantique au cours de la décennie 1951-1960, ses anomalies et son évolution, en relation avec la circulation atmosphérique (M. Rodewald)

D'après les observations de la température de la mer effectuées par les navires météorologistes stationnaires (NMS) et représentatives de l'état thermique de l'océan Atlantique en général, la décennie 1951-1960 a été plutôt chaude, l'anomalie moyenne étant de +0,4 °C (moyenne des neuf NMS). L'étude de quelques données supplémentaires conduit à un ordre de grandeur de +0,5 °C pour l'océan dans son ensemble.

La tendance au cours de la décennie 1951-1960 a cependant été à un net refroidissement. L'anomalie moyenne de l'ensemble des NMS s'est abaissée de 0,55 °C pour les trois années 1951-1953 à +0,28 °C pour 1958-1960. Un nouveau refroidissement décennal de cette importance annulerait l'anomalie positive. En tenant compte d'autres données le résultat obtenu est analogue mais plus positif.

La tendance décennale de 1951-1960 a été loin d'être uniformément répartie. La tendance sur le nord-est de l'Atlantique a été nettement à l'inverse de celle de l'ouest et du sud. Ce phénomène a été examiné en le comparant aux variations de la circulation atmosphérique.

De manière générale, on a observé une large extension vers le sud du tourbillon polaire (dépression d'Islande) et cela semble avoir été la cause du refroidissement décennal observé et de ses singularités.

DISCUSSION

H. H. Lamb. Studies of the pressure field from month to month and year to year indicate that it is essential to distinguish between changes produced by variations of the intensity and by alterations of the position of key features. Most pressure difference indices in the Northern Hemisphere seem to show decreasing, not increasing, circulation intensity during the 1950s. On the other hand there has been a remarkable progressive southward displacement of the Iceland low towards the position of ship C in mid-Atlantic—i.e., towards about 50°N.30°-40°W., as shown by some of Dr. Rodewald's diagrams. This southward trend is so far unexplained : it began in the winter months some years before the modest increase of the sea ice north of Iceland became noticeable, and it now appears to affect most times of the year. Thus the increased windiness in the temperate zone of the Atlantic 40°-65°N. may perhaps be due to the Iceland low pressure activity moving to a position central in the region, the increased intensity of circulation appearing as a somewhat localized exception. Quieter circulation appears particularly to have set in in higher latitudes.

M. Rodewald. Certainly my findings are preliminary and are only for the area covered by the ocean weather stations. I am inclined to say that mean pressure difference indices may not always indicate the real intensity of circulation. For instance, in the case of a more frequently and/or more sharply changing circulation pattern, the mean pressure difference over a certain period may not reflect the real strength of circulation. In this respect, the mean wind speed—derived from about eight observations per day—seems to me to give a more direct and better index of the circulation intensity. As to the mean wind speed, there was an increase from the period 1951-53 to 1958-60 at all nine North Atlantic Stations. This increase was greatest at the position of ocean weather station C, but was also well pronounced at the northern stations A and M.

L. A. Ramdas. Surface temperature is immediately controlled by evaporation from the ocean surface. Will increased evaporation account for the lowering of temperature and vice versa?

M. Rodewald. Certainly evaporation, depending, to a great extent, on wind velocity, is an important factor in determining the temperature of the surface layer of the sea. Increasing wind forces will act in lowering the surface temperature and vice versa. But there are many other factors which determine the behaviour of sea-surface temperatures, such as, for example, radiation, cloudiness, and advection in the air as well as in the sea.

J. Namias. In view of the difference of atmosphere-ocean effects according to season it would seem desirable to stratify the data by seasons. This might offer more clues to the physical causes of the ocean surface temperature variations.

Incidentally, the circulation fluctuations shown by Dr. Rodewald produced many weather and climate fluctuations in eastern United States, e.g., increased hurricanes, increased meridional movement of extratropical cyclones, and increased warmth. All of these phenomena appear to be dependent (and interactive with) the general circulation.

M. Rodewald. Breaking down the study into seasons certainly may clarify some questions. It should and may easily be done in a further study.

C. C. Wallén. I wonder if possibly the increase of temperature during the 1950s in the north-eastern Atlantic might have been smaller than during earlier decades and therefore only shows up as a relative maximum compared with the decline in the south and south-west. If that is the case, the cooling in the south and south-west may be connected with a long-term change in the general circulation which is gradually spreading in its effects upon sea temperatures.

M. Rodewald. No comparison has been made between the warming trend during the fifties to that of former decades in the north-eastern Atlantic area. But it may be said that the year 1960 was by far the warmest year within the last decade at ocean weather station M in the Norwegian Sea. One has to wait for the next years in order to see whether the West Atlantic cooling will spread to the north-east, or not.

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CLIMATIC FLUCTUATION OVER THE OCEANS AND IN THE TROPICAL ATLANTIC[1]

by

P. R. Brown

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I. OVER THE OCEANS

INTRODUCTION

An investigation is being carried out into the climatic fluctuation of surface air and sea temperatures over the Atlantic from individual British ships' meteorological observations punched on cards, and from such observations as were punched by Germany about the time of the second world war. The latter observations include those from ships of many occupied nations during the war.

The period of the investigation goes as far back as there exist a sufficient number of such observations from these sources: this is usually not further back than 1870-80.

The investigation also includes surface pressure for the North Atlantic between 30° and 60° N. since over a large part of this region pressure observations are thought to be just sufficient to compute reasonably reliable means. It should be mentioned that some ship observations which include air and sea temperatures do not include pressure. Pressure readings from ships from British and German sources only started in appreciable numbers well after 1900. So far not enough means of pressure have been evaluated to build up a picture of the regional variation of this element.

RESULTS

Although the total number of observations might at first seem large the number available in one 5° or 2° by 5° square for an individual month is usually small considering the area of the square. Further, the individual temperatures in a 5° or 2° by 5° square vary considerably; one reason being that the latitudinal extent of a 5° square is 300 nautical miles and of a 2° by 5° square is 120 miles and the mean horizontal latitudinal variations both of air and sea temperature are appreciable. Hence the significance of the results for any individual square might therefore be considered doubtful by themselves. However, the fact that there is generally only a gradual transition of anomalies from square to square supports the assumption that the means computed do give a reasonable overall representation of the actual climatic fluctuation of air and sea temperature.

Over much of the Atlantic where it is bounded on both east and west sides by land it would appear that the climatic temperature fluctuation over a band of latitude is largely made up of two components: (*a*) a general trend applying to all the region and (*b*) a temperature variation superimposed on (*a*) which is of opposite character over the eastern and western parts of the ocean; this is probably due to the variation of the intensity of the pressure systems in the central portions (longitudinally) of the ocean; for instance, an increase in the intensity of low pressure in the Iceland region could be expected to bring more of the colder air and water (the East Greenland Current) to the western ocean in the latitude of this region and more warmer air and water (the North Atlantic Drift—from the Gulf Stream) in the eastern part of the ocean, under consideration. This idea is not in disagreement with Bjerknes (1960) who formulated the view that a deepening Iceland low (increasing cyclonic wind stress) is associated with the cooling of the ocean surface due to increased upwelling and similarly decreasing cyclonic wind stress is associated with the warming of the sea surface; such variations of temperature would be associated with both western and eastern regions of the low pressure area and hence it would contribute to (*a*) above.

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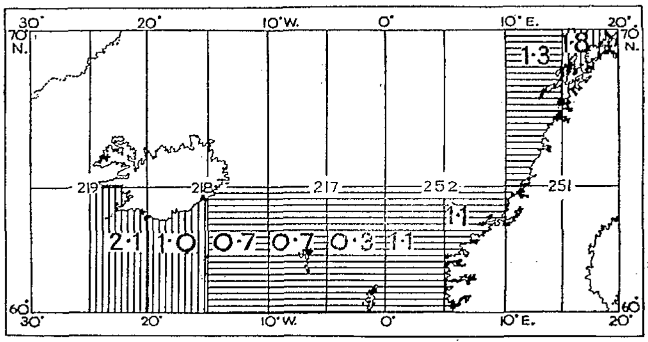

FIG. 1. Increase of decadal annual mean sea temperatures (°C.) from decade 1910-19 to decade 1940-49. The vertical shading denotes areas in which mean sea temperature increased from decade 1930-39 to decade 1940-49 and horizontal shading the areas in which temperature decreased.

GREENLAND AND NORWEGIAN SEAS

The results of the investigation for the Atlantic between 60° and 70° N. were published by the present author in the *Quart. J. R. Met. Soc.* (Brown, 1953).

The means of air and sea temperature for this area and for the Atlantic between 30° N. and 30° S. were computed for each square of 5° latitude and 5° longitude; for any given month all observations were used for the 10-year period giving an equal weight to each observation. The annual means for each decade were computed from the 10-year monthly means evenly weighted.

The results show a general trend of increase in air and sea temperatures in the area 60°-70° N. during the present century up to the 1930-39 decade. Some of the results seem to suggest that a decrease of temperature set in during the 1940-49 decade: however, this was a warmer decade than the much earlier decades, for example, 1910-19 (see Fig. 1).

The fluctuations in the eastern and western parts of the ocean were of different character: this point has been discussed above.

ATLANTIC (30°-60° N.)

The means for this area are being computed for 2° latitude by 5° longitude squares. This part of the investigation is only partially completed and means for only four 10° squares have so far been evaluated.

Mean air temperatures for each year, where available, in the period 1880-1959 are shown for four areas in Fig. 2. These areas are 42°-44° N.50°-55° W., 40°-42° N.50°-55° W., 50°-52° N.10°-15° W., and 50°-52° N.25°-30° W. The sea-surface temperatures for each year, where available, for the same period and areas, are shown in Fig. 3.

The graphs for the area around 43° N.52°30′ W. for both air and sea temperature show little trend averaged over the whole period. They do, however, show a downward trend from the 1890s to the period 1912-21 and a warming trend from then till 1937. Unfortunately observations were not available in the war years 1940-45. There was a rising trend in the years 1947-1950/54. Thereafter there was a fall from then till 1959 of some 2.5° C. in the mean annual air and sea temperatures.

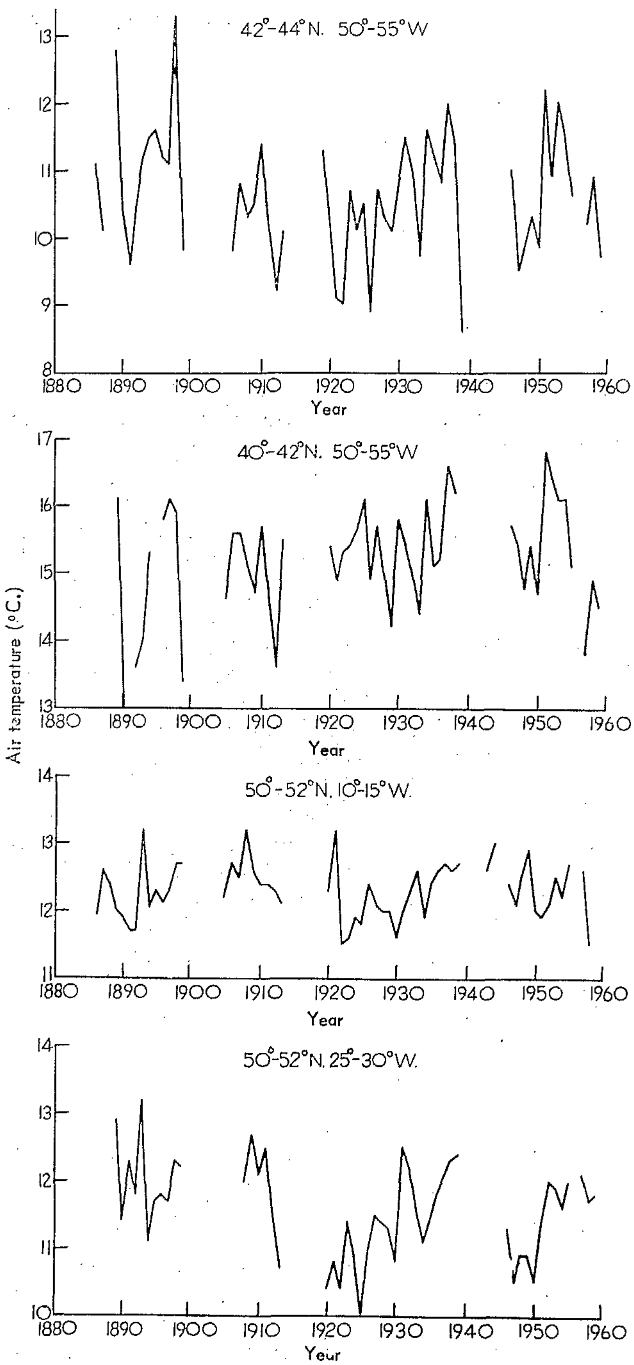

FIG. 2. Annual means of air temperature.

The graphs for the area around 41° N.52°30′ W. show an increasing trend of both air and sea temperature from 1890 to the early 1950s. The rise in the mean annual sea temperature from 1890 to 1952 was 3.9° C., and the rise in the mean annual air temperature from 1890 to 1951 was 3.8° C. There was a falling tendency from 1951-52 until 1959.

The graph for the mean annual air temperature for the area around 51° N.12°30′ W. shows little average trend over the whole period, although it does show a markedly warming trend from 1922 to 1939. Mean annual sea temperature also shows this rising tendency from 1922 to 1939 and also there was a small average rising tendency for sea temperature over the whole period.

The graphs of mean air and sea temperature for the area around 51° N.27°30′ W. both show a markedly rising trend between the years 1920 and 1939 but little trend when averaged over the whole period. The graph for sea temperature shows generally the same character as that arrived at by Bjerknes for the position 52°30′ N.27°30′ W.

The means of sea temperature for January and July for the area 56°-58° N.15°-20° W. are shown in Fig. 4. The means for both January and July show a rising trend since 1919: before that time the observations available show a cooling trend for July.

TROPICAL ATLANTIC (30° S.-30° N.)

The results of the investigation for this area are given in a paper presented to this symposium.

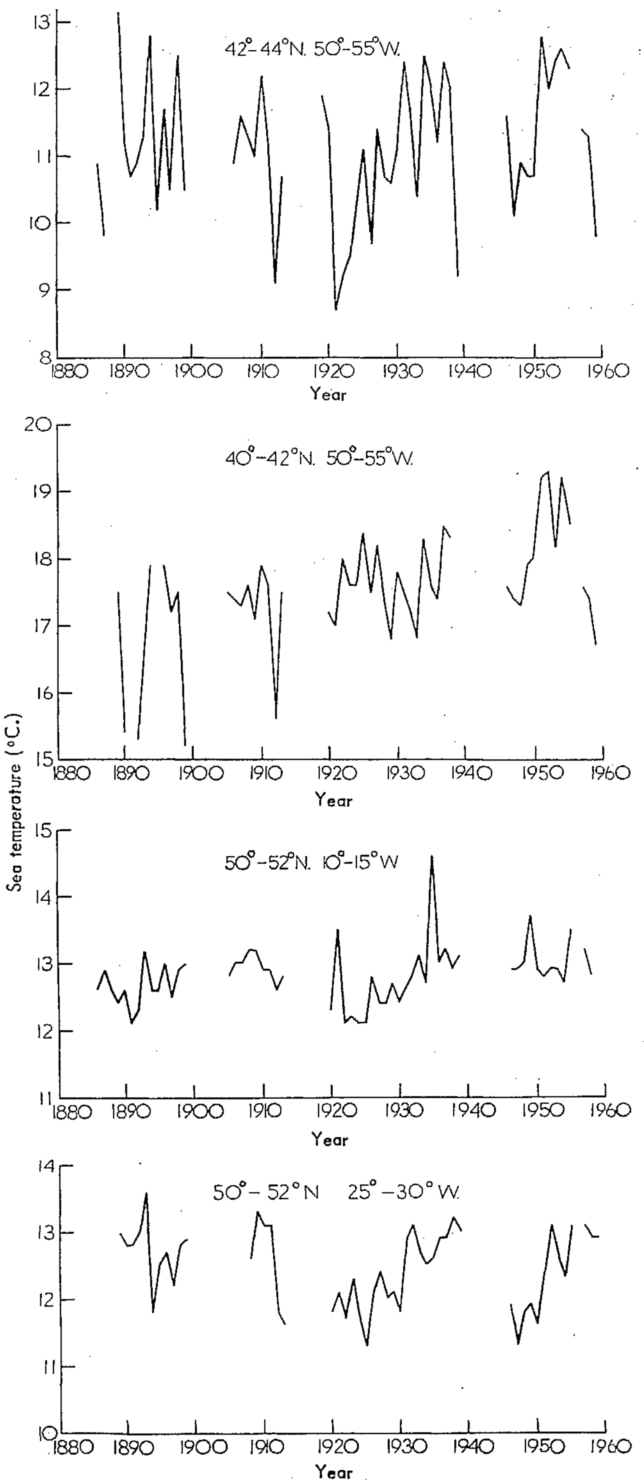

Fig. 3. Annual means of sea temperature.

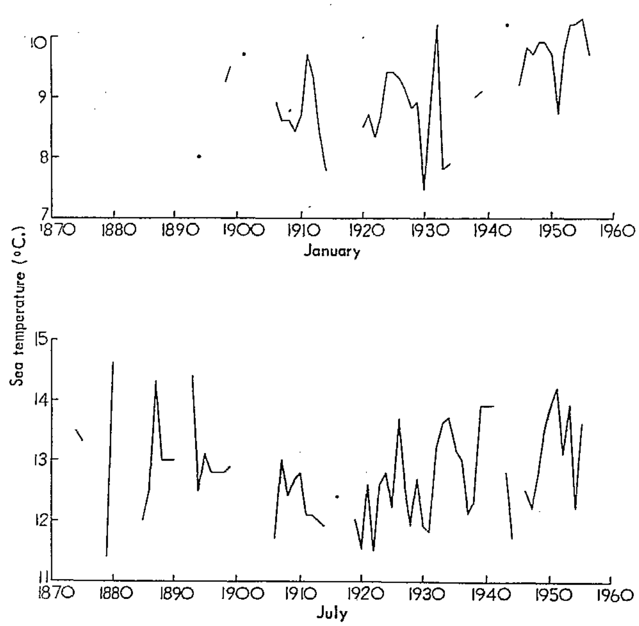

Fig. 4. Sea temperature in area 56°-58° N.15°-20° W. in January and July.

II. IN THE TROPICAL ATLANTIC

INTRODUCTION

The intention in this part is to present the results of an investigation into the climatic fluctuation of surface air and sea temperature over the Atlantic between 30° S. and 30° N. It is part of a larger investigation which it is hoped to carry out for the whole Atlantic: a similar one has been carried out for the Atlantic north of 60° N. (see earlier) and at present a start is being made on one for the Atlantic between 30° N. and 60° N.

CRITICISM OF DATA

The Meteorological Office holds about 5 million punched cards from British voluntary observing ships and 8 million which have been duplicated from those for ship observations held in Germany. Some 2.2 million of these cards are for the area we are concerned with in this paper, i.e., the Atlantic between 30° N. and 30° S. (see Fig. 5). The same criticisms apply to these observations as were described in the previous part (Brown, 1953).

METHOD

The area of the Atlantic between 30° N. and 30° S. was divided up into 5° squares using the Marsden system of notation as shown in Fig. 5. It should be noted that the Marsden notation for 5° squares, i.e., A, B, C and D, is arranged differently in the four quadrants of the earth; an example of the orientation of these sub-squares for each quadrant is shown in Fig. 5 for the four 10° squares which adjoin the position where the Equator meets the Greenwich meridian.

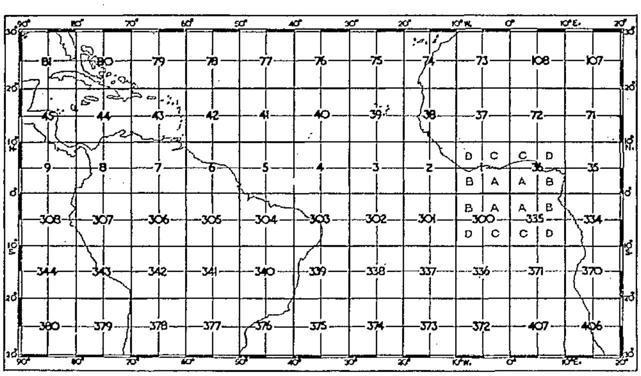

FIG. 5. Chart showing Marsden square areas.

The procedure for computing the means of air and sea-surface temperature for each 5° square was the same as that described in the first part of this article.

Means were not computed for individual years for each month as the number of observations were not sufficient to arrive at anything like a reliable value for the mean of an individual month. The fact that means are not available for some of the individual months in some of the years in each decade and that there are large gaps in the records during the war years also prevented the complication of running decadal means which would have been advantageous.

Yearly means for each decade have normally been computed only when the whole 12 months are available. If, however, 11 of the 12 are available for a particular decade, together with the whole 12 for the previous or subsequent decade, the annual mean for that decade has been computed from

$$\bar{T} = \frac{\Sigma^{11}\bar{t}\,\Sigma^{12}\bar{t_1}}{12\,\Sigma^{11}\bar{t_1}}$$

where $\bar{T}$ is the annual mean for the decade, $\Sigma^{11}\bar{t}$ and $\Sigma^{11}\bar{t_1}$ are the sums of the same 11 monthly means for the decade and the previous or subsequent decade and $\Sigma^{12}\bar{t_1}$ is the sum of the 12 monthly means for the same previous or subsequent decade. For a very few decades the annual mean has been computed for a particular decade when only 10 of the 12 monthly means are available for this decade together with the whole 12 for a previous or subsequent decade using a similar formula to that above.

The means of the annual decadal values of the air and sea temperatures for the period 1910-39 were computed and the anomalies for each decade compiled on the basis of the semeans. The anomalies of air temperature for each decade for each 5° square are shown in graphical form in Fig. 6. The means of air temperature for the period 1910-39 are shown against each graph. The numbers of observations used in the compilation of the means for each decade for each 5° square are shown in Table 1.

The anomalies of sea-surface temperature for each decade for each 5° square are shown in Fig. 7 and the means of sea temperature for the period 1910-39 are shown against each graph. The numbers of observations used in the computations of the means for each decade are generally similar to those used in the compilations for air temperature as shown in Table 1.

The regional distribution of the anomalies of air temperature for each decade are shown in Figs. 8 to 14 and those for sea temperature in Figs. 15 to 21.

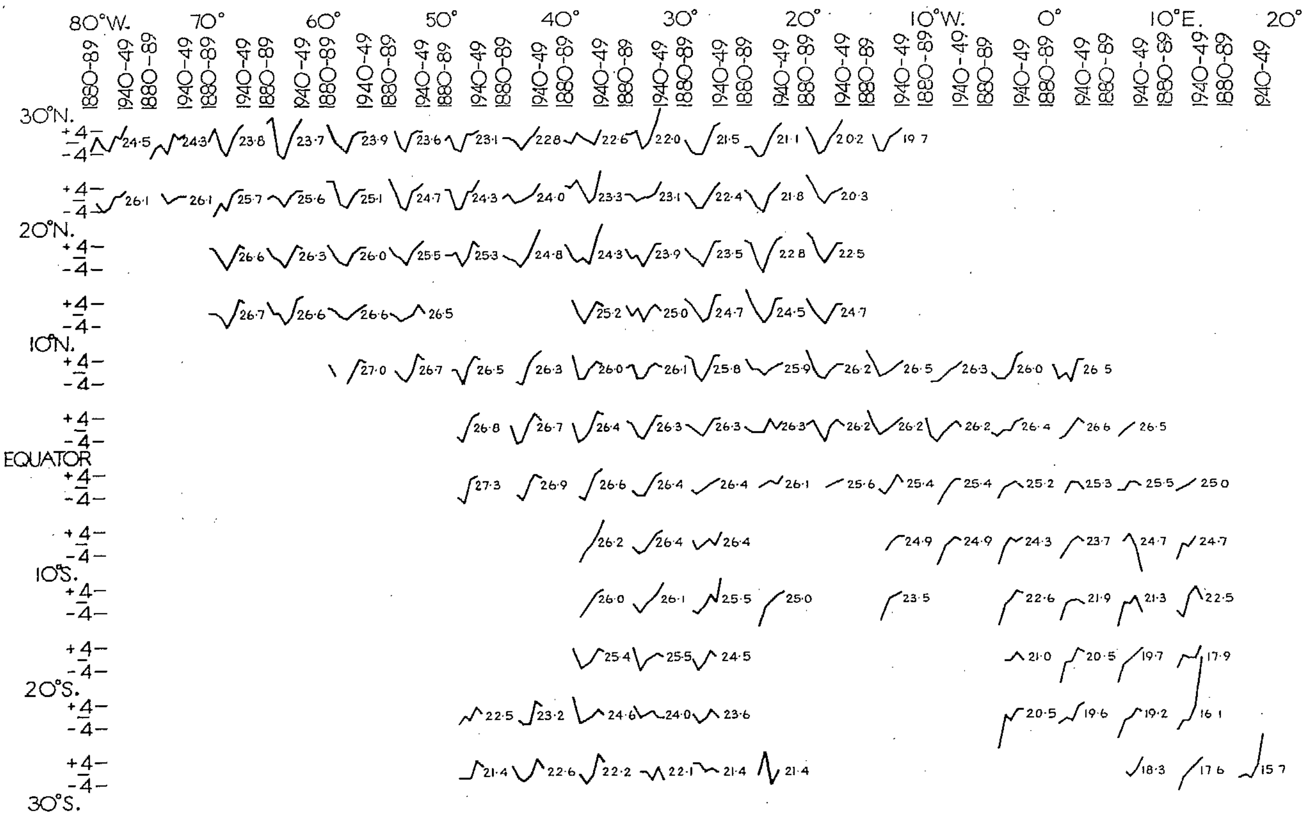

FIG. 6. Anomalies of air temperature for each decade.

DISCUSSION OF RESULTS

Although the total number of observations might at first seem large the number available in one 5° square for an individual month is usually small considering the area of the square. Further the individual temperatures in a 5° square vary considerably; one reason being that the latitudinal extent of a 5° square is 300 nautical miles and the mean horizontal latitudinal gradients, both of air and sea temperature, are appreciable. Hence the significance of the results for any individual square might therefore be considered doubtful by themselves. However, the fact that there is generally only a gradual transition of anomalies from square to square as shown in Figs. 8 to 21 supports the assumption that the decadal means computed do give a reasonable overall representation of the actual climatic fluctuation of air and sea temperature. It is likely that a few means, however, may not be truly representative as a rather more uneven distribution than usual with regard to time and space within the square may have caused considerable bias in the computation of these few means.

Figs. 6 and 7 show the general character of the climatic fluctuations over the area. It will be first noted that the fluctuations of the means of sea and air temperature show a close similarity, as shown by Brown (1953) in a previous investigation; indeed the fluctuations of individual sea and air temperatures show a close similarity as shown by Smed (1947).

It will be seen that while there has been an overall rise of sea and air temperature from 1880-89 to 1940-49 there have been during parts of this period, however, large falls over some of the area and this might be true over all the area had observations been sufficient in all 5° squares over the full period 1880-1949. Furthermore the diagrams show that the character of the fluctuation has been very different over different parts of the area. The types of variation may be divided roughly into three categories. First those in the areas north of the Equator which show a cooling in the earlier decades, a marked minimum in the decade 1910-19 and then an increase which tends to level off in some instances in the decade 1940-49. Secondly, in the south-western part of the area south of 5° S. there is a transition polewards from a steadily rising temperature from 1900 to 1909 to one which fluctuated somewhat haphazardly. Thirdly, in the south-eastern part of the area there is generally a steadily rising temperature until either the 1930-39 or the 1940-49 decade.

The fact that there is no minimum over most of the

Table 1. Number of observations used in compilation of means for each decade (shown in Fig. 6)

FIRST AREA

Marsden square	Sub-square	1880-89	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49
080	D	473	1,434	3,399	5,602	8,251	7,055	898
	C	277	440	1,624	2,142	5,941	5,011	1,307
	B		169	1,020	1,650	889	1,003	64
	A			807	1,049	5,012	3,448	1,058
079	D	521	719	1,854	2,077	5,001	5,058	1,376
	C	563	392	1,155	1,290	4,090	4,295	1,132
	B		219	404	329	2,357	4,145	1,173
	A	554	591	2,852	2,560	6,700	11,425	2,458
078	D	441	353	1,631	2,018	5,569	7,525	2,107
	C		268	3,234	3,421	5,958	8,718	2,409
	B	702	388	3,098	2,864	5,342	7,270	2,223
	A	504	803	577	860	2,228	3,967	1,141
077	D	737	1,059	2,122	2,506	5,035	7,009	1,490
	C	1,670	2,607	1,407	1,749	1,935	3,694	870
	B	671	952	194	447	1,062	2,425	607
	A	1,448	3,815	714	901	287	458	344
076	D	2,090	2,611	1,655	1,351	574	1,189	425
	C	813	1,086	587	595	159	615	188
	B	1,996	2,182	1,489	885	311	354	223
	A	1,062	1,064	1,041	736	269	1,083	169
075	D	565	593	506	626	190	897	166
	C	2,595	3,376	6,338	6,960	3,305	6,645	798
	B	810	1,082	2,064	2,097	345	1,472	168
	A	2,941	3,596	13,650	15,187	11,199	14,100	1,483
074	D	1,712	5,097	18,690	27,031	28,029	23,700	4,158
	C		320	1,183	2,208	1,929	2,301	711
	B	554	3,700	10,528	16,950	21,358	17,216	4,693
043	D	407	1,080	1,703	2,629	8,491	11,371	2,242
	C	788	586	1,859	2,965	3,804	5,607	1,793
	B	460	201	446	1,427	3,648	4,824	1,665
	A	1,468	1,271	638	1,577	2,374	2,901	1,187
042	D	1,075	1,093	244	198	1,453	333	866
	C	681	1,067	291	207	931	2,189	584
	B	1,216	871	492	671	1,128	2,859	955
	A	482	201	215	238	149	801	240
041	D	490	425	293	184	96	320	247
	C	1,153	1,116	839	665	183	263	174

region south of the Equator during the decade 1900-09 may be because no means were computed as there were insufficient observations in this region prior to 1900.

Willett (1950) in discussing the zonal distribution of the climatic warming since 1885 states that it has been most pronounced poleward of 40° N. (a fact which is generally agreed) and in the first two zones south of the Equator, i.e., from the Equator to 20° S. The results obtained in this investigation do not tend to support the view that the warming up in this century is more marked in the Atlantic in the zone 0°-20° S.

SECOND AREA

Marsden square	Sub-square	1880-89	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49
040	D	1,689	1,881	1,198	1,181	219	1,039	105
	C	1,235	1,240	1,760	1,984	251	1,599	126
	B		903	1,325	2,092	295	1,527	126
	A	1,647	1,325	1,069	1,520	344	830	174
039	D	2,367	3,191	3,672	6,111	3,646	7,092	616
	C	1,047	2,114	7,574	15,745	15,641	15,739	1,991
	B	4,149	5,353	7,249	14,010	11,430	14,779	1,333
	A	819	1,539	4,223	8,487	8,983	7,245	1,667
038	D	430	2,897	4,260	8,034	12,574	10,993	3,558
	B	611	2,911	4,407	8,178	14,890	19,914	3,402
006	D	731	182		105	190	500	542
	C		229	316	424	225	358	904
005	D		164	327	326	105	1,070	497
	C	208		658	1,060	236	1,703	250
	B			507	858	307	1,916	554
	A		182	923	2,200	236	2,052	685
004	D		724	603	1,295	323	653	2,469
	C	1,895	1,521	1,365	1,451	488	974	590
	B		251	297	591	228	1,036	1,856
	A	1,993	2,152	4,864	9,606	7,209	9,670	640
003	D	5,064	6,521	12,619	21,837	19,292	17,579	149
	C	2,637	3,575	3,998	3,141	3,112	4,002	211
	B	5,038	7,411	10,811	15,871	13,970	10,791	484
	A	3,508	4,177	2,785	2,436	781	797	937
002	D	570	2,145	2,829	3,895	3,170	3,682	2,080
	C	268	2,132	3,886	6,718	10,687	9,576	2,504
	B	656	896	1,225	615	190	135	347
	A	421	2,461	2,334	4,313	2,221	3,335	2,312
001	D		40	263	560	1,059	701	66
	C		207	361	845	1,380	424	59
	B	142	699	2,193	4,131	8,107	6,570	1,238
	A		301	892	2,027	4,890	4,375	482
036	C		277	822	1,850	3,078	799	167
	B			857	1,440	3,629	2,962	
	A			216	356	1,613	2,757	96
304	B			260	170	159	325	
	A			535	926	366	811	232

than in the zone 0°-20° N., but owing to lack of observations prior to 1900 this does not definitively contradict Willett, whose conclusions were based on land station records.

One of the largest direct causes of the climatic fluctuation of temperature must be changes in the circulation of the atmosphere and ocean. Confirmation of this is found in the fact that where the horizontal variation of temperature is great, for example, as in the high latitudes of the North Atlantic (Brown, 1953) the difference between the magnitude and characteristics of the climatic fluctuation in the eastern and western portions of an oceanic zone which is bounded on the east and west by land, is much greater than

THIRD AREA

Marsden square	Sub-square	1880-89	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49
303	D			717	1,523	1,632	1,114	140
	C		352	11,560	21,092	19,923	18,881	3,002
	B			756	1,126	446	2,066	907
	A		226	10,962	20,307	18,267	19,838	2,304
302	D		163	2,299	2,239	1,063	658	259
	B		230	4,510	4,762	2,612	1,699	614
	A			700	823	288	196	185
301	C				2,620	213	158	205
	B				280	181	186	310
	A			1,140	1,990	151	247	291
300	D			644	1,273	1,201	1,157	686
	C			2,192	3,572	4,985	3,439	2,166
	B			2,516	4,391	5,899	4,120	2,573
	A			679	943	1,412	1,167	185
335	D				254	891	513	47
	C			526	723	800	498	116
	B			183	451	1,670	1,111	112
	A				123	1,099	781	108
334	C			217	311	1,938	904	
	A			99	143	646	576	
339	D		182	14,410	23,326	20,330	17,638	2,795
	C		287	4,353	2,868	2,270	766	304
	B			10,148	19,046	18,069	16,144	2,581
	A		282	6,793	6,515	4,944	3,011	780
338	D		218	3,158	2,885	1,170	413	
	B		173	2,742	2,332	1,053	526	110
	A			413	312	149	169	99
337	A			387	244	153	256	143
336	C				185	179	226	293
	A			189	246	2,130	1,661	1,413
371	D			1,672	2,192	2,731	2,830	911
	C			2,059	3,837	4,483	5,586	2,048
	B			784	1,106	1,042	894	95
	A			2,182	3,106	4,037	4,097	1,485
370	C			846	1,199	3,557	1,698	83
	A			445	476	2,989	1,516	45

where the horizontal gradients are small as, for example, in the tropical Atlantic. This is what we would expect if the change of circulation was a major cause.

One particular point of interest is the large rise in temperature in the coastal waters off south-west Africa in the period 1945-49. Both the sea and air temperatures in this area are influenced by the upwelling of the cold water off the coast, an upwelling which greatly decreases from time to time. It seems likely that this increase in temperature was due at least in part to an upwelling which was considerably below normal during some of the period 1945-1949.

FOURTH AREA

Marsden square	Sub-square	1880-89	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49
376	D			7,152	13,805	17,521	11,161	1,979
	C		205	859	10,300	6,164	4,708	1,243
	B			921	1,930	4,062	1,284	332
	A			10,938	20,323	19,683	14,416	3,056
375	D			1,355	703	769	352	138
	C			1,924	1,454	758	438	138
	B		235	9,376	9,776	7,049	5,603	973
	A		200	2,268	1,061	996	517	288
374	D		86	5,520	3,552	1,471	595	
	C			1,939	1,211	370	342	
	B		36	4,672	3,143	1,381	483	
372	A			128	110	106	246	172
407	D				724	556	805	476
	B			2,144	3,941	4,801	3,865	2,553
	A			383	533	292	482	382
406	D			563	1,935	1,847	707	79
	C			2,656	5,433	6,141	4,889	2,929
	A			1,616	2,567	4,122	1,831	440

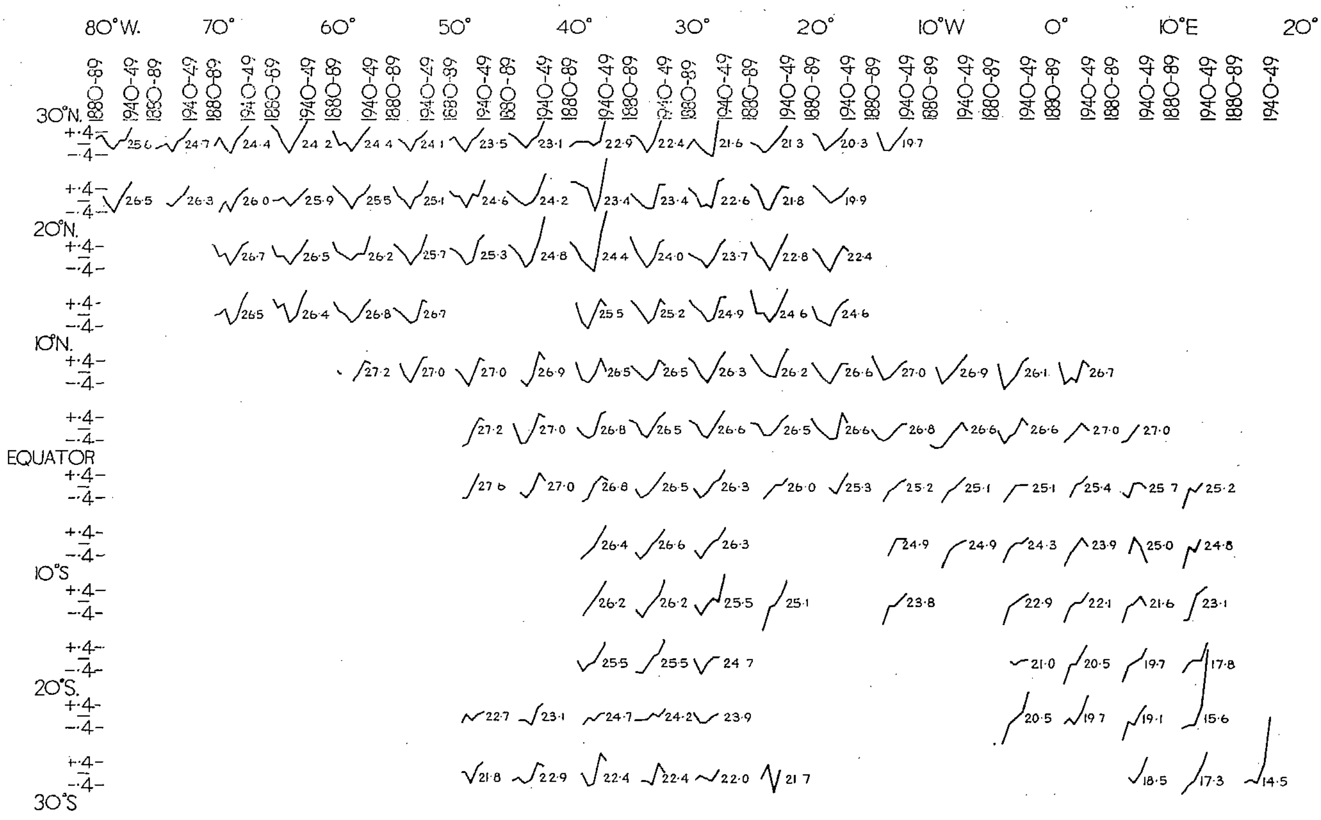

FIG. 7. Anomalies of sea-surface temperatures for each decade.

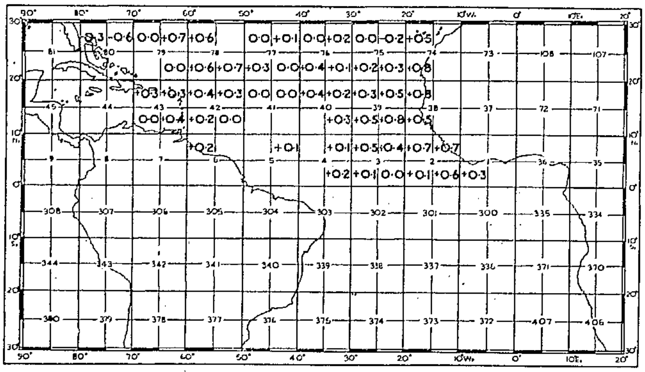

FIG. 8. Anomalies of air temperature (°C.) for decade 1880-89.

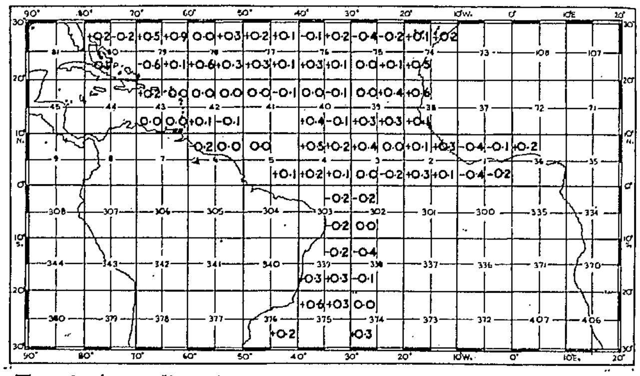

FIG. 9. Anomalies of air temperature (°C.) for decade 1890-99.

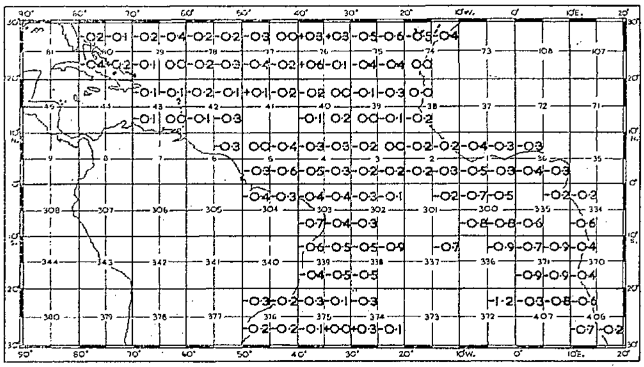

FIG. 10. Anomalies of air temperature (°C.) for decade 1900-09.

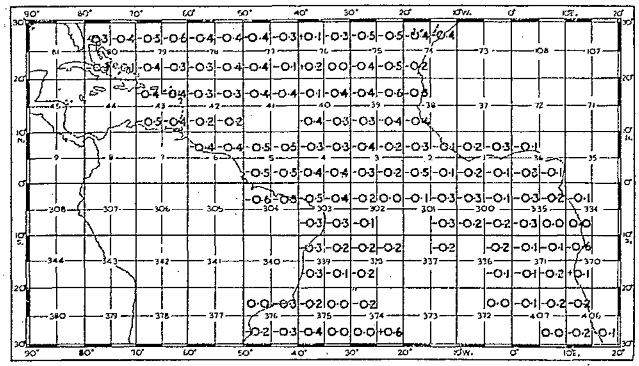

FIG. 11. Anomalies of air temperature (°C.) for decade 1910-19.

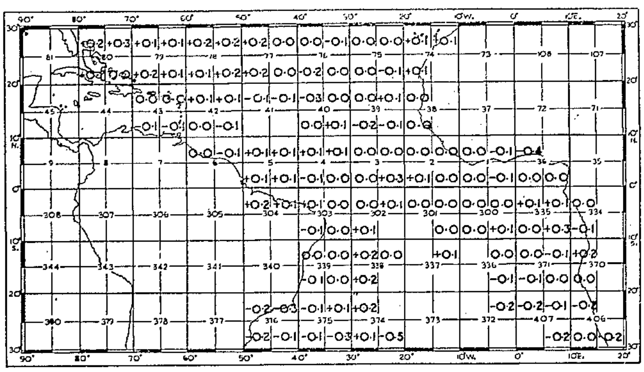

FIG. 12. Anomalies of air temperature (°C.) for decade 1920-29.

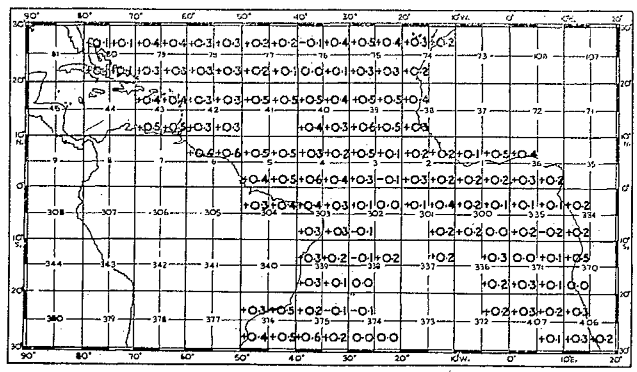

FIG. 13. Anomalies of air temperature (°C.) for decade 1930-39

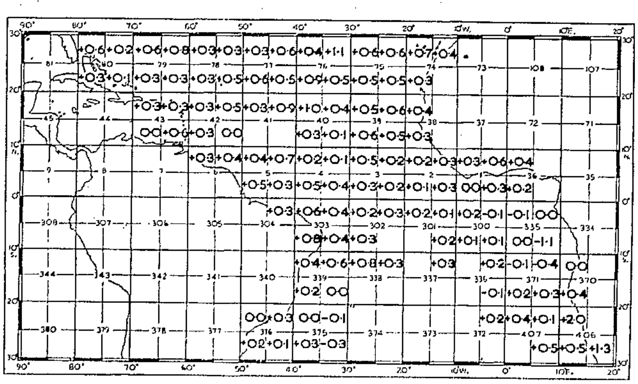

FIG. 14. Anomalies of air temperature (°C.) for decade 1940-49.

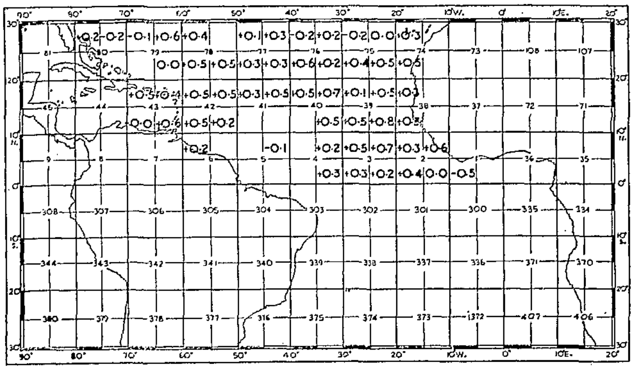

FIG. 15. Anomalies of sea-surface temperature (°C.) for decade 1880-89.

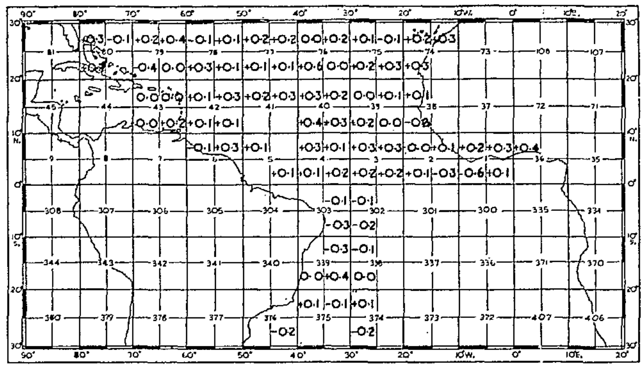

FIG. 16. Anomalies of sea-surface temperature (°C.) for decade 1890-99.

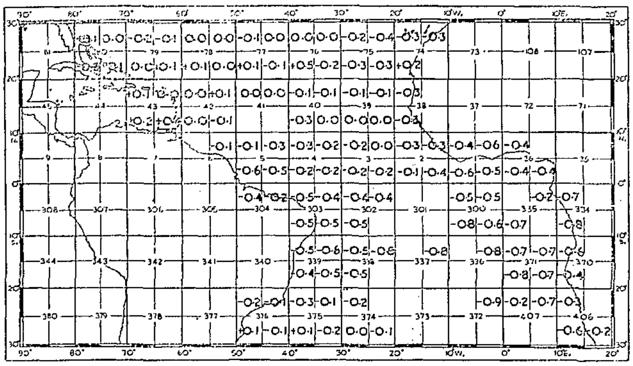

FIG. 17. Anomalies of sea-surface temperature (°C.) for decade 1900-09.

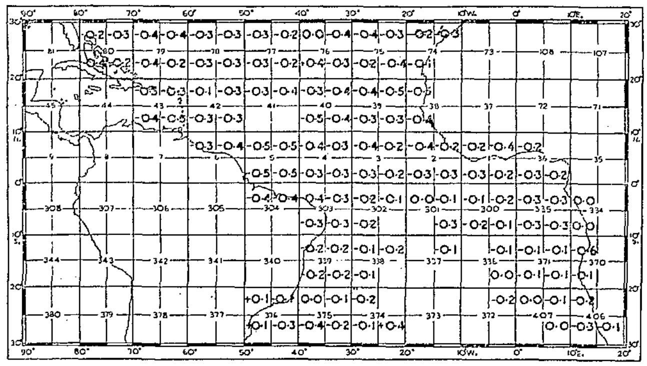

FIG. 18. Anomalies of sea-surface temperature (°C.) for decade 1910-19.

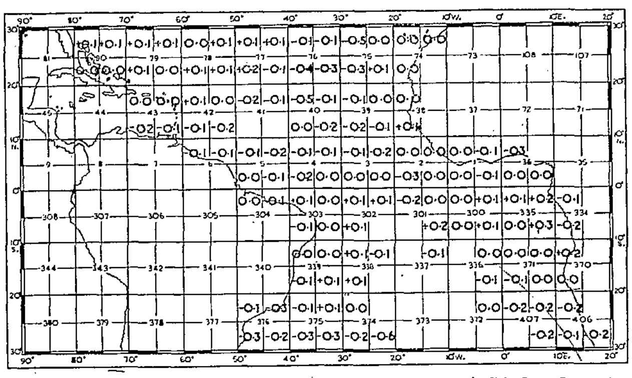

FIG. 19. Anomalies of sea-surface temperature (°C.) for decade 1920-29.

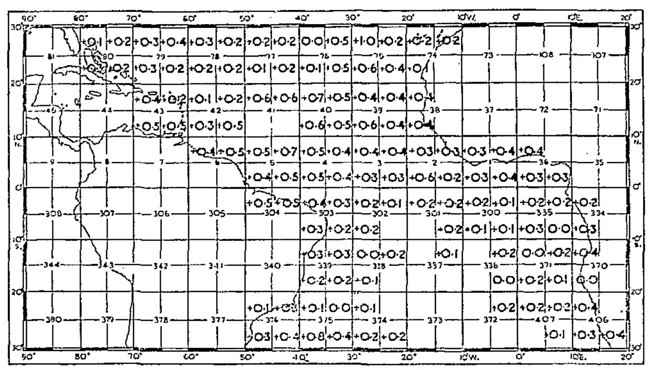

FIG. 20. Anomalies of sea-surface temperature (°C.) for decade 1930-39.

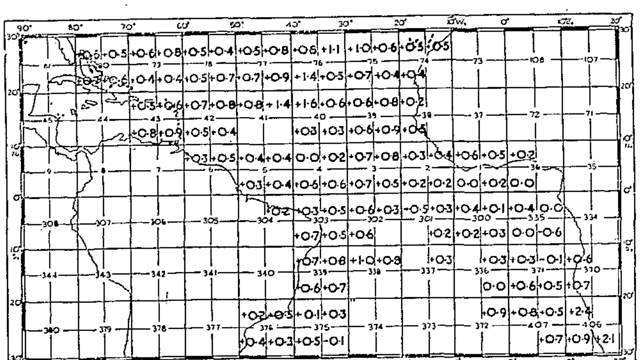

FIG. 21. Anomalies of sea-surface temperature (°C.) for decade 1940-49.

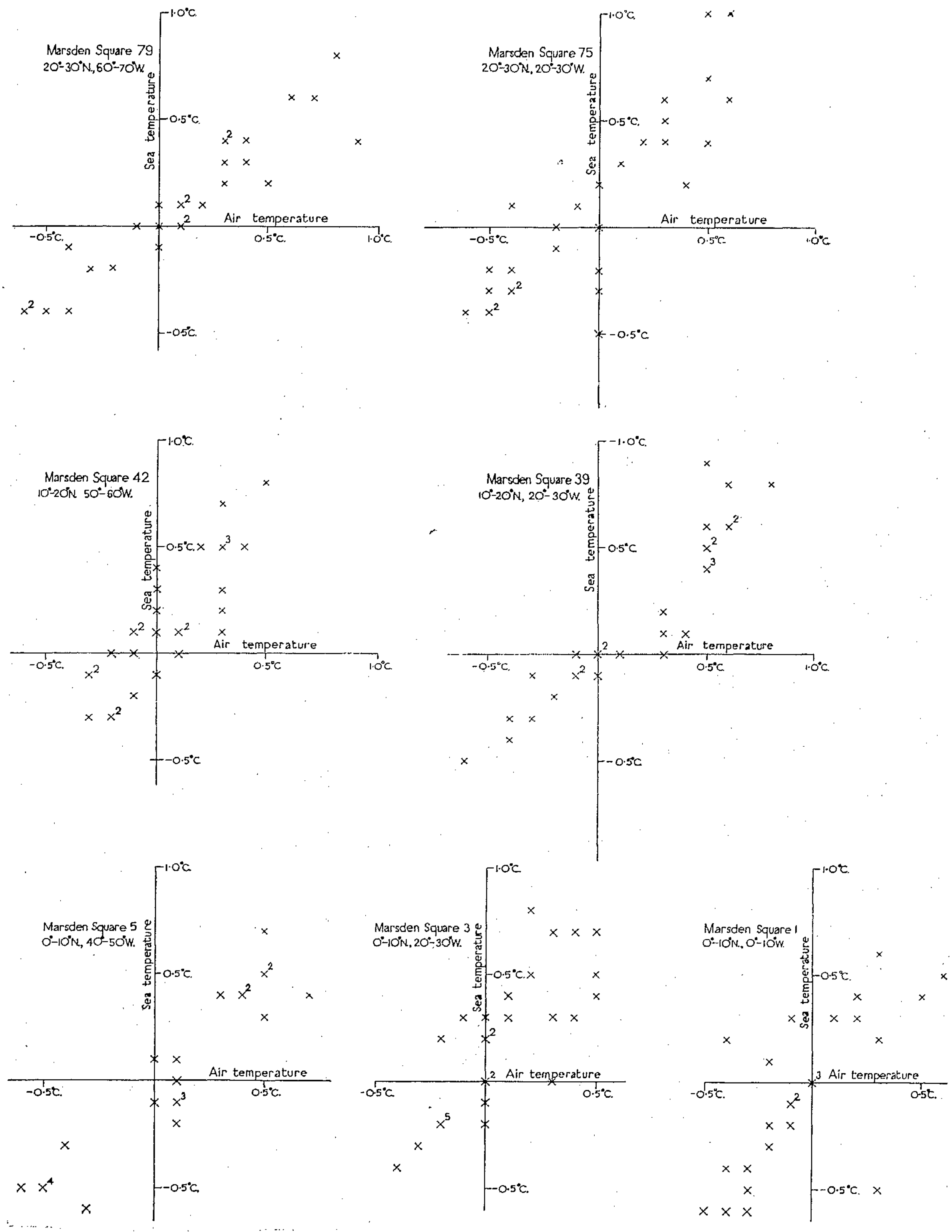

FIG. 22. Decadal anomalies of air temperature against decadal anomalies of sea temperature 0°-30° N.

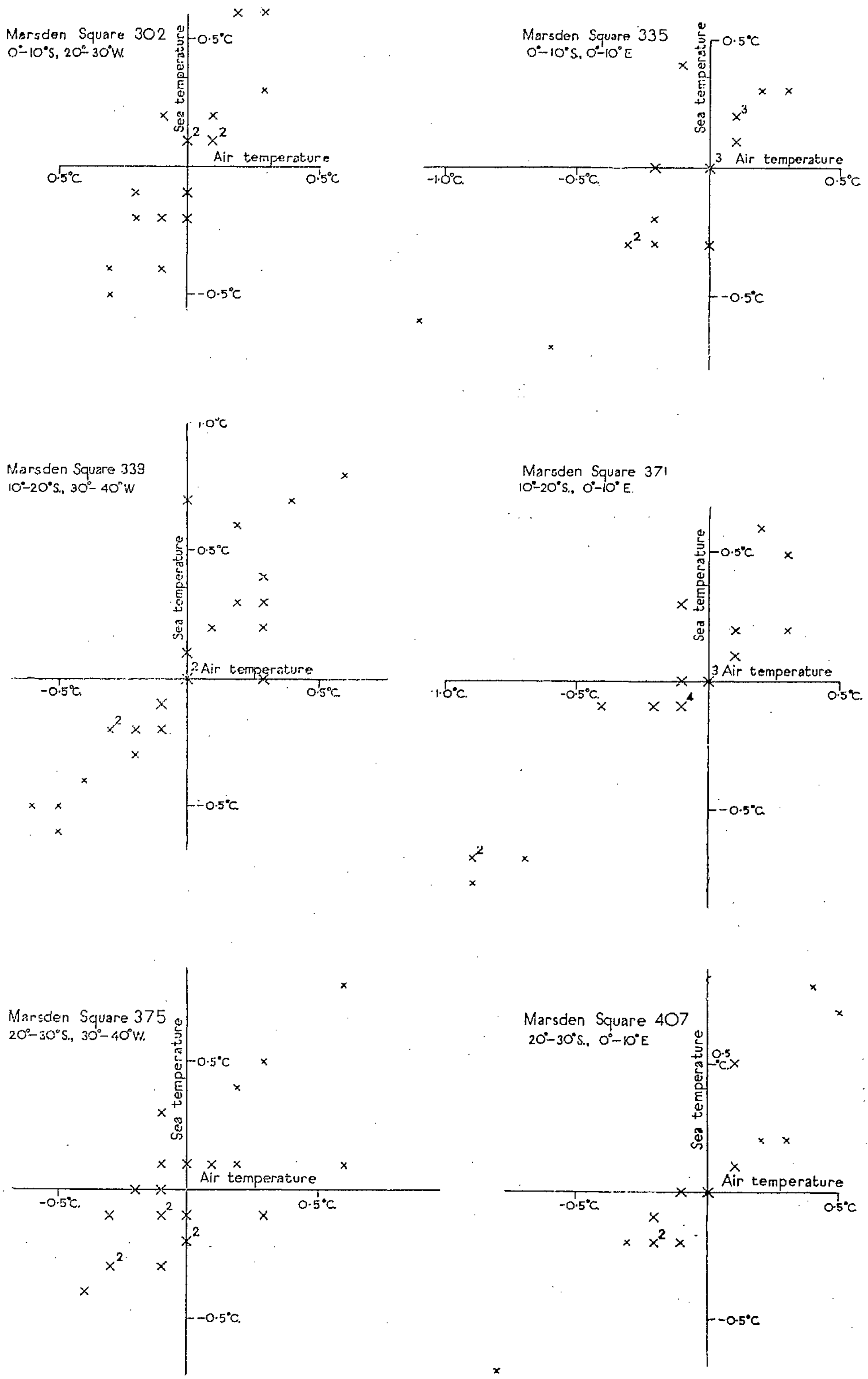

FIG. 23. Decadal anomalies of air temperature against decadal anomalies of sea temperature 0°-30° S.

The decadal anomalies of air temperature were plotted against the anomalies of sea temperature for Marsden squares 1, 3, 5, 39, 42, 75 and 77 in the Northern Hemisphere and squares 302, 335, 339, 371, 375 and 407 in the Southern Hemisphere. The plots for each of the 5° sub-squares are all shown on the diagrams for the 10° Marsden squares. The results for the Northern and Southern Hemispheres are shown in Figs. 22 and 23 respectively. Where there is more than one plot at a particular point the number of plots has been shown by a figure.

It will be seen from these diagrams that the slope of the regression line of sea temperature on air temperature tends to be greater in lower latitudes than in higher latitudes in both hemispheres, i.e., it tends to be greater in the bands of latitude 0°-10° than in the bands 20°-30°. This suggests that in the latitudes 10° S.-10° N., i.e., equatorial regions, the major direct cause of the climatic fluctuation of the surface air and sea temperatures is likely to be sea-surface temperature. One cause of the fluctuation of sea-surface temperature could well be the variation in the degree of upwelling of cold water.

CONCLUSION

There has been a marked increase of air and sea temperature during the present century in the Atlantic between 30° N. and 30° S. commencing over much of the area from 1910 to 1919, but the character of the fluctuations between 1880 and 1949 has varied considerably over the area.

RÉSUMÉ

Les fluctuations climatiques sur les océans et dans la partie tropicale de l'Atlantique (P. R. Brown)

I. Sur la base d'observations météorologiques faites de 1870 à 1949, à titre bénévole, par les navires, on a établi des moyennes décennales des températures de l'atmosphère et des eaux océaniques pour tous les « carrés » de 5° de côté compris entre le 60e et le 70e degré de latitude N.

Les résultats indiquent que, dans l'ensemble, les températures de l'atmosphère et des eaux océaniques dans la zone comprise entre le 60e et le 70e degré de latitude N. se sont élevées depuis le début du siècle jusqu'en 1930-1939. Certains donnent à penser que les températures auraient commencé à baisser au cours de la décennie 1940-1949, encore que celle-ci ait été plus chaude que celles du début du siècle, par exemple 1910-1919 (voir fig. 1). Les fluctuations des températures dans les régions océaniques orientale et occidentale sont d'une autre nature.

Les données recueillies par des navires ont également servi à établir des moyennes mensuelles et annuelles des températures de l'air et des eaux océaniques pour certains « carrés » (2° de latitude sur 5° de longitude) entre 1880 et 1959, période que couvraient ces observations. Différentes moyennes annuelles sont données dans les figures 2 et 3, et différentes moyennes mensuelles dans la figure 4.

II. Sur la base d'observations météorologiques faites à titre bénévole par des navires entre 1880 et 1949, il a été établi des moyennes décennales des températures de l'atmosphère et des eaux de l'Atlantique pour tous les « carrés » de 5° de côté compris entre le 30e degré de latitude N. et le 30e degré de latitude S. On montre que les chiffres ainsi obtenus peuvent être considérés comme d'une exactitude suffisante.

La nature des fluctuations observées n'est pas partout la même à l'intérieur de la zone considérée : elle se modifie progressivement d'une région à une autre. En gros, on peut distinguer trois types de fluctuations. Dans les régions situées au nord de l'équateur, on enregistre un refroidissement pendant les premières décennies, un minimum nettement marqué pendant la période 1910-1919, puis un relèvement des températures qui, par endroits, tendent à se stabiliser de 1940 à 1949. Dans la partie sud-ouest de la zone considérée, au sud du 5e degré de latitude S., une élévation constante de la température à partir de 1900-1909 fait place progressivement, à mesure que l'on descend vers le pôle, à des fluctuations assez désordonnées.

Enfin, dans la région sud-est, la température s'est, dans l'ensemble, réchauffée régulièrement jusqu'en 1930-1939 ou 1940-1949.

DISCUSSION

J. S. SAWYER. I wish to draw attention to the systematic trends shown by the sea temperatures in the equatorial Atlantic as shown by the graphs due to P. R. Brown and shown by Mr. Lamb. These trends based on five-year means are maintained over 10 years or more. This, taken with the larger amplitude in sea than air temperature, indicates that the sea temperature in the equatorial belt should be considered seriously as a factor outside the atmosphere which may lead to longer-term weather trends.

H. H. LAMB (speaking for P. R. BROWN). This is a point of considerable interest, which may for instance have been involved in the decreased rain yields from the equatorial system about the epoch of low temperatures in the tropical Atlantic from 1900 to 1930. Nevertheless the changes of sea-surface temperature may themselves depend on the atmospheric circulation—e.g., increased upwelling or increased equatorward transport of cooler surface water from other latitudes associated with the maximum strength of the trade winds about the dates mentioned.

E. KRAUS. What is the observational evidence and significance for a change of sea temperature in tropical latitudes?

H. H. LAMB (speaking for P. R. BROWN). The magnitude of the change since the minimum sea temperature around 1920 in the tropical Atlantic amounts to up to +0.5 to +1° C. in some squares. The reality is indicated by the large number of ships' observations contributing to the result: 2.2 million observations over the tropical latitudes alone between 1880 and 1949 and many of the individual squares gave results based on several thousand observations. These numbers have probably eliminated the effects of experimental error in the measurements.

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ON THE NATURE OF CERTAIN CLIMATIC EPOCHS WHICH DIFFERED FROM THE MODERN (1900-39) NORMAL

by

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INTRODUCTORY

Climatic changes during the last five or six thousand years appear, at some times, to have allowed sufficient vegetation for primitive men and animals to travel across what are now deserts in north Africa, central Asia and northern Mexico-south-western United States of America, and, at other times, to have cut off these routes of trade and migration. Within the last thousand years various categories of evidence suggest that there was, at first, rather little permanent ice on the Arctic seas and, later, such a great extension of this ice that grain growing was for centuries impossible in Iceland and the total evacuation of that country was considered; at the same time, the cod fishery almost disappeared even from the Faroe Islands. In the worst decades Scotland, as well as parts of Scandinavia and Iceland, experienced famine; upland farms and villages in England and Germany may have been abandoned partly for this reason.

The last hundred years, or rather more, have seen a significant warming over most of the world, particularly the Arctic. The limits of open water and of the cod fishery (cod population effectively checked by the 2° C. isotherm of water temperature), as well as those of very diverse biological species, have been displaced poleward in the Northern Hemisphere. Glaciers have shrunk. During about the same period, the levels of water bodies and the discharges of rivers in the lower latitudes (in both the arid and equatorial zones) have generally gone down materially, e.g., the Great Salt Lake of Utah, the Caspian Sea, the East African lakes and the Nile. Corresponding changes of mean annual rainfall have been reported, amounting in some places to 30-40 per cent; though India appears to have been more or less unaffected, and China and Japan show more complex variations (with rainfall minima about 1900 and 1940). Most of the trends ot the past hundred years have halted or show signs of reversal since 1940, though in China in 1960 extreme aridity was again reported.

HISTORICAL SURVEY

At least four climatic epochs since the Ice Age seem likely to repay more study by meteorologists than they have so far received: (*a*) the post-glacial climatic optimum (warm period culminating between about 5000 and 3000 B.C.); (*b*) the colder climatic epoch of the early Iron Age (culminating between about 900 and 450 B.C.); (*c*) the secondary climatic optimum in the early Middle Ages (broadly around A.D. 1000-1200 or rather longer); (*d*) the Little Ice Age (cold climate very marked between about A.D. 1430 and 1850).

The first step must be to build up knowledge of the world climatic patterns prevailing during these epochs. The following outlines can already be discerned:

POST-GLACIAL OPTIMUM. WARM EPOCH (CIRCA 5000 TO 3000 B.C.)

The distribution and general extent of land ice was probably not very materially different from now, and the world sea level similar to today.

The extent of ice on land, decreasing throughout the warm epoch, may have reached its minimum around 2000-1500 B.C.; i.e., after the main part of the warm epoch was over.

By soon after 4000 B.C. the world sea level had risen to about its present level (Godwin, Suggate and Willis, 1958), or possibly a few metres above (Brooks, 1949, p. 362; Fairbridge, 1961, p. 158). The rise over the previous 10-12,000 years from its minimum stand in the Ice Age can be primarily attributed to reduction of the ice sheets on land to somewhere near their present extent. Isostatic effects, however, altered the geography near the former ice sheets; there were extensive submerged lands and shallow seas for some thousands of years (see, for example, development of the Baltic and North Sea between about 8800 and 5000 B.C. in Zeuner, 1958, p. 50-3). Because of this, and because of rather higher ocean temperatures than now (1° C. in the tropical Atlantic (Emiliani, 1955) and probably several degrees in the Arctic (Brooks, 1949, p. 370), the present general sea level could have been attained at a time when the land ice was still slightly more extensive than now.

The Arctic Ocean, with much open water, was probably ice-free at least in summer, though not the channels of the Canadian Archipelago (Brooks, 1949, p. 143).

Fossil marine fauna (molluscs and edible mussels) and evidence of past vegetation and bog growth indicate much higher sea and air temperature than now quite generally in high latitudes north and south, e.g., at Spitsbergen (Brooks, 1949, p. 142, 362; Schwarzbach, 1959, p. 59, 153). Camel remains found in Alaska and tiger in the New Siberian Islands, approx. 75° N., are attributed to this period (Alissow, Drosdow and Rubinstein, 1956, p. 327) but probably imply temperate, not tropical conditions.

In the (present) temperate zone of the Northern Hemisphere temperatures were higher than now and there is evidence of a northward anomaly, especially before 5000-4000 B.C., of the atmospheric circulation.

The vegetation belts were displaced poleward and to greater heights above sea level than now. In Europe the summer temperatures can be estimated as prevailingly 2-3° C. higher than now (Schwarzbach, 1950, p. 153; Godwin, 1956), in North America rather less above present levels (Schwarzbach, 1961, p. 285). Winter temperatures, though possibly conditioned by anticyclones, can never have attained the severity now reached in air streams coming over the continents from the polar ice. The snow line was 300 metres above the present level in central Europe (Schwarzbach, 1961). Annual mean temperatures in Europe were about 2° C. higher than now (West, 1960). Since the fringe of the dry-climate landscape of the steppe reached Leningrad and the Volga Basin (Alissow *et al.*, 1956; see also Buchinsky, 1957, chapter 1), at least in the period up to about 4000 B.C., it seems safe to assume that the subpolar depressions and the axis of the main anticyclone belt were generally displaced north at that time in the European sector, perhaps by as much as 10° of latitude.

Later in the warm period there were considerable and long-lasting variations of rainfall, and it has been suggested that the climate of Europe became generally wetter after the development of an enlarged Baltic, perhaps as early as 5000 B.C. Depressions presumably tended to pass on more southerly tracks than formerly, gradually coming nearer to their present general latitudes. Milder, more oceanic winters would help maintain high annual mean temperatures.

In the Sahara and deserts of the Near East from about 5000-2400 B.C. there was an appreciably moister climate than now (Butzer, 1957, 1958).

The evidence, archaeological and zoological, is especially convincing as regards the early part of this period. Desiccation of the climate, possibly beginning well before 2400 B.C., might have a somewhat delayed effect because of the higher water table and presumably more extensive oases.

The high pressure belt presumed generally well north of the Mediterranean around 5000 B.C. and after. Africa and the Near East could come under the influence of broadened trade-wind and equatorial zones and more widespread summer (monsoon) rains. With this pattern winter rains in the latitude of the Mediterranean may also have occurred.

Gradually, the effects of the high pressure belt returning to lower latitudes seem to have been increasingly felt and, with increasing aridity in the region, by 3000 B.C. some of the animal migrations were cut off.

In Hawaii also the "climatic optimum" period gives evidence of greater rainfall than now in the (widened?) trade-wind zone.

In the southern temperate zone, a moister epoch, apparently rather warmer than now, was experienced though the temperature anomalies seem to have been less than in Europe. The evidence is largely from the extent and distribution of forest species in southernmost South America and New Zealand (Auer, 1958, 1960; Cranwell and von Post, 1936; Schwarzbach, 1950). Firm conclusions regarding the prevailing latitudes covered by the subtropical high pressure and west wind belts must await further work in other areas. (Work on the poor floras of the smaller islands in the southern temperate zone has, however, been able to throw no light on this matter, since no changes are apparent there.) It seems clear that in the earlier post-glacial period between about 7000 and 5000 B.C. Tierra del Fuego had had a rather dry, anticyclonic climate with prevailing west winds and limited forest extent on the west side only; New Zealand had a distribution more similar to that of today. During the warm-climate period which followed the forest spread in New Zealand warmth-loving species seem to have gained and wind directions appear to have been rather more variable than earlier (expanded equatoria and trade-wind zones?). The dates depend sufficiently on radio-carbon tests and can be confidently accepted for comparisons with the Northern Hemisphere (Auer, 1958).

Antarctica also experienced a warm period after the main Ice Age (when the Antarctic ice sheet had been several hundreds of metres thicker than now). Ahlmann (1944) tentatively, but doubtless rightly, identified this with the time of the post-glacial warm epoch in the northern and southern temperate zones.

The dating of the warmest epoch in the Antarctic as contemporaneous with that in the other climatic zones may be accepted as required by the results of radio-carbon dating of changes of world sea level (Godwin *et al.*, loc. cit.) and of the climatic changes in Tierra del Fuego, near 55° S.

In the Wohlthat Mountains, near 72° S.10° E., temperatures were so many degrees higher than now that there were considerable streams of running water and fluvial erosion of the landscape; between 600 and 1,890 metres above sea level lakes were formed which have subsequently frozen solid and remain as "fossils" (Ahlmann, 1944).

Flohn (1952, p. 171) estimates that annual temperatures in this epoch were 2°-3° C. higher than now in the Antarctic and in Tierra del Fuego and also on the Himalayan Mountains.

POST-GLACIAL CLIMATIC REVERTENCE. EARLY IRON AGE COLD EPOCH (CIRCA 900-450 B.C.)

Brooks (1949, p. 143) suggested that the sharp worsening of the climate of Europe, which came with floods and storms and advances of the Alpine glaciers between about 1400 and 500 B.C., following a much more gradual decline of temperature for centuries previously, implies and coincided with rather sudden re-formation of the "permanent" pack-ice cover on the Arctic Ocean north of 75°-80° N.

Regarding the recession in the temperate zone, most of the present glaciers in the Rocky Mountains south of 50° N. were formed about this time, certainly after 2000 B.C. (Matthes, 1939). In the Austrian Alps glaciers advanced to near the same limits which they regained, or more generally passed, around A.D. 1600 (Firbas and Losert, 1949). In Europe generally the most impressive feature is the evidence of a sharp increase of wetness.

There was a widespread re-growth of bogs after a much drier period (Godwin, 1954). This change ("recurrence surface" or *Grenzhorizont*) is still the most conspicious feature of peat bog sections all over northern Europe from Ireland to Germany and Scandinavia, represented by a change of colour from the black lower peat to the lighter upper layers. Lakeside dwellings in central Europe were flooded and abandoned (Brooks, 1949), and ancient tracks across the increasingly marshy lowlands in England and elsewhere in northern Europe were adapted to changed conditions or abandoned too (Godwin and Willis, 1959).

In Russia forest had spread farther south than in the warm epoch, advancing for instance along the lower Dnieper, and the species represented (beech, hornbeam, fir rather than oak) indicate some lowering of the summer temperatures. It is not clear whether any important dry period occurred in Russia, as it did farther west in Europe, between the end of the warmest epoch and the sharper Iron Age recession (Buchinsky, 1957).

In the Mediterranean and North Africa the climate seems to have been drier than during the climatic optimum, but not so dry as today. Rainfall was apparently not quite so rare as now in summer. Roman agricultural writers (e.g., Saserna) noted that around 100 B.C. the vine and the olive were spreading north in Italy to districts where the weather was formerly too severe: from this it would appear that the preceding centuries had had a cooler climate also in the Mediterranean.

The southern temperate and Antarctic zones had also entered a colder period by around 500-300 B.C. In southern New Zealand the evidence is consistent with prevailing westerly winds, but in Tierra del Fuego spread of the forest to cover the whole island on both sides of the watershed indicates quite frequent easterly winds and hence depression tracks on the whole in lower latitudes than now (Auer, 1960; Cranwell and von Post, 1936).

SECONDARY CLIMATIC OPTIMUM (CIRCA A.D. 1000 TO 1200)

This epoch appears to show most of the same characteristics as the post-glacial epoch both in the Northern Hemisphere and in the Antarctic, only in less degree, perhaps because of its shorter duration.

The Arctic pack ice had melted so far back that appearances of drift ice in waters near Iceland and Greenland south of 70° N. were rare in the 800s and 900s and apparently unknown between 1020 and 1200, when a rapid increase of frequency began. This evidence hardly supports Brooks' suggestion that the Arctic Ocean again became ice-free during this epoch, though "permanent" ice was probably limited to inner Arctic areas north of 80° N. and possibly not including the Canadian Archipelago (to judge from occasional exploits there by the Old Norse Greenland colonist).[1] From the evidence of early Norse burials and plant roots in ground now permanently frozen in southern Greenland, annual mean temperatures there must have been 2°-4° C. above present values. It seems probable that sea temperatures in the northernmost Atlantic were up by a similar amount.

In western and middle Europe vineyards extended generally 4°-5° latitude farther north and 100-200 metres higher above sea level than at present (Lamb, 1959). Estimates of the upper limits of the forests and of tree species on the Alps and more northern hills in central Europe range from 70 to 200 metres above where they now stand (Gams, 1937; Firbas and Losert, 1949). These figures suggest mean summer temperatures about 1° C., or a little more, above those now normal.

In North America archaeological studies in the upper Missisippi valley (approx. 45° N.) suggest a warm dry epoch, followed by a change to cooler, wetter conditions after A.D. 1300 (Griffin, 1961).

1. Glaciological and other studies of Arctic ice islands, and their presumed growth when formerly part of the Ellesmere Land ice shelf, have not so far been reduced to an agreed time scale (Crary, 1960, p. 34; Stoiber *et al.*, 1960, p. 71). It seems most probable, however, that the ablation period in progress in the early 1950s began only about 40 years ago and that the total age of the ice is 620 years or less, implying growth during the Little Ice Age epoch and that net ablation prevailed before that, during the secondary climatic epoch, in the Canadian Archipelago.

In lower latitudes Brooks (1949, p. 327, 355) names this as a wet period in central America (Yucatan) and probably in Indo-China (Cambodia). There is evidence of greater rainfall and larger rivers in the Mediterranean and the Near East (Butzer, 1958, p. 12). There is some evidence of a moister period in the Sahara from 1200 or earlier, lasting until 1550 (Brooks, 1949, pp. 330-8).

In southernmost South America the forest was receding rapidly to western aspects only, indicating a drier climate than in the previous epoch and more predominant westerly winds.

On the coast of east Antarctica, at Cape Hallett, a great modern penguin rookery appears from radiocarbon tests to have been first colonized between about A.D. 400 and 700, presumably during a phase of improving climate, and to have been occupied ever since (Harrington and McKellar, 1958). This tends to confirm the earlier assumption of explorers of the Bunger Oasis in east Antarctica of a period of marked climatic improvement about a thousand years ago, since which there has been only a modest reversion.

THE LITTLE ICE AGE (CIRCA A.D. 1430-1850)

There is manifold evidence of a colder climate than now from most parts of the Northern Hemisphere.

The Arctic pack ice underwent a great expansion, especially affecting Greenland and Iceland, and by 1780-1820 sea temperatures in the North Atlantic everywhere north of 50° N. appear to have been 1°-3° C. below present values (Lamb and Johnson, 1959). Indirect evidence suggests that these (or even slightly lower) water temperatures were already reached by the 1600s.

Decline of the forests at the higher levels in central Europe between about 1300 and 1600 evidently had some catastrophic stages, especially after 1500, and Firbas and Losert (1949) believe this may have been the time of principal change of vegetation character at levels above 1,000 metres since the post-glacial climatic optimum. (In Iceland the relict woodland surviving from the climatic optimum virtually disappeared early in this epoch, doubtless partly by human agency.) Also near the Atlantic coast of Scotland eye-witness reports of the time (Cromertie, 1712) suggest widespread dying off of woods in the more exposed localities, presumably because of miserable summers and increased damage from salt-spray. In Europe around 50° N. it seems, however, that the prevailing summer temperatures were mostly about their present level (in the 1700s slightly above), though the winters were generally more severe.

Some notably severe winters also affected the Mediterranean. Glaciers advanced generally in Europe and Asia Minor, as well as in North America, and snow lay for months on the high mountains in Ethiopia where it is now unknown.

The Caspian Sea rose and maintained a high level until 1800. Records of the behaviour of the Nile suggest that this was a time of abundant precipitation in Ethiopia but very low levels of the White Nile, which is fed by rainfall in the equatorial belt: the equatorial rains were evidently either weak or displaced south.

The evidence generally points to an equatorward shift of the prevailing depression tracks in the Northern Hemisphere and more prominent polar anticyclones.

The Southern Hemisphere seems largely to have escaped this cold epoch until 1800 or after, though by then temperatures were possibly somewhat lower than today in some parts of the southern temperate zone. Between 1760 and 1830 the fringe of the Antarctic sea ice appears to have been generally a little south of its present position and the southern temperate rain-belt apparently also displaced south.

Recession followed after 1800-30 until 1900 or later. The rain zone and depression tracks moved north and there were great advances of the glaciers in the Andes and South Georgia, as well as some extraordinarily bad years for sea ice on the southern oceans (Aurrousseau, 1958; Findlay, 1884). This recession in the southern temperate and sub-Antarctic zones was, however, out of phase with the trend by then going on in the Northern Hemisphere. Since 1900 the temperature of the southern temperate zone as a whole may have been rising like that of other zones (Callendar, 1961); in the sub-Antarctic the rising trend began even later and may be out of phase with the latest trend in the Northern Hemisphere (Willett, 1950; Murray Mitchell, 1961).

SUMMARY OF THE HISTORICAL SURVEY

The first three epochs appear to demonstrate respectively: (*a*) climatic zones displaced towards high latitudes, equatorial/monsoon rain belt widened; (*b*) climatic zones displaced towards low latitudes, equatorial belt narrowed; (*c*) as (*a*) but in less degree.

These variations fit with the sequence of contractions and expansions of the circumpolar vortex proposed by Willett (1949), with minor modifications of date and extra detail thanks to recent additions to knowledge.

The last epoch appears to present a different pattern, with an equatorward shift of the climatic zones in the Northern Hemisphere accompanying a (probably smaller) poleward shift in the Southern Hemisphere, followed by return movements in both hemispheres during the nineteenth century.

Climatic fluctuations in the present equatorial, arid, temperate and polar zones have been such as accord with these changes.

The amplitude of the temperature fluctuations appears to have been much greatest in high latitudes, so that the meridional gradient of surface temperature, at least between 50° and 70° N. must have been materially less in the warm epochs than in the cold ones. It appears, however, that the temperatures on mountains even in low latitudes were raised 2°-3° C. in the warm epochs[1] and lowered by 1°-2° C. below present values during the Little Ice Age. This means that the possibility remains that the meridional (Equator-Pole) gradient of upper air temperature was actually less during the cold epochs, the surface temperatures in high latitudes being particularly unrepresentative at such times because of frequent strong inversions (Lamb and Johnson, loc. cit.).

Climatic trends in the Far East bear a rather complicated and partly inverse relationship to those elsewhere e.g., evidence of generally late cool springs in Japan A.D. 1000-1200, milder winters between about 1700 and 1900 than before or since (Arakawa, 1956, 1957; Lamb and Johnson, loc. cit.)]. From study of variations within the last two centuries Yamamoto (1956) describes how this inverse relationship tends to come about: (*a*) during periods of strengthened zonal circulation of the atmosphere (strengthened Siberian anticyclone and weak polar anticyclone in the Asian sector) Japan experiences more cold air from the continental interior in winter (and some Arctic outbreaks in the rear of depressions); (*b*) during periods of weaker zonal circulation (Siberian anticyclones weaker or displaced north-west, polar anticyclones covering more of northern Asia) the main cold air mass in winter streams west over central Asia towards Europe, and Japan comes more under the influence of Pacific anticyclones and mild oceanic air. However, farther north, the Okhotsk Sea develops more ice at such times, under the influence of the polar anticyclones, and this produces a tendency for poor summers in Japan.

Superimposed upon, and running through, the bold climatic phases and trends here defined many workers have found evidence of apparent periodic oscillations, particularly affecting rainfall but presumably also affecting the latitudes of the most frequent depression tracks over Europe and Asia.

A periodicity of 180-200 years has been suggested by variations in the Baltic ice and levels of the Caspian Sea (Betin, 1957), one of 400 years from Chinese data (Link and Linkova, 1959), one of about 600 years from recurrent regeneration layers ("Recurrence surfaces" or *Grenzhorizonte*) in the peat bogs in many parts of temperate Europe and a periodicity of 1,700-2,000 years from variations in the rivers, lakes and inland seas in European Russia and in central Asia.

There seems no doubt, however, that the four epochs described earlier are those which represent the greatest departures from present day conditions. If periodic variations of any agency influencing the Earth and its atmosphere be involved, it nevertheless seems that in these epochs some special conjunction of circumstances —possibly including external circumstances such as volcanic dust—must have come into play.

It may be significant that the two cold epochs more or less coincide with III and IV of the post-glacial world-wide waves of volcanic activity (I-IV) identified by Auer (1958, p. 229; 1959, p. 208). Radio-carbon dates of these volcanic phases are: I — around 7000 B.C. II — 3000-250 B.C.; III — around 500-0 B.C.; IV — around A.D. 1500-1800. Moreover III was marked by volcanic activity over both hemispheres, e.g., Kamchatka, Iceland, Andes and Tristan da Cunha (see also Thorarinsson *et al.*, 1959); whereas IV seems to have been largely in the Northern Hemisphere and equatorial zones, apart from the Southern Hemisphere eruptions of 1835 and certain later years. Thus the different climatic distributions deduced for these epochs correspond well with a difference that may reasonably be presumed in the geographical distribution of dust veils in the high atmosphere.

METEOROLOGICAL INVESTIGATIONS OF CHANGES IN THE GENERAL ATMOSPHERIC CIRCULATION

BY SURFACE PRESSURE MAPS BACK TO 1750

Monthly m.s.l. pressure charts have been constructed in the British Meteorological Office, covering as much of the world as possible, for each January and each July back to the earliest years for which usable observation data could be found. The internal consistency checks provided by a network of observing stations, some in each area having long series of observations, have made it possible, after tests for probable error of the isobars, to reconstruct the pressure field for a worthwhile area of Europe back to 1750. Pressure distribution over the North Atlantic Ocean from as early as 1790 can be established within a tolerable error margin (standard error ±2.5 mb. in January, ±1.0 mb. in July) by using 40-year means. The method, sources of data and tests used have been published elsewhere (Lamb and Johnson, 1959).

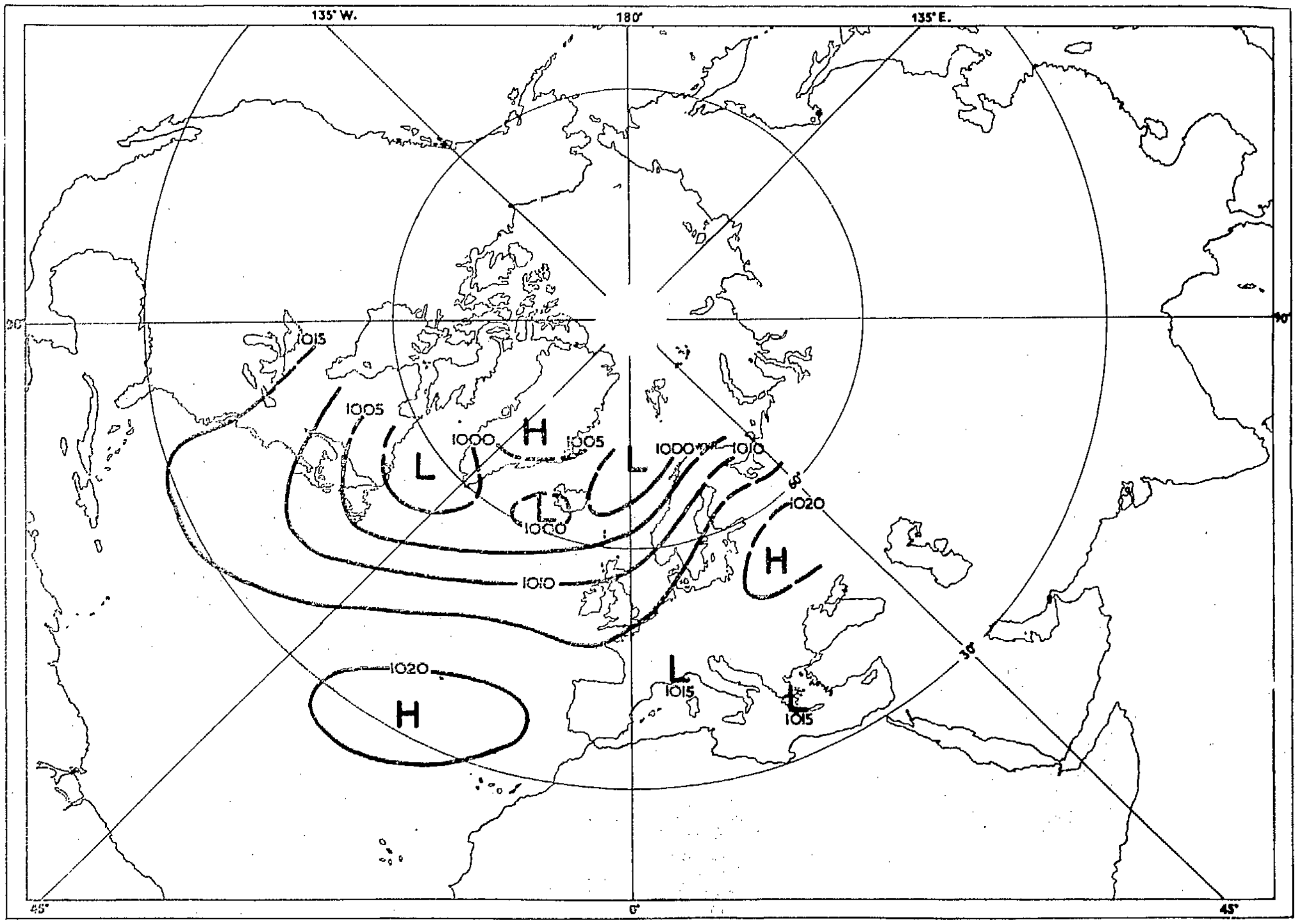
Fig. 1 and 2 show the 40-year average m.s.l. pressure in January and July respectively for the earliest possible period over the Atlantic Ocean (1790-1829) compared with the modern normal charts based upon the *Historical Daily Weather Maps* (1900-39). Solid lines are used for the isobars where the pressure values can be regarded as known within the error margins mentioned above, broken lines are used where the general pattern of the pressure field is reasonably certain but the values are not good enough for useful measurements to be based upon them.

January

Average pressure gradients have increased in January from the period around 1800 to the present century [cf. Fig. 1 (*a*) and (*b*)].

1. From Himalayan evidence, quoted by Flohn (1952). Evidence from other regions desirable.

1a



1b

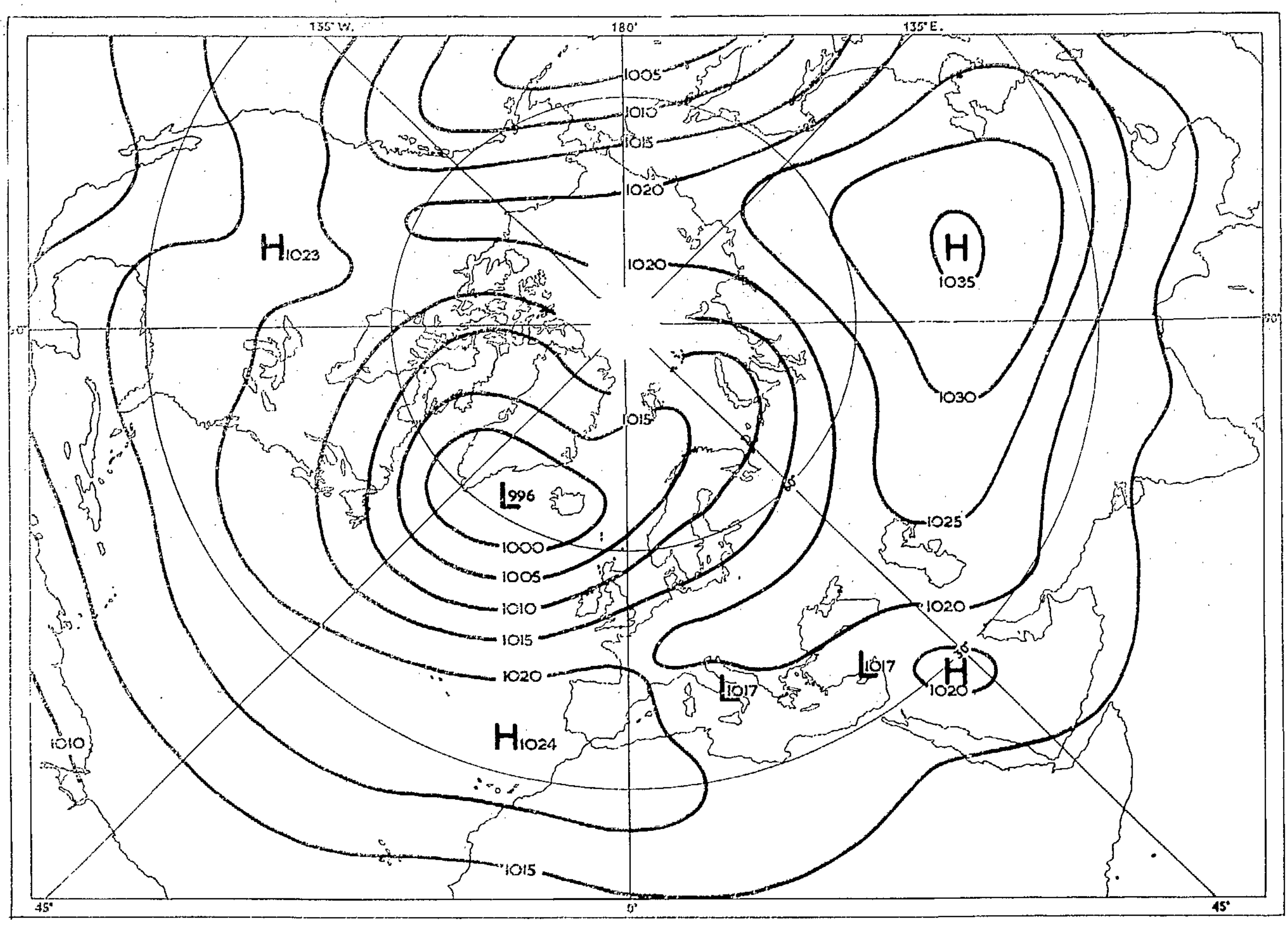
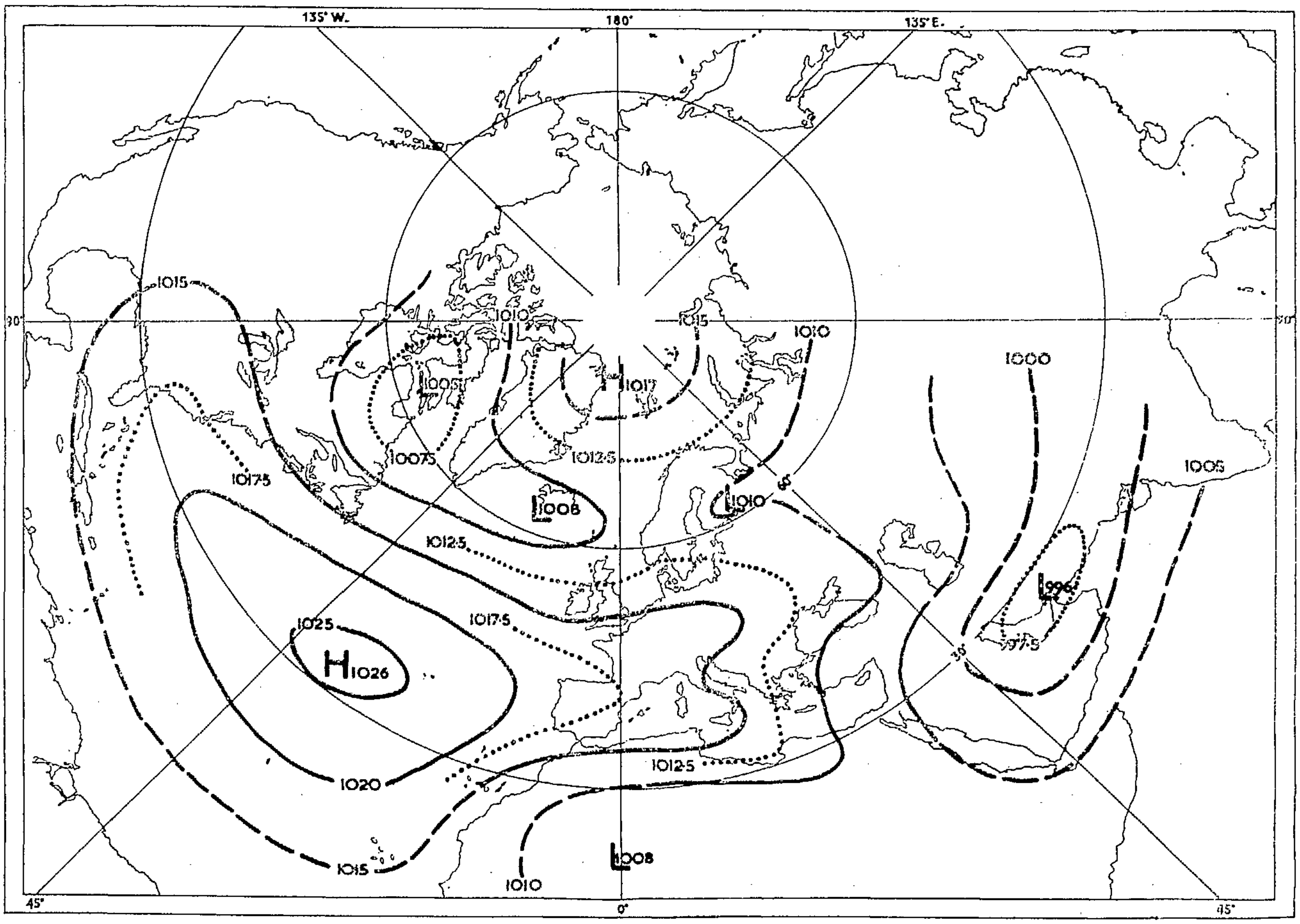


FIG. 1. Average m.s.l. pressure for January : (*a*) 1790-1829 ; (*b*) 1900-39.

2a



2b

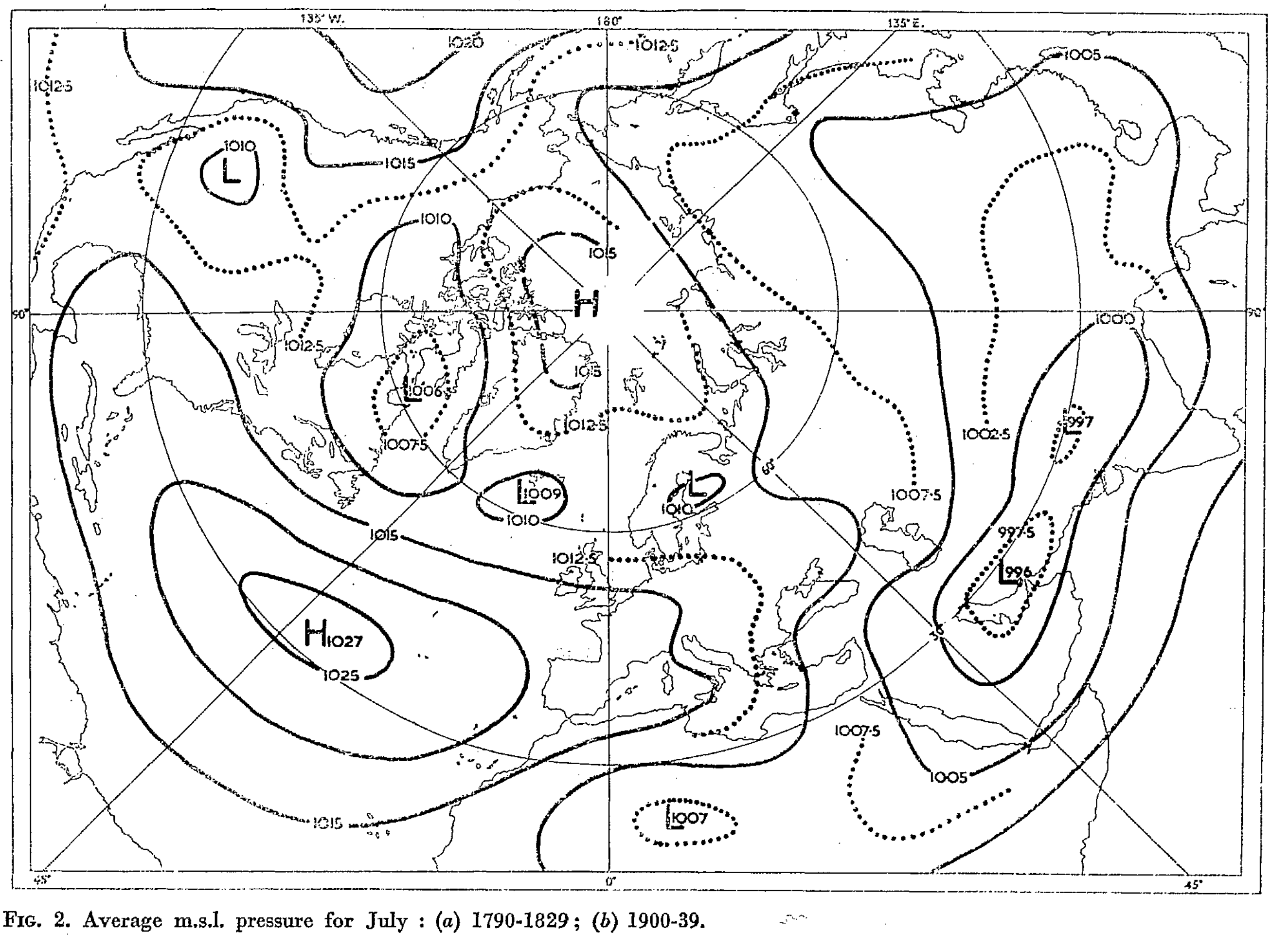


FIG. 2. Average m.s.l. pressure for July : (a) 1790-1829 ; (b) 1900-39.

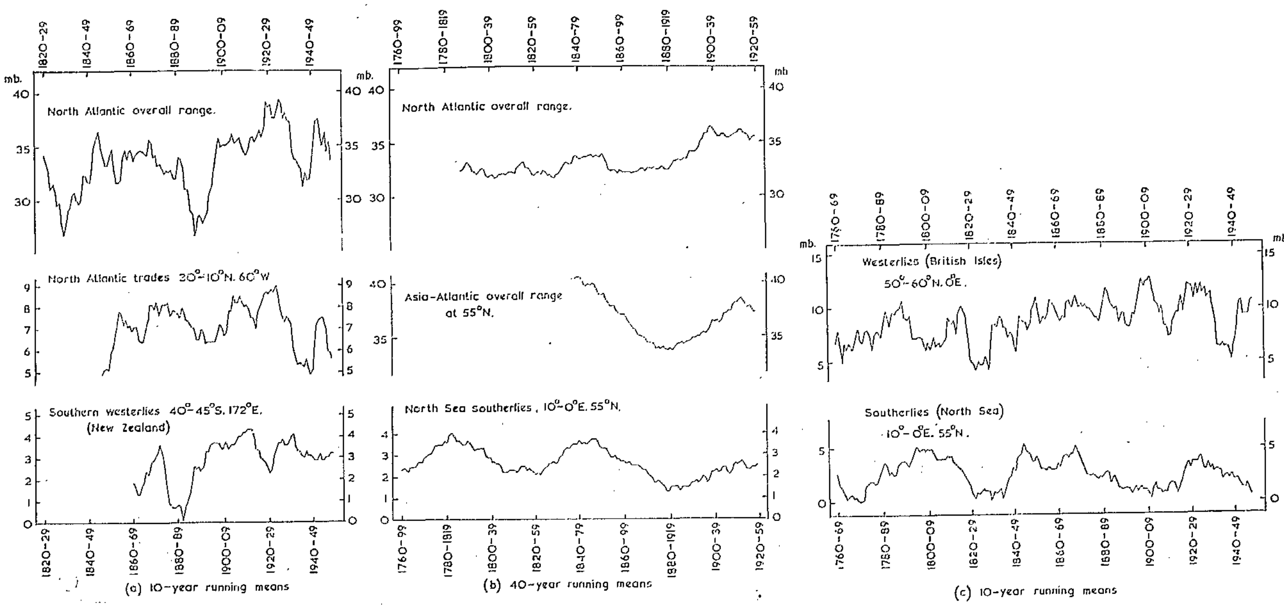


FIG. 3. Pressure difference indices of circulation intensity in January.

In Fig. 3 a limited selection of pressure difference indices of circulation intensity in January are presented. From these, and others not shown, it is seen that the increase of intensity of the zonal circulation since the middle or earlier part of the nineteenth century is a world-wide phenomenon, affecting at least the westerlies and trade-wind zone in the North Atlantic and the southern westerlies. The peak intensity of the zonal circulation so far was reached about 1930 in the North Atlantic and 1910 in the Southern Hemisphere. Over the North Atlantic the increase of the zonal circulation from around 1800 to 1930 appears to amount to 5-10 per cent. Changes in the extent of Arctic ice (for which the North Atlantic is virtually the only outlet) appear, however, to amplify circulation changes in this sector.

It is an advantage of the map method that indices of circulation vigour can be measured at points where the main air streams are best and most regularly developed. Comparison of numerous correlation coefficients between measures of the same air stream taken at different points have demonstrated that such indices are the most representative (Lamb and Johnson, 1959). The Northern Hemisphere indices in Fig. 3 have been chosen in this way, but, for the earliest years, and in the Southern Hemisphere, it is still necessary to make measurements only near where there happen to be observing stations. The monthly mean pressure gradient between 50° and 60° N. for westerlies over the British Isles, used in Fig. 3 (*c*) to cover a longer period than any of the indices in Fig. 3 (*a*) or (*b*), is an index linked with the overall pressure range between Azores maximum and Iceland minimum in January by a correlation coefficient of about +0.6 (1800-79, +0.62; 1880-1958, +0.56—both statistically significant beyond the 0.1 per cent level). It is reproduced here because it shows the increase of vigour of the westerlies from a generally lower level in the eighteenth century.

The period around 1790-1830 was evidently one of rather notable minimum strength of the zonal circulation in January, though there had been another minimum earlier, probably before 1750.

The variations in the mean strength of the North Atlantic westerlies nicely parallel the changes of mean January temperature in Britain and central Europe. The mean January temperature of central England (Manley, 1953) between about 1740 and 1850, was for instance, over 1.5° C. lower than between 1900 and 1940. Since this type of temperature trend is typical for the colder half of the year, it is reasonable to suppose that other months have also partaken in the change of strength of the North Atlantic westerlies.

The mean meridional component, which is much weaker than the mean zonal component, of the circulation (meridional component measured by pressure differences along 55° N.) does not appear to have shared the increasing trend of the zonal circulation in January, but seems rather to show a long-term fluctuation with a possible period of around 60 to 70 years.

The importance of considering the meridional circulation and the zonal circulation separately in connexion with the recent warming of the Arctic has been further demonstrated by Petterssen (1949) and by Wallén (1950, 1953) who discovered that between 1890 and 1950 the frequency of northerly meridional situations decreased and that of southerly meridional situations increased markedly in the region of the Norwegian Sea and

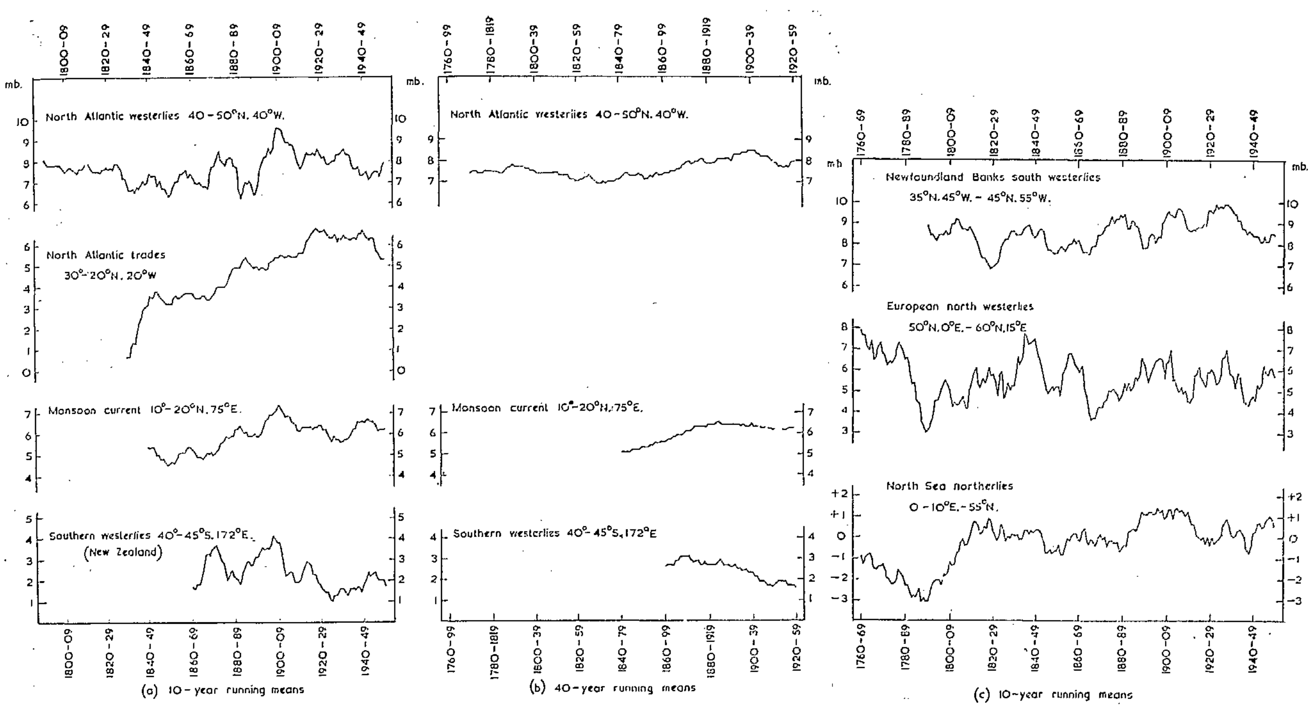


FIG. 4. Pressure difference indices of circulation intensity in July.

Scandinavia; since 1950 northerly meridional situations have once more become prominent. This discovery might be related to changes of wave-length (and displacement of the preferred positions for troughs and ridges) in the upper westerlies of which we shall give further evidence later.

Variations of the meridional component of the circulation, especially the winter southerlies over the North Sea, must be linked in some way with the occurrence of blocking anticylones, which is also subject to variations possibly with periods of 60-90 years. Since no persistent trend is found in the meridional component, the generally colder winters of the period around 1800 and earlier are mostly to be explained by weakness of the mean westerly flow towards Europe rather than by blocking, which was only really prominent at long intervals both in the epochs of weak and of stronger westerlies.

July

Changes in the July circulation from 1790-1829 to 1900-39 (Fig. 2) are much less obvious than those in January, though Europe seems to have had a weaker and more anticyclonic pressure field in the earlier period.

The changes are better seen from the trends of the intensity indices shown in Fig. 4. (Following the principle of measuring pressure gradients where the main air streams are best and most regularly developed, the most representative indices of the July circulation are not found at the same points as those used for January.) The general nature of these curves is an increase of intensity from low values around the middle of the nineteenth century to high values in the twentieth century. A major peak intensity of such indices generally seems to have been passed between 1900 and 1950—mostly in the decades 1900-09 or 1920-39—but again appears earlier in the Southern Hemisphere around 1890-1920 (1897-1906 New Zealand, 1908-17 Chile).

The rather stronger July circulation in the Northern Hemisphere before 1800-50 seems to have shown different patterns from those prevailing in the present century. Hints of rather lower pressure in the Labrador region (east of the North American cold trough) and of higher pressure over central and northern Europe are developments that might be expected to accompany the persistence of a cold surface (with some permafrost and remnants of ice and snow) in somewhat lower latitudes than now occurs.

The mean meridional components of the circulation, illustrated in Fig. 4 (*c*) by the pressure difference between 0° and 10° E. at 55° N. (northerly wind component over the North Sea), in July appear to show a rising trend. This is apparent also over the China Sea and is probably involved in the increasing gradient for south-westerly winds over the Newfoundland Banks [Fig. 4 (*c*)]. The North Sea index rises from the 1790s to the present century; if there are any real oscillations superimposed, the period seems to be 70-90 years—between peaks around 1820 and 1900 and between minima in the

1780-90s, the 1850s and 1940s—and the rising trend may be still continuing.

Summary

Increases of strength of the zonal circulation have been found in January and July over widely separated parts of the globe, apparently being quite general from around the middle of the last century and culminating around 1930 in the Northern Hemisphere and 1900-10 in the Southern Hemisphere. The trend of some indices suggests that an overall increase of energy may have been going on since well before 1850 in July as well as January. Possibly the rather stronger summer circulation over the North Atlantic and neighbouring longitudes in the late 1700s than in the mid-1880s should be regarded as a local difference associated with the presence of some persistent snow and ice in rather lower latitudes before, say, 1830 than at any time since. Increased strength of the general circulation has probably occurred in most months of the year. The increase from *circa* 1800 to 1930 in the strength of the zonal circulation over the North Atlantic in January amounts to between 5 and 10 per cent, but in general is probably less than this.

A general rise in the winter temperatures in Europe accompanied the increased vigour and prevalence of the westerlies. Summer temperatures showed a much smaller, and not statistically significant, fall.

Changes of average latitude of the main zones of the atmospheric circulation have also been studied. They seem to show a general equatorward displacement, especially of the sub-polar depression track, in winter and summer, by 2-4° of latitude in those periods and regions where sea ice has attained an abnormally great extent—e.g., around 1800 in the North Atlantic and around 1900 near Chile. A progressive equatorward trend of the northern and southern high pressure belts in the Atlantic sector in January during the present century is so far unexplained.[1]

A tendency for increased ice on the Arctic seas in this sector since about 1940 may be a consequence of this. In July the trend seems to have been the other way till about 1930. Over the Indian Ocean and Australian sectors of the Southern Hemisphere the main pressure belts have all moved 2°-4° south in January and north in July during the present century,[2] displacements whose trend seems to follow that of the intensity of the (monsoon) pressure gradients developed over Asia, especially the winter northerlies and summer southerlies over eastern Asia, passing its extreme point and reversing broadly around 1930.

AN IMPORTANT AND SEVERE STAGE IN THE CLIMATIC CHANGE SINCE 1800

Regarding the recent period of climatic recovery from the Little Ice Age and strengthening atmospheric circulation, with warming of most latitude zones and increasing aridity in the desert zone (see Butzer, 1957*b*), the particularly strong Northern Hemisphere circulation of the 1920s and 1930s and of the decade 1900-09, at least as regards the sector between North America and Europe, has already attracted the attention of meteorologists (see Wagner, 1940; Scherhag, 1950; Lamb and Johnson, 1959). The peculiar characteristics of the 1830s do not, however, seem to have received notice, perhaps because it has not previously been possible to present circulation maps. The mean pressure distributions for January and July for each decade since 1750 can now be presented and those for 1830-39 are shown here in Fig. 5.

This decade stands out from the series 1750 to date in several respects:

1. Highest pressure generally over Europe and the Mediterranean.
2. Most northerly position of the high pressure belt in this sector.
3. Lowest pressure in Gibraltar, evidently with easterly winds and probably a still greater low pressure anomaly to the south and south-west.
4. Very high temperatures at Gibraltar (unhomogenized series but positive anomalies of 2°-4° C. in both winter and summer months appear common in the 1830s).
5. Fragmentary reports of an abnormal climatic régime at Madeira, tending to warmth and summer drought, and at Malta, where the persistent (summer and winter) drought raised public alarm, particularly between 1838 and 1841—incidentally leading to the institution of regular rainfall measurements.

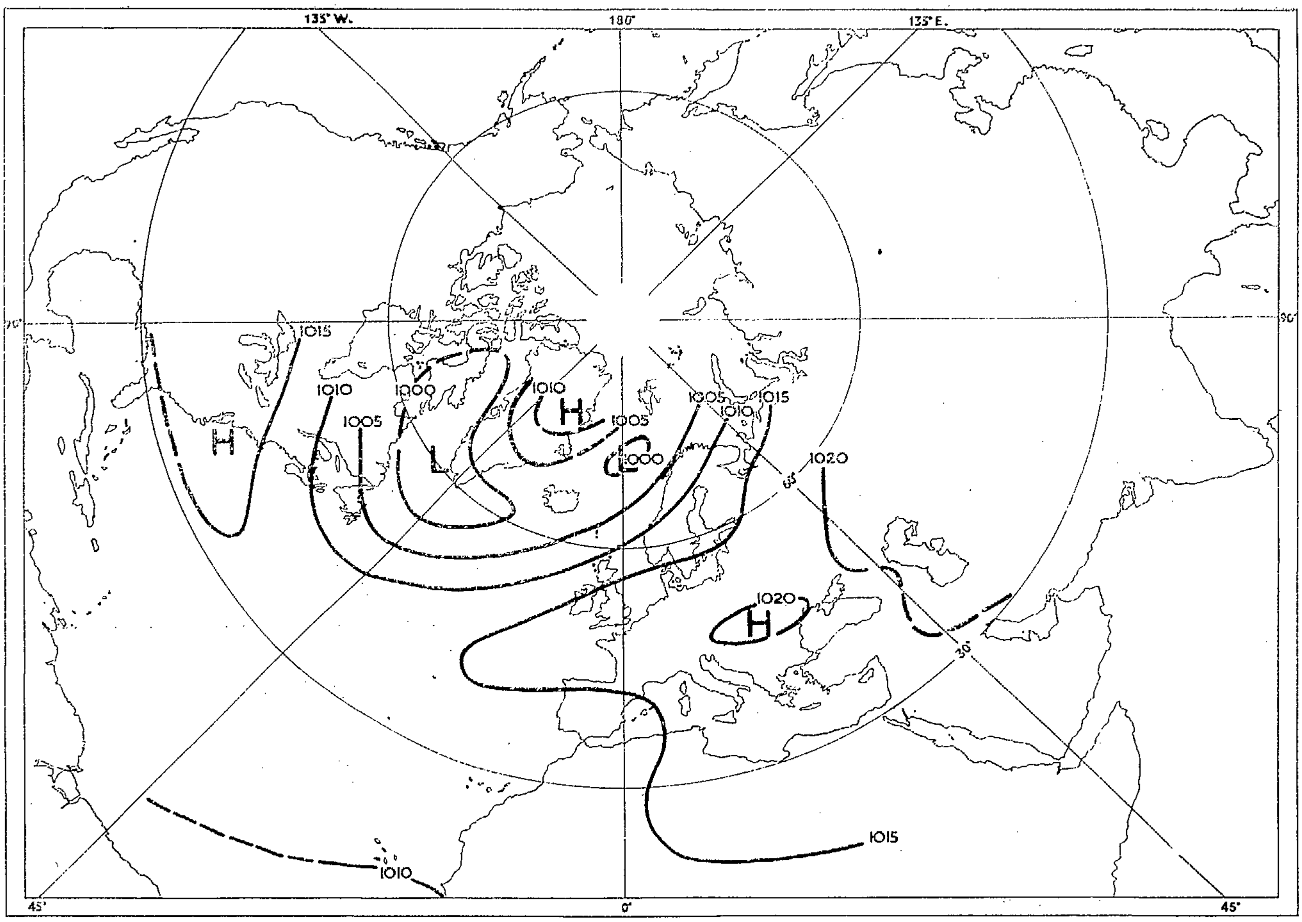
It would probably be worth while to devote effort to establishing fuller information about the climate (and displacements of the normal climatic zones) during this period, particularly over North Africa and perhaps generally over as much of the world as possible.

At present, it seems relevant to point to the following circumstances:

1. A general upward trend of intensity of the zonal circulation was probably already well under way, and may have been so since before 1750 [see British Isles curve in Fig. 3 (*c*)]. This is also suggested by a study of the North Atlantic trade winds from 1827 onwards, using ships' logs, by Privett and Francis (1959): it appears, moreover, that the 1830s were a decade of strong trades, somewhat above the smoothed trend.
2. The 1830s more or less coincided with pronounced peaks in summer and winter (1820-33 and 1838 in

1. Willett (1961) has lately reported on an index of solar activity which shows a highly significant negative correlation with the latitude (but no relation with the intensity) of the strongest upper westerlies across North America in January over the period 1900-60. A smaller negative correlation coefficient between relative sun-spot number and the latitude of the westerlies was also obtained. Hence the extremely disturbed sun in recent sun-spot cycles may have some bearing on this equatorward trend of the pressure and wind zones in the North Atlantic.
2. The January trend affecting summer rainfall in Australia was first reported by Kraus (1954), who does not, however, seem to have been aware of the reverse tendency in the southern winter.

5a



5b

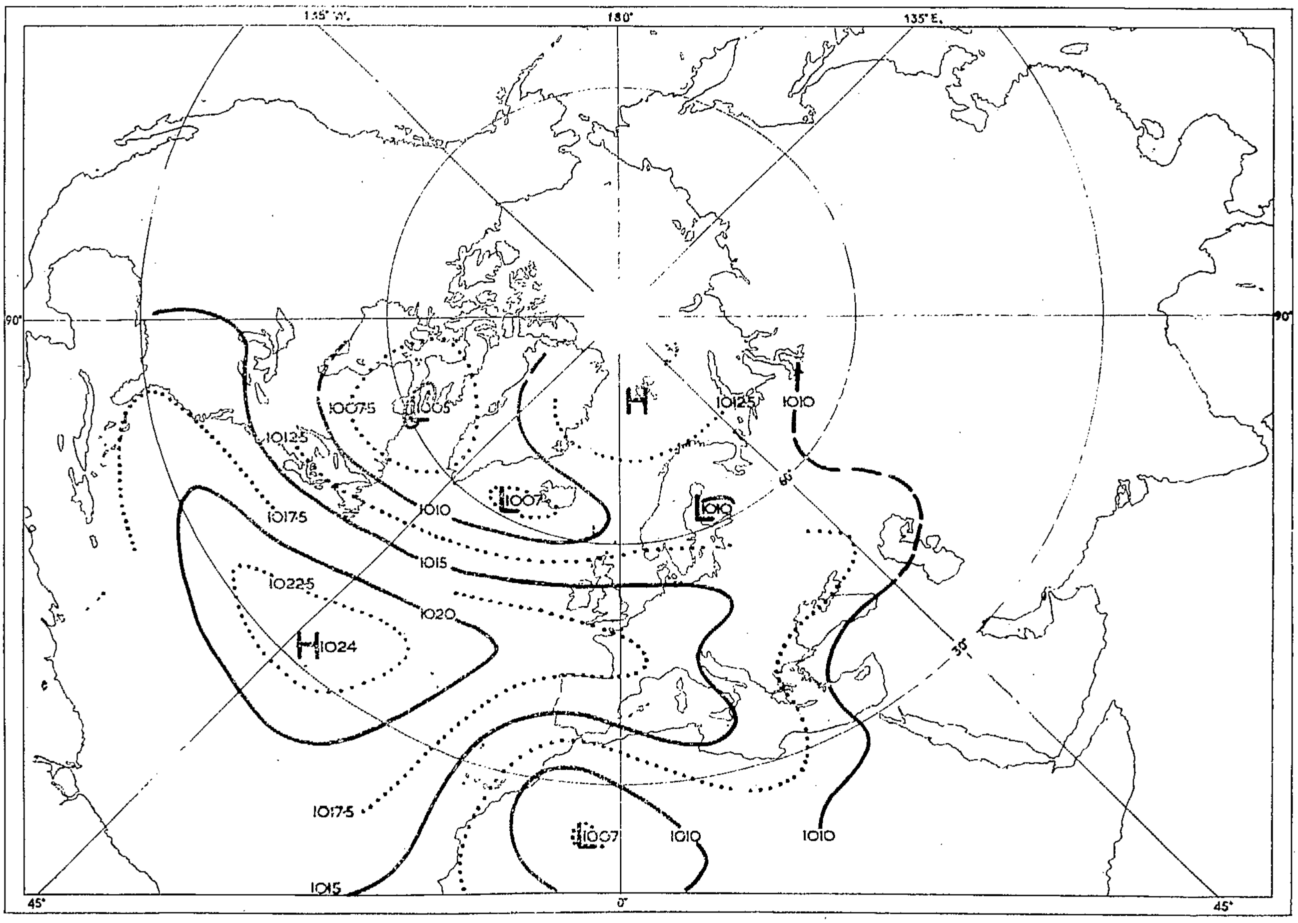


FIG. 5. Average m.s.l. pressure for 1830-39 : (*a*) January; (*b*) July.

January, 1830-39 in July) of Scandinavian blocking anticyclones—just possibly a periodic phenomenon with perioditicies of 60-90 years associated with solar events (see Scherhag, 1960, p. 91). There were some exceptionally high monthly mean pressures in the January of this period at Trondheim and St. Petersburg (though St. Petersburg also had a few very low ones), with exceptionally strong, and prevalent, westerlies to the north and easterlies to the south.

3. Iceland and Greenland records suggest that enormous quantities of Arctic ice were broken up during the 1830s and drifted away into the Atlantic, followed by a period 1840-54 when ice was hardly ever seen near Iceland and when the permanent ice had retreated greatly both east and west of Greenland.
4. Sydney and Adelaide had long dry periods about this time—Sydney from the 1820s to the early 1840s, Adelaide through the 1840s and possibly earlier, implying prevalence of far southern positions of the anticyclone belt and depression tracks in that sector of the Southern Hemisphere. In Chile increasing rainfall in the Santiago district from 1820 onwards (after a long very dry epoch) has been taken as a sign of the temperate and subpolar depression belt returning northwards.
5. The Antarctic sea ice seems also to have been more erratic in the 1830s and after than in the preceding decades. In 1832, 1840-44 and 1855 enormous amounts of ice broke away into latitudes between 60° and 40° S. but seem to have left the higher latitudes unusually ice-free.

The Arctic ice never regained the extent which it apparently had before 1840. The circulation maps also make it doubtful whether any truly analogous patterns have occurred in recent years with those before 1840—a point which may be significant for long-range forecasting.

CONSIDERATION OF THE PROBABLE UPPER AIR CIRCULATION IN THE PERIOD AROUND 1800

Figs. 6 and 7 display the longitudes of lowest and highest m.s.l. pressure over the North Atlantic in January and July from 1790 to the present time. The latitudes used were chosen (*a*) to make use of the most reliable portions of the isobaric charts and (*b*) to be where the identifiable features are related to the prevalent cyclogenetic and anticyclogenetic effects east of upper troughs and ridges respectively.

The wave length L of a standing wave is taken to be expressed by the Rossby formula

$$U = \frac{\beta L^2}{4\pi^2}$$

where U is the prevailing zonal velocity of the upper westerlies and β is the rate of change of the Coriolis

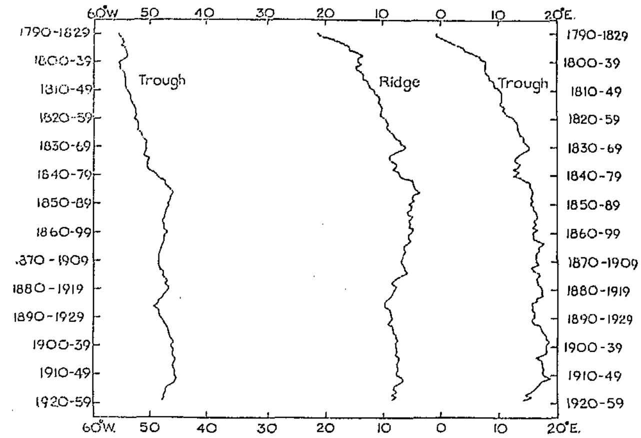


FIG. 6. Longitudes of the semi-permanent surface pressure troughs and ridges at 45° N. in the Atlantic sector in January (40-year running means).

parameter with latitude at the latitude of the mainstream of the westerlies.

Both Figs. 6 and 7 show that the longitude spacing of surface systems generally increased and decreased at times when the indices of circulation intensity were increasing and decreasing respectively. This is particularly clear with the spacing between the West Atlantic trough and mid-Atlantic ridge which are closest to the mainstream of the upper westerlies: the spacing of these surface features should correspond to about half a wave length. This result appears to give qualitative confirmation of the changes of circulation intensity found from the surface pressure gradients. But both in January and July the change of wave length is surely too great (implying at 25 to 30 per cent change of intensity) to be accounted for wholly in this way. It seems therefore

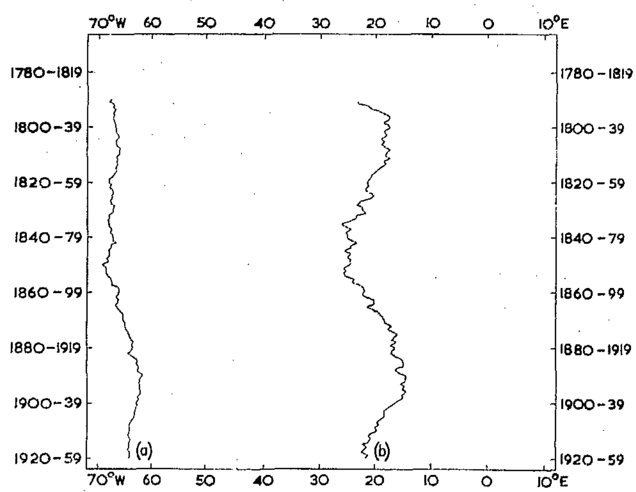


FIG. 7. Longitudes of the semi-permanent surface pressure troughs and ridges in the Atlantic sector in July (40-year running means) : (*a*) longitude of trough at 55° N.; (*b*) longitude of ridge at 55° N.

that some slight change of latitude of the strongest upper westerlies must also have taken place; in particular, a poleward displacement, of a few degrees of latitude from the times of weak circulation around 1800-50 to the epoch of strongest circulation in the present century seems to be implied.

The consistency of these trends suggests that the surface patterns, and in particular the longitudes of certain features, may be used judiciously to indicate probable changes in the main tropospheric westerlies aloft. This principle is the basis of the experimental investigations described in this and the following section.

A likely first approximation to the 1,000-500 mb. thickness patterns prevailing over the North Atlantic in January and July around A.D. 1800 was obtained (Fig. 8) by considering the average sea-surface temperatures observed between 1780 and 1820 (Lamb and Johnson, 1959) and shifting the mean thickness isopleths from their modern positions by the same amount as the sea-surface isotherms. Broadly this preserved nearly saturated adiabatic equilibrium with the sea-surface temperature, except for the highest thicknesses in January and the lowest thicknesses in July where vertical stability prevails over some parts of the Atlantic—these exceptions were, however, at the edges of the region over which surface pressures could be mapped.

Over the neighbouring land regions some slight equatorward displacement of the thickness values in the period around 1800 would be implied if a join-up with those over the ocean is to be achieved. Such a displacement might have been produced either by the dynamic effects of modified or southward-displaced upper westerlies or, more directly, by a small reduction of the effective insolation.

The latter suggestion gains *a priori* plausibility because Wexler (1956), in an attempt to explore the possibility of explaining Ice Age phenomena (precipitation pattern and atmospheric circulation) in terms of a persistent 20 per cent reduction of the insolation due to volcanic dust, obtained estimated anomalies of the 700 millibar and deduced surface pressure patterns which amounted to a remarkable qualitative prediction of the pressure charts subsequently constructed by Lamb and Johnson (1959) from actual data for the period around A.D. 1800. In particular, Wexler predicted as features of the January pattern an elongated polar trough and intensified frontal activity along the Atlantic coast of the United States, higher pressure over Greenland and more prominent cold northerly flow over the Norwegian Sea and North Sea affecting the coasts of Scandinavia and Britain.

Wexler moved the modern normal insolation isopleths by distances sufficient to reduce the amount of insolation by 20 per cent. Over the relatively cloud-free snow-covered interior of the continent he assumed the 1,000-700 mb. thickness values to be controlled by the insolation and moved the thickness lines by the same amount, so as to coincide with the same insolation.

Applying Wexler's argument in reverse to the 1,000-500 mb. thickness distribution around A.D. 1800, we see in Fig. 8 (*a*) and (*b*) that a reasonable join-up with the thickness isopleth positions over the North Atlantic could be achieved if the isopleths over North America (and continental Eurasia and Africa) were shifted by an amount to correspond with a 5 per cent reduction of insolation or rather less—possibly with any reduction between 0 and 5 per cent or a little over. (This seems not unreasonable in view of the 5 to 10 per cent reduction of circulation vigour over the North Atlantic in winter and the smaller reductions found at other seasons and places.) The only regions which did not fit were: (*a*) the coastal region near Newfoundland and Labrador, where a greater reduction of mean thickness over the sea (and neighbouring land) may reasonably be attributed to colder water and more ice; (*b*) western and central Europe, where greater reductions of thickness seem to be required and may perhaps be taken as dynamic, i.e., linked with the other evidence of a shorter wave length and more western position of the quasi-permanent trough in the upper westerlies.

Figs. 9 and 10 show the 500 mb. patterns derived by using these thickness patterns and 1,000 mb. contours corresponding to the actual pressure fields.

Since sea temperatures 1780-1820 were available for the North and South Atlantic Ocean, it seemed worth while to apply a similar experiment to the great ocean region as a whole, excluding areas disturbed by strong water currents, strong upwelling and zones of intense cloudiness (as in the equatorial and subpolar rain-belts). The zones of strong water currents and of upwelling are only fringe regions of the ocean but their delineation is unavoidably somewhat uncertain and arbitrary. Over the broad remaining regions of the ocean, where both positive and negative anomalies occurred, it seems likely that the general (overall average) level of surface-water temperature and of 1,000-500 mb. thickness is controlled by the amount of insolation actually penetrating the atmosphere to the surface. The results of trying the obviously crude assumption that this was the whole explanation of shifts of sea temperature (and thickness) isopleths since 1800 were: (*a*) over the North Atlantic between 30° and 55° N., including the fringes where cold currents were probably expanded—an indicated reduction of insolation in 1780-1820 by 7 or 8 per cent (almost certainly too large); (*b*) over the North Atlantic between 30° and 55° N., omitting the fringes —a reduction of 3 to 4 per cent; (*c*) over the North and South Atlantic between 50° N. and 40° S., omitting the fringes and the equatorial rain-belt—a reduction of 0.7 to 1.5 per cent.

The result under (*c*) is possibly too small because the most extensive region of colder surface north of 50° N. is excluded and apparently other cold areas near 40° S. We may guess that anomalies in the great Pacific

8a

8b

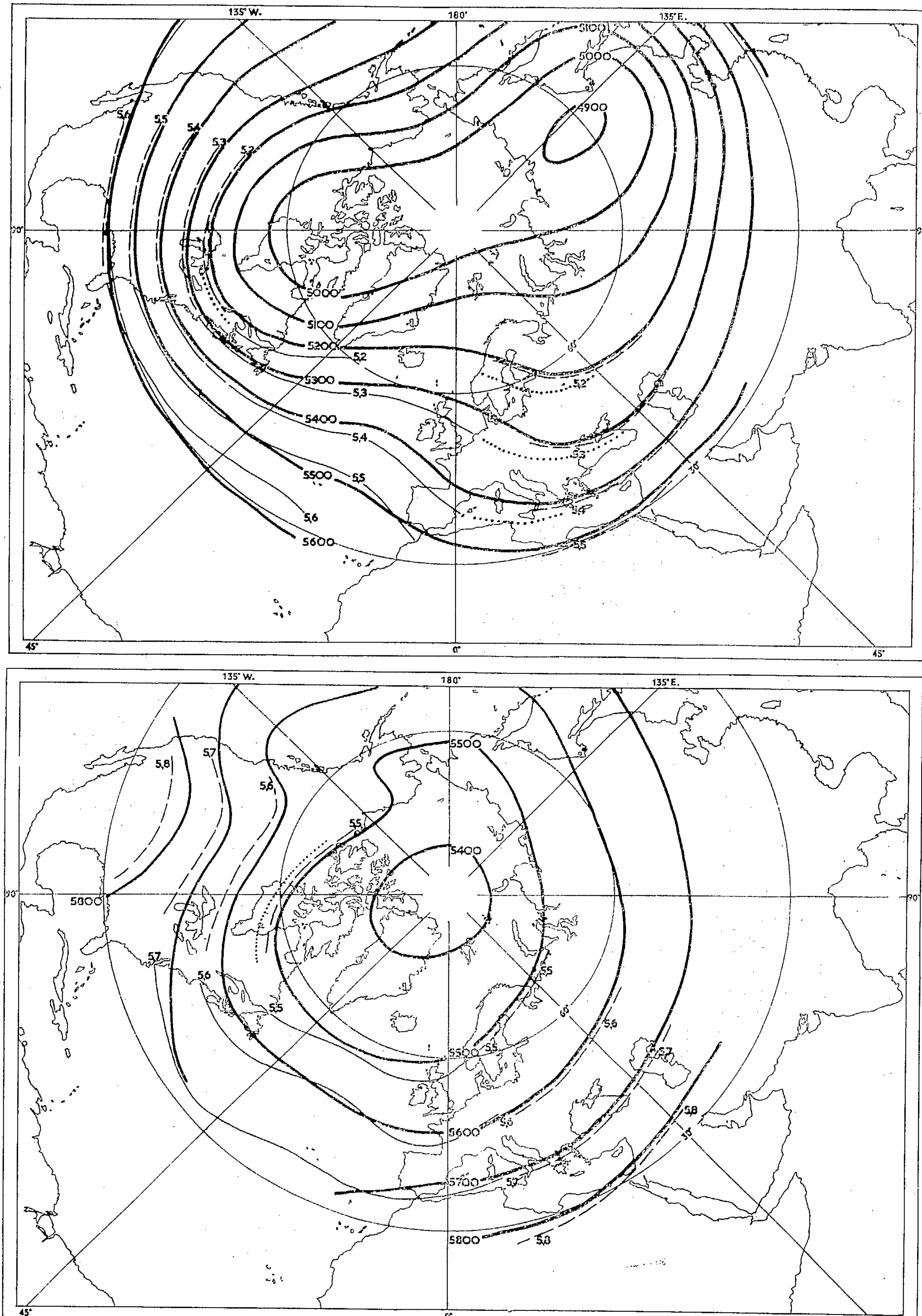
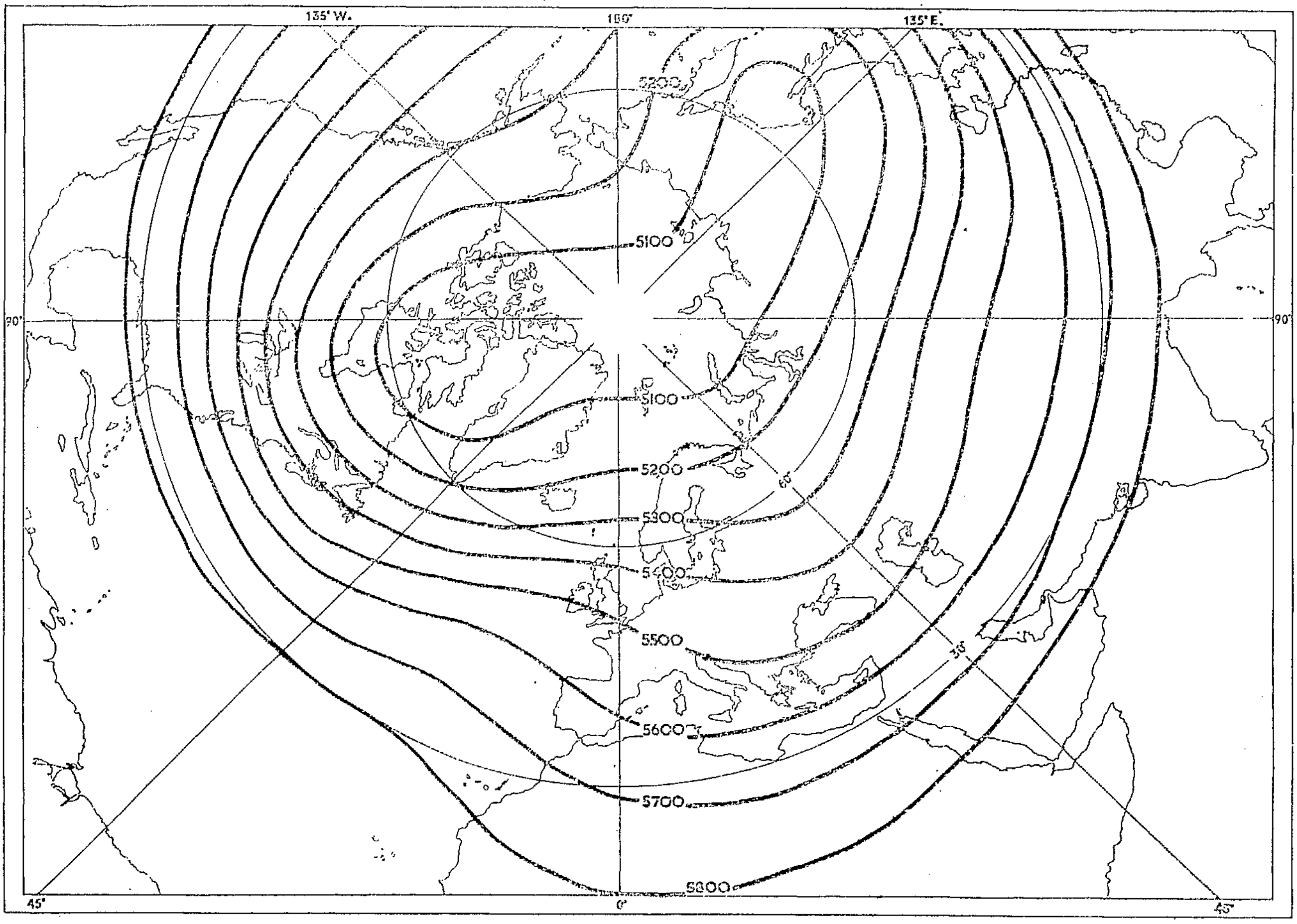


FIG. 8. Average 1,000-500 mb. thickness : (*a*) January ; (*b*) July. Bold lines averages for recent years : (*a*) 1950-58 ; (*b*) 1949-57. Narrow lines suggested for 1780-1820 from sea temperatures. Broken lines suggested for about 5 per cent reduction of insolation.

9a



9b

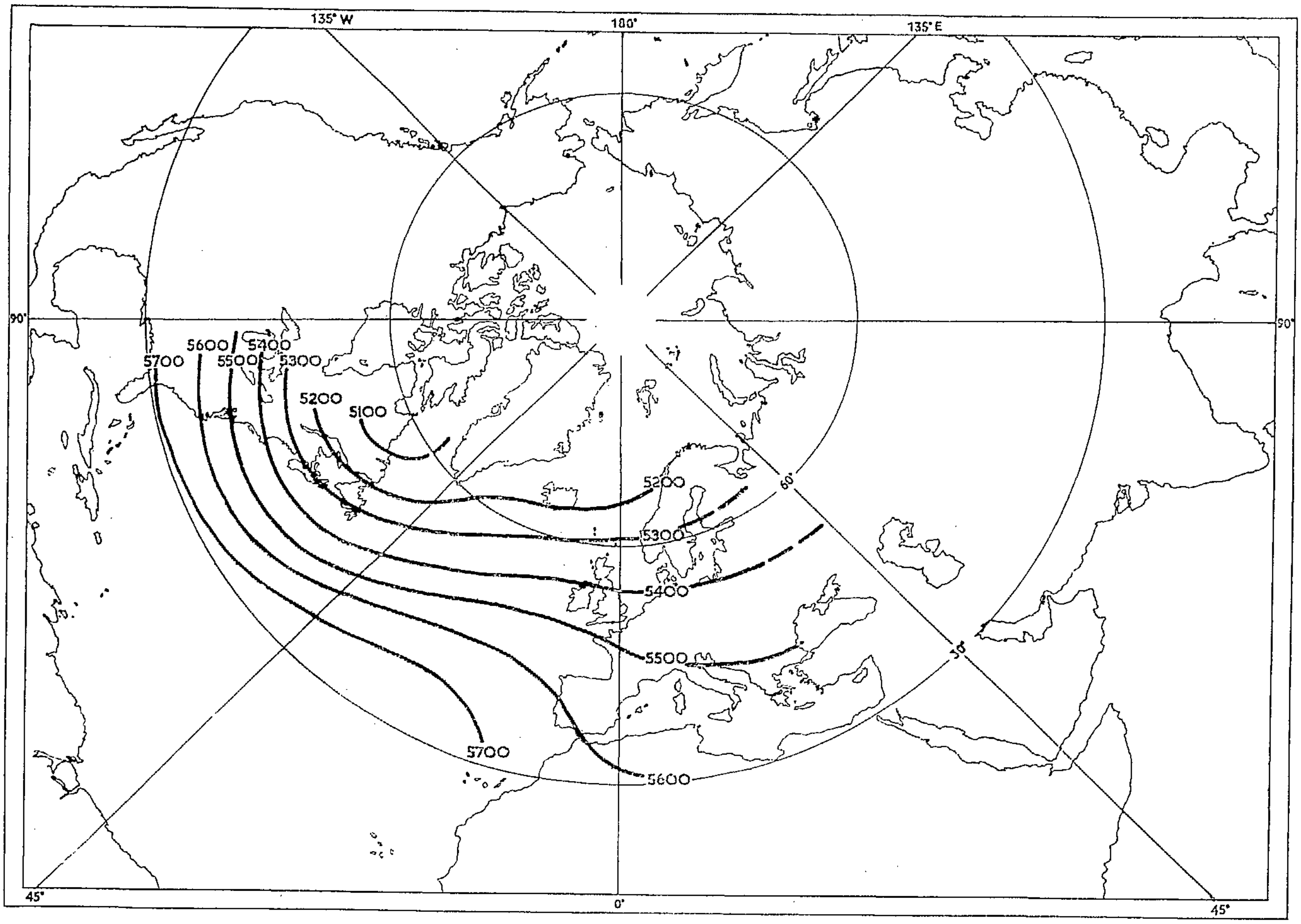
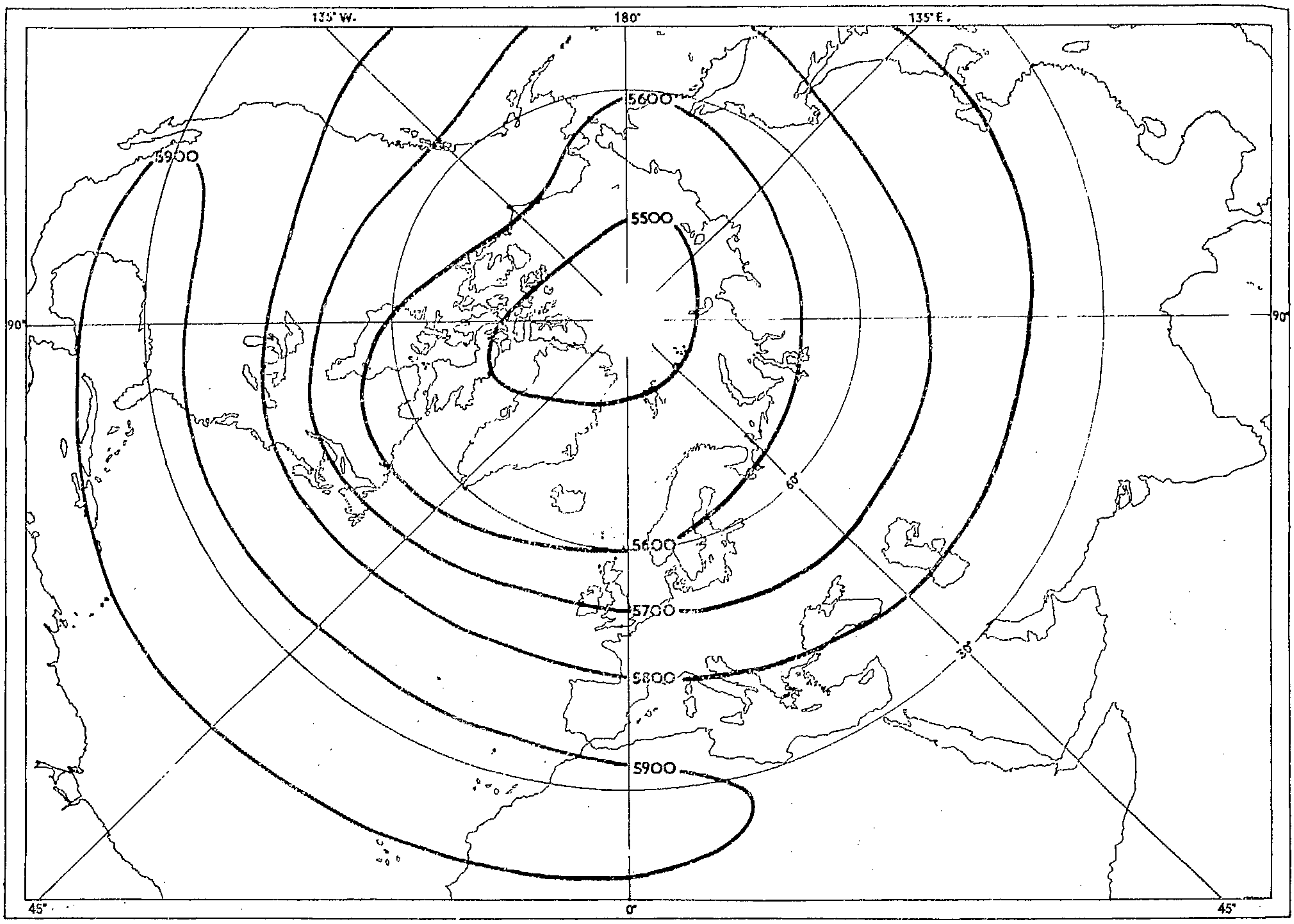


FIG. 9. Average 500 mb. contours for January : (*a*) 1949-58 ; (*b*) 1780-1830. (Based on Figs. 1 (*a*) and 8 (*a*).)

10*a*



10*b*

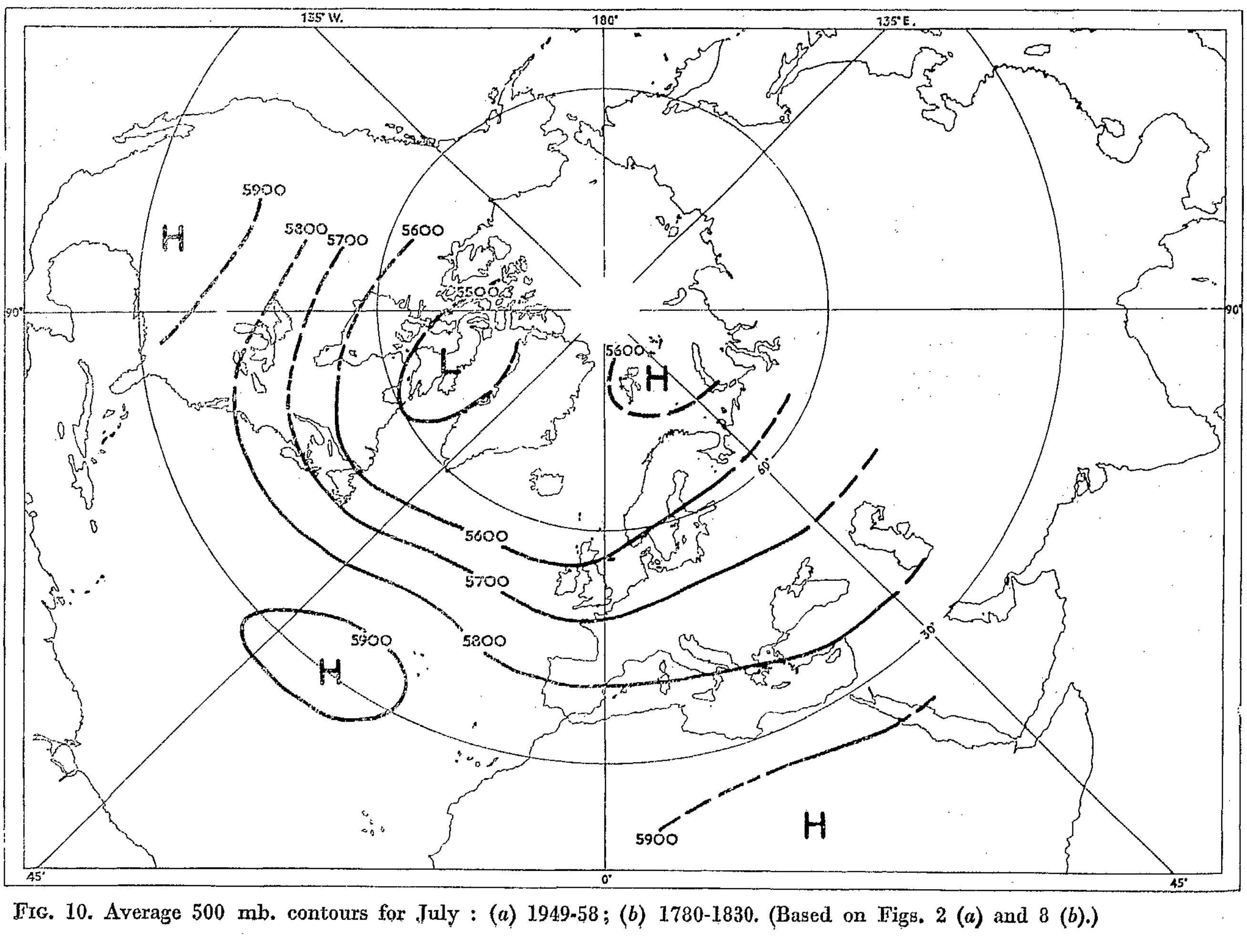


FIG. 10. Average 500 mb. contours for July : (*a*) 1949-58 ; (*b*) 1780-1830. (Based on Figs. 2 (*a*) and 8 (*b*).)

Ocean were smaller, though on the whole in the same sense.

Summing up it seems therefore that there is a case for supposing a small reduction of, say, 1 to 2 per cent in the average available insolation over the surface of the globe during the epoch 1780 to the 1820s compared with the present century. Over the Northern Hemisphere the reduction may have been rather over 2 per cent. We notice, however, that the greatest displacement of the isopleths was over the North Atlantic Ocean, so that the increased Arctic ice and spread of cold water north of 50 °N. was playing perhaps the most immediately important part in modifying the atmospheric circulation pattern at that time. It seems further to be implied by the 500 mb. changes in Figs. 9 and 10 that the circulation, although perhaps generally rather weaker around 1800, was locally strengthened where the cold surface over the continents and the Labrador current reached rather lower latitudes than today. Other features indicated were a shortened wave length[1] and large amplitude waves.

AN EXPERIMENT IN THE SYSTEMATIC TREATMENT OF DOCUMENTARY WEATHER RECORDS SINCE A.D. 800

Efforts are being made to extend our pictures of the monthly mean atmospheric circulation over Europe still farther back. Several decades before 1750 can be covered by numerous well kept registers of wind and weather —e.g., on board navy ships berthed for a month or more in various harbours from the Baltic and Iceland to the Mediterranean (and possibly farther afield). Assembly of this data takes time and could perhaps profitably be pursued in different countries. It is known that there were drastic climatic vagaries in the decades that can be covered, particularly the 1690s.

A wealth of manuscript information from still earlier times regarding the character of particular months and seasons exists in state, local, monastic, manorial and personal accounts and chronicles. Compilations have been made by meteorologists and others in many countries, so that by now it is possible to attempt numerical assessment of various phenomena, though much care is needed and special techniques have to be devised to watch and allow for changes in the fullness of reporting.

As a first attempt at systematic use of this material to reveal something about the changes in the prevailing atmospheric circulation from the warm climate period of the early Middle Ages right through the Little Ice Age to the present day, the reports from different places in Europe between 45° and 55° N. and between Ireland and Russia were used. This is a particularly suitable region for study because it is always affected by the behaviour of the mainstream of the zonal circulation aloft and because reports are most abundant there. One can commonly compare contemporary events in the Mediterranean, Scandinavia and elsewhere. Immediate objects in view were to establish the climatic sequence in Europe more firmly, and in more detail, and to discover how far different longitudes underwent similar experiences.

The most reliable surface weather indications in the early manuscripts relevant to this study were thought to be:

1. Severity or mildness of the weather prevailing in the main winter months of December, January and February. The effects upon landscape, transport and the agricultural economy are likely to have been reported in all important cases. It should be possible to identify confidently the persistent spells: mild winter by rains, flooding and thunderstorms even in continental regions, also by early or out-of-season flowering of plants; severe winters by frozen rivers, lakes and seaways, and by many sorts of privation and damage.
2. Raininess or drought in summer. Again the effects upon the landscape and upon agriculture are reasonably sure to have achieved mention in all outstanding cases. Wet summers produce flooding and ruined crops, though highly coloured accounts of individual thunderstorms may occur in otherwise good summers. Dry summers are known by parched ground and dwindling rivers, whilst the grain crops are usually good; forest fires are also particularly liable to occur. The rain character of a summer is surer of faithful recording than the temperature, since an oppressive heat wave might well be the only recorded reference to temperature in an otherwise poor summer.

Since long spells of weather of set character persisting from July to August are one of the most prominent features (Lamb, 1953) of the climate of temperate Europe (early recognized in the Saint Swithin and Seven Sleeper legends), and since the circulation patterns involved presumably correspond to the quasi-stationary pattern attained at the climax of the summer heating of the hemisphere in the individual years, July and August only were used as the time unit for summer.

The compilations available included: Buchinsky's (1957) for the Russian plain (references especially to the Ukraine, the Moscow region and Poland); Hennig's (1904), chiefly covering central Europe and Italy, but also including references to other places between Ireland and Poland; Easton's (1928) regarding winters in western (and central) Europe between Scandinavia and the Mediterranean; Vanderlinden's (1924) for Belgium; an unpublished collection kindly made

1. Betin (1957) has noticed an interesting variation of climatic behaviour in Europe which seems likely to be related to changing wave length and most frequent ridge and trough positions. Over the eighty years of decreasing ice between about 1870 and 1950 there was a negative correlation coefficient between Baltic ice and the level of the Caspian Sea, which is fed by rainfall in the Volga Basin, whereas the longer term trends of both since 1550 run parallel. Presumably between 1870 and 1950 cyclonic or anticyclonic conditions over the Baltic tended to cover the Volga Basin too, whereas for a long period previously this was not the case.

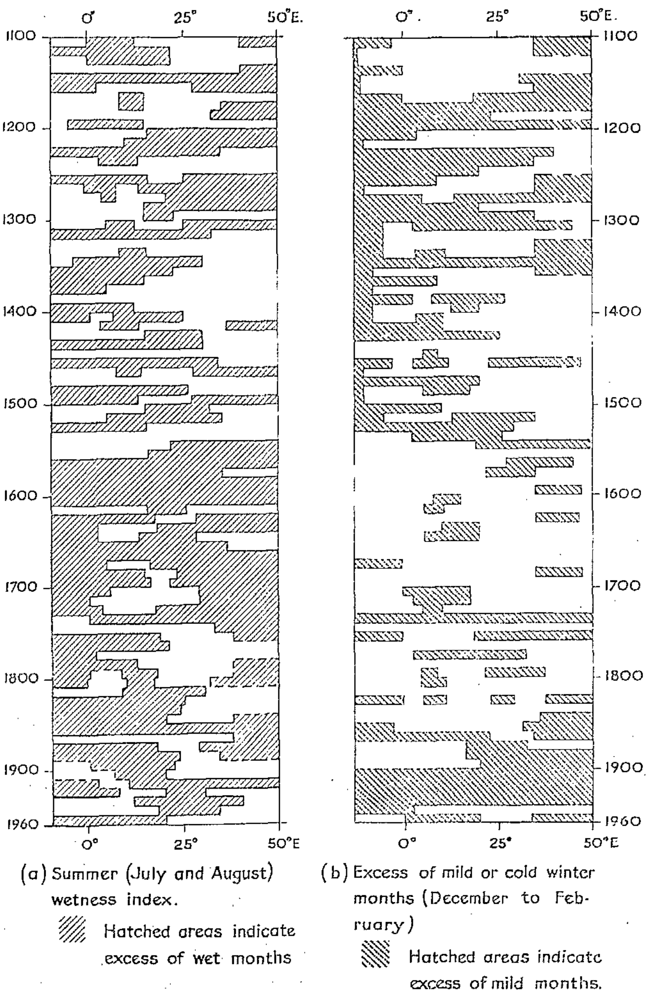


FIG. 11. Summer wetness index and winter mildness (or severity) in different European longitudes near 50° N. by decades from 1100 to 1959.

available by D. J. Schove for the British Isles, including use of C. E. Britton's chronology of early time (1937) and original sources. Amplifying evidence from vine harvests in Luxembourg (Lahr, 1950), Baden (Muller, 1953) and ice on the Baltic (Betin and Preobazenskij, 1959) was also considered.

Crude numerical indices were then defined and applied to the years in groups of not less than a decade (thus eliminating uncertainties in early times regarding the exact year of a particular occurrence). Data for some groups of years appear full and self-consistent from quite early times—e.g., remarkable warmth and dryness of central European summers between A.D. 988 and 1000—but a complete sequence of decade characteristics can hardly begin before A.D. 1100. So as not to make too great demands in terms of approximately uniform standards of reporting only the simple indication of excess of mild or cold, wet or dry for individual decades is here attempted (Fig. 11). Half-century means of the following indices appeared, however, to give reliable numerical values from an earlier date, and have been tentatively extended back to A.D. 800.

1. Winter severity index. The excess number of unmistakably mild or cold winter months (December, January and February only) over months of unmistakably opposite character per decade—excess of cold months counted negative. (Unremarkable decades score about 0. Extreme decade values of the index in Europe range from about +10 to —20.)
2. Summer wetness index. Each month (July and August only) with material evidence of drought counted 0, unremarkable months 0.5, months with material evidence of frequent rains and wetness counted 1. (Unremarkable decades score about 10. Extreme decade values of the index in Europe range from about 4 to 17.)

For the epoch since regular weather observations became available, these were preferred for identifying notably wet or dry, mild or severe months.

The earliest and longest records here used are a daily weather register from Hesse 1621-50 (Lenke, 1960), central England temperatures from 1680 to 1952 (Manley, 1953, and private communication), rainfall in England and Wales from 1727 (Nicholas and Glasspoole, 1931) and in Holland from 1735 (Labrijn, 1945).

The problem of welding the earlier and later series of months considered notable into a single series was tackled by studying overlap periods of several decades for which both instrument measurements and descriptive chronicles were to hand. The overall numbers of months marked as displaying noteworthy anomalies remained satisfactorily steady between 1100 and 1550 at about one-third of all the winter months and 40 per cent of the Julys and Augusts. (The frequency of months noted in the Russian chronicles was an exception, being fairly steadily about half that for more western longitudes and tending to concentrate on months of disastrous severity: index values obtained from this source were therefore doubled to assimilate them to the others.) Rather higher frequency of months noted as extreme between about 1550 and 1700 was thought more likely due to the peculiar climate of that time than to relaxed criteria of extreme weather. The criteria adopted in using the instrument records of the period since 1680 to 1800 therefore were: (*a*) winter months counted as mild or severe if the temperature anomaly exceeded the standard deviation from the longest period mean; (*b*) Julys and Augusts counted as wet or dry if the rainfall measured was within the highest or lowest quintile.

The possibility of a slight "change of zero" in the 1700s or early 1800s must, however, still be borne in mind. With this reservation Fig. 11 displays the course of the summer and winter climate of Europe in different longitudes near 50 °N., by decades, from 1100 to 1959.

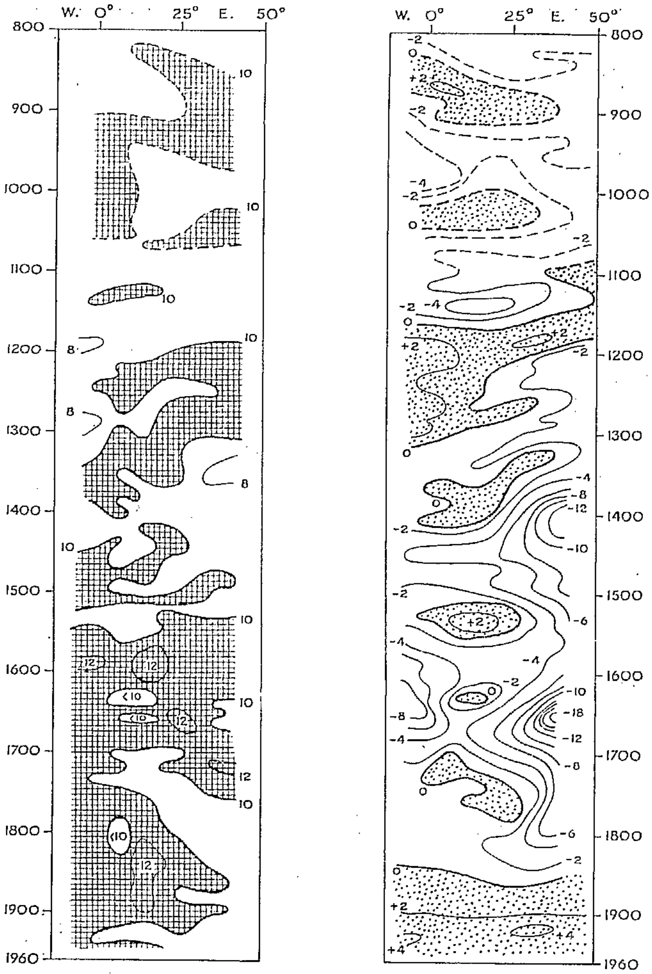
All longitudes are not always affected by the same anomalies at the same time. Correlation coefficients between the winter index values in Britain and Germany and in Britain and Russia 1100-1750 were respectively +0.45 and +0.31: these both appear statistically significant at the 1 per cent level, but in both cases coefficients with reversed sign were found in some centuries during this period.

Comparisons of the winter severity index in Europe with an indicator of winter character in Japan—the freezing dates of Lake Suwa (Arakawa, 1954)—produced no significant correlation coefficients.

There seems (Fig. 11) to have been more tendency for like character of the winters, and of the summers, in all European longitudes between 1150 and 1250—in the case of the winters as late as 1350 or after—and since 1850 than at most other times. These have been the periods of most predominance of mild winters, presumably with westerly winds sweeping far across Europe, and good summers. The predominance of mild winters, greatest between 1150 and 1300, but also noteworthy in certain earlier and later periods (Fig. 12 also), was punctuated by individual decades with cold winters everywhere in Europe near 50° N. There were roughly half-century intervals between the decades with most mild winters, also between those with most cold winters—perhaps another suggestion of a periodicity in the occurrence of blocking anticyclones over North Europe.

Between 1550 and 1700 all hints of this oscillation are lost owing to the heavy preponderance of cold winters, especially in Russia and Britain. This distribution suggests that the westerlies were weak and that northerly windstreams over the Russian plain and over the Norwegian Sea were important—the latter would tend to explain the very rapid worsening of the ice situation in Iceland and Greenland waters, especially after 1550. Preponderance of wet summers (Julys and Augusts) in all European longitudes near 50° N. between 1550 and 1700 is also noticeable.

Examining the smoothed trends of summer wetness and winter severity indices presented by the running five-decade (half-century) average values in Fig. 12, one apparently discovers a general westward progress across Europe of a region of maximum summer wetness between 1250 and 1400-1500 and a corresponding eastward progress during the climatic recovery between about 1700 and 1900. Also shown is a general westward retreat from about 1200 onwards of the predominance of mild winters and a return movement (more clearly seen from the isopleths for predominance of cold winters withdrawing east) between 1700 and 1900. There are complexities of detail which tend to obscure these trends, but summer and winter sequences—the one of temperature, the other of a different element—appear to run parallel during both the climatic decline preceding the Little Ice Age and the recovery afterwards. Moreover the fact that any semblance of an orderly progression



(a) High summer wetness index.

(b) Winter severity index

FIG. 12. Summer wetness and winter severity indices in different European longitudes near 50° N. (overlapping half-century means) from 800 to 1959. Cross hatching indicates excess of wet Julys and Augusts. Dots indicate excess of mild Decembers, Januarys and Februarys.

should be revealed by such primitive data may seem surprising and possibly justifies one in disregarding complexities.

Viewed in this light, the epochs 1550-1700 and about 1000-1200 appear as times of standstill, when the trend was halted and whatever fluctuations went on affected all European longitudes alike. These are perhaps properly regarded as the culminating periods respectively of the Little Ice Age and of the warm climate (secondary optimum) before it.

Fig. 12 even suggests a still earlier period, between 800 or earlier and 900, of eastward spread across Europe of a region of predominantly mild winters and dry summers. Six to ten notably severe winters seem to have occurred rather earlier, between 764 and 860, mostly still more remarkable in the eastern Mediterranean (ice on the Adriatic, the Bosphorus, Dardanelles and Nile); there was apparently only one more similar occurrence afterwards—in 1011—until the 1600s.

Severe winter weather in Europe is related to a westward and southward shift (or expansion) of the cold trough in the upper westerlies normally found nowadays over eastern Europe; mild winter weather is similarly closely related to the East Atlantic warm ridge (Fig. 9). Wetness of the summers depends not only on proximity to the depression track (around 62° N. in this sector nowadays), but tends to be most pronounced in the region of the upper cold trough normally discernible over Europe and immediately east thereof (Fig. 10).

Westward and eastward movements of the features displayed in Figs. 11 and 12 before and after the Little Ice Age are such as might accompany respectively shortening and lengthening of the waves in the upper westerlies downstream from a more nearly anchored ridge in the vicinity of the Rocky Mountains.

The experiment was therefore tried of measuring the apparent longitudinal displacements of the features identified on Figs. 11 and 12, with the following results:

Winter: in 1550-1700 maximum winter mildness some 20°-30° longitude west of today's and in 1150-1300 once more about today's position.

Summer: in 1550-1700 greatest predominance of wet Julys and Augusts 15°-30° longitude farther west than in recent times; before 1300 farther east then nowadays.

Table 1 summarizes measurements, and directly derived estimates, of parameters relating to the circulation over the North Atlantic sector.

The latitude of the strongest flow at the 500 mb. level is taken as the middle of the zone of closest packed isopleths in the neighbourhood of the point of inflexion (between trough and ridge) in mid-Atlantic. The latitude of the depression track is taken over the eastern Atlantic between about 20° W. and 10° E., in order to be related to the 500 mb. measurement yet more indicative of weather in temperate Europe.

The longitude of the European upper trough is measured in 45°-55° N., the same latitude zone to which the summer wetness and winter severity indices (Figs. 11 and 12) apply. The estimates of wave length, and of change of wave length from the modern normal, allow for a smaller sympathetic westward or eastward movement of the cold trough near the Atlantic margin of North America.

TABLE 1. Key parameters of the atmospheric circulation, North Atlantic sector

	Modern normal 1900-39 (1949-58 500 mb. values)	Extreme years in the early 1940s (partly after Scherhag)	Little Ice Age culminating period 1550-1700	Early Middle Age warm epoch 1000-1200
Summer (July)				
Latitude of strongest 500 mb. flow	48° N.	50°-52° N.		
Departure from modern normal	—	+3°		
Longitude of European trough at 500 mb.	10°-20° E.	15°-20° E.	0°-10° W.[1]	
Departure from modern normal	—	Slight +	—15° to 30°	+10
Wave length change implied (°longitude)	—	+6°	(—10° to 20°)[2]	(+5° to 10°)
Wave length (°longitude)	78°	84°	(65°-70°)	(83°-88°)
Latitude of depression track	62° N.	65° N.		
Departure from modern normal	—	+3°		
Winter (January)				
Latitude of strongest 500 mb. flow	60° N.	55°-60° N.		
Departure from modern normal	—	—3°		
Longitude of European trough at 500 mb.	40°-50° E.	25°-33° E.	10°-20° E.[1]	
Departure from modern normal	—	—15°	—20° to 30°	Slight
Wave length change implied (°longitude)	—	—10° to 15°	(—20°)	
Wave length (°longitude)	120°-130°	110°	(100°-110°)	
Latitude of depression track	68° N.	65° N.		
Departure from normal	—	—3°		

1. Values read off the charts for the period around 1800.
2. Values in parentheses are derived estimates; all other values measured from the charts and diagrams.

These measurements appear to admit the solutions in terms of change of latitude and/or intensity of the main circulation features which are outlined in the following paragraphs:

LITTLE ICE AGE CULMINATING PERIOD 1550-1700

SUMMER

Either flow weakened by about 30 per cent or strongest flow shifted south by 5° or more. The likeliest solution, following the indications regarding intensity changes and latitude shifts on the charts around 1800 and earlier, including fragmentary charts for the 1690s, appears to be southward shift of the main flow by 4°-5°, with only trivial, if any, weakening of the summer circulation in the North Atlantic sector.

Main depression track was 57°-60° N. over the eastern Atlantic sector, possibly rather south of 57° N. over the ocean itself, but reaching 60° N. over Russia.

There should have been also a change in prevailing wave number, five to six waves having been normal around the hemisphere, possibly at times a good fit with a five-wave pattern which might become correspondingly firmly established. (The modern normal wave length is intermediate between that required for a four- and a five-wave pattern.)

Using the indications of Fig. 10 (*b*), we may judge the likeliest positions for summer cold troughs in middle latitudes in a five-wave pattern during the Little Ice Age epoch as (*a*) near 60°-70° W.; (*b*) 0°-10° W.; (*c*) 60°-70° E.; (*d*) 130°-140° E.; (*e*) 130° W.

WINTER

Either flow weakened by about 30 per cent or strongest flow shifted south by 5° or more. The likeliest solution seems to be that the flow was in general weakened over the North Atlantic by 5-10 per cent in winter and the mainstream shifted south by 3°-5°.

Main depression track was 63°-65° N. It is obvious from the charts around 1800 that this position of the main depression track allowed for a scatter with many more depressions than now entering the Mediterranean.

There should have been a change of wave-number around the hemisphere from the twentieth-century predominance of three-wave patterns at the times of most vigorous winter circulation, especially in January, to one where four-wave patterns were commoner, often even at the peak intensity of the winter circulation. (This is a feature which has tended to reappear in recent years, in the weaker and southward displaced circulations in several winters of the 1940s and 1950s.)

Using the indications of Fig. 9 (*b*), we may judge the likeliest positions for winter cold troughs in middle latitudes in the Little Ice Age epoch as: (*a*) 80°-90° W.; (*b*) 10°-20° E.; (*c*) 110°-130° E.; (*d*) more variable in position, but probably tending to be near enough to North America at times to reduce the Rocky Mountains warm ridge to insignificance. (This is a suggestion which might explain an apparent tendency even in the nineteenth century for severe winters to occur simultaneously in western and eastern North America and Europe.)

EARLY MIDDLE AGES WARM EPOCH 1000-1200

SUMMER

Either flow 30 per cent stronger than now or strongest flow shifted north by 3° to 5° from the modern normal. The likeliest solution seems again to be that the main anomaly was one of latitude position.

Main depression track over the eastern Atlantic was 65°-67° N. Presumably there was considerable similarity with 1959 and the best summers of the 1930s and 1940s in Europe (1933-35, 1941-43, 1945, 1947, 1949); the marked aridity of the 1100s in Europe probably means that the depression track was then a degree or two still farther north, passing near the east coast of Greenland and generally near 70° N. in the European sector. This would be consistent with the suggestion of little floating ice on the Arctic seas south of 80° N. and an anticyclone belt over Europe, whilst Mediterranean summer droughts should have experienced more breaks than nowadays.

WINTER

The evidence suggests a more northerly position of the depression track than now, perhaps allowing the same wave length as nowadays with a rather weaker atmospheric circulation. If we assume that a depression track in the Barents Sea was common owing to the less extent of ice, there may have been periods when a two-wave pattern was attained at the climax of the winter circulation vigour. The cold belt across Europe near 50° N. (Figs. 11 and 12) in the winters of the 1100s would then be most readily attributed to easterly winds with a long land track, as would also occur in other years and decades when blocking anticyclones were prominent. This pattern would probably imply more rain-giving depressions in the Mediterranean than normal in the winters of the twentieth century, but also less extreme cold than at those times when northerly outbreaks over Russia and the Norwegian-Greenland Sea were commoner (e.g., around A.D. 800 and 1600.

Botanical studies, which already suggest an important increase of total rainfall in northern Europe around 1200-1300 and a drier time between 1700 and 1800 (anticyclonic summers and winters in central eastern Europe indicated by the charts of 1750-1800), may be able to add more firm indications of the prevailing temperatures, rainfall and latitudes of depression tracks in different centuries. Further evidence might also come from similar studies of documentary records of seasonal weather character in the latitudes of the Mediterranean and northern Europe and in the Far East, whilst archaeological studies in the Americas may have a part to play.

TENTATIVE GENERAL CONCLUSIONS

The climates of the different epochs here discussed are amenable to interpretation largely in terms of (*a*) intensity changes and (*b*) latitude shifts of the main limbs of the zonal circulation, accompanied by appropriate changes of wave length and trough positions in the belt of westerlies. The latitude and longitude changes must have had direct consequences in modifying climates in every latitude zone and have perhaps been more conspicuous than the changes of circulation strength.

There is some evidence for supposing that both the circulation in general and the radiation available were weakened during the Little Ice Age A.D. 1430-1850 by a few per cent in the Northern Hemisphere and perhaps by about 1-2 per cent over the world, most probably due to volcanic dust. Correspondingly, it might be reasonable to suppose that the circulation in general, and (more doubtfully) the radiation available, were slightly above their twentieth-century strength in the early Middle Ages (especially 1000-1200), though it would be safer to assume that they were not far different from modern values. Possibly the chief difference between the modern situation and that of the early Middle Ages warm epoch and of the major post-glacial climatic optimum around 5000-3000 B.C. lies in the duration of these warm epochs and the sea temperatures consequently attained in the Atlantic and Arctic.

As the energy of the circulation increased (at least between 1800 and recent decades) the Northern Hemisphere circulation seems in general to have shifted poleward, perhaps mainly controlled by the displacement of the main thermal gradient accompanying the shrinking Arctic ice and winter snow cover on land.

It is clear that the extended Arctic ice and cold water of the period around A.D. 1800 and earlier modified the Atlantic sector circulation, causing peculiarly great latitude shifts there and even local strengthening of the circulation and thermal gradients near the southern extremities of the extended cold troughs—in an epoch when over wider regions the energy was reduced.

Correspondingly, in the early Middle Ages warm epoch, when the energy generally available may be supposed to have been greater (if only because of higher sea temperatures), the circulation seems to have been not always stronger than now (and possibly sometimes weaker) in northern Europe. The likeliest reason for this seems to be the remoteness at that time of the Arctic ice limit. Indeed, the patterns of that time may have some bearing upon what would happen in various latitudes if the Arctic ice were artifically disposed of.

When the general atmospheric circulation increases in energy the strongest (most disturbing) effects should be expected in those sectors where a broad quasi-permanent ice or cold-water surface has protruded farthest towards low latitudes. At times very strong circulations and very abnormal patterns might then be produced and become very variable from year to year if the protrusion of Arctic ice were to break up or shrink rapidly. The peculiar climatic course of the 1830s in the North Atlantic and neighbouring regions should probably be viewed in this light. The decade was one of extreme variations between persistent blocking and intense zonal circulations, most strongly developed in unusually high latitudes, so that the low values of some of the intensity indices in that decade may be misleading —indices taken in what are at most other times the best positions being just then unrepresentative.

Wexler has pointed out that any long-period changes in the insolation available should produce a much quicker response over the great land masses than in the oceans and regions of quasi-permanent ice. This seems to be supported by our study of the state of the general circulation around 1800, when a trend towards increasing energy may (according to some indications) have been already under way for about a century, and we observe a peculiarly great equatorward displacement of the circulation over the North Atlantic Ocean.

Peculiar instability of the climate in the Atlantic-European sector at various times between 1250 and 1550, with harsh alternations of wet and dry, warm and cold years in various (especially eastern) parts of Europe in the 1300s and (especially) 1400s, may perhaps be regarded as a phenomenon of the trend towards colder climate and increasing areas of snow and ice surface crudely corresponding to the vicissitudes of the 1830s during the recovery trend.

Clearly general trends of circulation strength must be judged by measures of the circulation in many different parts of the world and allowance made for passing phases in which misleading effects arise in regions affected by persistent ice or cold water—especially the North Atlantic.

To judge the position of the most recent decades in relation to longer-term trends it may be necessary to consider whether the appearance of rhythmic changes of wave position, wave length and circulation intensity affecting Europe—rises to maxima around 1100 and 1900-30 and a minimum around 1650—represents some long-period oscillation. So far the evidence seems against this, since the fluctuation was probably asymmetric in time—the decrease spread over 300-500 years, the recovery nearly complete in 150-200 years—and the Southern Hemisphere was probably not affected. Nevertheless there is a good deal of evidence that the general circulation has for the time being fallen away from its maximum intensity around 1900-30—evidently not due to volcanic dust—and the trend of the North Atlantic circulation towards lower latitudes in winter (and probably other seasons) needs watching and explaining. In this connexion the case made out for solar weather relationships by Willett (1949, 1961) and Baur (1956, 1958) cannot be ignored.

RÉSUMÉ

De la nature de certaines époques climatiques qui se sont écartées de la « normale » moderne (1900-1939)
(H. H. Lamb)

L'auteur fait tout d'abord l'inventaire de nos connaissances actuelles sur la répartition des principales périodes chaudes et froides depuis la dernière glaciation, en s'attachant plus particulièrement aux indices de déplacements vers les pôles ou vers l'équateur des trajectoires de dépressions et des zones sèches. Quelques indices semblent montrer que les différences principales entre la récente période de réchauffement de l'Arctique et les périodes chaudes antérieures les mieux établies ont été : *a*) la durée ; et par conséquent, *b*) les températures océaniques superficielles et la superficie des glaces arctiques atteintes.

Les suggestions de Wexler concernant les anomalies de circulation générale qui apparaîtraient durant une période de réduction notable du rayonnement incident sont à nouveau examinées en relation avec les types de circulation que l'on sait maintenant avoir existé sur les régions européennes et atlantiques et les longitudes avoisinantes au cours de la période de climat froid aux environs de 1800. Ces types de circulation tendent à confirmer les vues de Wexler sur les effets probables des poussières volcaniques : *a*) par l'action directe de voiles de poussière répétés ; *b*) indirectement, par suite de l'extension des glaces polaires et de l'abaissement de la température des mers.

Cette période voisine de 1800 se situe vers la fin d'une époque qui a duré plusieurs siècles dans l'hémisphère nord, et il semble actuellement que l'anomalie la plus évidente a été un déplacement vers l'équateur par rapport à la normale actuelle de la circulation générale atmosphérique sur l'océan Atlantique-Nord. Un déplacement correspondant du Gulf Stream et de la dérive atlantique nord s'est apparemment produit. L'intensité de la circulation générale a été un peu inférieure aux valeurs actuelles, mais a été probablement encore moindre avant 1800. Il semble possible d'en déduire une première estimation de la réduction relative de l'insolation pendant le « petit âge glaciaire » (environ 1430-1850).

D'autres indications sur la nature du « petit âge glaciaire » et sur la période chaude du début du moyen âge (maximum vers 1000-1200) qui l'a précédé sont tirées de l'étude systématique des documents de l'histoire climatique européenne depuis 800. Les effets de ces diverses périodes climatiques sur les latitudes plus basses sont examinées.

Une attention particulière est accordée à une décennie ou plus d'extrême désorganisation de la structure climatique normale sur l'Europe et la Méditerranée aux environ des années 1830.

Pour finir, une rapide estimation de la situation actuelle est tentée, en relation avec les principales tendances climatiques.

DISCUSSION

H. Flohn. Mr. Lamb has put before us an admirable amount of evidence including some more or less indirect results of large-scale variations in the upper-air pattern. Recent investigations based on the wind observations at the 700-metre level in the Alps (Sonnblick since 1886, Zugspitze since 1901) have revealed that the position of the upper troughs and ridges over Europe has undergone substantial variations which apparently fit well into the results of Mr. Lamb.

H. H. Lamb. Dr. Flohn's study of the resultant wind directions in different groups of years since 1880-1900 at the approximately 3,000-metre-high summits of Sonnblick and Zugspitze nicely confirms the actual occurrence of longitudinal displacements of the mean positions of upper ridges and troughs in the European sector. My reconstructions of the mean pressure fields and circulation patterns of the last 250 years suggests that the variations of longitudinal position of the upper ridges and troughs are reflected in mean surface pressure and prevailing weather. From a very recent investigation I believe this linkage may also be applied to the Southern Hemisphere westerlies : changes in the trough positions in the southern westerlies indicated at their northernmost fringe in July point to a general increase of wave length (and perhaps therefore of prevailing strength) from at least 1850-60 up to some time early in the present century, followed by some decline. This appears to confirm our measurements of the strength of the southern westerlies over Chile and New Zealand and perhaps carries our knowledge of the trend back a decade or two further.

R. Fairbridge. Two points should be made about the post-glacial climatic optimum of 5000 to 3000 B.C.:

1. The scale of Mr. Lamb's four climatic phases should perhaps be plotted on logarithmic paper, since the oldest is 2,000 years, and the younger ones only a few hundred years.
2. The sea level in the climatic optimum was "similar to today" according to Mr. Lamb. In comparison to the Ice Age (with m.s.l. of 100 metres), this is broadly true, but geological evidence shows that the climatic optimum sea level was about +3 metres. Since 1 mm. of sea level change equals 0.36×10^{12}m.^{3} of glacial melt-water, a sea level 3 metres higher than today means roughly 1×10^{15}m.^{3} less glacial ice on the mountains of that time; this is consistent with the paleobotanical climatic data.

H. H. Lamb. I agree that the different durations of the outstanding phases of climate which I described is important and accounts for some of the differences between the respective warm epochs. Nevertheless, whatever periodic oscillations may or may not have been going on—e.g., on time scales from half a century to a few centuries in length—the periods I have indicated were undoubtedly the extreme ones, specially stressed perhaps by some extraneous variable such as the occurrence or non-occurrence of volcanic dust.

K. W. Butzer. This very interesting paper by Mr. Lamb is an occasion to comment with particular reference to the climatic anomalia associated with the so-called post-glacial climatic optimum.

The evidence cited by Mr. Lamb in favour of a northward shift of the subtropical high pressure cells is from European Russia. The pollen data at its sourse is, however, without absolute dating and chronologically rather difficult to assess. It is, in my opinion, inconclusive at this point.

Another aspect of the same problem: evidence of intensity of contemporary moist conditions in lowland Egypt decreases from latitude 25° to 20°. This suggests the dry axis of the Sahara was still close to latitude 20° N. Again the Majorca record (near 40° N.) shows noticeably moist conditions contemporary to the maximum post-glacial sea level. This does not seem to warrant the reconstruction Mr. Lamb suggests for this, as yet, unsolved problem.

H. H. Lamb. I was hoping that some of those who are more familiar than I with the evidence and its limitations from fields outside meteorology would add comments of this kind showing where the reconstruction is weaker or firmer than elsewhere. It seems to me, however, that in the post-glacial optimum in western Europe the evidence points to a really high latitude for the near high pressure belt—perhaps 50° N. or so. It may be that this high pressure system was an intrusion from the Atlantic, which commonly ended in northerly winds over Russia or a little farther east. Majorca could easily have a moist régime with this pattern. I understand that farther south on the southern half of what is now the western Sahara (in Niger territory especially) there were at that time lakes inhabited by fish in large numbers as far north of the source of the moisture in the Gulf of Guinea as 16°-20° N. In the eastern Sahara and in the Near Eastern desert areas, I well believe the changes from today's pattern were less marked. Another probable aspect of the situation in the western longitudes was less intense development of the arid zone than nowadays, perhaps because of more frequent variations of latitude of the high pressure system.

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ON THE CLIMATIC VARIATION

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During the period of observation by means of instruments all elements of the weather have been subjected to a variation especially in the polar and temperate zones, where, at a lot of stations, the trend of temperature has been nearly the same.

A climatic fluctuation may be revealed in various ways. For example, over a given period: (*a*) all winters may have become milder or colder; (*b*) mild winters may have become more frequent or rarer; or (*c*) cold winters may have become more frequent or rarer.

Table 1. The minimum and maximum mean temperature at Copenhagen for January, February, July, August and the year during the 30-year periods from 1811 up to 1960

Period		1811-40	1841-70	1871-1900	1901-30	1931-60
		°C.	°C.	°C.	°C.	°C.
January	Min.	—5.9	—4.4	*—6.7*	—2.6	—6.4
	Max.	2.9	3.2	3.4	*3.7*	3.1
February	Min.	*—7.8*	—7.4	—6.2	—6.0	—6.7
	Max.	3.4	3.0	2.6	3.4	*3.8*
July	Min.	14.3	*13.0*	14.2	14.7	15.4
	Max.	*20.7*	19.3	19.0	*20.7*	19.9
August	Min.	13.6	*12.8*	14.1	13.3	14.2
	Max.	20.6	*20.7*	18.3	18.3	19.8
Year	Min.	*5.3*	6.0	6.0	6.6	6.5
	Max.	9.2	8.6	8.7	9.0	*9.9*

The coldest January occurred during the period 1871-1900 and the coldest February in 1811-40, whilst the mildest January occurred during the period 1901-30 and the mildest February in 1931-60 (see Table 1).

For the summer months both July and August had a minimum in 1841-70, whilst July had a maximum in 1811-40 and in 1901-30 and August had a maximum in 1841-70. The mean yearly temperature had a minimum in the first and a maximum in the last of the 30-year periods.

The absolute lowest temperature since 1860 occurred in February 1871 (—25.0° C.) and the highest in July 1914 (33.0° C.). In the country (Denmark) as a whole the absolute lowest temperature occurred in January 1942 (—31.0° C.) and the highest in August 1911 (35.8° C.).

It will be seen from Table 2 that cold winters have become less frequent and the mild ones more frequent during the present century than during the last. The number of very cold January ($\leq$ N —2.5° C.) and February months was 14 during the period 1811-40 and 1841-70, but only 6 in 1901-30 and 9 in 1931-60. On the other hand the number of very mild ($\geq$ N +2.5° C.) January and February months was only 4 in 1841-70 but 9 in 1901-30 and 8 in 1931-60.

It will also be noted from Table 3 that the frequency of cool summers has decreased at the same time as the frequency of warm summers has increased. During 1931-60 no very cool ($\leq$ N —2.5° C.) summers occurred, whilst in 1871-1900 no very warm ($\geq$ N +2.5° C.) summers occurred.

During the present century no very cold ($\leq$ 6.3° C.) years have occurred, whilst very mild ($\geq$ 9.3° C.) years only have occurred during the last 30-year period from 1931 up to 1960.

Fig. 1 shows the monthly and yearly variation of temperature at Copenhagen from 1798 up to 1960. Table 4 gives the maximum and minimum values of 30-year normals in degrees Centigrade and the corresponding periods.

It will be seen from Table 4 that the temperature variation has a maximum range of 2.4° in January and a minimum range of 0.9° in June, whilst for the year as a whole the range is 1.4°.

Fig. 2 shows running 30-year normals of temperature in January at several stations in Europe and the United States. It is evident that for many stations the curves resemble each other.

Figs. 3 (*a*) and 3 (*b*) are maps showing the temperature change in January and July at land and coastal stations

TABLE 2. The number of cold, normal (N) and mild winter months at Copenhagen during 30-year periods from 1811 up to 1960

Period	Mean temp. (°C.)	1811-40	1841-70	1871-1900	1901-30	1931-60
January (N = 0.0)	≦ —2.5	8	6	5	2	3
	≦ —1.5	14	13	8	6	4
	< 0.0	21	19	20	12	12
	= 0.0	0	1	0	2	1
	> 0.0	9	10	10	16	17
	≧ 1.5	5	5	7	7	8
	≧ 2.5	3	2	4	6	3
February (N = 0.0)	≦ —2.5	6	8	7	4	6
	≦ —1.5	8	11	9	8	7
	< 0.0	16	17	17	12	12
	= 0.0	0	0	0	0	0
	> 0.0	14	13	13	18	18
	≧ 1.5	5	7	5	8	9
	≧ 2.5	2	2	2	3	5
January and February (N = 0.0)	≦ —2.5	14	14	12	6	9
	≦ —1.5	22	24	17	14	11
	< 0.0	37	36	37	24	24
	= 0.0	0	1	0	2	1
	> 0.0	23	23	23	34	35
	≧ 1.5	10	12	12	15	17
	≧ 2.5	5	4	6	9	8

TABLE 3. The number of cool, normal (N) and warm summer months and cold, normal (N) and mild years at Copenhagen during 30-year periods from 1811 up to 1960

Period	Mean temp. (°C.)	1811-40	1841-70	1871-1900	1901-30	1931-60
July (N = 17.0)	≦ 14.5	2	5	1	0	0
	≦ 15.5	7	9	4	3	1
	< 17.0	16	18	14	14	6
	= 17.0	1	2	0	0	0
	> 17.0	13	10	16	16	24
	≧ 18.5	5	2	2	5	8
	≧ 19.5	3	0	0	2	2
August (N = 16.5)	≦ 14.0	3	2	0	1	0
	≦ 15.0	5	6	5	6	1
	< 16.5	21	19	21	19	8
	= 16.5	0	1	0	2	0
	> 16.5	9	10	9	9	22
	≧ 18.0	4	6	1	1	9
	≧ 19.0	3	4	0	0	4
July and August	≦ N —2.5	5	7	1	1	0
	≦ N —1.5	12	15	9	9	2
	< N	37	37	35	33	14
	= N	1	3	0	2	0
	> N	22	20	25	25	46
	≧ N +1.5	9	8	3	6	17
	≧ N +2.5	6	4	0	2	6
Year (N = 7.8)	≦ 6.3	2	3	2	0	0
	≦ 6.8	8	10	4	1	2
	< 7.8	16	22	18	12	5
	= 7.8	0	1	1	2	1
	> 7.8	14	7	11	16	24
	≧ 8.8	5	0	0	4	14
	≧ 9.3	0	0	0	0	5

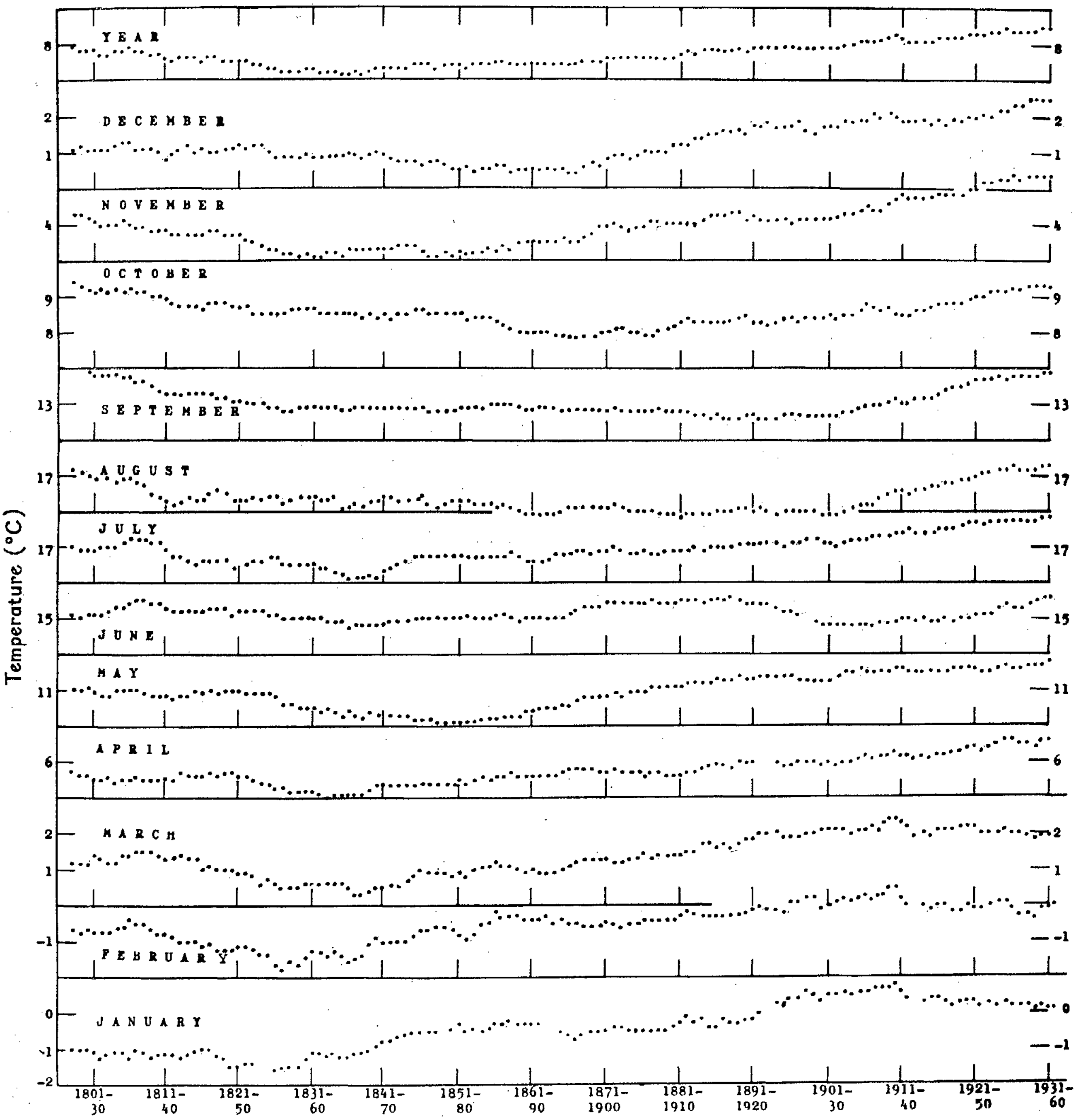

FIG. 1. Running 30-year normals of temperature, Copenhagen.

TABLE 4. The variation of a 30-year normal of temperature (°C.) at Copenhagen

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Maximum	0.8	0.5	2.4	6.6	11.8	15.6	17.8	17.3	14.0	9.4	5.4	2.5	8.5
Period	1910-39	1910-39	1910-39	1925-54	1931-60	1931-60	1930-59	1926-55	1798-1827	1798-1827	1926-55	1929-58	1930-59
Minimum	—1.6	—1.8	0.3	5.0	10.1	14.7	16.1	15.8	12.6	7.9	3.1	0.4	7.1
Period	1826-55	1827-56	1838-67	1833-62	1851-80	1836-65	1838-67	1881-1910	1893-1922	1866-95	1829-58	1867-96	1838-67
Range	2.4	2.3	2.1	1.6	1.7	0.9	1.7	1.5	1.4	1.5	2.3	2.1	1.4

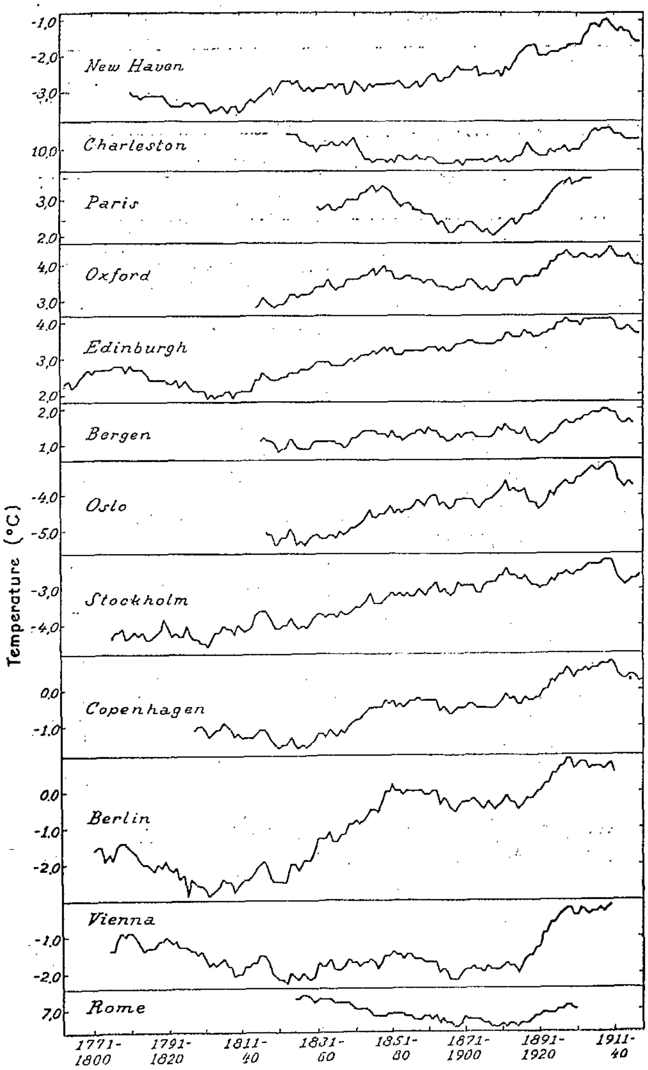

FIG. 2. Overlapping 30-year normals of temperature (°C.) January. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 6.)

in a great part of the world. It will be noted that in January the temperature has risen considerably in the temperate and polar zones in the Northern Hemisphere; in July the rise is considerable only in Scandinavia and the United States. For the year as a whole the temperature has risen 1° in the northern polar zone from 1910 up to 1940.

It must be borne in mind that the air temperature at the surface is not a reliable indicator of the heat content of the atmosphere. In the winter there can be a thin cold layer of air just over the ground, whilst the upper air temperature may be much above normal. On the other hand, a thin layer of air near the ground may have above normal temperature, whilst the upper air can have below normal temperature.

Fig. 4 shows 30-year running normals of yearly precipitation at stations in Australia, India and Europe. The curves do not resemble each other.

Fig. 5 is a map showing the change in yearly precipitation at land and coastal stations. It is evident that precipitation is a very variable element.

Fig. 6 shows running normals of mean annual temperature and yearly precipitation at Copenhagen. It will be seen that there is no simple connexion between these elements.

Figs. 7 (*a*) and 7 (*b*) are graphical representations of running 30-year normals of pressure in January in northwestern Europe and Ivigtut (Greenland). At times the curves have a similar trend.

Figs. 8 (*a*) and 8 (*b*) are maps indicating the change of pressure in January and July. It will be noted that, in January there is a decrease of 3 mb. in Ireland and of 2 mb. in south Greenland, whilst in Asia and the Canary Islands there is an increase of 2 mb. In July there is a decrease of 2 mb. in south-western Europe and 1 mb. between Scotland and Iceland, whilst between the United States and West Africa there is a increase of 1-2 mb.

Corresponding with the changes of pressure, the pressure gradient and the wind must also have varied both in direction and in force.

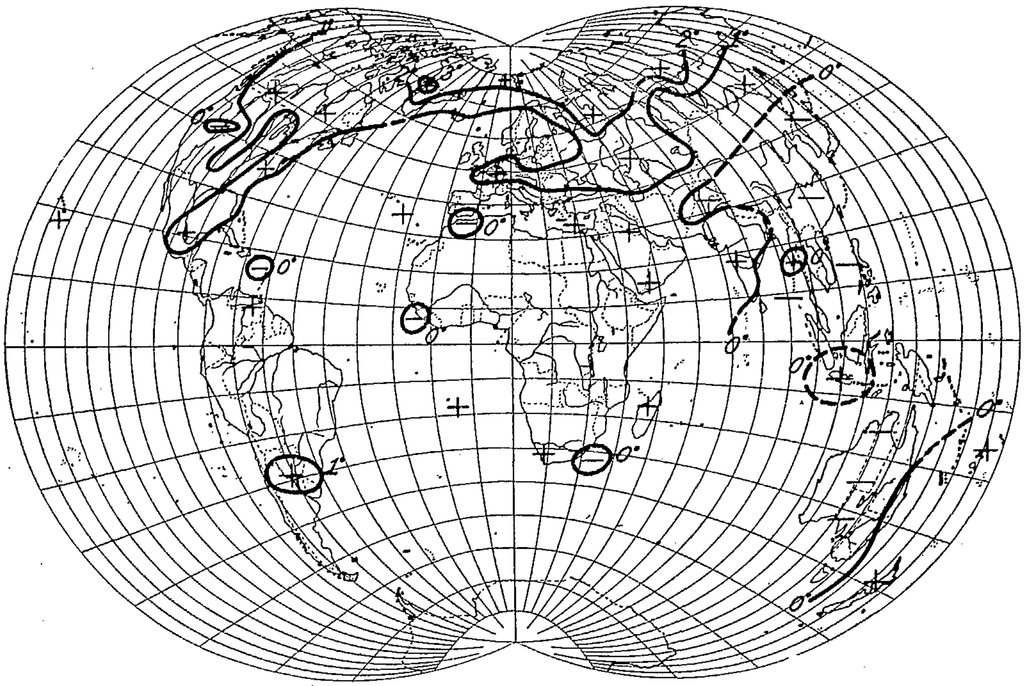

FIG. 3 (*a*). The variation of temperature, $T_{1911\text{-}40} - T_{1881\text{-}1910}$ °C. January. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 26.)

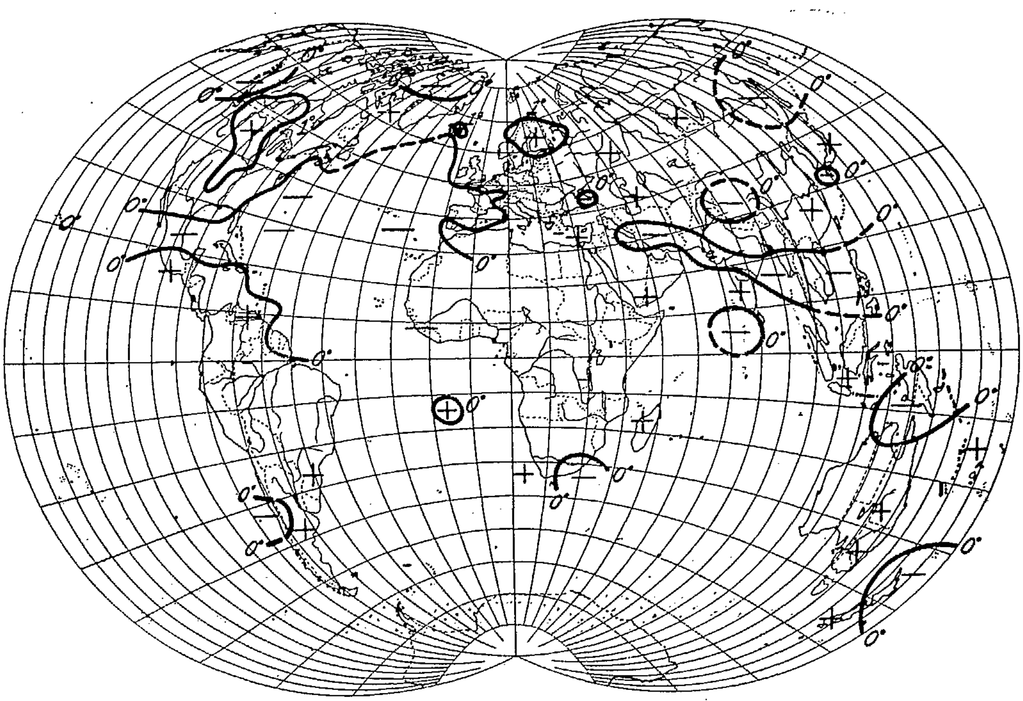

FIG. 3 (*b*). The variation of temperature, $T_{1911\text{-}40} - T_{1811\text{-}1910}$ °C., July. (From "Recent climatic fluctuations" *Folia Geographica Danica*, Copenhagen, 1949, Fig. 27.)

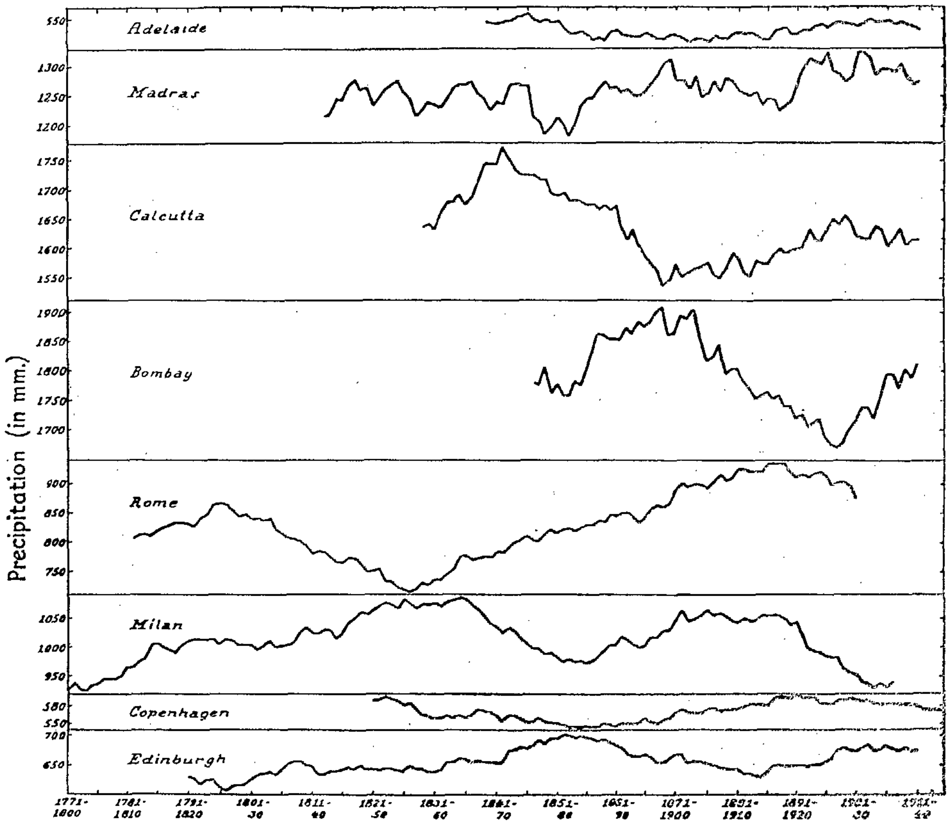

Fig. 4. Overlapping 30-year normals of precipitation, mm./year. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 46.)

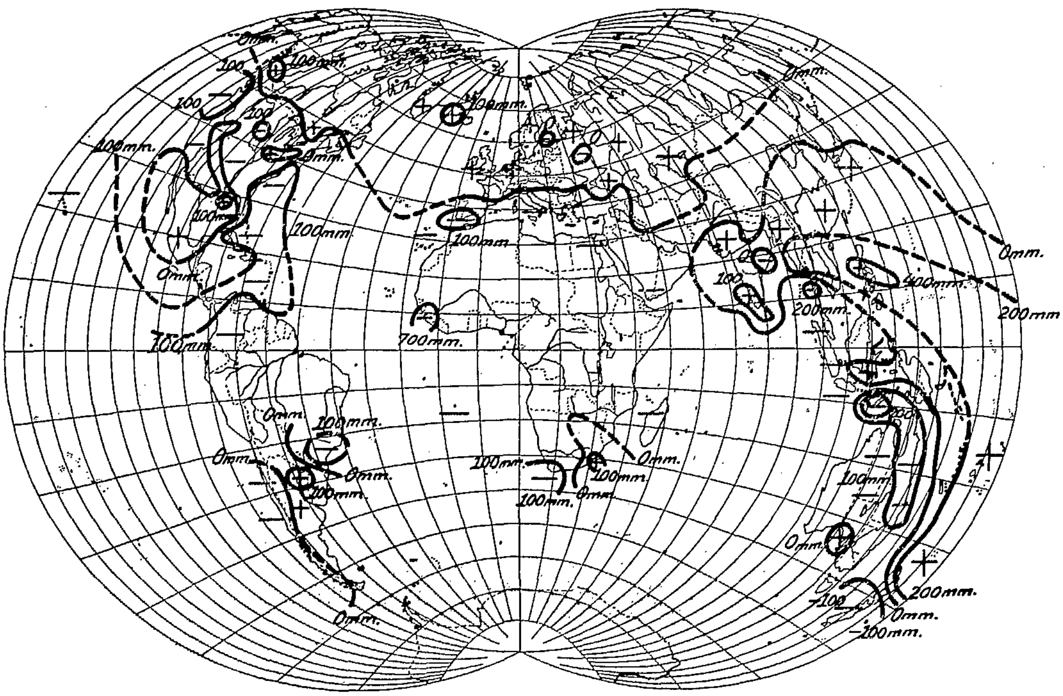

Fig. 5. The variation of precipitation, $R_{1911\text{-}40} - R_{1881\text{-}1910}$ mm./year. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 60.)

TABLE 5. Variation of temperature, $T_{1931\text{-}60} - T_{1901\text{-}30}$

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Jacobshavn	3.2	3.1	1.8	0.4	0.5	1.1	0.7	—0.2	—0.1	0.3	0.3	0.8	1.0
Bodø	—0.9	—0.5	0.1	0.2	0.4	0.7	0.8	0.6	1.1	1.1	1.3	1.0	0.5
Haparanda	—0.4	0.3	—0.4	0.3	0.9	0.6	0.7	1.0	0.6	0.7	1.7	1.6	0.6
Bergen	—0.2	—0.3	0.3	0.1	1.0	0.6	0.8	1.2	0.9	0.8	1.4	0.8	0.6
Stockholm	—0.4	—0.5	—0.3	0.8	0.9	1.2	1.0	1.4	1.0	0.7	1.2	1.4	0.7
Copenhagen	—0.4	—0.1	—0.2	0.6	0.5	0.8	0.7	1.4	1.2	0.8	1.3	0.8	0.6
Schleswig	—0.7	—0.5	—0.4	0.7	0.3	0.8	0.5	1.1	1.0	0.5	1.1	0.4	0.4
Munich	—0.6	—0.4	0.1	1.0	0.2	0.8	0.8	0.7	1.0	0.5	0.8	—0.2	0.4
Cape Town	0.5						—0.1						0.2

TABLE 6. Variation of temperature, $T_{1951\text{-}60} - T_{1901\text{-}30}$

	January	July	Year
Copenhagen	0.0	0.3	0.6
Tokyo	1.3	0.7	
Buenos Aires	0.5	0.9	
Cape Town	0.6	—0.2	0.1
Djakarta	0.5	0.4	
Auckland	0.9	—0.1	

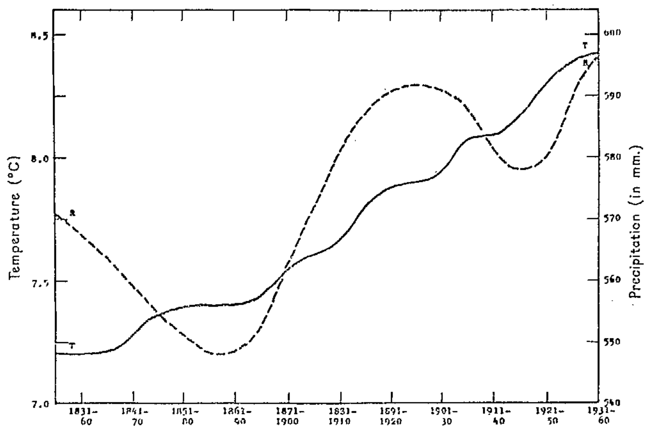

FIG. 6. Running 30-year normals of temperature (T) and precipitation (R), Copenhagen.

For example, at Vestervig in Jutland the south-easterly and north-easterly winds have become more frequent and the winds between south and west have become rarer. In July the south-easterly and south-westerly winds have become more frequent and the westerly and northerly winds have become rarer up to 1950.

At De Bilt in Holland the south-easterly winds have become more frequent and the south-westerly winds rarer in the winter, whilst in the summer the southerly and north-westerly winds have become more frequent and the westerly and south-westerly winds rarer up to 1950.

It is conceivable that if the variation is not simply fortuitous, the present climatic fluctuation is due to more than one cause.

The most significant causes are probably: variation in solar radiation; urbanization (increase of carbon dioxide, water vapour, smoke and dust in the air); and volcanic eruptions.

An increase in the solar radiation could lead to an increase in the general circulation; but initially, this might cause a rise in temperature on the eastern side and a fall in temperature on the western side of the great stationary lows in the Northern Hemisphere. Later on, a general rise in temperature could be expected.

An increase in the carbon dioxide and water vapour content of the atmosphere might bring about a steady rise in temperature all over the world, whilst an increase of smoke and dust could cause a fall. It is possible that the effect of smoke and dust in the air may compensate the effect of carbon dioxide and vapour.

In large parts of the polar and temperate zones the climatic fluctuation has been good for fauna and flora. The more prolonged and warmer summers have made it possible to harvest twice in many places where previously only one harvest was possible. The boundary line for both animals and plants has moved farther north and higher up the mountains. Up to 1950 Denmark has been enriched by not less than 25 new species of birds, the Faroe Islands by 8, Iceland by 6 and west Greenland by 5 new species; in north Scandinavia spruce and pine grow better than before, and so on. All this speaks for itself, even if some evolution among both animals and plants has been taken into account.

It is particularly interesting that cod fish first began to frequent the Greenland waters in greater quantities between 1910 and 1920 when the climatic improvement commenced and the prevailing wind around south Greenland changed from north-west to south-east.

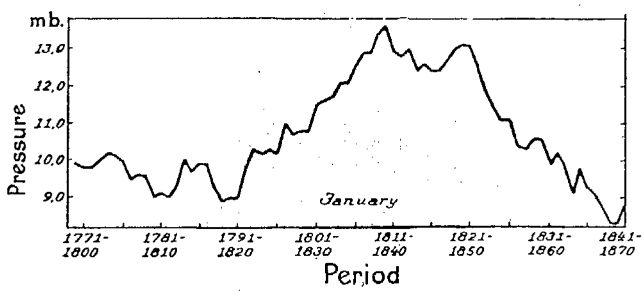

FIG. 7 (*a*). Edinburgh. Overlapping 30-year normals of pressure (mb.) (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 62.)

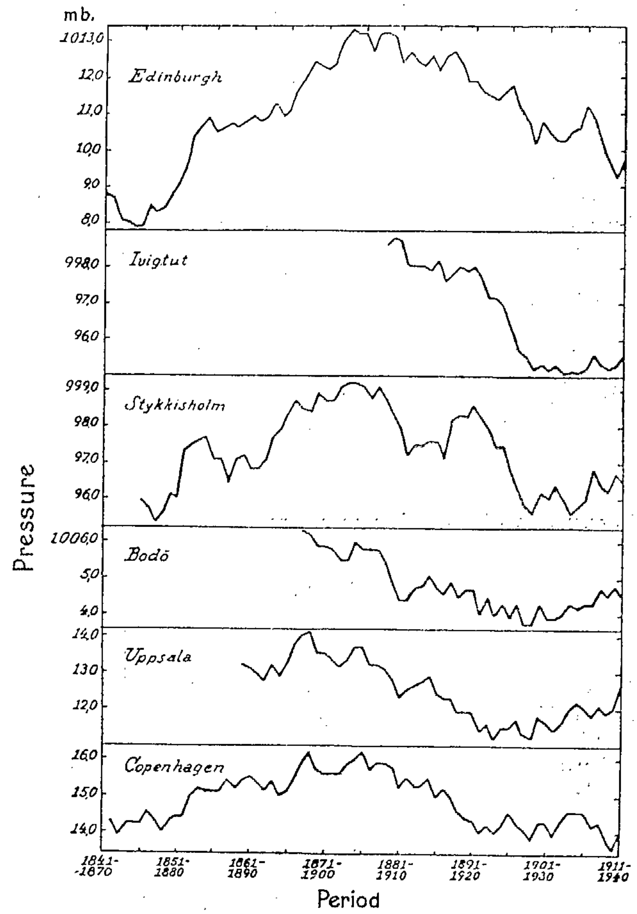

FIG. 7 (*b*). Overlapping 30-year normals of pressure, mb., January (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 61.)

RÉSUMÉ

Variations climatiques (L. Lysgaard)

Depuis que des observations météorologiques ont été entreprises, des variations climatiques considérables ont été enregistrées, notamment dans les régions tempérées et polaires.

Les documents disponibles illustrent les changements intervenus en ce qui concerne la pression, la température, les précipitations et les vents jusqu'en 1950 dans de nombreuses stations, et jusqu'en 1960 à Copenhague. Des cartes montrent les écarts relevés de 1910 à 1940 : $N_{1910\text{-}1940} - N_{1880\text{-}1910}$. Le nombre des taches solaires a également subi d'importantes variations.

Les fluctuations de courte durée peuvent être dues à des causes fortuites telles qu'éruptions volcaniques; quant aux fluctuations de plus longue durée, elles peuvent résulter notamment de la variation des radiations solaires, ou d'une augmentation de la teneur en anhydride carbonique de l'atmosphère, du fait de l'urbanisation.

L'amélioration du climat a exercé une influence sensible sur l'agriculture; c'est ainsi que la production agricole du Danemark s'est considérablement accrue depuis quelques années.

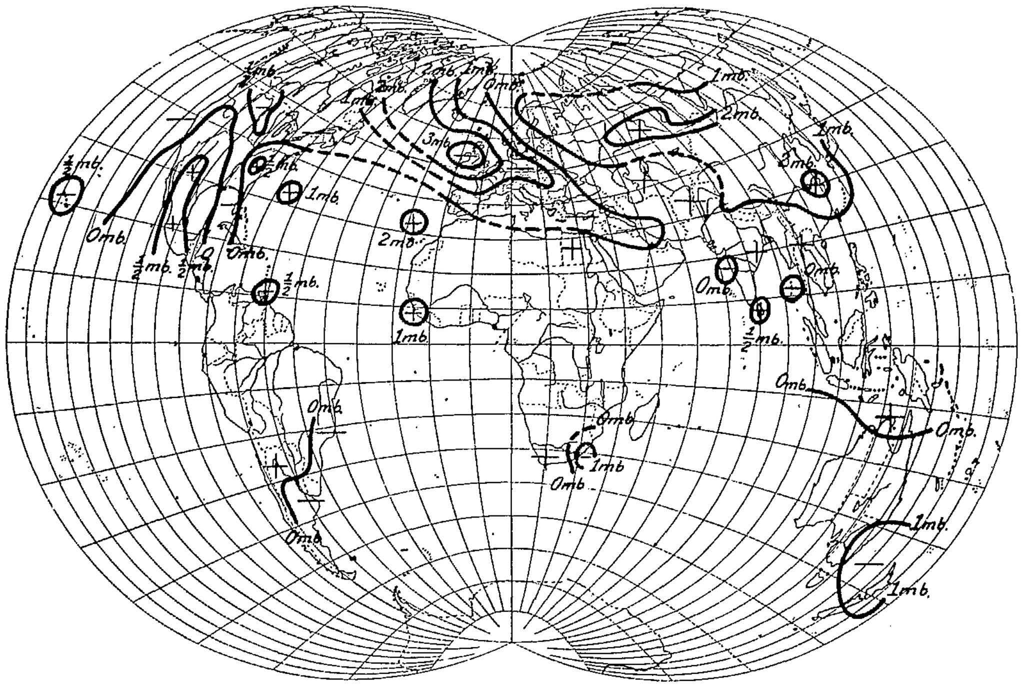

FIG. 8 (*a*). The variation of pressure, $P_{1911\text{-}40} - P_{1881\text{-}1910}$ mb., January. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 70.)

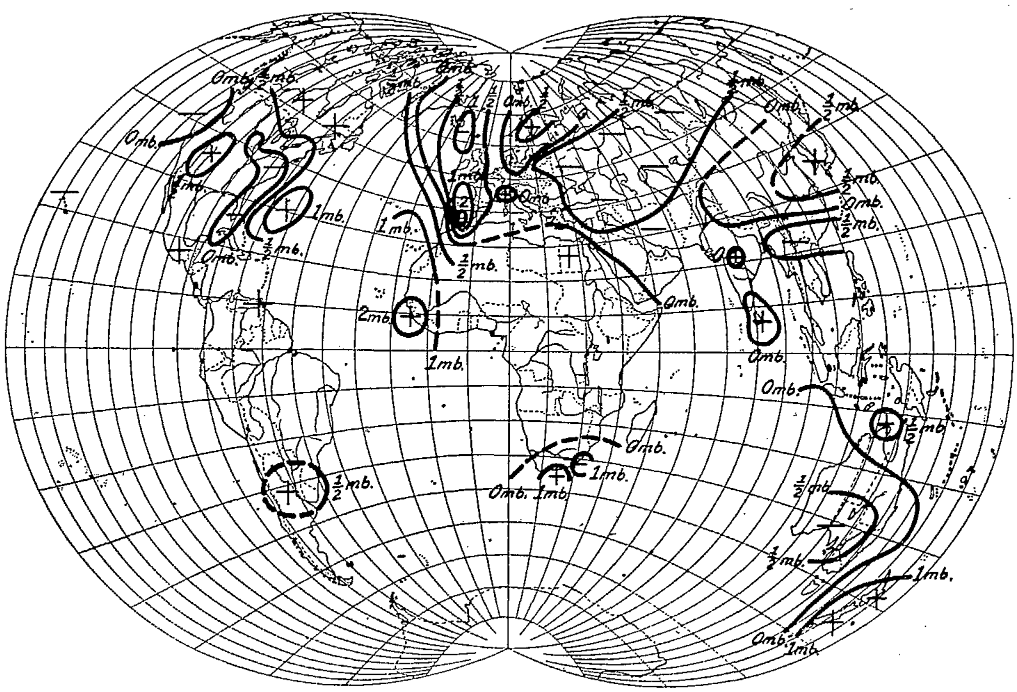

FIG. 8 (*b*). The variation of pressure, $P_{1911\text{-}40} - P_{1881\text{-}1910}$ mb., July. (From "Recent climatic fluctuations", *Folia Geographica Danica*, Copenhagen, 1949, Fig. 71.)

ON THE WORLD-WIDE PATTERN OF SECULAR TEMPERATURE CHANGE

by

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INTRODUCTION

The writer has recently presented new evidence of fluctuations of global mean temperature within the present century (Mitchell, 1961*b*). This evidence was based on an updating (through the year 1959) of the zonally averaged temperature trends originally derived by Willett (1950) from world weather records data.

The fluctuations have consisted primarily of the well-known warming of the earlier decades of the century, and a tendency for cooling since about 1940 which appears to have not only halted but reversed the warming in most latitudes.

In the present paper, the writer proposes to review the evidence of such global temperature trends, with particular attention to their statistical significance and to their geographical pattern.

ZONALLY INTEGRATED TRENDS, 1880-1960

As described by Mitchell (1961*b*) the basic data used to derive the zonally integrated trends consisted of the series of differences between consecutive five-year (pentad) averages of temperature at each of a large number of stations distributed as uniformly as possible over the earth (not more than one station per 10°-latitude-longitude square). The stations were then grouped by 10°-latitude bands, and the temperature-difference series were averaged over all stations within each 10° band. Cumulative sums of these averaged differences were then used as a measure of inter-pentadal temperature changes in the band. This procedure served to minimize the irrelevant influence of temporal variations of station network on the results. Finally, global and hemispheric average trends were derived by forming suitably weighted averages of the 10°-latitude band indices.

Considering first the trends of global mean annual and winter temperature, shown as the solid curves in Fig. 1, we find rather uniform rates of warming from the 1880s[1]

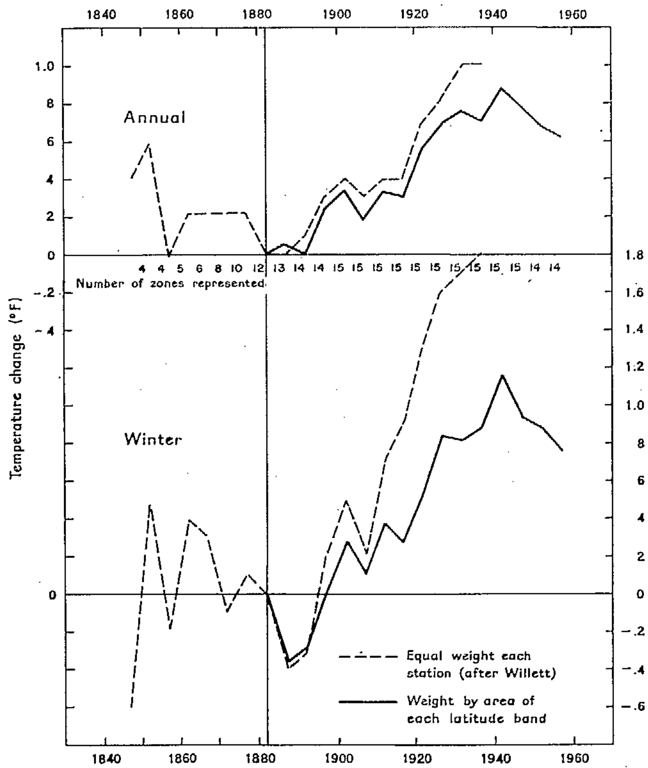

Fig. 1. Trends of world mean temperature, shown for successive pentads relative to the 1880-84 pentad. Annual average data above, and winter-season data below. Solid curves are area-weighted averages of data in Table 5 for each of indicated total number of 10°-latitude bands, through the year 1959. Dashed curves are unweighted averages of data for all selected stations through the year 1939, after Willett (1950).

1 In Figs. 1-3 the pentad centred on 1882 was recognized as the first pentad for which all latitude bands (except the polar extremities) were represented by some data.

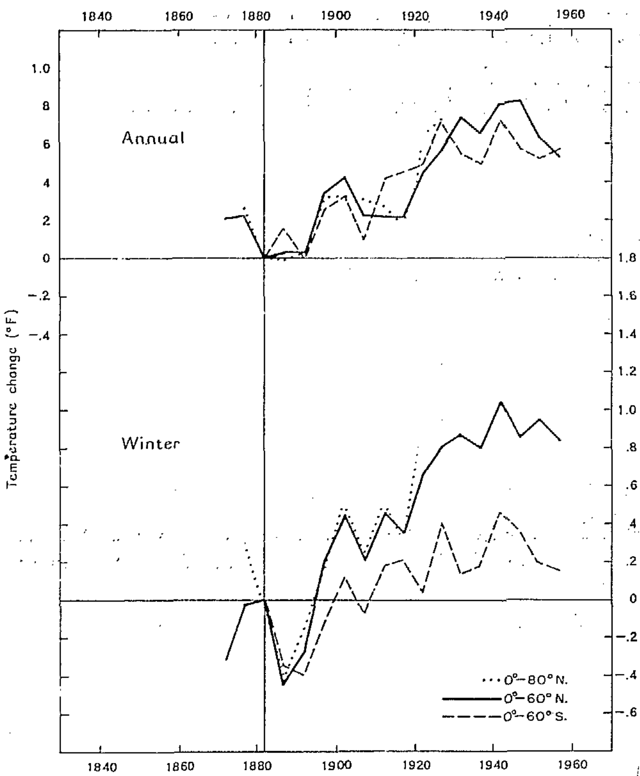

FIG. 2. Trends of mean temperature in Northern and Southern Hemispheres, by pentads, within indicated latitude limits. Annual average data above and winter-season data below. All curves are area-weighted averages of 10°-latitude band data in Table 5.

to the early 1940s, and a marked tendency for cooling since the early 1940s. Average temperatures in recent years have apparently returned to about the levels of the 1920s.

Turning next to a comparison of the zonally integrated trends for the Northern and Southern Hemispheres, shown in Fig. 2, we find that the trends have been

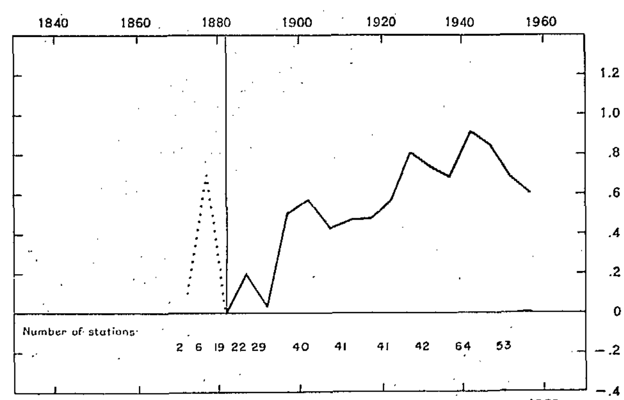

FIG. 3. Trend of annual mean temperature in tropics (30° N.-30° S.) by pentads, based on numbers of stations indicated.

qualitatively similar in both. Inasmuch as the magnitudes of temperature changes are known to be a strong function of latitude (at least in the Northern Hemisphere), the trend for the Northern Hemisphere has been shown in Fig. 2 for 0°-60° N. as well as for 0°-80° N., to compare with the trend for 0°-60° S. (Climatological data for higher southern latitudes are virtually lacking.) Inclusion of data for 60°-80° N. in the Northern Hemispheric averages are seen in Fig. 2 (dotted curves) to increase the magnitude of the net secular trend of that hemisphere by as much as half although the added data represent only a one-seventh increase of surface area.

Of special interest for this symposium, perhaps, is the fact that the tropics have shared in the secular warming of the past century, as well as in a tendency for cooling since the 1940s. Fig. 3 shows the pentadal variation of annual mean temperature since 1880 in the zone between 30° N. and 30° S. The net warming in this zone had reached nearly 1° F. from about 1880 to 1940, and the cooling since about 1940 has thus far totalled about −0.3°F.

Callendar (1961) has also published zonally integrated values of mean annual temperature change in different increments of latitude. For the six decades ending with 1950, when Callendar's data terminated, these changes have been found to agree closely with the changes derived from my own and Willett's data (see Landsberg and Mitchell, 1961). This is reassuring in view of dissimilar data selection and analysis procedures in the two studies. In terms of difference between consecutive 30-year periods, this comparison is shown in Table 1.[1]

REPRESENTATIVENESS OF ZONALLY INTEGRATED TRENDS

Fig. 4 indicates the geographical locations of all stations that contributed at least 20 years of data to the trends illustrated in the previous figures. The most casual glance at Fig. 4 serves to remind us that in speaking of average trends over large parts of the world we are really speaking primarily of trends over the continents and a few relatively well populated archipelagos. Large expanses of ocean, especially in the Southern Hemisphere, are completely devoid of historical data (areas outlined in Fig. 4). With this fact in mind, let us next consider the representativeness of the available data from two different points of view. First, to what extent are the temperature trends shown in Figs. 1-3 representative of the principal areas of civilization—i.e., primarily the continental land masses and archipelagos—for which data are comparatively abundant? Second, to what extent are the calculated trends representative of the earth as a whole, and therefore indicative

1. Inasmuch as Callendar did not treat global data available since 1950, it is impossible to compare notes with him concerning evidence of the recent culmination of the warming.

TABLE 1. Thirty-year change of annual mean temperature (°F.), 1890-1920 to 1920-50[1]

Zone	After Callendar		After Willett and Mitchell	
	Inclusive latitudes	Δ	Inclusive latitudes	Δ
World	60° N.-50° S.	+0.41	60° N.-50° S.	+0.37
North temperate	60°-25° N.	+0.70	60°-30° N. 60°-20° N.	+0.64 +0.57
Tropical	25° N.-25° S.	+0.31	30° N.-30° S. 20° N.-20° S.	+0.35 +0.39
South temperate	25°-50° S.	+0.25	20°-50° S. 30°-50° S.	+0.10 +0.08

1. Callendar's data are 1891-1920 to 1921-50; Willett and Mitchell's data are 1890-1919 to 1920-49.

of variations of the net planetary atmospheric heat budget?

TRENDS AS REPRESENTATIVE OF THE DATA AREAS (REGIONS OF ABUNDANT DATA)

Let us postulate that the stations whose data have been used in this trend study are randomly distributed over the region of available data outlined in Fig. 4 (hereafter denoted for simplicity as the "data areas", which roughly coincide with the continents). By the methods given in my research paper (Mitchell, 1961*a*) we can then obtain an estimate of the standard error of the zonally averaged trends as representative of the data areas. An outline of these methods and some statistics necessary for their application here are given in an appendix at the end of the paper.

Trends of mean annual and winter temperature since 1890 are summarized along with their associated standard errors for various latitude zones of the world in Tables 2 and 3. The trends are shown as 30-year changes from 1890-1919 to 1920-49 (the same intervals as in Table 1) in Table 2 and as 10-year changes from 1940-49 to 1950-59 in Table 3. The first period coincides with the great "world-wide" warming, and the second coincides with the cooling evident in Figs 1-3 which followed. It is clear from these tables that both the warming and subsequent cooling were shared by (the data areas of) the Northern and Southern Hemispheres and the tropics. The statistical significance of the warming was moderately high in the Southern Hemisphere (trend equal to 2-3 standard errors) and extremely high elsewhere as well as for the world as a whole (trend equal to 4-7 standard errors).

The significance of the cooling has also been moderately high, but has varied substantially with latitude and season. (The trend for winter in the Northern Hemisphere was comparable to its standard error; all other trends shown in Table 3 are about two or three times their standard errors.) The recent cooling in the tropics, as well as the annual average cooling for the world as a whole, has been highly significant (exceeding about 3 standard errors, corresponding to significance levels of 99 per cent and higher).

TRENDS AS REPRESENTATIVE OF THE WORLD AS A WHOLE

In view of the sizeable oceanic regions of the world totally devoid of data, it is only with certain reservations that the trends noted above can be taken as representative of planetary average conditions. Until such time as these data gaps have been filled, either by conventional ocean weather stations, by automatic weather buoys, or possibly by indirect sensing techniques involving artificial earth satellites, secular fluctuations of temperatures in these areas can never be determined with much confidence.[1]

In order to evaluate the available trend data as a measure of planetary average conditions, we will adopt approaches described below.

In the first approach, we assume that the unknown trends averaged for the no-data areas are identically zero. That is to say, the no-data areas (open oceans) are presumed not to have participated to an appreciable extent in any of the net temperature changes measured elsewhere (the data regions). Inasmuch as there is little justification—either empirical or theoretical—for supposing that average trends over the oceans are normally opposed in sign to those over the continents, this assumption provides the basis for a conservative test of the statistical significance of the observed trends as

1. Climatological analyses of synoptic ship reports of air and sea temperature have been made which have some value in this regard. Except for certain well-travelled shipping lanes in the northern oceans, however, irregular timing and spacing of the observations and various sources of inhomogeneity greatly complicate the interpretation of long-term trends evident in such data.

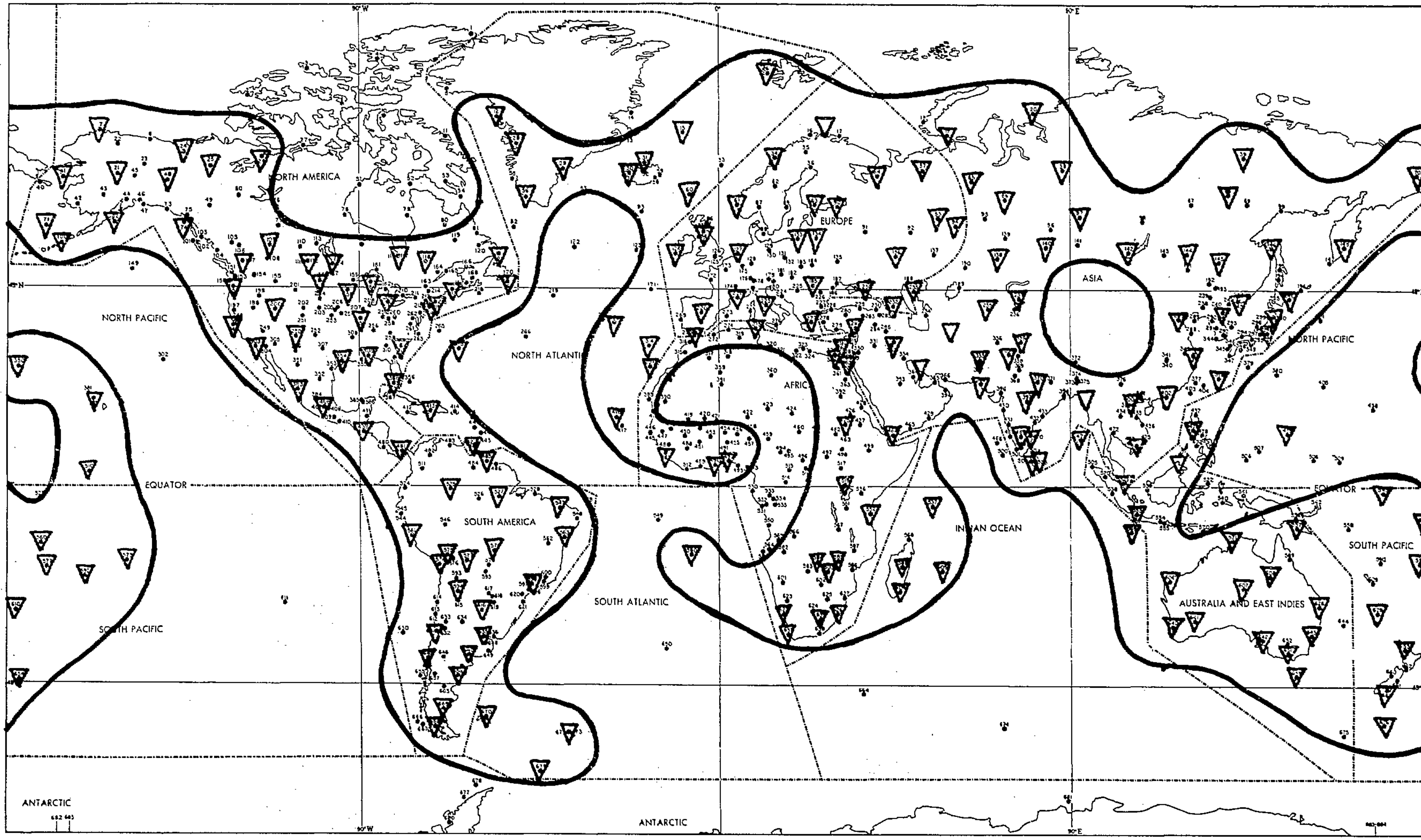

Fig. 4. Locations of stations contributing at least 20 years of data to 10°-latitude band trends in Table 5. Heavy lines circumscribe world areas of good data coverage.

TABLE 2. Thirty-year temperature change (°F.), 1890-1919 to 1920-49, Δ, selected latitude belts; standard error of estimate SE(Δ) for data areas; significance ratio $|\Delta|$ to SE(Δ) applicable to areas of good data coverage (t) and whole earth (t_g), assuming zero net temperature change in areas of no data

Latitude zone	Annual			Winter		
	$\Delta \pm$ SE(Δ)	t	t_g	$\Delta \pm$ SE(Δ)	t	t_g
World						
80° N.-60° S.	+0.49 ±0.07	6.7	4.3	+0.71 ±0.11	6.2	4.5
60° N.-60° S.	+0.39 ±0.07	5.9	3.4	+0.44 ±0.10	4.6	3.0
Northen Hemisphere						
80° N.-0°	+0.64 ±0.09	6.8	5.1	+1.14 ±0.18	6.5	5.0
60° N.-0°	+0.43 ±0.07	6.3	4.4	+0.61 ±0.13	4.9	3.4
Tropics[1]						
30° N.-30° S.	+0.35 ±0.09	3.8	2.0	+0.49 ±0.12	4.0	2.2
Southern Hemisphere						
0°-60° S.	+0.34 ±0.11	3.0	1.3	+0.28 ±0.15	1.9	1.0

1. Winter value for tropics is average in January, February, and December north of Equator and in June, July, and August south of Equator.

TABLE 3. Ten-year temperature change (°F.) 1940-49 to 1950-59; standard error of estimate for data areas; and significance ratios for data areas for whole earth (see heading to Table 2)

Latitude zone	Annual			Winter		
	$\Delta \pm$ SE(Δ)	t	t_g	$\Delta \pm$ SE(Δ)	t	t_g
World						
80° N.-60° S.	—0.19 ±0.06	3.3	1.8	—0.23 ±0.09	2.4	1.1
60° N.-60° S.	—0.17 ±0.05	3.3	1.7	—0.17 ±0.08	2.1	0.6
Northern Hemisphere						
80° N.-0°	—0.26 ±0.09	2.9	1.7	—0.22 ±0.17	1.3	0.7
60° N.-0°	—0.23 ±0.08	3.0	1.6	—0.10 ±0.14	0.8	0.1
Tropics[1]						
30° N.-30° S.	—0.24 ±0.06	3.6	1.9	—0.26 ±0.09	2.9	1.5
Southern Hemisphere						
0°-60° S.	—0.11 ±0.07	1.6	0.8	—0.23 ±0.09	2.6	0.9

1. Winter value for tropics is average in January, February, and December north of Equator and in June, July, and August south of Equator.

representative of planetary conditions. Accordingly, let the change of planetary mean temperature in a given latitudinal band i, between any two time intervals, be given by

$$\bar{\delta}_i = C_i\delta_i + (1 - C_i)\,\delta'_i, \qquad (1)$$

where δ_i is the average trend for the data areas, δ'_i is that for the no-data areas (here assumed identically equal to zero), and C_i is the percentage total area of the band at least 1,000 miles distant from any historical-record station within the zone.[1]

In this way we may calculate globally representative trends corresponding to the data-area trends in Tables 2 and 3 by the formula

$$\bar{\Delta}_0 = \Sigma C_i w_i \delta_i, \qquad (2)$$

where the w_i are proportional to the areas of the 10° bands involved ($\Sigma w_i = 1$). These trends, in turn, may be expressed as ratios to the same standard errors as before, by which we prescribe that the error of estimation of the (zero) trends in the no-data areas is hypothetically equal to that of the changes in the data areas. The resulting ratios (i.e., values of t_g, also shown in Tables 2 and 3) are suitable for estimating the statistical significance of the trends from the planetary point of view. It will be seen in Table 2 that the observed warming trends between 1890 and 1949, with the exception of those in the Southern Hemisphere, remain highly significant (2-5 standard errors). According to Table 3, however, the cooling since 1940 loses much of its significance when viewed in this manner.

In a second approach to this problem, let us consider

1. This figure represents the shortest geographical distance at which the spatial correlation coefficient of mean temperature changes typically diminishes to zero. It is found from empirical evidence that this distance is nearly independent of latitude, at least in the Northern Hemisphere. Values of C for each 10°-latitude band are shown in Table 7.

the following question: What range of hypothetical average temperature change in the no-data areas (i.e., what values of δ'_i) can apply such that, when these are averaged with the measured trends for the data areas, the resulting trends are not significantly different from zero? If such values of δ'_i, denoted as Δ'_c, can be declared unreasonable, then we are justified in accepting the measured trends as evidence not only of redistributions of heat within the atmosphere, but also of changes of the heat budget of the whole planetary atmosphere.

For this purpose, we may set the global trend equal to its expected value

$$\overline{\Delta_c} = \overline{\Delta_o} + [\Sigma(1 - C_i)w_i]\Delta'_c, \tag{3}$$

with $\overline{\Delta}_o$ given by (2), and define t_o such that $t_o > t_g = \overline{\Delta}/\mathrm{SE}(\overline{\Delta})$. If for convenience the sign of $\overline{\Delta}_o$ is always taken as positive, and that of Δ'_o adjusted to agree, we are then led to the inequality

$$\Delta'_c < \frac{t_o\,\mathrm{SE}(\overline{\Delta}) - \overline{\Delta}_o}{\Sigma(1 - C_i)w_i}. \tag{4}$$

For $t_o = 2.58$ (corresponding to the 99 per cent significance level), and for the stipulation that $\mathrm{SE}(\overline{\Delta}) = \mathrm{SE}(\Delta)$, ranges of Δ'_c are shown in Table 4 for the same periods of record and latitude zones as in Tables 2 and 3. With the help of the maps of secular change to be presented in the next section, these values for the no-data areas have been tentatively evaluated as definitely reasonable, marginally reasonable, or unreasonable. Although such an evaluation must at this stage be taken as provisional, it has been extremely difficult by this means to avoid the conclusion that the warming trends for the world as a whole, and for the Northern Hemisphere in particular, are truly planetary in scope. On the other hand, it cannot yet be demonstrated in this way beyond a reasonable doubt that the net cooling since the 1940s has likewise been planetary in scope. That this cooling is of such nature, however, seems reasonable and this should be verifiable if the cooling in the data areas were to continue for another decade or two in the future.

GEOGRAPHICAL PATTERN OF TRENDS

It is patently clear that the zonally integrated trends thus far discussed are not representative of trends at all longitudes within the zones. In order to reveal the pattern of changes, the data for solid-record stations have been differenced between certain 10- and 20-year periods, and these differences mapped as shown in Fig. 5 (*a-f*).

Figs. 5 (*a*) and 5 (*b*) show the 20-year changes of annual-average temperature and winter-season temperature, respectively, from 1900-19 to 1920-39. These charts are directly comparable to those published by Willett (1950, his Figs. 5 and 6), but they have been analysed independently. Comparison of the two sets of analyses reveals a number of differences, primarily in areas of poor data coverage. These differences, which give an indication of the degree of subjectivity involved in making such analyses, are not, however, sufficient to obscure the salient features of the change field evident in both these and Willett's figures. The greatest changes are seen to have been the warming of the Arctic, particularly in the Atlantic sector, and, in the winter season,

TABLE 4. Hypothetical temperature change (°F.) in no-data areas, Δ'_c, such that planetary average change estimated by observed change in data areas, Δ, is not significantly different from zero;[1] and evaluation of reasonableness[2]

Latitude zone	Thirty-year change 1890-1919 to 1920-49		Ten-year change 1940-49 to 1950-59	
	Annual	Winter	Annual	Winter
World				
80° N.-60° S.	< —0.27 (U)	< —0.46 (U)	> —0.09 (?)	> —0.30 (R)
60° N.-60° S.	< —0.12 (U)	< —0.08 (U)	> —0.10 (R)	> —0.34 (R)
Northern Hemisphere				
80° N.-0°	< —0.68 (U)	< —1.22 (U)	> —0.23 (?)	> —0.90 (R)
60° N.-0°	< —0.35 (U)	< —0.28 (U)	> —0.21 (R)	> —0.92 (R)
Tropics				
30° N.-30° S.	< +0.11 (?)	< +0.11 (?)	> —0.09 (R)	> —0.19 (R)
Southern Hemisphere				
0°-60° S.	< +0.24 (R)	< +0.39 (R)	> —0.21 (R)	> —0.25 (R)

1. Computed by equation (4) with $t_o = 2.58$, corresponding to 99 per cent significance level. Values of Δ for comparison are shown in Tables 2-3.
2. R = definitely reasonable, ? = marginally reasonable — hence, true planetary trend may have been zero.
U = unreasonable, hence true planetary trend was non-zero.

a broad zone of cooling throughout southern Eurasia. Some cooling is also evident over Canada, over much of South America and southward to Antarctic, and over parts of southern and western Africa. Warming extended in a more or less continuous zonal belt between about 20° and 40° N., being interrupted only in the Asian sector. This warming took in most of the arid zones of the Northern Hemisphere. The proportion of the total earth's surface which experienced warming during this period was evidently quite large, perhaps as much as 85 per cent for the case of annual temperatures.

Figs. 5 (*c*) and 5 (*d*) show the subsequent 20-year changes from 1920-39 to 1940-59. Although this period coincided with a very small net change of world mean temperature, as can be inferred from Fig. 1, it is clear from these figures that many parts of the world were experiencing appreciable net temperature changes at the time. The earlier warming of the Arctic had apparently terminated, and a fairly extensive area of cooling also appeared over (or at least surrounding) the southern Indian Ocean. Cooling also developed in a meridional band approximately parallel to the principal mountain ranges of the Americas.

The patterns of 10-year change of annual and winter mean temperature from 1940-49 to 1950-59 are shown in Figs. 5 (*e*) and 5 (*f*). This period, according to Figs. 1-3, was one of net cooling over much of the earth.

While the Arctic as a whole appears to have cooled since 1940 the degree of cooling has not been geographically uniform. The greatest cooling appears to have been confined to northern Siberia, the west coast of Greenland (probably including Baffin Bay and the eastern Canadian archipelago), and the St. Elias Range-Rocky Mountain region in Alaska and extreme western Canada. Another area of marked cooling included western South Africa, and this may have extended southward over a considerable portion of the sub-Antarctic.

Fig. 5 (*e*) indicates that, in all, about 80 per cent of the total earth's surface has probably been involved in the net annual cooling since 1940. Four or five areas of net warming nevertheless stand out in Figs. 5 (*e*) and 5 (*f*). These include the United States and south-eastern Canada, eastern Europe, the Pacific coast of Asia, the Brazilian Plateau, and western portions of the Indian Ocean.

Comparing the period of net world-wide warming [Figs. 5 (*a*) and 5 (*b*)] with the period of net cooling [Figs. 5 (*e*) and 5 (*f*)], we are drawn to the following conclusions.

First, although, as we have previously noted, zonally integrated trends over large portions of the earth appear to have been parallel, the trends in individual geographical locations have borne very little systematic relationship to these. That is to say, the trends in most individual localities are not well correlated—either positively or negatively—with the global average trends.

Second, the geographical patterns of change are not predominantly a matter of oscillation of temperature from one time interval to another, as one might expect if a simple strengthening and weakening of the general circulation were responsible. Rather, the patterns appear to have changed in more or less independent modes.

In order to clarify the extent to which the temperature change fields are related to concomitant changes of the general circulation, the writer has differenced the January and the July decadal mean sea level pressure charts for 1940-49 and 1950-59, copies of which were generously supplied to the writer by H. H. Lamb and A. I. Johnson. These are shown respectively in Figs. 6 (*a*) and 6 (*b*). The January pressure change in the Northern Hemisphere, and the July pressure change in the Southern, may be compared with the simultaneous winter temperature change from 1940-49 to 1950-59 shown in Fig. 5 (*f*). From such a comparison, it is evident that most of the areas of strong interdecadal mean temperature changes can be attributed with little difficulty to interdecadal mean wind-field changes. Specifically, one may note the following.

The marked winter-season cooling in south-eastern Alaska and the Yukon evidently coincided with an equally impressive change of pressure gradient in that area in January, which favoured an increased local frequency of Arctic air masses from the Canadian interior.

The warming in the north-eastern United States and south-eastern Canada coincided with a weakening of the normal north-westerly gradient wind from the Hudson Bay region, which permitted a higher incidence of warm maritime air masses to reach the area in the 1950s. Much the same relationship can be noted between the warming and the circulation change in the vicinity of Japan from the 1940s to the 1950s.

The change of the pressure field across North America, like that across Europe, was such as to favour an intensified zonal flow in those areas. In the case of North America, this may have resulted in increased precipitation and downslope heating consistent with the observed warming over and eastward of the Rocky Mountain Plateau in the United States. In the case of Europe, the strengthened westerlies probably decreased the incidence there of polar outbreaks from Siberia.

In the Southern Hemisphere, similarly direct relationships between the winter temperature and July circulation changes can be noted. However, even relatively large pressure changes are insufficient to produce radical changes of the energetic zonal circulation of the Southern Hemisphere. Consequently, it is not surprising that the temperature changes associated with the pressure changes have been smaller in magnitude there and have in some instances been smeared over broader ranges of longitude than is true of the Northern Hemisphere.

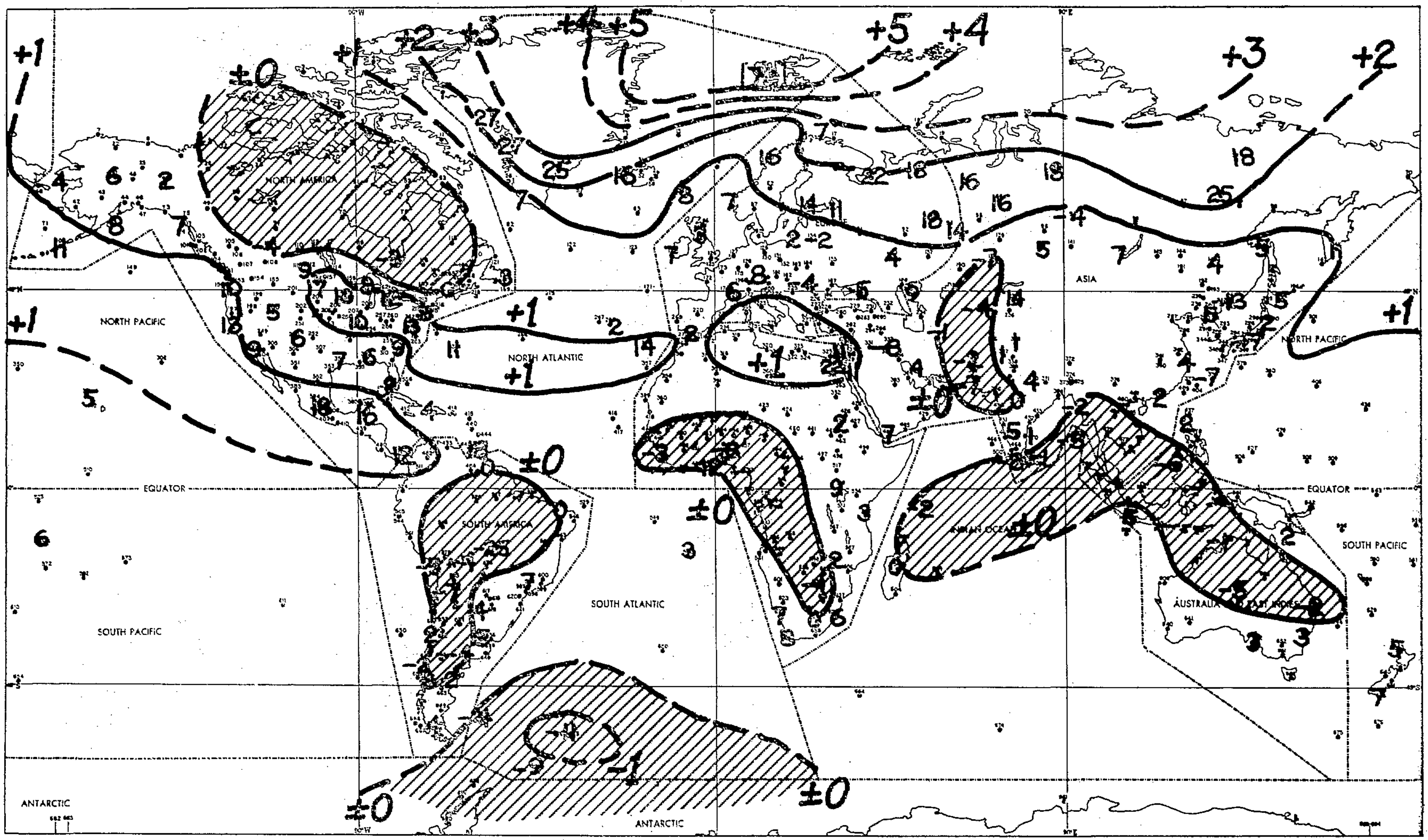

FIG. 5. Changes of annual and winter mean temperature between periods of record indicated. Station data shown in tenths of degrees Fahrenheit; isolines are whole degrees Fahrenheit. Areas of negative change are shaded.

(*a*) Annual. Twenty-year change 1900-19 to 1920-39.

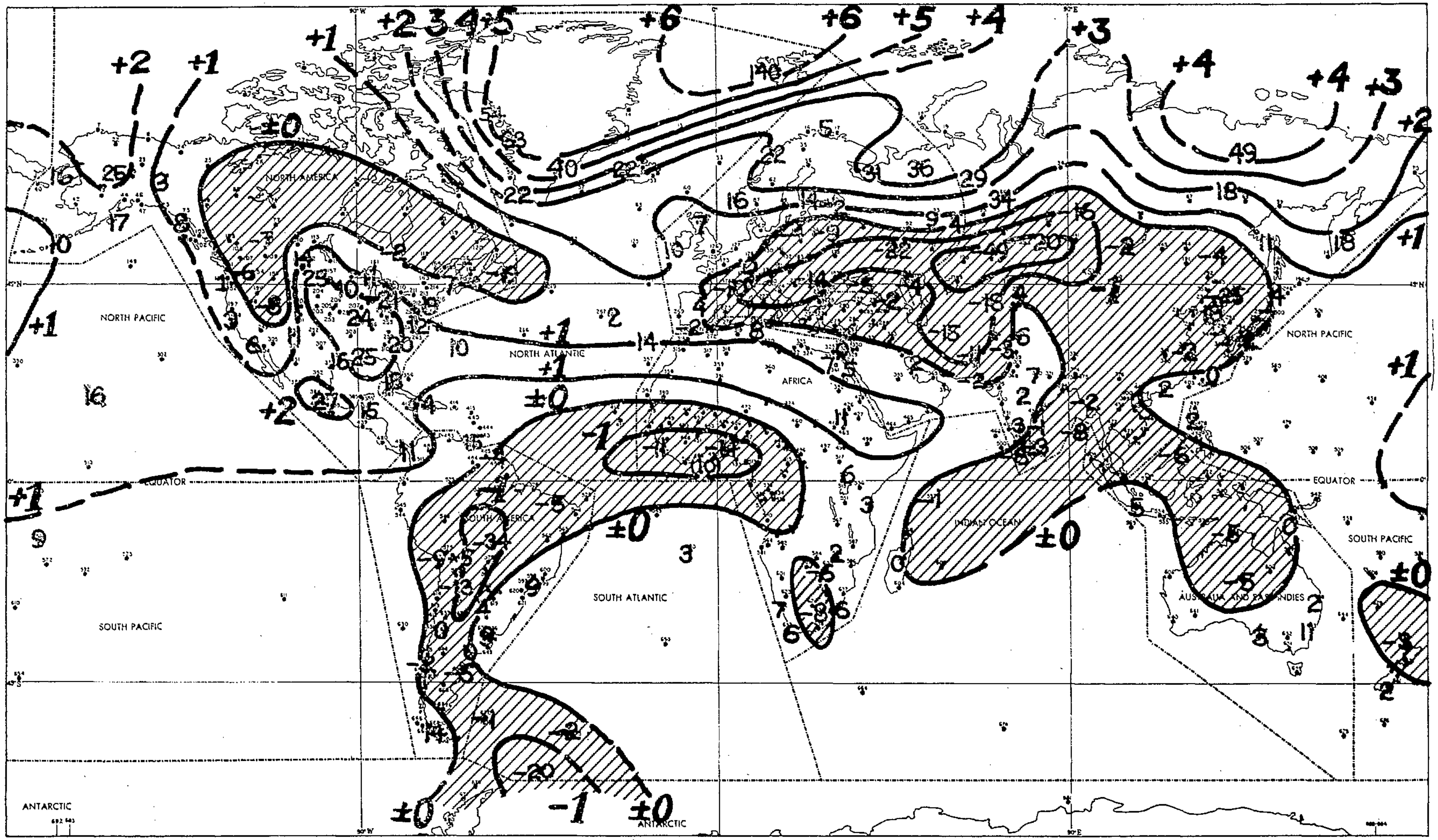

FIG. 5 (*b*). Winter. Twenty-year change 1900-19 to 1920-39.

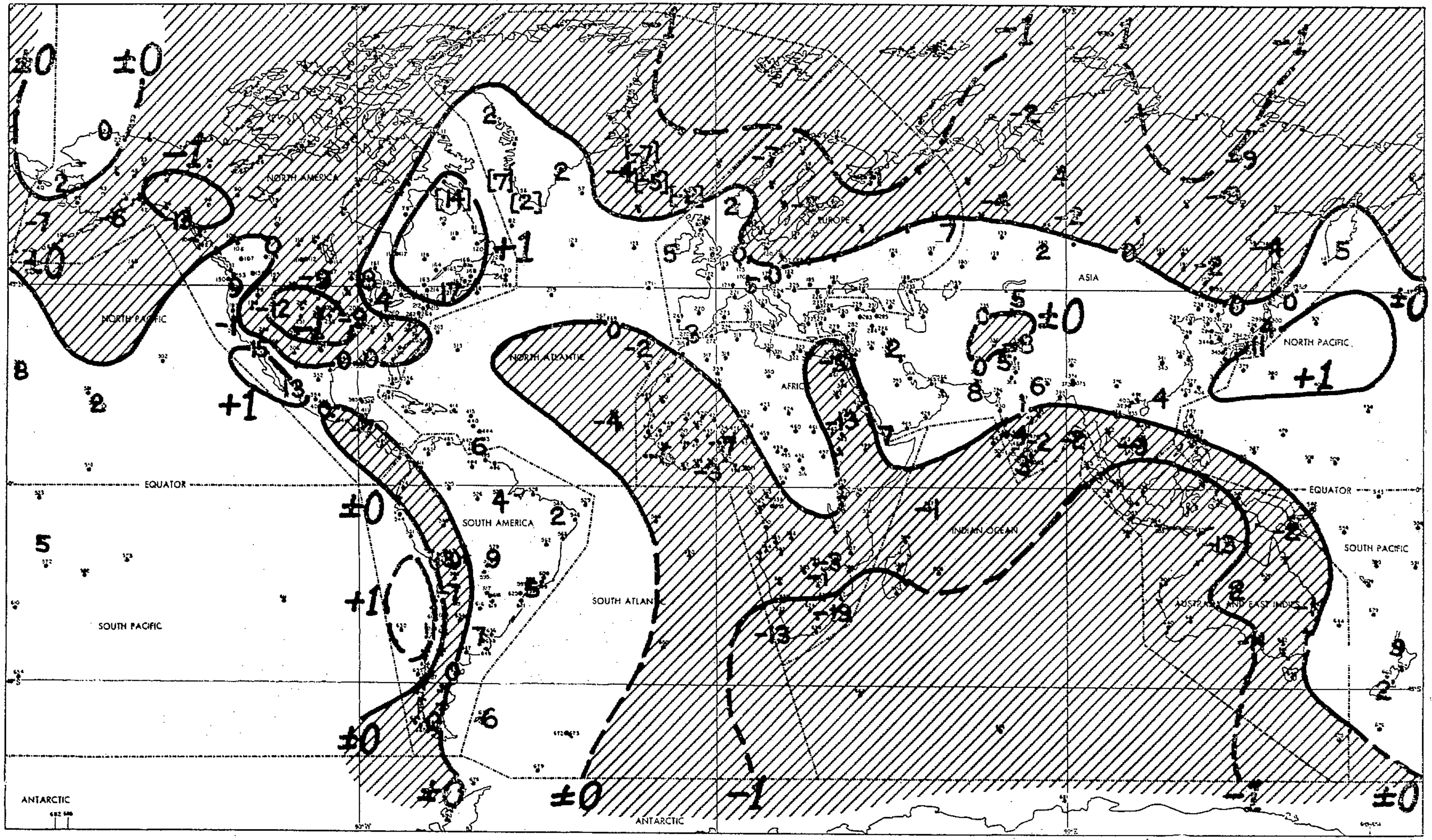

FIG. 5 (*c*). Annual. Twenty-year change 1920-39 to 1940-59.

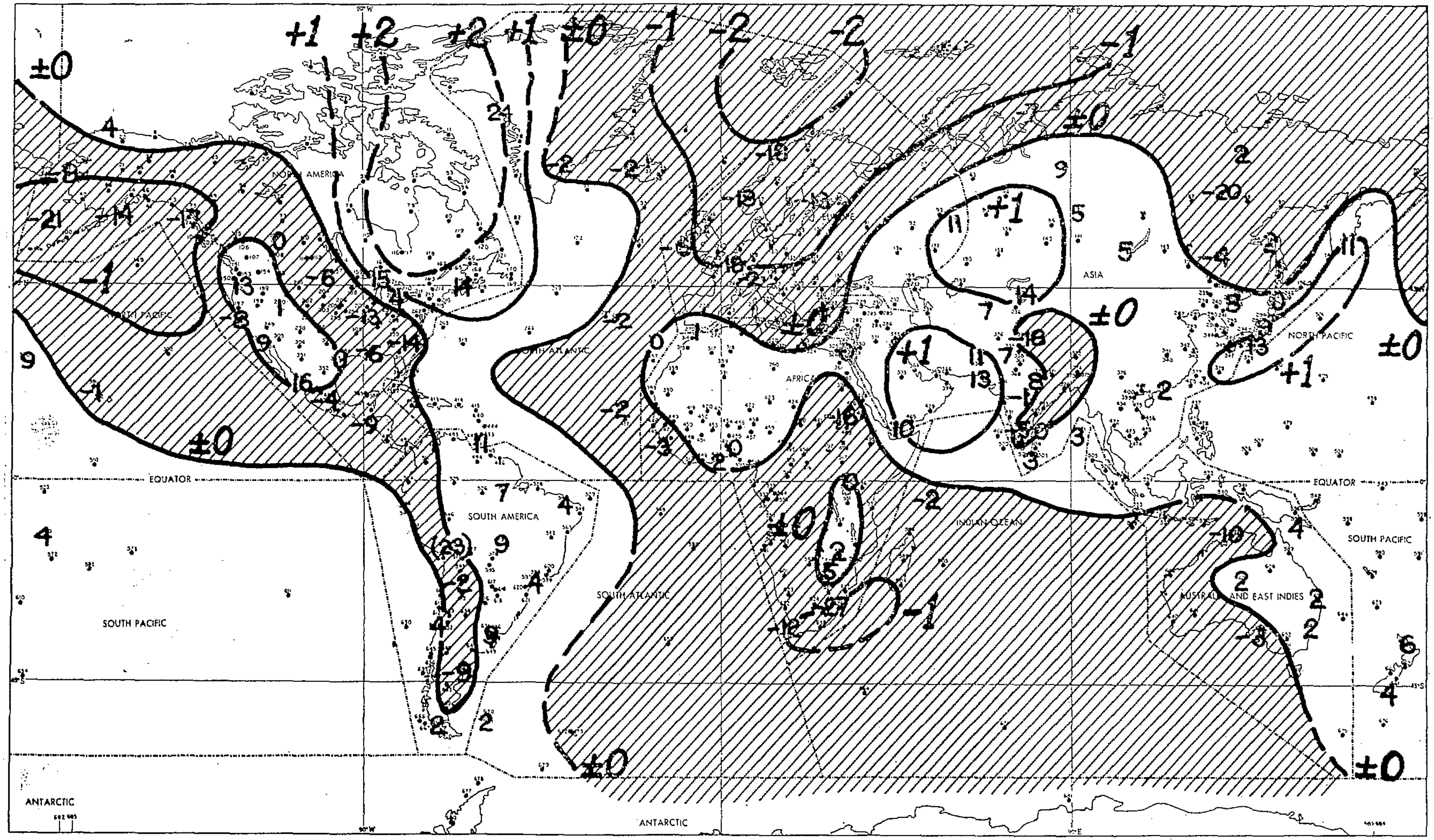

FIG. 5 (*d*). Winter. Twenty-year change 1920-39 to 1940-59.

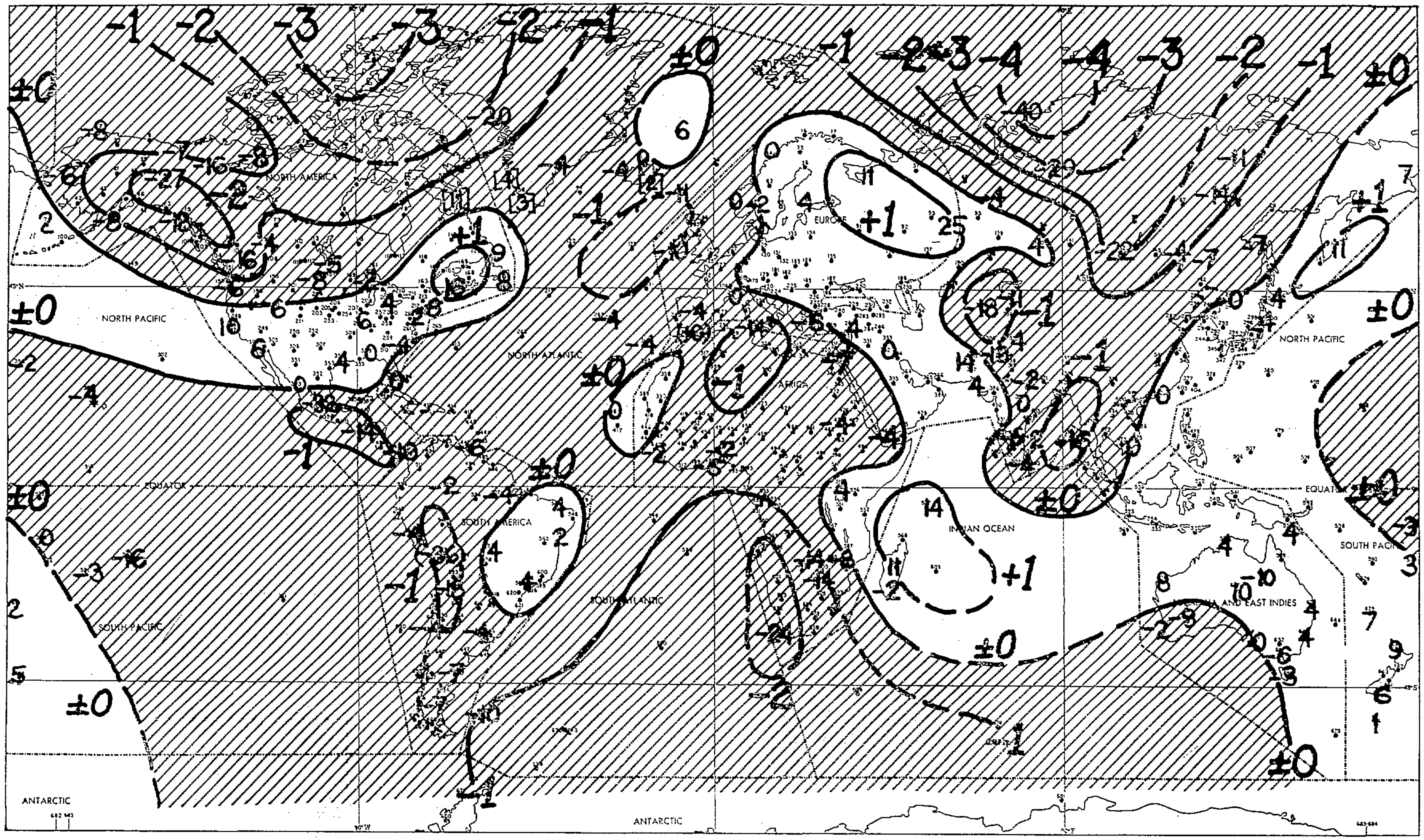

FIG. 5 (*e*). Annual. Ten-year change 1940-49 to 1950-59.

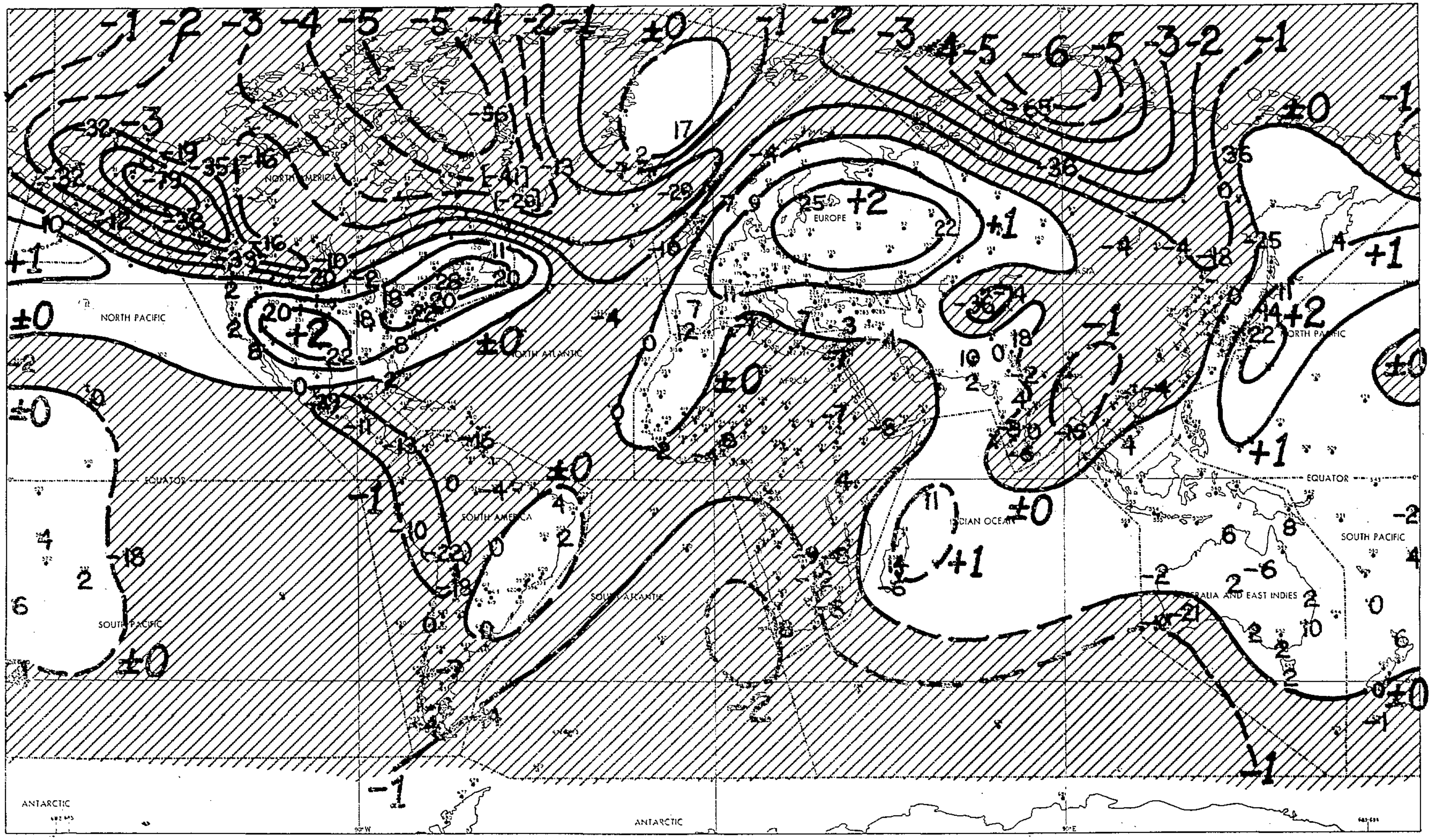

FIG. 5 (*f*). Winter. Ten-year change 1940-49 to 1950-59.

(a)

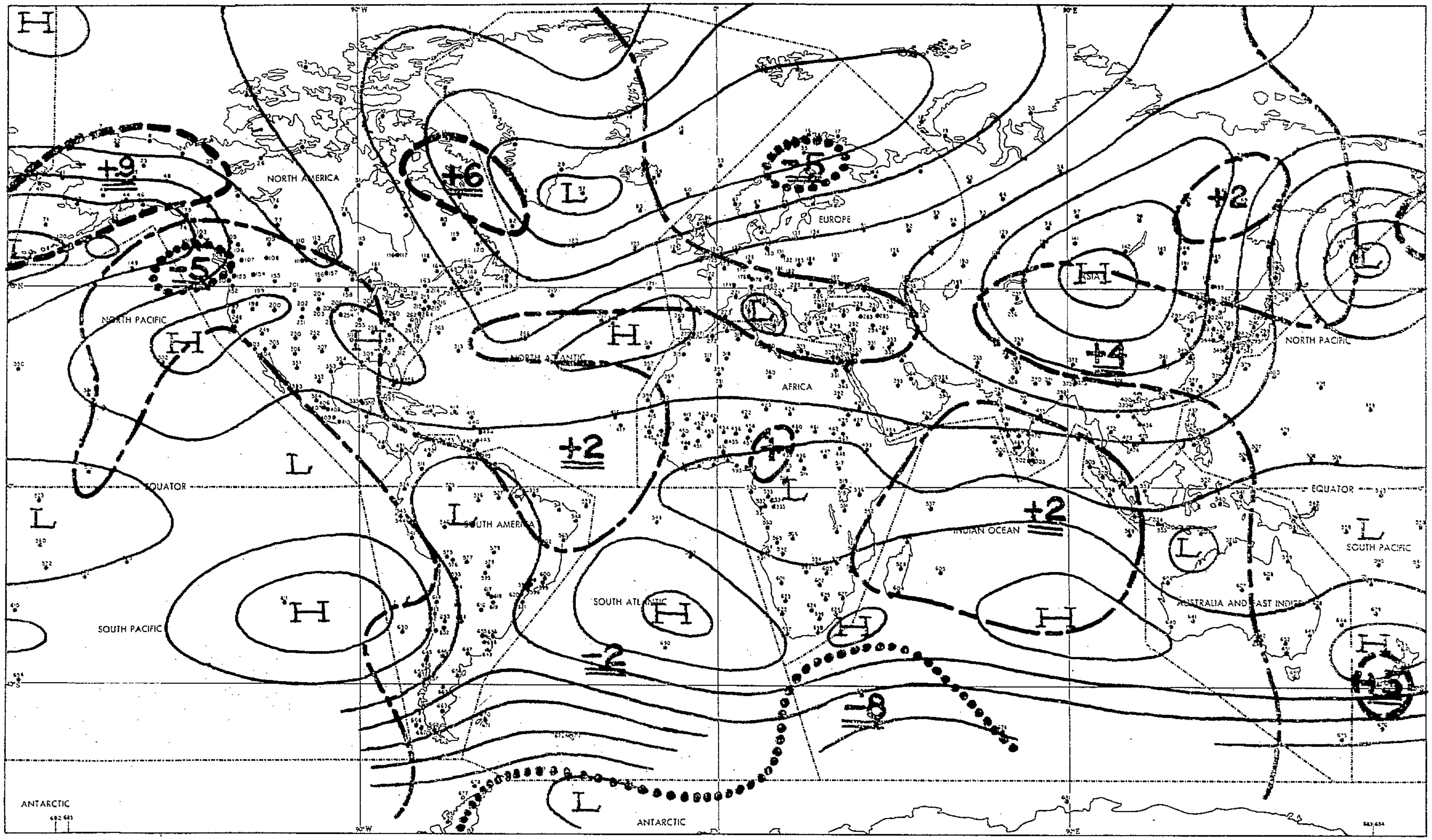

FIG. 6. Mean sea level pressure field 1950-59, and changes from 1940-49, in mb., (*a*) January and (*b*) July. Mean pressure based on charts of Lamb and Johnson, and change field derived by graphical subtraction of same.

(b)

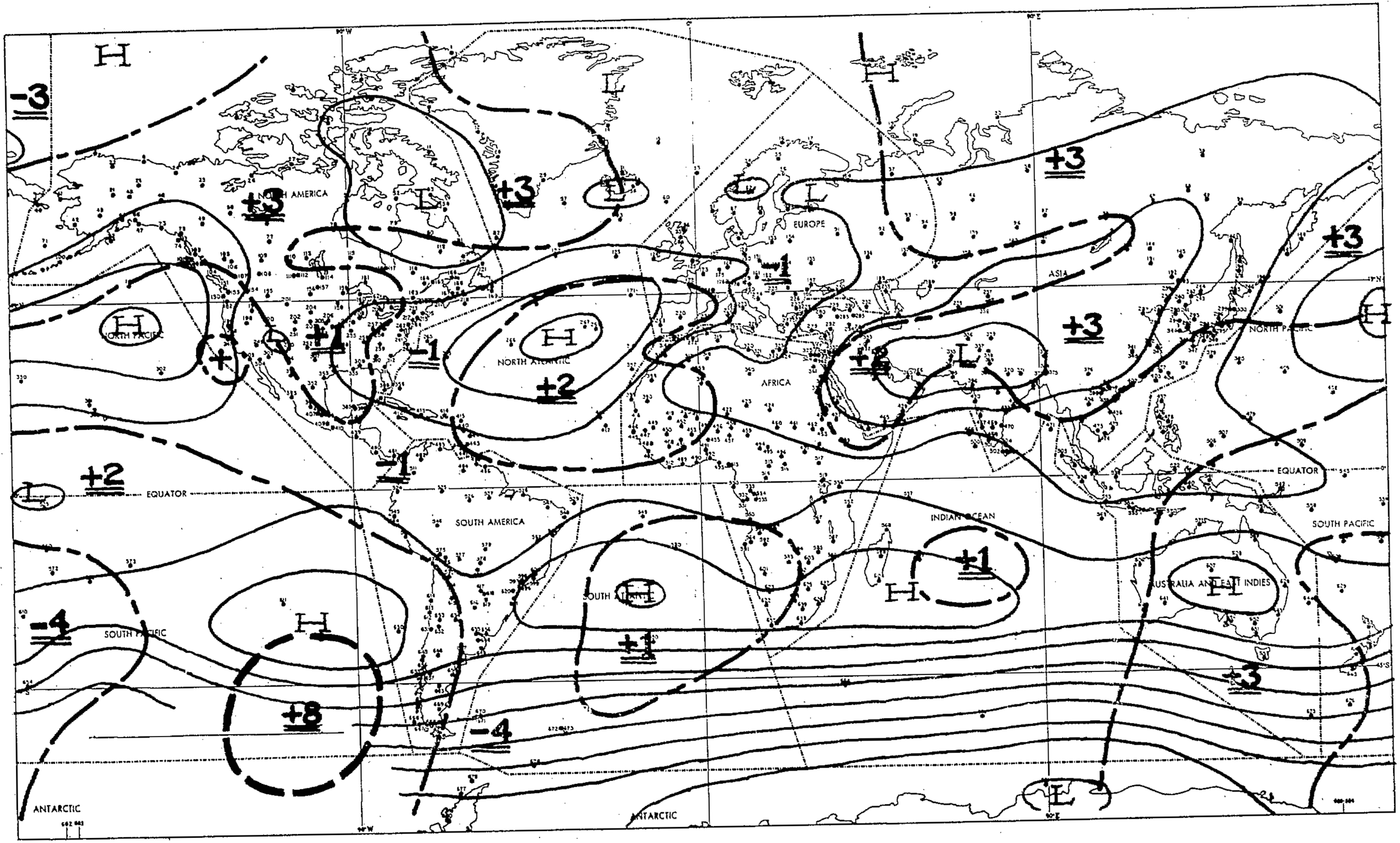
NORTH AMERICA
EUROPE
ASIA
AFRICA
NORTH ATLANTIC
NORTH PACIFIC
SOUTH AMERICA
SOUTH ATLANTIC
SOUTH PACIFIC
INDIAN OCEAN
AUSTRALIA AND EAST INDIES
EQUATOR
ANTARCTIC
H
L
-3
+3
+1
-1
+2
-1
+3
+3
+3
+2
-1
+1
+1
-4
+8
-4
+3

Fig. 6.

CONCLUDING REMARKS

Owing to the characteristic irregularity of secular trends in climatic data, maps of mean temperature change from one time period to another may be considerably altered in their appearance with relatively modest changes in the lengths and dates of the time periods being compared. For this reason, the patterns of change shown here in Figs. 5 (*a-f*) cannot be unambiguously integrated with the patterns of change published by other writers for different averaging intervals, even when the changes are centred on the same years as those illustrated here.

With the above difficulty in mind, the writer selected the 20-year and 10-year periods of averaging to coincide respectively with a 40-year run (1900-39) of nearly monotonic global warming, a 40-year run (1900-39) of zero net global temperature change, and a 20-year run (1940-59) of monotonic global cooling. By this means, it was hoped that a systematic relationship between the geographical pattern of change and the sign of the net global temperature change would emerge. Such a relationship, however, was not to be found.

It must tentatively be concluded that changes of average global temperature are not necessarily associated with preferred geographical modes of temperature change, nor indeed with those of circulation change.

Should this circumstance apply also to the case of climatic changes over longer time intervals (e.g., historical and geological epochs), the representativeness of local evidence of such changes would of course be correspondingly limited.

On the other hand, it would appear that globally integrated changes of temperature may offer a relatively "noiseless"—if not a unique—measure of long-period changes in the global heat budget. An empirical means may thus be at hand for distinguishing the primary thermal response of the atmosphere to factors responsible for secular climatic change, from the secondary thermal fluctuations of a quasi-random character attributable to the inherent dynamic instability of the atmosphere.

A preliminary assessment of the globally integrated trends in terms of various quantitative theories of climatic change has now been published (Mitchell, 1961*b*).

APPENDIX

DETERMINATION OF STANDARD ERRORS OF ZONALLY AVERAGED TEMPERATURE CHANGES IN DATA AREAS

The areally averaged change of mean temperature from a reference time 0 to time y, for a region containing a well-distributed network of stations, can be estimated as

$$\tau_y - \tau_o = \sum_{i=1}^{y} \frac{1}{n_i} \sum_{s=1}^{n_i} d_{si}, \tag{5}$$

where d_{si} is the difference of reported mean temperature at station s from time $i-1$ to time i, and where n_i is the number of stations with data sufficient to compute a d_{si}.

The standard error of estimate of the regional temperature difference, given by equation (5), is closely approximated by

$$\mathrm{SE}(\tau_y - \tau_o) = \left[\sum_{i=1}^{y} \frac{1}{n_i} - \sum_{i=2}^{y} \frac{n_{i,\,i-1}}{n_i\, n_{i-1}}\right]^{1/2} s(e), \tag{6}$$

where $n_{i,\,i-1}$ is the number of stations in the region supplying temperature differences between times $i-2$ and $i-1$ and also between times $i-1$ and i. Here $s(e)$ is the standard error of the d_{si} as estimators of the regional temperature difference, assumed to be quasi-constant with time (see Mitchell, 1961*a*).

The curves in Figs. 1-3 are based on weighted averages of the series of relative temperature in 10°-latitude bands. Each of the latter series, in turn, has been derived by means of equation (5) applied to five-year (pentadal) mean station temperatures, accumulated backward in time from the 1955-59 pentad (τ_o). The relative temperature for each pentad y of the series possesses an error variance given by squaring equation (6), and hereafter denoted by $v(\mathrm{E}_y)$ for brevity. Values of $(\tau_y - \tau_o)$ and of $v(\mathrm{E}_y)$ for annual and winter mean temperatures in each 10°-latitude band are given back to the 1880-84 pentad in Tables 5 and 6 respectively.

The temperature changes shown in Tables 1 (right-hand column), 2, and 3 are the differences between two temporal averages of curves such as those illustrated in Figs. 1-3. The standard errors of such change values, also given in Tables 2 and 3, are derived by the equation

$$\mathrm{SE}(\Delta) = [\Sigma w_i^2 v(\overline{\mathrm{E}}_a - \overline{\mathrm{E}}_b)_i]^{1/2}, \tag{7}$$

where w_i is the fraction of the total surface area of the i^{th} constituent 10°-band, and $v(\overline{\mathrm{E}}_a - \overline{\mathrm{E}}_b)$ is the error variance of the temperature change in the i^{th} band calculated by a procedure noted below, and in which

TABLE 5. Mean temperature by pentads[1], expressed as departures in °F. from 1955-59 pentad, each 10°-latitude band from 80° N. to 60° S.

Pentad Number (v)	Pentad Inclusive years	80° N.–70	70–60	60–50	50–40	40–30	30–20	20–10	10–0°	0°–10	10–20	20–30	30–40	40–50	50–60° S.
							Annual mean temperature								
1	1950-54	0.8	0.7	0.0	0.2	—0.1	0.2	0.1	0.2	0.1	0.1	—0.2	—0.1	—0.3	0.0
2	1945-49	0.1	0.9	0.1	0.3	—0.1	0.1	0.9	0.3	—0.1	0.3	0.0	0.1	—0.3	0.0
3	1940-44	0.7	1.3	0.1	0.3	—0.3	—0.1	0.9	0.6	—0.1	0.4	0.1	0.0	—0.2	0.9
4	1935-39	0.9	1.2	0.5	0.4	—0.4	—0.5	0.8	0.1	—0.1	0.1	0.1	—0.1	—0.1	—0.5
5	1930-34	—0.2	1.0	0.2	0.7	—0.3	—0.5	0.8	0.4	—0.1	0.1	0.1	0.1	—0.3	0.0
6	1925-29	—1.2	0.3	0.1	0.2	—0.6	—0.7	1.0	0.2	—0.2	0.6	0.3	0.2	0.1	—0.3
7	1920-24	0.1	0.0	0.3	0.1	—0.7	—0.5	0.3	0.1	—0.5	0.6	—0.2	—0.3	—0.2	0.1
8	1915-19	—3.7	—0.9	—0.4	—0.2	—0.8	—0.9	—0.1	0.4	—0.3	0.1	0.0	—0.1	—0.1	—0.3
9	1910-14	—3.3	0.0	0.2	—0.2	—1.2	—0.9	—0.1	0.4	—0.5	0.2	0.1	0.2	—0.3	—0.9
10	1905-09	—2.8	0.0	—0.1	—0.6	—1.2	—0.8	0.1	0.6	—0.5	—0.1	—0.4	—0.4	—0.6	—1.1
11	1900-04	—3.1	—0.6	0.1	—0.4	—0.9	—0.7	0.5	0.6	—0.9	0.0	0.3	—0.2	—0.5	—0.2
12	1895-99	—3.9	—0.5	—0.1	—1.2	—0.8	—0.5	0.5	0.6	—0.9	—0.4	0.1	—0.2	(—0.1)	—0.3
13	1890-94	—4.1	—0.5	—0.3	—1.2	—1.0	—0.8	—0.1	0.2	—1.5	—0.8	—0.4	—0.6	(1.1)	(—0.9)
14	1885-89	—4.3	—1.1	—0.3	—1.2	—1.0	—0.9	—0.2	0.4	(—1.1)	(—0.5)	—0.1	—0.4	(1.0)	—
15	1880-84	—3.6	—1.0	—0.2	—1.6	—0.7	—0.9	—0.5	0.5	(—1.6)	(—0.6)	—0.5	—0.5	(1.1)	—
							Winter mean temperature								
1	1950-54	0.2	1.2	—1.3	0.3	0.1	0.8	0.2	0.1	—0.2	0.2	0.2	0.0	—0.1	0.2
2	1945-49	0.5	1.5	—0.9	—0.9	—0.7	0.4	1.1	0.4	—0.2	0.1	0.5	0.4	0.4	0.1
3	1940-44	1.4	2.1	—0.3	0.1	—0.6	0.2	1.1	0.4	—0.4	0.2	0.6	0.1	0.3	1.5
4	1935-39	1.9	2.1	—0.8	—0.3	—0.6	0.0	1.1	—0.1	—0.3	—0.1	0.7	0.1	0.5	—1.0
5	1930-34	—1.1	1.9	—1.0	0.0	—0.2	—0.2	1.0	0.1	—0.4	—0.3	0.9	0.0	—0.1	—0.3
6	1925-29	—3.3	1.5	—0.4	—0.2	—0.7	—0.5	0.9	0.3	—0.7	0.2	0.6	0.3	1.3	0.1
7	1920-24	—4.3	—0.1	—0.5	—0.6	—0.8	—0.2	0.3	0.4	—1.3	0.2	0.5	—0.6	0.7	0.2
8	1915-19	—9.3	—2.0	—2.0	—0.1	—1.0	—0.9	—0.1	0.5	—0.7	—0.1	0.5	—0.4	1.1	0.2
9	1910-14	—9.2	—0.7	—1.2	—0.1	—1.1	—0.7	—0.3	0.7	—0.9	—0.4	0.7	0.1	1.5	—0.6
10	1905-09	—9.7	—1.4	—2.2	—0.9	—1.1	—0.9	—0.3	0.8	—0.6	—0.3	0.3	—0.5	0.4	—0.7
11	1900-04	—8.0	—1.3	—1.8	—0.5	—0.9	—0.8	0.2	0.7	—0.8	0.0	0.7	—0.1	0.6	—0.7
12	1895-99	—10.4	—1.7	—2.4	—0.5	—1.0	—0.8	—0.4	0.5	—1.5	—0.9	0.6	—0.1	(0.5)	0.3
13	1890-94	—8.7	—1.5	—3.5	—1.5	—1.6	—0.7	—0.6	0.1	—1.9	—1.6	—0.4	—0.5	(1.6)	(0.5)
14	1885-89	—10.1	—2.0	—2.5	—1.7	—2.3	—1.5	—0.5	0.0	(—1.3)	(—0.8)	0.2	—0.7	(1.2)	—
15	1880-84	—9.1	—2.2	—2.2	—1.3	—1.5	—0.2	—0.1	—0.5	(—1.9)	(—0.6)	0.9	—0.7	(3.0)	—

1. Values in parentheses are based on data for only one station.

errors of estimate of temperature change in the constituent bands are assumed to be mutually independent.

The error variance of the difference between two temporal averages of $(\tau_y - \tau_o)$, each average being taken over N pentads, can usually be approximated with acceptable accuracy by

$$v(\overline{\mathrm{E}}_a - \overline{\mathrm{E}}_b) = \frac{1}{\mathrm{N}}\left[\left|\sum\nolimits_a v(\mathrm{E}_y) - \sum\nolimits_b v(\mathrm{E}_y)\right| + \frac{v(e)}{\bar{n}}\right], \tag{8}$$

where the summations extend over the N pentads involved in each interval being compared, where $v(e)$ is the square of $s(e)$ previously defined, and where $\bar{n}$ is the average number of stations whose data are used to compute the $(\tau_y - \tau_o)$ in these intervals.[1]

The standard errors of the 30-year changes shown in Table 2 have been computed by use of equations (7) and (8). Those of the 10-year changes 1940-49 to 1950-59, shown in Table 3, were computed by a more exact method involving use of (7) in which each $v(\overline{\mathrm{E}}_a - \overline{\mathrm{E}}_b)$ was derived from the equation

$$v(\overline{\mathrm{E}}_a - \overline{\mathrm{E}}_b) = \frac{v(e)}{2}\left[v(\mathrm{E}_4) - v(\mathrm{E}_2) + \left\{\frac{1}{n_3} + \frac{1}{2}\left(\frac{1}{n_2} - \frac{1}{n_4}\right)\right\}\right], \tag{9}$$

where the numerical subscripts apply to the pentad

1. If the intervals are not contiguously chosen, $\bar{n}$ is the average number of stations for the total period of record involved.

TABLE 6. Error variance $v(E_y)$ of annual mean temperature[1] by pentads relative to 1955-59 pentad (in °F. squared); number n_y of stations used between pentads; and number $n_{y,y-1}$ (in parentheses) where different from n_y, each 10° latitude band from 80° N. to 60° S.

Pentad		Northern Hemisphere							
Number (v)	Inclusive years	80° N.–70	70–60	60–50	50–40	40–30	30–20	20–10	10–0°
1	1950-54	4	5	12	14	16	9	9	5
		0.56	0.69	0.19	0.09	0.04	0.05	0.03	0.05
2	1945-49	3	6 (5)	14 (12)	14	16	9	9	5
		0.75	0.69	0.19	0.09	0.04	0.05	0.03	0.05
3	1940-44	5 (2)	20 (6)	26 (13)	19 (14)	19 (16)	9 (7)	10 (8)	8 (5)
		0.90	0.69	0.19	0.09	0.04	0.06	0.03	0.05
4	1935-39	5	19 (18)	26	19 (18)	21 (19)	11 (9)	9	8
		0.90	0.71	0.19	0.09	0.04	0.06	0.04	0.05
5	1930-34	3	17	24 (19)	14 (13)	17 (12)	12 (8)	11 (8)	10 (7)
		1.20	0.73	0.22	0.12	0.06	0.07	0.04	0.05
6	1925-29	6 (3)	17	24	16 (14)	19 (17)	14 (12)	12 (11)	11 (10)
		1.20	0.73	0.22	0.12	0.06	0.07	0.04	0.05
7	1920-24	6	17 (15)	24 (22)	20 (16)	21 (19)	16 (14)	13 (12)	11
		1.20	0.75	0.22	0.12	0.06	0.07	0.04	0.05
8	1915-19	3	14 (13)	13	17	23 (21)	12	11	10
		1.58	1.34	0.30	0.13	0.06	0.08	0.04	0.05
9	1910-14	3	15 (13)	13 (12)	17	23	12	11	10
		1.58	1.36	0.31	0.13	0.06	0.08	0.04	0.05
10	1905-09	2	21 (15)	24 (13)	20 (17)	23	12	10	8
		1.95	1.36	0.31	0.13	0.06	0.08	0.05	0.06
11	1900-04	2	19	23	19	21	11 (10)	9	7
		1.95	1.38	0.31	0.14	0.06	0.08	0.05	0.06
12	1895-99	2	15	21	19	21	11	8	6
		1.95	1.43	0.32	0.14	0.06	0.08	0.05	0.07
13	1890-94	2	14	21	19	19	11	8	6
		1.95	1.44	0.32	0.14	0.07	0.08	0.05	0.07
14	1885-89	2	13 (12)	17	19	18	10	7	5 (4)
		1.95	1.48	0.35	0.14	0.07	0.09	0.06	0.08
15	1880-84	2	11	15 (14)	18	17	8	6	4
		1.95	1.53	0.37	0.14	0.07	0.10	0.06	0.10
	k	4.0	3.5	5.0	3.7	2.6	2.4	2.2	1.8

numbers, counted backwards from the 1955-59 pentad (number 0).[1]

The derivation of the equations in this appendix, together with a more rigorous discussion of the validity of their application, are given in [3].

SUPPLEMENTARY DATA

Various supplementary data are given for each 10°-latitude band in Table 7. These include: (*a*) changes of mean temperature and their associated standard errors as estimates for the data areas, corresponding to the periods of record shown in Tables 2 and 3; (*b*) values of $v(e)$ and C, defined in the text, which are required for evaluation of standard errors $v(E_y)$ given by equation (6) and of other quantities given by equations (2) and (3); and (*c*) the percentage of each latitude band that is land covered, and the percentage of the total earth's surface contained in each latitude band [proportional to the weights w_i in equations (2), (3), and (7)].

1. Combination of equations (6) and (9) yields

$$v(\bar{E}_a - \bar{E}_b) = \frac{v(e)}{4}\left[\frac{1}{n_1} + \frac{4}{n_2} + \frac{1}{n_3} - \frac{2n_{2,1}}{n_1 n_2} - \frac{2n_{3,2}}{n_2 n_3}\right],$$

where the $n_{i,i-1}$ — symbols are as defined under equation (6). This form of (9) is more useful for direct calculation.

TABLE 6 *(continued)*

Pentad Number (v)	Inclusive years	0°	10	20	30	40	50	60° S.
1	1950-54	6 0.05	10 0.04	12 0.04	9 0.04	4 0.06	4 0.08	
2	1945-49	7 (6) 0.05	10 0.04	13 (12) 0.04	9 0.04	4 0.06	4 0.08	
3	1940-44	11 (6) 0.05	14 (9) 0.04	16 (13) 0.04	11 (9) 0.04	5 (4) 0.06	5 (4) 0.08	
4	1935-39	11 (9) 0.06	13 0.05	12 0.05	9 0.05	4 0.08	4 0.09	
5	1930-34	6 (5) 0.09	11 (8) 0.06	9 0.06	8 0.05	3 0.10	3 0.12	
6	1925-29	7 (6) 0.09	11 0.06	9 0.06	8 0.05	3 0.10	3 0.12	
7	1920-24	8 (7) 0.09	12 (11) 0.06	10 (9) 0.06	8 0.05	3 0.10	3 0.12	
8	1915-19	7 0.09	9 (8) 0.08	9 0.07	8 0.05	3 0.10	3 0.12	
9	1910-14	6 0.10	9 0.08	9 0.07	8 0.05	3 0.10	3 0.12	
10	1905-09	5 0.11	8 0.08	9 0.07	8 0.05	3 0.10	3 0.12	
11	1900-04	5 0.11	8 0.08	9 0.07	8 0.05	3 0.10	2 0.16	
12	1895-99	4 0.12	5 0.11	6 0.10	8 0.05	1 0.27	2 0.16	
13	1890-94	2 0.20	4 0.13	5 0.11	7 0.06	1 0.27	1 0.32	
14	1885-89	1 0.35	1 0.44	5 0.11	7 0.06	1 0.27	0 —	
15	1880-84	1 0.35	1 0.44	2 0.26	7 0.06	1 0.27	0 —	
	k	1.6	1.9	1.6	1.4	1.5	1.5	

1. For error variance of winter mean temperature, multiply $v(E_y)$ in table by k in same latitude band.

TABLE 7. Miscellaneous data for 10°-latitude bands[1]

Band	Temperature change ± standard error of estimate for data areas (°F.): 30-year change 1890-1919 to 1920-49, Annual	30-year change, Winter	10-year change 1940-49 to 1950-59, Annual	10-year change, Winter	$s(e)$ Annual	$s(e)$ Winter	C	Percentage land cover	Percentage of total area of earth
90°-80° N.	—	—	—	—	—	—	0.0	10	0.8
80°-70° N.	+3.55 ±0.90	+8.40 ±1.79	0.0 ±0.76	—0.85 ±1.51	1.50	3.00	0.80	30	2.2
70°-60° N.	+1.20 ±0.78	+2.93 ±1.47	—0.75 ±0.65	—1.20 ±1.22	1.86	3.50	0.86	70	3.7
60°-50° N.	+0.32 ±0.33	+1.53 ±0.75	—0.10 ±0.33	—0.05 ±0.74	1.50	3.35	0.93	57	5.0
50°-40° N.	+0.97 ±0.18	+0.28 ±0.35	—0.20 ±0.23	+0.35 ±0.43	1.12	2.16	0.82	52	6.2
40°-30° N.	+0.58 ±0.12	+0.52 ±0.20	+0.15 ±0.15	+0.60 ±0.25	0.84	1.35	0.72	43	7.1
30°-20° N.	+0.40 ±0.15	+0.75 ±0.23	+0.10 ±0.17	+0.10 ±0.26	0.65	1.00	0.57	38	7.9
20°-10° N.	+0.65 ±0.13	+1.17 ±0.19	—0.85 ±0.13	—1.00 ±0.20	0.53	0.78	0.51	26	8.4
10°- 0° N.	—0.18 ±0.15	—0.30 ±0.19	—0.35 ±0.17	—0.35 ±0.22	0.49	0.65	0.43	23	8.7
0°-10° S.	+0.58 ±0.30	+0.52 ±0.39	+0.15 ±0.17	+0.20 ±0.22	0.55	0.70	0.38	24	8.7
10°-20° S.	+0.52 ±0.32	+0.60 ±0.44	—0.30 ±0.16	—0.05 ±0.22	0.64	0.89	0.62	22	8.4
20°-30° S.	+0.12 ±0.19	+0.23 ±0.24	—0.15 ±0.14	—0.45 ±0.18	0.70	0.88	0.54	23	7.9
30°-40° S.	+0.22 ±0.10	+0.30 ±0.12	—0.10 ±0.15	—0.25 ±0.17	0.60	0.71	0.38	11	7.1
40°-50° S.	—0.08 ±0.32	—0.45 ±0.40	+0.10 ±0.19	—0.40 ±0.23	0.51	0.63	0.22	3	6.2
50°-60° S.	+0.65 ±0.32	+0.27 ±0.40	—0.45 ±0.20	—0.70 ±0.25	0.55	0.68	0.22	1	5.0
60°-90° S.	—	—	—	—	—	—	(0)	41	6.7
World averages							0.50	29.2	

1. For definitions of $s(e)$ and C, refer to text.

ACKNOWLEDGMENTS

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RÉSUMÉ

La répartition mondiale des variations séculaires de température (J. Murray Mitchell, Jr.)

L'auteur examine les changements enregistrés depuis 1880 dans la température moyenne du globe et il évalue la mesure dans laquelle les données disponibles permettent de déterminer ces variations avec exactitude.

La tendance au réchauffement observée depuis quelques dizaines d'années dans le monde entier paraît s'être renversée peu après 1940. Les températures moyennes semblent avoir évolué de manière parallèle dans les deux hémisphères, mais l'insuffisance des données relatives aux régions océaniques empêche de déterminer avec précision l'ordre de grandeur de ces changements.

L'auteur expose et compare la répartition géographique des variations annuelles et hivernales enregistrées de 1900 à 1960 durant diverses périodes de dix et de vingt ans. Les variations de la circulation générale sont nettement démontrées comme la cause principale de ces écarts régionaux.

Les variations observées dans la température mondiale seraient d'une grande importance pour étudier les causes définitives des changements séculaires du climat.

DISCUSSION

E. Kraus. Perhaps the most interesting part of the evidence presented by Dr. Murray Mitchell, Dr. Rodewald and some of the other speakers is the way in which it falls into a pattern. Not only air temperature, but also subtropical rainfall, the tendency of hurricanes to move along certain tracks or sea-surface temperatures, show a reversal of the preceding climatic trend during the last one or two decades. The true physical significance of Dr. Murray Mitchell's result lies, perhaps in the combined evidence, based on so many different variables.

B. Dzerdzeevskii. I think that Dr. Mitchell's paper is very interesting and that the results he obtained are extremely important. I am certain that progress can be made on investigations into climatic change only by using world-wide data and by analysing the " world-wide connexions " among the meteorological observations and circulation characteristics embracing at least one hemisphere.

I also believe that dividing the long-period data into shorter periods is very useful; but it seems to me that it is preferable to use the natural periods or " epochs " of different duration. The dividing of climatic data can be fulfilled by analysing the circulation data. Indeed it is not easy. Although such analyses considerably increase the amount of work, the results obtained prove to be more valid.

J. Murray Mitchell. Dr. Dzerdzeevskii's remarks are greatly appreciated. With regard to his suggestion to partitioning the climatological data according to natural periods, I am very sympathetic to this view and, in a way, this is what I have tried to do. I believe that my curves of world mean temperature (see Fig. 1) might be interpreted as part of a rhythm somewhere between 60 and 90 years in period. Evidence for periods near 80 or 90 years has of course been suspected in the past. It may indeed be worth while to study changes of world-wide climate in and between the various phases of such a presumed rhythm. However, if the pre-eminence of such rhythms is ever refuted by new information, as it may well be, we should, I think, be willing to abandon this approach without further ado.

J. Namias. In examining Dr. Mitchell's figures 5(*f*) and 6(*a*), I would like to point out an important connexion between the pressure distribution and its change and the field of temperature change—both for the decades between the 1940s and 1950s. The areas of warming over the United States and Europe which Dr. Mitchell mentioned and indeed associated with the strong development of the Gulf of Alaska centre action following repeated outburst of cold Alaskan air. It is well known from my own studies that this situation produces fast westerlies, rapid zonal movements of cyclones along the Canadian border, and flooding of the United States by mild Pacific air—the polar air being " contained " in Canada. The European warmth is associated with a well-developed Icelandic low, which is in turn associated with cold outflowing air masses from the east Canadian tundra. This system drives mild Atlantic air masses into Europe. Hence the cooling in northern latitudes especially over Alaska and the Yukon, and the development of this cold air over the Gulf of Alaska in effect sets up areas of warmth which lessen the degree of apparent hemispheric or global cooling.

J. Murray Mitchell. Dr. Namias' interpretations are a valuable addendum to my own brief comments on this matter, and I thank him.

C. C. Wallén. Like other speakers I wish to express my great interest in and admiration for the contribution given by Dr. Mitchell. There are just two points which I would like to raise because they have bearing on my own home area. It was surprising to me to find that Dr. Mitchell refers to the Scandinavian area as one where pressure has fallen during the recent period of decreasing world temperature indicating rather an increase of temperature. This necessarily must be due to the selection of the period of comparison : in this case the forties and the fifties. Already seven years ago, using temperature records from Sweden, I pointed out that the so-called " recent climatic fluctuation " upwards trend seemed to have changed into a decline. A recent study of the differences in temperature and pressure between the periods 1901-30 and 1931-60 shows a definite decline of temperature in Scandinavia coupled with an increase of 9 mb. in pressure in the northern parts. Splitting up the period 1931-60 and looking separately at the forties and fifties evidently means that a slight recovery in the overall downwards trend that has occurred in the fifties, in northern and central Europe, seems to have been given too much emphasis.

I wish also to state how much I agree with Dr. Kraus that this downwards trend in temperature should be considered significant from a physical point of view although it may not be so from a statistical point of view. It certainly renders itself extremely well to studies of the relationship between changes in climate elements on one side and fluctuations in the general circulation.

In this connexion I should wish to mention that in the recent study for Scandinavia mentioned above I have also tried to find some causes for the temperature decline in winter from 1901-30 to 1931-60 in terms of changes in the general circulation. Evidence definitely shows that the decline is coupled with an increase of easterly to north easterly circulation types indicating a shift westwards in the mean position of ridges and troughs. This seems to go well with the explanation for overall decline in temperature during historical periods that has been given earlier by Dr. Lamb.

J. Murray Mitchell. Let me comment on Dr. Wallén's first point merely by observing that, in studies of the relation between circulation changes and climate changes, one frequently comes to somewhat different conclusions depending on which averaging periods are compared. In many parts of the world, this is probably due to the use of inhomogeneous data, but I doubt very much that this is the case in Scandinavia. When such discrepancies occur, there seems to be no recourse but to make a more refined analysis of available data, of the exemplary kind for which Dr. Wallén himself is well known.

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CLIMATIC FLUCTUATIONS STUDIED BY USING ANNUAL FLOWS AND EFFECTIVE ANNUAL PRECIPITATIONS[1]

by

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INTRODUCTION

SUBJECT

Analyses of climatic fluctuations by using the data of annual flows and derived effective annual precipitations[2] from many river gauging stations around the world are the subject of this paper.

Many efforts have been made in the part either to discover the regularity or to prove the randomness[3] in the fluctuations of some climatic or hydrologic events on annual basis. The analysis here is intended to add some new elements to this old problem.

SELECTION OF PHENOMENA FOR THE STUDY OF FLUCTUATIONS

The study of climatic fluctuations was restricted to time series of annual flows and effective annual precipitations, because they are considered here as relatively the most reliable series for investigation of climatic changes related to the water resources problems. The run-off at a river gauging station integrates the effects of climatic factors on large areas, and some bias inherent to point measurements (of rainfall, temperature, and similar) is thus eliminated. The analysis of data of rainfall, temperature, tree rings, sediment deposits (varves) and others has shown either inconsistency[4] and non-homogeneity[5] in data, difficult to correct, or a built-in dependence model (biological model in tree rings, or sedimentation model in varves), which does not exist in data of annual flows and effective annual precipitation.

BASIC APPROACH

Generally, two opposite standpoints may be distinguished among the results of studies of climatic fluctuations, with many positions between the two opposite views.

Approach of oscillatory movements

This standpoint is based on assumptions that moon effect, sun-spot fluctuations and other solar activities, cosmic effects, persistence in ocean and air-mass movements, and the like, create a persistent or even oscillatory movement of high and low values, which combined with random effects make the future values of a time series depend on the previous ones. The hidden periodicities are often being advanced from investigation of small samples of climatic factors. The non-significance of differences between parameters of observed and stochastic time series is usually neglected by this standpoint.

Approach of randomness and stochastic processes

This standpoint starts from the fact that the natural fluctuations of annual values are very close to random sequence, if some influences of known regression effects are eliminated. The examples of these effects are: storage of water and heat in oceans, atmosphere, earth; regression effect created by the methods used in defining the time series; end effect of the time unit used; especially retardation of water due to water storage in river basins in annual flow fluctuations; etc. Very small departures, considered as non-significant, of computed statistical parameters from those of the random series or series derived from random time series by stochastic processes are emphasized by this point of view. The fact that those statistical parameters have consistent

1. This research in fluctuations of annual run-off was sponsored originally by the United States National Bureau of Standards and the United States Geological Survey; it is now sponsored by the United States National Science Foundation.
2. Effective annual precipitation defined as total annual precipitation minus total annual evapotranspiration in a river basin.
3. Randomness is deffned here in classical way, that there is no systematic link between successive values of an infinite time series.
4. Inconsistency is defined here as systematic errors due to measuring or computational techniques.
5. Non-homogeneity is defined here either as man-made effects, or accidents in nature (fires, land-slides) which change the measured values in comparison with the virgin values.

departures in the same direction from the same statistical parameters of random or stochastic series is neglected in this standpoint, even though those departures can be considered non-significant.

Many scientists agree that the random component in series of annual flows and effective annual precipitation is very high, but add that something exists beyond the known storage effects, because of that consistency in departures of statistical parameters between the observed and random or stochastic time series.

The controversy lies mainly in the way that these departures are explained and related to some physical or non-physical causes.

The approach of this paper is the analysis of the mentioned departures between the time series of observed annual flows, or derived effective annual precipitations, and the random or stochastic time series, and the explanations for these departures, which divide the two standpoints.

The use of the moving average by smoothing the original time series in order to study the fluctuations of a phenomenon is avoided in this study. From the studies of Slutzky (1937) it is well known that its use creates, of itself, fluctuations which may lead to erroneous conclusions. The random series becomes stochastic (non-random) series, when the method of the moving average is used. The series will be used here with their unchanged member values.

The random time series is considered in this paper as bench mark or yardstick series. The stochastic series as derived from random series by known processes are a further extension of bench mark random series.

STATISTICAL TECHNIQUES USED

The following statistical parameters were selected for use in this paper:

1. Serial correlation coefficients and correlograms. They give a simple method of studying the dependence in successive terms of a time series. They are convenient, and especially the first serial correlation coefficient, when the absolute values of serial correlation coefficients are small. This is the case usually with time series of annual river flows and effective annual precipitations.
2. Range. It is defined for a part of time series as the difference between previous maximum and previous minimum on the cumulative curve of departures.

DATA USED

Data used consists of annual flows and of stored water in river basins at the end of water years for 140 river gauging stations from many parts of the world, and namely: 72 from the United States of America, 13 from Canada, 37 from Europe, 10 from Australia, 1 from New Zealand, 4 from Africa, 2 from Japan and 1 from the Middle East.

The sizes of river basins range from 2.5 km^2 to 2.5 million km^2, but the majority are from 800 to 80,000 km^2. The annual average flows are in the range of 2.8-2,800 m.^{3}/sec., with an average yield up to 30 lit./sec./km.^{2}.

The length of records is 40-150 years. Seven stations of long record are specially studied: River Göta at Sjötorp-Vänersborg (Sweden), 150 years; River Rhine at Basle (Switzerland), 150 years; River Nemunas at Smolininkai (Lithuania, U.S.S.R.), 132 years; River Danube at Orshava in Iron Gates (Rumania), 120 years; St. Lawrence River, at Ogdensburg, New York (U.S.A.), 97 years; River Mississippi at St. Louis, Missouri (U.S.A.), 96 years; and River Neva at Petrokrepost (U.S.S.R.), 76 years.

DETERMINATION OF EFFECTIVE ANNUAL PRECIPITATIONS

FIRST APPROXIMATION DETERMINATION OF EFFECTIVE ANNUAL PRECIPITATION

The effective annual precipitation is defined here as:

$$P_e = P_i - E_1 = V_i + W_e - W_b = V_i - \Delta W_i \qquad (1)$$

where P_e = effective annual precipitation for a given water year and a river basin (net available water in each water year for a river basin, or net input of water from atmosphere into a basin); P_i = total annual precipitation on that river basin and for a given water year; E_i = total annual evapotranspiration (total water losses from the basin, from surface and underground waters, into the atmosphere); V_i = annual water flow volume of a river for a given water year; W_b = total stored water in a river basin at the end of a water year; W_e = total stored water in a river basin at the beginning of the corresponding water year; ΔW_i = difference of stored water for the end and beginning of a water year (positive in wet water years, negative in dry water years).

As there are usually great errors in the determination of P_i and E_i for a river basin, starting from precipitation and evaporation measurements on limited number of individual points, the effective annual precipitation was obtained for this paper exclusively by using W_b and W_e, or their difference ΔW_i. The value of ΔW_i was determined for the approximate values W_b and W_e.

The mean flow recession curve of average daily or average monthly flows was determined for each station, and for the season around the end or beginning of water years, and they were approximated by exponential functions, either of the type $Q = Q_o e^{-ct}$, or of the type $Q = Q_o e^{-ct^n}$, with Q_o the initial discharge, Q (any discharge of recession curve), and t (time) as variables, with c, or c and n, the parameters which characterize the equations of mean flow recession curves. The inte-

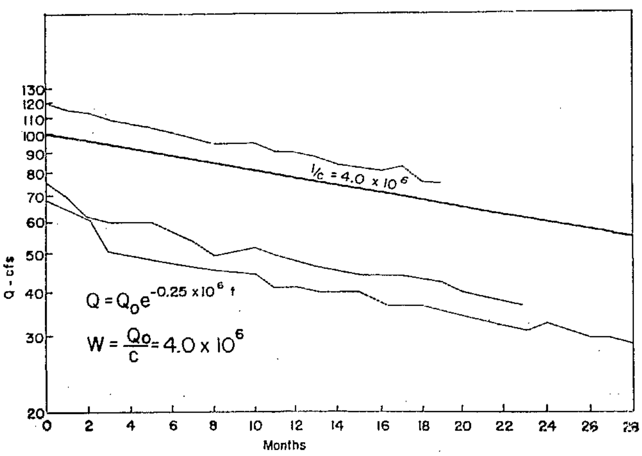

FIG. 1. Determination of the mean recession curve of Ashley Creek, Utah, by using monthly flows, for the purpose of compiling the water carry-overs from one water to another.

gration of the above functions of mean recession curves, from given Q_o for $t = 0$, to t = infinite give the volume of water W, or the stored water in a river basin. In this case, W_b or W_e are functions (for given c, or for given c and n) of the discharge Q_o at the end of a water year, if this end occurs during a recession curve period (for the United States, Europe and Canada the end was on 30 September, and the beginning of the next water year on 1 October). In case a flood wave (rising level especially) occurs at the end of a water year, a special procedure was followed to obtain the stored water volume W.

The illustration of this method of determining W is given in Fig. 1 (Ashley Creek, Utah). The recession curve of monthly flows is a straight line in semi-log paper, with the average c-value equal to 0.25×10^{-6} for the simple exponential function. In this case the integration of the volume from $t = 0$ and Q_o to t = infinity gives $W = Q_o/c$, or in this example $W = 4.0 \times 10^{-6} Q_o$, with Q_o = discharge on 1 October. By using equation (1) for each water year, as $P_e = V_i - \Delta W_i$, the effective annual precipitations were computed as a first approximation for all river gauging stations and for all water years.

The computed series of annual flows in modular coefficients as $U_i = \frac{V_i}{V_a}$, where V_a = average annual flows, and derived series of effective annual precipitations in modular coefficients as $Y_i = \frac{P_e}{V_a}$, are used as basic time series for analyses of climatic patterns.

As the effective annual precipitations represent the net input of water in a river basin for a water year, this is the water volume after the storage effects of the surface and underground reservoirs and other storage capacities in a river basin were excluded. As they represent annual flows without a carry-over of water from year to year, the interdependence among the successive values of effective annual precipitations should be smaller than for the annual flows, as will be be shown later.

TRUE VALUES OF EFFECTIVE ANNUAL PRECIPITATIONS

The true value of the effective annual precipitations, is, however,

$$P_i = V_i - \Delta W_i \pm (E_i + I_i + H_i + G_i) \tag{2}$$

where E_i = random error in annual flows (usually small for annual river flows); I_i = inconsistency or systematic errors, produced by measuring and computation techniques, in general given as trends or jumps, or their combination; H_i = non-homogeneity or change in the virgin flow, produced by different man-made influences or accidents in the river basin; G_i = error in determining ΔW_i approximately by using in this study the average recession curves, instead of a recession curve for each individual water year and gauging station.

The experience shows that the influence of I_i, H_i, and G_i may be important, and that these factors and errors cannot be often neglected in treating the fluctuations of annual flow and of effective annual precipitation.

In some cases the patterns in fluctuations of flows determined as dependence of successive values of time series could be explained partly by the inconsistency and non-homogeneity in data. The sufficient accuracy of computed members of the two time series V_i and ΔW_t should not be assumed *a priori*.

RELATION OF EFFECTIVE ANNUAL PRECIPITATIONS AND ANNUAL RIVER FLOWS

Assuming that an input of water in all storage capacities in a river basin is random, and that the outflow of stored water follows an exponential function (which is close to reality for most of underground and uncontrolled surface storage spaces), the output of water will be a stochastic time series of the type

$$U_i = b_o Y_i + b_1 Y_{i-1} + b_2 Y_{i-2} + \dots \tag{3}$$

where $b_o, b_1, b_2 \dots$ are monotonically decreasing and positive coefficients, with $\sum_{o}^{\infty} b_j = 1$. This equation is valid also, if the Y_i values are non-random, but an approximate exponential outflow law may be applied to storage capacities of a river basin, In nearly all cases, due to a fast outflow of water from storage spaces, the infinite series on the right side of equation (3) may be replaced by m members. Practically m does not pass 10 (the case of annual flows of the St. Lawrence River at Ogdensburg, New York, with a tremendous storage capacity of Great Lakes). In this case $\sum_{o}^{m-1} b_j = 1$, neglecting the insignificant tail beyond $(m - 1)$ value of b_j.

The property of equation (3) is that the standard deviation of U series becomes smaller than that of Y series under given four conditions for b coefficients. Equation (3) is a general type of linear equation for moving average model (Markov chains), and this type of moving average attenuates the extremes of Y series in producing U series.

As the effective annual precipitation is the difference of precipitation P_i and evapotranspiration E_i, the properties of Y series, therefore, depend on both series P_i and E_i. Because P_i and E_i are usually dependent among them, and particularly when the ratio of effective and total precipitation $\frac{P_e}{P_i} = 1 - \frac{E_i}{P_i}$ is small, the characteristics of Y series depend on three factors: P_i, E_i, and $E_i = f(P_i)$. If P_i values would be of random sequence or close to it, and if $E_i = f(P_i)$ were of a complex relationship (not a simple linear function), the Y series would be non-random. Therefore, E_i plays an important effect on the type of time series which can approximate the series of effective annual precipitation.

PATTERNS IN CLIMATIC FLUCTUATIONS MEASURED BY FIRST SERIAL CORRELATION COEFFICIENT OF BOTH ANNUAL FLOWS AND EFFECTIVE ANNUAL PRECIPITATIONS

FREQUENCY DISTRIBUTIONS OF FIRST SERIAL CORRELATION COEFFICIENT

Procedure

The first serial correlation coefficient, defined as the correlation coefficient of successive pairs of annual flows or effective annual precipitations, was used as a measure of dependence of successive values in the two time series (flow and precipitation), or as an index of the possible climatic fluctuation patterns.

The unbiased first serial correlation coefficient is given in classical statistical books as:

$$r_i = \frac{\sum_{1}^{N} U_i U_{i+1} - \frac{1}{N-1} \sum_{1}^{N-1} U_1 \sum_{1}^{N-1} U_{i+1}}{(N-2)\, s_i s_{i+1}} \qquad (4)$$

where U_i denotes any member of annual flow time series (Y_i of effective annual precipitations), U_{i+1} is the next member to U_i, so that (U_i, U_{i+1}) represents the successive pairs of members of the time series, N = total number of members in a time series, $N - 1$ is total number of correlated pairs, s_i is the standard deviation of $(N - 1)$ first members, and s_{i+1} is the standard deviation of $(N - 1)$ last members of the time series, with r_1 = first serial correlation coefficient.

The unbiased standard deviation is given in classical books of statistics as:

$$s_i = \left[\frac{1}{N-2} \sum_{1}^{N-1} U^2_i - \frac{1}{(N-2)(N-1)} \left(\sum_{1}^{N-1} U_i\right)^2\right]^{1/2} \qquad (5)$$

For s_{i+1}, U_i is replaced by U_{i+1}.

The digital computer was used to determine the first serial correlation coefficients for all 140 stations, and s_i and s_{i+1} through equation (5) were used in this computation. The r_1 values were determined for both series: U (annual river flows), and Y (effective annual precipitations).

For a pure random time series (fluctuation of a random variable), considered as an open series (or that $N - 1$ pairs are used for the computation of the first serial correlation coefficient) in contrast with a circular time series for which the last term is supposed to be succeeded by the first term of the series (in which case there are N pairs), R. L. Anderson (1941) gives the expected value with the symbol $E(r_1)$ (the mean value of r_1 distribution) of the first serial correlation coefficient for circular time series as:

$$E(r_1) = -\frac{1}{N-1} \qquad (6)$$

and the variance of distribution of first serial correlation coefficient as

$$\mathrm{var}\, r_1 = \frac{N-2}{(N-1)^2} \qquad (7)$$

which both converge toward zero by an increase of N. For $N \geqq 40$ the open time series gives r_1 values close to those of circular series. As the practical minimum of years is 40 ($N_{min} = 40$), the maximum value of $E(r_1)$ is -0.0256, which is close to zero. The standard deviation s_r of r_1 is maximum for N minimum. In case of $N_{min} = 40$ it is $s_r(\max) = 0.158$, which is a relatively high value. For the maximum value of $N = 150$ years in the study of 140 stations, $s_r(\min) = 0.082$, also a rather large value. Therefore, it is to be expected that the values of r_1 for many stations, under the assumption of random fluctuations, would cover a relatively large range, both positive and negative values, with the mean close to zero.

The legth of time series for 140 stations is different, with the mean value $N_m = 55$, and extremes 37 and 150. The cumulative frequency distributions of 140 values of first serial correlation oceflicient for both U series and Y series are given in Fig. 2. The theoretical cumulative frequency distribution of random time series is plotted also, for $N_m = 55$, with the mean -0.018 and standard deviation 0.135.

Results

Many values of r_1 are negative: 16 (or 11.4 per cent) for U series, and 26 (or 18.6 per cent) for Y series. The approximate corrections for carry-over has nearly doubled the number of negative r_1 values in Y series as compared with U series. The mean r_1 value for U series is 0.176 and that for Y series 0.130. The difference represents 35 per cent of the value for Y series. The water carry-over in river basins is thus the cause of at least 35 per cent of the mean positive value of first serial correlation coefficient of U series. The median values are 0.160 and 0.115 respectively, with difference being 39 per cent of the median value for Y series. Therefore, one-third to two-fifths of positive first serial correlation coefficient of series of annual flows is explained by the water storage effect in river basins.

The first serial correlation coefficients of log U_i (or log Y_i) have shown the same patterns as the first serial correlation coefficients of U_i (or Y_i). The differences between r_1 values for log U_i series and U_i series (or for log Y_i series and Y_i series) are relatively small, and either positive or negative. There is no clear pattern to be distinguished among two sets of r_1 values (U_i versus log U_i, Y_i versus log Y_i).

The difference between the first serial correlation coefficients of U series and of Y series increases with an increase of parameter $\frac{W}{A}$, given in feet, as the ratio of mean annual carry-over (W) to the area of river basin (A). Generally the greater $\frac{W}{A}$ the greater is the difference $r_1(U) - r_1(Y)$.

A general trend is also derived, when the specific yield of river basins, q in lit./km.^{2}, is related to the decrease of the first serial correlation coefficients of U series to the corresponding value of Y series. The smaller the specific yield, the greater is, on the average, this difference of r_1 values. This can be easily explained by the fact that for given topographical and geological conditions in a river basin, for its given area, the available space for underground and surface water storage in relation to mean annual run-off is greater on the average in dry climates (small specific yields) than in humid climates (great specific yields).

Fig. 2 shows, that the slope of curves (1) and (2) in the range of 20-95 per cent of probability can be well fitted by straight lines, or by normal probability function. The slope of both these curves is the same and is equal to the slope of the cumulative distribution of an infinite set of random time series with N = 55 (equal to mean length of series U and Y).

The results of the analysis of 140 stations show that the arid regions have on the average the greater values of r_1 for both U and Y series than the humid regions. The example of the region of the Upper Colorado River Basin and around it (14 stations) shows this trend clearly, as given in Fig. 3. The legend of the figure

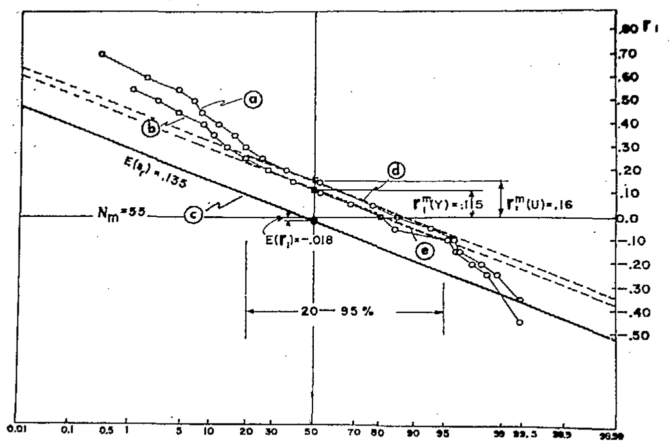

FIG. 2. Cumulative frequency distributions of first serial correlation coefficients (r_1) for 140 river stations, using carthesian-probability scales : (1) U_i series, computed; (2) Y_i series, computed; (3) random series for N = 55; (4) U_i series, fitting a straight line for range 20-95 per cent; (5) Y_i series, fitting a straight line for 20-95 per cent range of cumulative frequency.

explains all plotted cumulative curves. The difference of median r_1 values of this semi-arid region and of 140 stations are 0.064 for U series, and 0.069 for Y series.

Example of effect of carry-over

As an example of a significant impact of water carry-over from one water year to another on the first serial

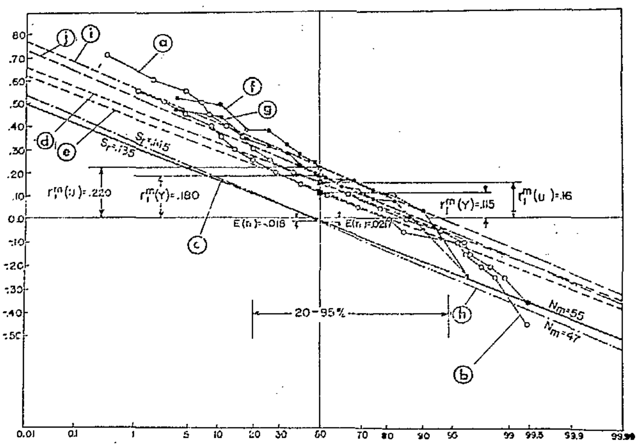

FIG. 3. Cumulative frequency distributions of first serial correlation coefficient : (1) for series of 140 stations and annual flows; (2) same as under (1) but for effective annual precipitation; (3) for random series, $N_m = 55$; (4) line parallel to line 3 through $r = 0.16$; (5) same as (4) through $r = 0.115$; (6) for series of 14 stations of Upper Colorado and annual flows; (7) same as under (6) but for effective annual precipitation; (8) for random series, $N_m = 47$; (9) line parallel to line 8 through $r = 0.22$; (10) same as (9) through $r = 0.18$.

correlation coefficient is the case of St. Lawrence River at Ogdensburg, New York. For the period of observations of 97 years, from 1860 to 1957, the first serial correlation coefficient of actual annual flows for St. Lawrence is 0.705. When the effect of stored water in the Great Lakes was taken into consideration, the first serial correlation coefficient of the effective annual precipitation was dropped to 0.094. If the stored water in the St. Lawrence River Basin outside the Great Lakes, which means in the small lakes, river and in the underground, would be taken into consideration also, then the first serial correlation coefficient of 0.094 would probably be decreased still further.

Discussion of results and conclusions

From the comparison of the distributions represented in Figs. 2 and 3 the following may be derived:

1. Cumulative frequency distributions of U series and Y series either for 140 or 14 stations (Upper Colorado) are very close to the straight lines (extremes excluded) on arithmetic-probability paper; or their first serial correlation coefficients are normally distributed.
2. Slopes of these lines, which represent the standard deviation of first serial correlation coefficient distributions, are also very close (at least for probabilities in the range 10-90 per cent) to the slopes of cumulative distributions of coefficients of random time series which have the same lengths as the mean length for U series and Y series.
3. Difference between the frequency distribution of first serial correlation coefficients for U and Y series, and the frequency distribution of random time series is only in the mean values of coefficients. The U and Y series have positive mean values of r_1, while the means of random series are negative but practically close to zero.
4. Differences between the means of first serial correlation coefficients for U and Y series, on one side, and the mean for corresponding random time series for 140 stations selected from many parts of the world are:

   $$\text{U series: } \Delta\bar{r}_1(\text{U}) = 0.160 + 0.018 = 0.178$$
   $$\text{Y series: } \Delta\bar{r}_1(\text{Y}) = 0.115 + 0.018 = 0.133$$

   or the sequence of effective annual precipitations are much closer to random series than the sequence of annual flows.
5. Main problem in detecting the patterns in fluctuations of annual flows and of effective annual precipitations by an analysis of distributions of first serial correlation coefficients is the interpretation of these differences in the means or medians of first serial correlation coefficients, first of U and Y series versus the random time series, and then of differences between U and Y series.
6. It seems that the arid and semi-arid regions have a greater difference between observed series and random series than the humid regions, as will be shown later in regional distributions of the first serial correlation coefficient.
7. Factors which cause the mean first serial correlation coefficients to be greater than zero in humid regions are more pronounced and emphasized in the semi-arid and arid regions. A complex relationship between evapotranspiration and precipitation in arid regions, as well as a complex law of evaporation of rainfall in the air before the rain falls on the earth in arid regions, may be partly responsible for this difference.
8. There are departures at the extremes of distributions of first serial correlation coefficients from the straight line passed through the median values with the slopes of corresponding random time series. Effects of glaciers and snow carry-over from year to year, sampling departures, and the use of mean length N of observed series for deriving the parameters of first serial correlation coefficient distributions for random time series may be partly responsible for these departures.
9. Supposing that the figures for U and Y series are true values, it can be concluded that the first serial correlation coefficients are substantially decreased by excluding the water carry-over from year to year. The carry-over is responsible for one large part of the greater values of median or mean first serial correlation coefficients of U series than those of random time series.
10. Equation (2) points out that the difference between the given values of effective annual precipitation and the true values of effective annual precipitations can be caused also by four types of errors: random errors, inconsistency, non-homogeneity, and the errors in determining the carry-over from year to year, apart from the carry-over effect (ΔW). The random errors only increase the standard deviation of the random time series. Random errors in annual flows are small and can be practically neglected. Any inconsistency (errors in one side which can change from place to place in time series or any inconsistency in the form of trends or jumps), and any non-homogeneity of data, and any error in computing the carry-over in a river basin, increase on the average the first serial correlation coefficients (Yevdjevich, in preparation, 1962).

REGIONAL DISTRIBUTION OF FIRST SERIAL CORRELATION COEFFICIENT

Fig. 4 shows the position of 72 river gauging stations in the United States. It is an example of regional distribution of first serial correlation coefficient. The solid lines divide 14 hydrological regions as designated by the United States Geological Survey. There are two

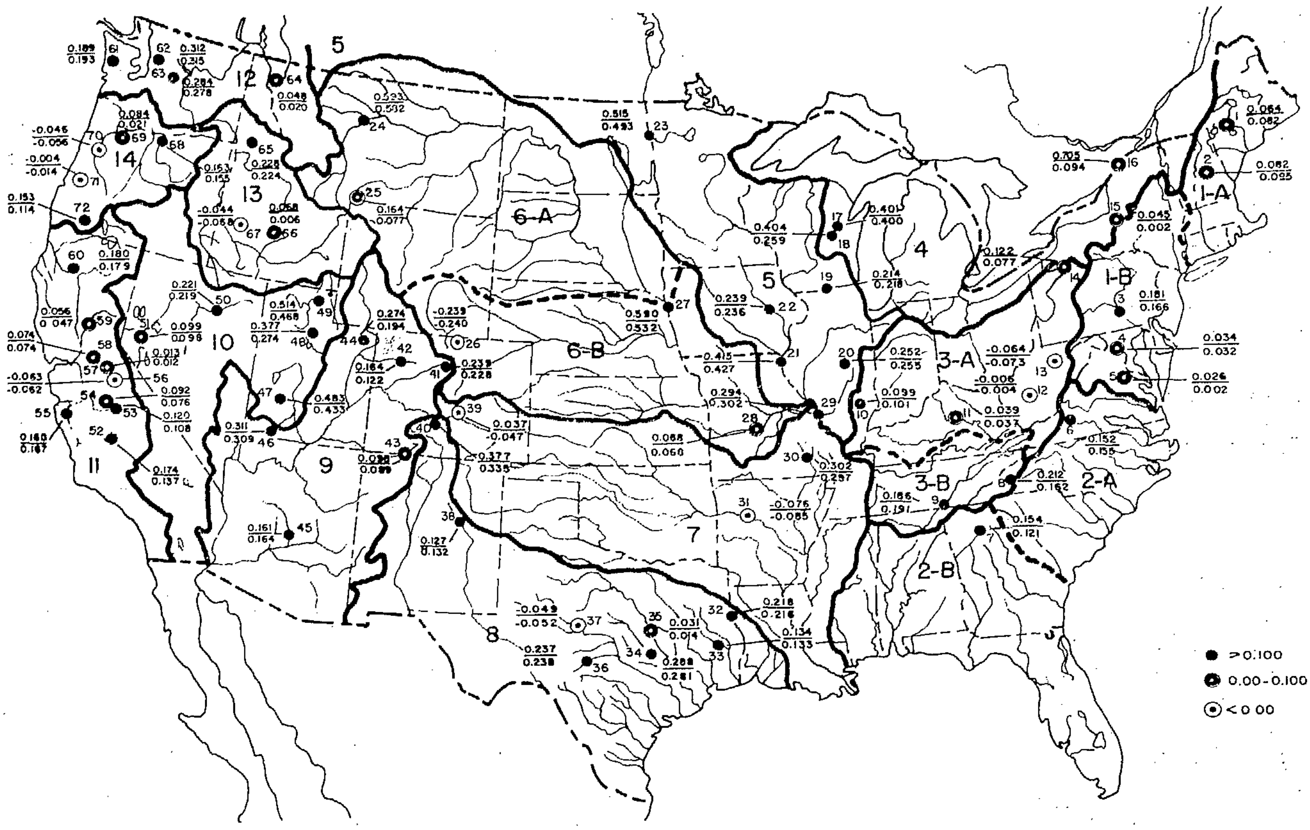

FIG. 4. Regional distribution of first serial correlation coefficient for annual flows (upper figure) and effective annual precipitations (lower figure) for 72 river gauging stations in the United States.

figures for each station: the upper figure is the first serial correlation coefficients for the annual flows, and the lower figure is the first serial correlation coefficients for the effective annual precipitations. Taking the effective annual precipitations as a measure, all stations having the first serial correlation coefficient greater than +0.10, and all stations having the first serial correlation coefficients lower than +0.10 are specially marked. The negative first serial correlation coefficient for the effective annual precipitations are given an additional sign. There are 48 stations which have the first serial correlation coefficient of Y series above and 37 stations below +0.10. There are 14 stations with negative first serial correlation coefficients.

The general conclusions from the results represented in Fig. 4 are:

1. The humid regions of the east and the west of the United States more frequently have the first serial correlation coefficients for the effective annual precipitation below +0.10 than above +0.10.
2. The dry regions in the Middle West and in the Rocky Mountains more frequently have the first serial correlation coefficients of the effective annual precipitations above +0.10 than below +0.10. The regions around the Gulf of Mexico would be considered as approximately having the same number of stations with first serial correlation coefficients above or below +0.10.

It can be concluded from this approximate analysis, that stations in arid regions are more likely to have greater first serial correlation coefficients for the effective annual precipitation than stations in humid regions.

It seems a quite attractive conclusion that, before any climatic reason is studied for explaining this difference in first serial correlation coefficients between arid and humid regions, or before any climatic reason is advanced for the positive mean first serial correlation coefficients in effective annual precipitation the effects of inconsistency, non-homogeneity, and errors in determining the volumes of carry-over should be first taken into consideration.

The man-made changes are very likely to affect more the flows of an arid region than of a humid region. However, the complex relationship relating the evaporation and precipitation, either in the air during rainfall, or especially on the earth surface, may be the other important factor affecting the above differences.

PATTERNS IN FLUCTUATIONS MEASURED BY CORRELOGRAMS

DEFINITION, GENERAL REMARKS AND PROCEDURE

Definition

The correlogram is defined as a graph of discrete points relating the serial correlation coefficients and the lag between successive correlated pairs of members of a time series.

General remarks

The correlogram is a measure and an indicator of independence or of the type of dependence among the members of a time series. A random time series, if it is sufficiently long, has a random sequence of coefficients in correlogram, but the serial correlation coefficients are confined within the confidence limits of a given probability.

The confidence limits on 95 per cent level for random time series were computed by using equation (8).

According to R. L. Anderson (1941), the confidence limits for random time series for 95 per cent level are approximately

$$R_{95\%} = \frac{-1 \pm 1.64\sqrt{N-k-2}}{N-k-1} \tag{8}$$

with the meaning that 5 per cent of the points of correlogram should be on the average outside the confidence limits.

Procedure

The serial correlation coefficients for the annual flows and effective annual precipitations were compiled by using the following equations, similar to equations (4) and (5) in which r_1 is replaced by r_k and unity by k:

$$r_k = \frac{\sum\limits_{1}^{N-k} U_i U_{i+k} - \frac{1}{N-k}\sum\limits_{1}^{N-k} U_i \sum\limits_{1}^{N-k} U_{i+k}}{(N-k-1)s_i s_{i+k}} \tag{9}$$

with

$$s_i^2 = \frac{1}{N-k-1}\left[\sum_{1}^{N-k} U_i^2 - \frac{1}{N-k}\left(\sum_{1}^{N-k} U_i\right)^2\right] \tag{10}$$

and for s^2_{i+k} the value i in equation (10) is replaced by $i+k$.

The computation of these unbiased serial correlation coefficients was carried out up to $m \leqq \frac{N}{4}$, where N = length of time series, by using a digital computer.

RESULTS

Correlograms for individual river stations with long records

From seven river stations of long record, already mentioned above, and whose correlograms are computed and studied, only three will be given here.

Fig. 5 gives the correlogram for the River Göta at Sjötorp-Vänersborg (Sweden), N = 150 years; Fig. 6

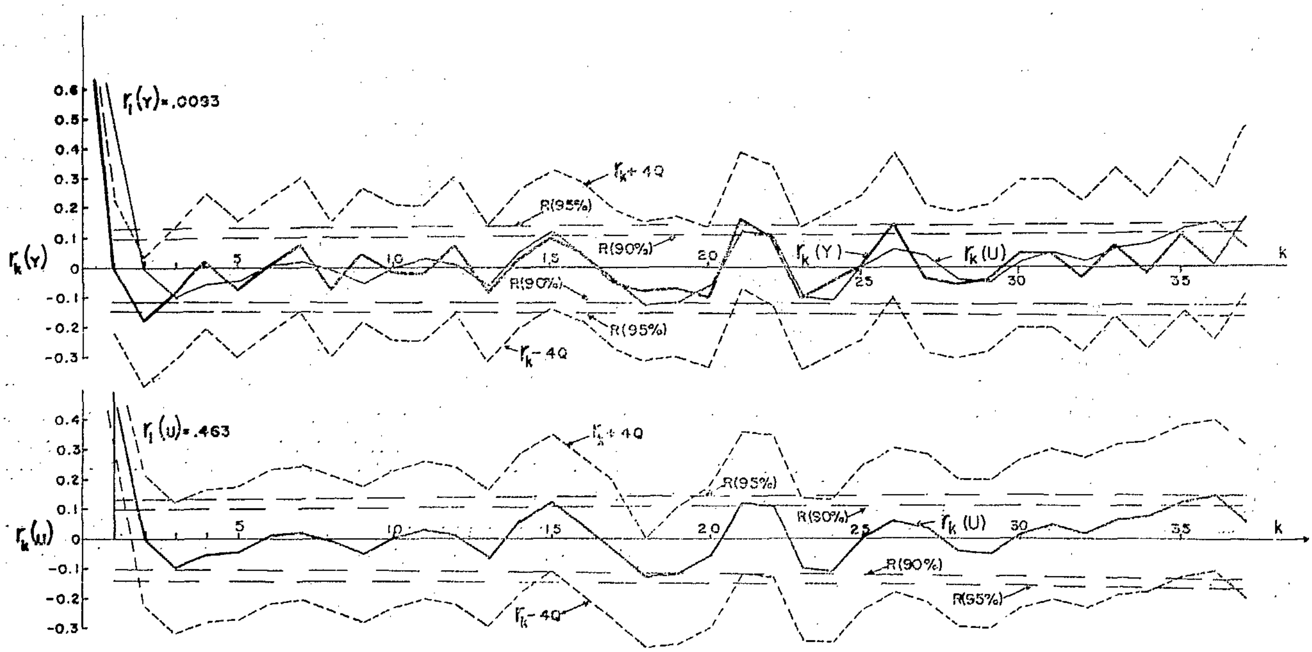

FIG. 5. Correlogram for River Göta at Sjötorp-Vänersborg.

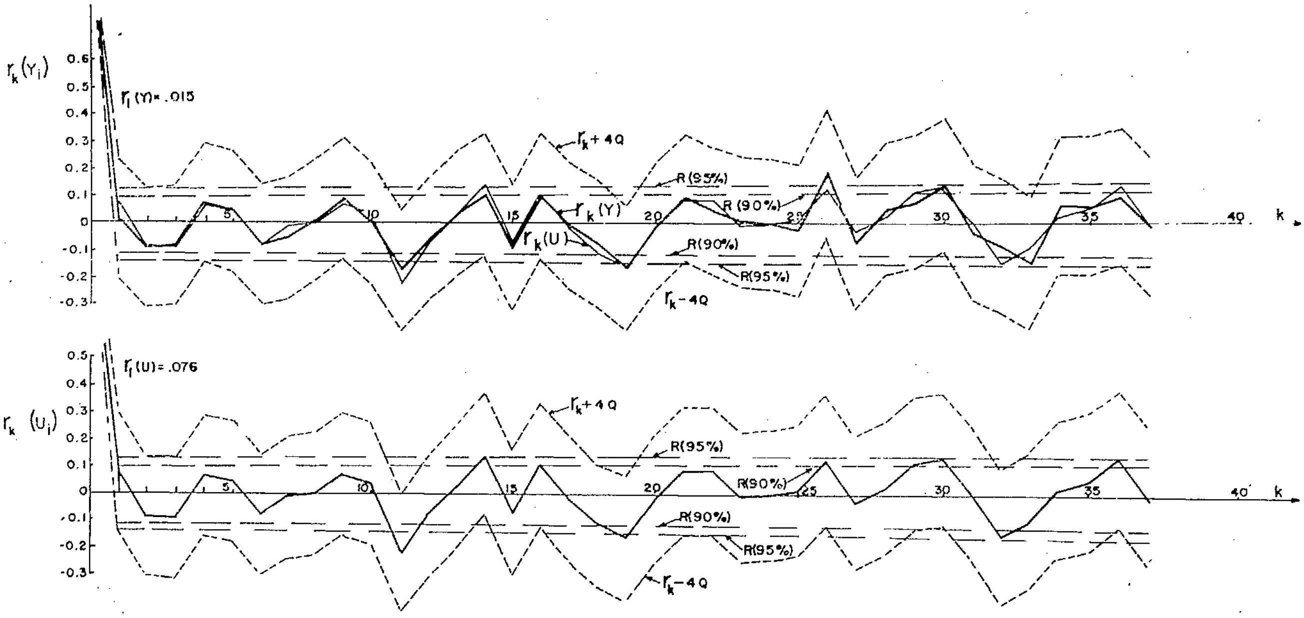

FIG. 6. Correlogram for River Rhine at Basle.

for the River Rhine at Basle (Switzerland), N = 150 years; and Fig. 7 for the St. Lawrence River at Ogdensburg, New York (U.S.A.), N = 97 years. The correlograms are given for both U and Y series, with confidence limit on 95 per cent level computed by equation (8), and similarly for 90 per cent level. The confidence limits of $r_k \pm 4Q$, where r_k = any correlation coefficient of lag k, and Q = probable error of r_k, are also given.

For the River Göta, Y series, the last value for $k = 37$ excluded, only two values of $r_k (k = 2, k = 21)$ exceed the 95 per cent confidence interval. The value $r_1 = 0.0093$ of Y series is very close to the expected value of random series of $r_1 = -0.0067$. By correction of water carry-over in river basin, the value $r_1 = 0.463$ of U series is reduced to value $r_1 = 0.0093$ of Y series.

For the River Rhine the correlograms of both series lie practically inside the confidence interval of 95 per cent level, because only two or three values of r_k exceed the limits. The $r_1 = 0.076$ of U series is reduced to $r_1 = 0.015$ of Y series by eliminating the effect of carry-over. The expected value of random series is $r_1 = 0.0067$.

The St. Lawrence River has three r_k values of Y series correlogram exceeding the confidence limits of 95 per cent level. The U series has a correlogram with significant positive r_k values from $r_1 - r_9$. The $r_1 = 0.705$ of U series is reduced by excluding river basin carry-over to $r_1 = 0.094$ of Y series.

Mean correlogram for 140 *river gauging stations*

Fig. 8 gives the average correlogram for 140 river gauging stations, obtained by using the mean value of each r_k. As time series are of different length N, and the number m of computed r_k is $\frac{N}{4}$, the mean number for each r_k is either $n = 140$ (up to $k = 10$), or smaller than 140, with only $n = 2$ for $k = 37$. The confidence limits are averaged in the same way, by summing up the limits for all stations and dividing the sum by the number n of the stations for a given lag k. Fig. 8 gives also the number n of r_k values for each k which were

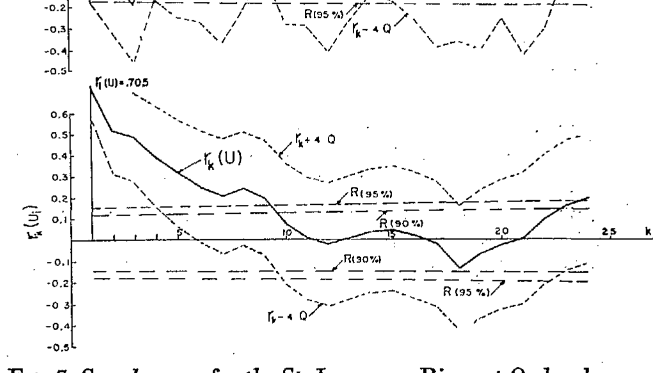

FIG. 7. Correlogram for the St. Lawrence River at Ogdensburg.

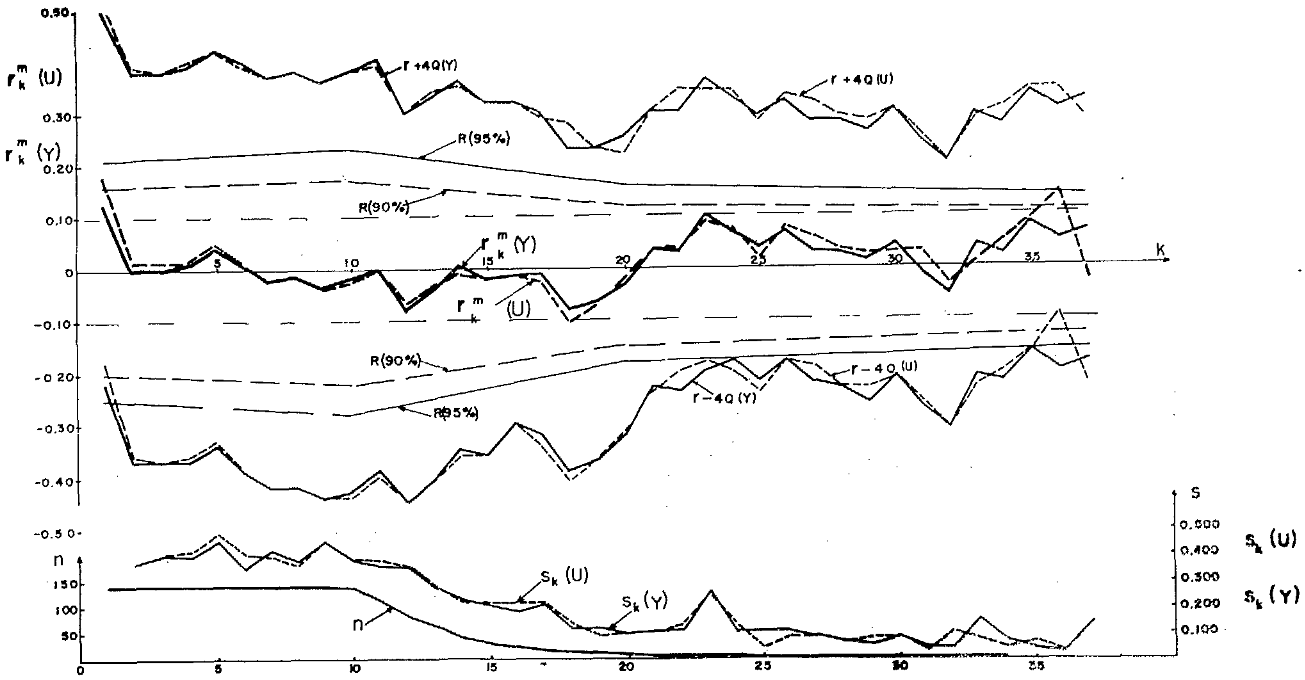

FIG. 8. Mean correlogram for 140 river stations, with mean confidence intervals (r_k 4Q), R (95 per cent) and R (90 per cent), with number n for each r_k, and the standard deviation s_k of r_k values around the mean value r_k.

used in computing the mean values, as well as the standard deviations s(U) and s(Y) of r_k values around the mean for each k. The confidence limits decrease with k, because of the averaging process, but theoretically the confidence limits should increase with an increase of k.

DISCUSSION AND CONCLUSIONS OF RESULTS

The analysis of correlograms, either of long-record stations or of the mean correlogram for 140 stations, points to the following:

1. The long-record stations (76-150 years of observations), regardless of some inherent inconsistency and non-homogeneity in data, have correlograms of Y series very close to random time series, because the number of r_k values exceeding the confidence limits is of the order of expected exceedances underlying the definition of limits.
2. The r_1 values of U series for seven long-record stations are mostly significantly different from zero, while this is not the case for Y series.
3. The St. Lawrence River is a typical example of the effect of water carry-over on the correlogram. The relationship of correlograms of U and Y series suggests the model of U and Y relationship of a moving average type, as expressed by equation (3), with b_j coefficients monotonically decreasing positive values, with their sum unity.
4. The long-record stations do not show any significant periodic movement (sun-spots, for example).
5. The mean correlogram for 140 stations clearly points out, that the values of r_k, except the mean value of r_1(U), are insignificantly different from zero, or from a random time series. The mean value of r_1(U) is greatly influenced by the effect of water carry-over.
6. The mean correlogram shows that neither the sun-spot average period of 11 years, nor the double sun-spot average period are of a significant influence on the effective annual precipitations. The lags 23-27 are, however, a little greater than zero (up to $r = 0.10$), but are inside the confidence interval.
7. Regardless which confidence limits are used (95 per cent level, 90 per cent level, $r_k \pm 4Q$), the correlograms of effective annual precipitations are not significantly different from random time series. If there would be a significant trend in climate changes all over the world, the correlogram would show this trend.

PATTERNS IN FLUCTUATIONS MEASURED BY RANGE

DEFINITION OF RANGE

The maximum range for a time series of length N and for the period N is defined as the difference of the

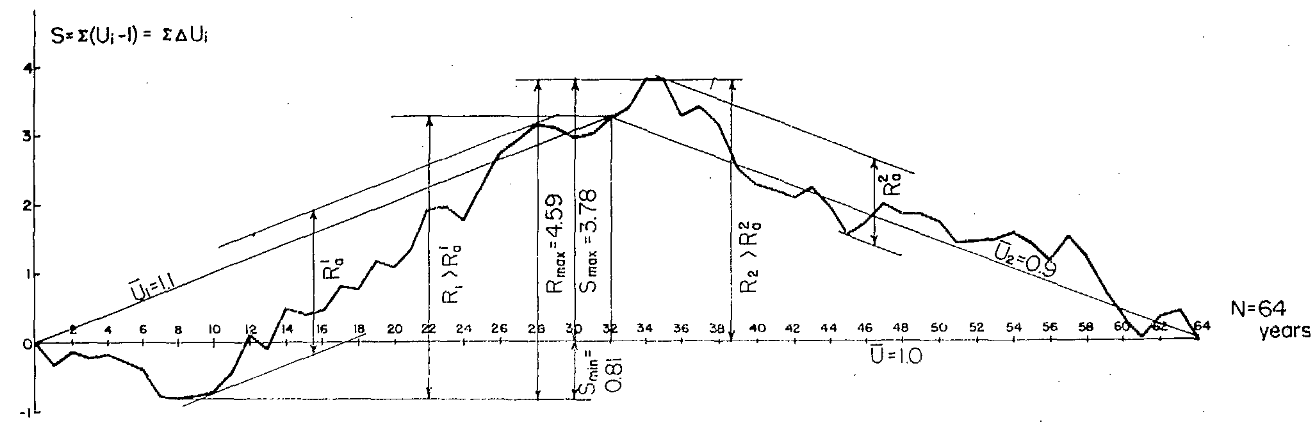

FIG. 9. Cumulation curve of departures of virgin annual flows (expressed as modular coefficients U_i) of Upper Colorado River at Lee Ferry, Arizona, from the mean $\overline{U} = 1$, for 64 years, with maximum range R_{max}, two adjusted ranges R^1_a and R^2_a, and maximum ranges R_1 and R_2 for two periods of $n = 32$ years.

maximum and minimum values on the cumulative curve of departures.

Fig. 9 gives the cumulative curve of departures for modular coefficients U_i of virgin annual flows of the Upper Colorado River at Lee Ferry. The maximum range for $N = 64$ years is defined as $R_{max} = S_{max} - S_{min}$, where S represents the values of the cumulative curve of departures. According to H. E. Hurst (1951), the maximum range for annual flows can be conceived as the maximum accumulated storage when there is never a deficit in outflow (equal to the mean discharge), or as the maximum deficit, where there is never any storage, or as the sum of accumulated storage and deficit, when both storage and deficit exist.

The basic characteristics for the above definition of range is the use of departures from the mean value of flows for N years, also, for the determination of range for shorter periods than N.

In a broader sense, any constant value U_o different from unity may be used to determine departures and the corresponding ranges.

The adjusted maximum range is defined by W. Feller (1951) as the difference of maximum and minimum of the cumulative curve of departures, but with the changing mean. If a period has a length of n years, smaller than N, the mean of period n is used for computing the departures and the adjusted range. An example of this maximum adjusted range is given in Fig. 9 for two periods of $n = 32$ years (first half and second half of the total period). The lines of means $\overline{U}_1$ and $\overline{U}_2$ are plotted, and by using lines parallel to them S_{max} and S_{min} are obtained for both half periods, and then the adjusted ranges R^1_a and R^2_a are determined. The use of the mean $\overline{U} = 1$ for determining the ranges for both 32-year periods gives the maximum range values R_1 and R_2, also shown in Fig. 9.

All these definitions of ranges, based on $\overline{U} = 1$, or any U_o, or as the adjusted range can be used, depending on the type of problem at hand. In using the range as a statistical technique for comparing the observed series with the random series the range defined on the basis of the mean for the period of observation of N years will be used here, though the basic study (Slutzky, 1937) from which this paper is derived discusses all concepts of range.

DISTRIBUTION OF RANGE OF DIFFERENT PERIODS FOR RANDOM TIME SERIES

General distribution function

Let a period of length of n years be fixed for study (i.e., 5 years, 10 years, 25 years, etc.). Let also the total period of N years be divided in m smaller n year periods, so that $m.n + n_1 = N$, where $n_1 < n$ is a residual. If the range was determined for each of m periods on the basis of the mean for the total period N, there would be m values of the maximum range, one for each of n year periods. The distribution of these maximum ranges may be conceived as a statistical technique for analysis of fluctuations.

Fig. 10 shows the eight values of R_8 for $n = 8$ years for the Upper Colorado River at Lee Ferry. There is a distribution of R_8-values, in this case ranging from 0.82 to 1.65. This corresponds to a fixed value $n = 8$, and for the mean as basic reference for computing the departures.

Assuming n as a variable, the reference value U_o also as a variable, a general four variables function

$$F(R, p, n, U_o) = 0 \tag{11}$$

with p = probability of the range R for given n and given U_o, can be determined either analytically (by using some approximation), or by numerical procedures in the case of a random series, or a stochastic series, with known basic distribution of U_i (or Y_i).

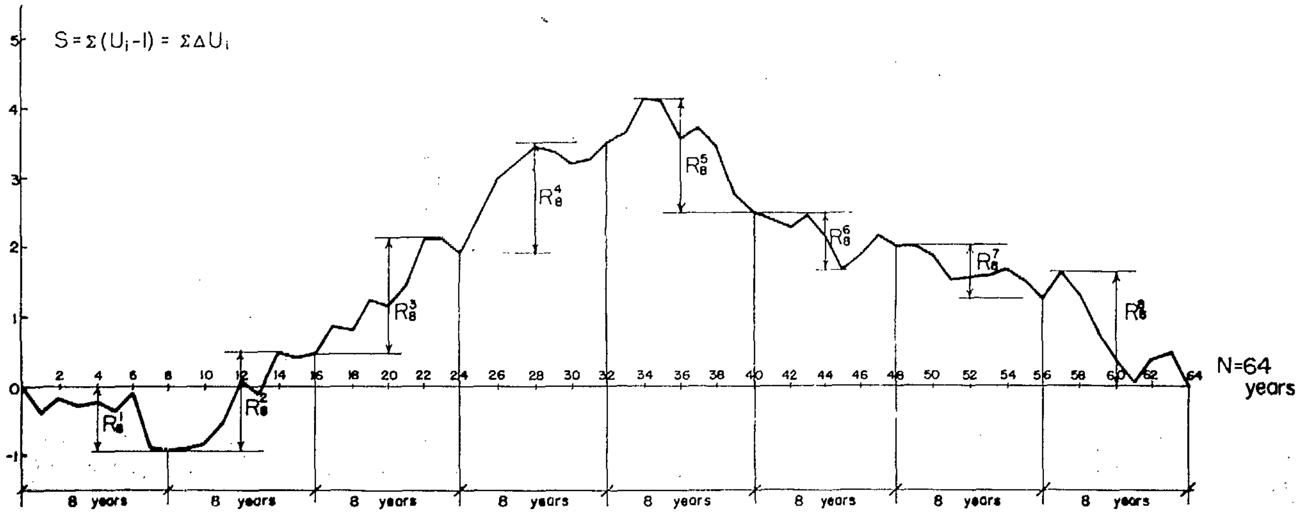

FIG. 10. Determination of ranges for eight periods, each 8 years long, for the homogeneous sample of annual river flows (reduced to depletion conditions in 1954-57) of Upper Colorado River at Lee Ferry, Arizona.

Distribution of ranges of random series as yardstick distribution

The range distribution theoretically developed for random series was used here as a yardstick to compare with the range distribution of annual flows and of effective annual precipitations.

The range distribution for both random and observed series was defined here by three statistical parameters: mean, coefficient of variation and skew coefficient. If the three parameters for given n and $\overline{U} = 1$ do not differ for the compared random and observed series in a significant manner, it is assumed that observed series is close to random series.

Distribution of range for a random series and large n

The asymptotic values for expected mean and for variance of the range of random series is given by W. Feller (1951)

$$\overline{R}_n = 1.5958\ldots s\sqrt{n} \simeq 1.6\, s\sqrt{n} \qquad (12)$$

and

$$S^2_n = \mathrm{var}\,(R_n) = 4s^2n\left(\ln 2 - \frac{2}{\pi}\right) = 0.2182\, s^2 n \qquad (13)$$

where s = standard deviation of time series of length N; n = length of period for which the mean range and variance of range are determined, $\overline{R}_n$ is the expected mean of range for period of length n, and S_n^2 is the variance of the range distribution.

It follows from equations (12) and (13) that the asymptotic value of the coefficient of variation of range distributions is a constant equal to 0.292.

The condition for the application of equations (12) and (13) is a large n value.

Distribution of range of a random series for small n

In case the random variable is normally distributed, the mean range for $n = 1$ is

$$\frac{\overline{R}_1}{s} = \int_0^\infty \sqrt{\frac{2}{\pi}}\, R_1\, e^{-R_1^2/2}\, dR_1 = \sqrt{\frac{2}{\pi}} \simeq 0.80 \qquad (14)$$

and variance of R_1

$$\frac{S_1^2}{s^2} = \int_0^\infty (R_1 - \overline{R}_1)^2\, p_1(R_1)\, dR_1 = \left(1 - \frac{2}{\pi}\right) = 0.363 \qquad (15)$$

where $\overline{R}_1/s$ and S_1^2/s^2 represent the mean and variance of a standardized variable with variance unity. When equations (14) and (15) are applied to modular coefficients, U_i and Y_i with mean unity and variance s^2, then

$$\overline{R}_1 = 0.80\, s;\ \text{and}\ S_1^2 = 0.363\, s^2$$

The range is a truncated distribution of half the normal distribution, with a skew coefficient

$$C_s = \left(2 - \frac{\pi}{2}\right)\left(\frac{2}{\pi - 2}\right)^{2/3} \simeq 0.995$$

The distribution of R_1 is given in Fig. 11.

For $n = 2$ the probability of range R_2 is

$$p_2(R_2) = \frac{2}{\sqrt{\pi}}\, e^{-R_2^2/4} \left[\int_0^{R^2/\sqrt{2}} \frac{e^{-t^2/2}\, dt}{\sqrt{2\pi}} + \sqrt{2}\, e^{-R_2^2/4} \int_0^{R_2} \frac{e^{-t^2/2}\, dt}{\sqrt{2\pi}}\right] \qquad (16)$$

where t = a standardized variable; R_2 = any range for $n = 2$; $p_2(R_2)$ = probability of a given range R_2.

The distribution of R_2 and its statistical parameters are computed by numerical integration of equation (16), and the distribution is shown in Fig. 11.

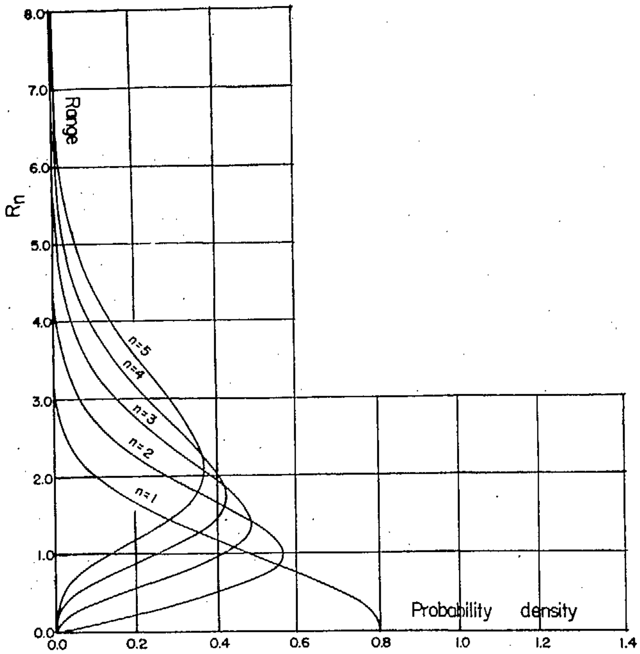

Fig. 11. Probability density distribution of ranges for $n = 1$, 2, 3, 4, and 5 for random time series of standardized normal variate.

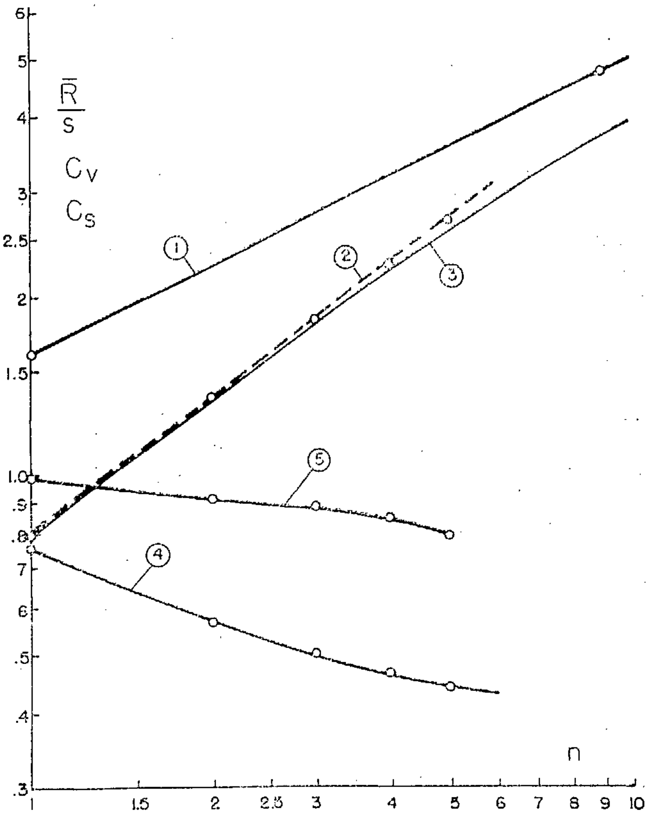

Fig. 12. The statistical parameters of range distribution of random time series of normal variable for small n (1-10) :

1. Mean range ($\bar{R}/s$), asymptotic values.
2. Exact values of mean range, obtained by numerical integration.
3. Mean range obtained by formula, given by Anis and Lloyd.
4. Exact values of coefficient of variation.
5. Exact values of skew coefficient.

The distributions and statistical parameters for R_3, R_4, and R_5 are also expressed in similar forms as equation (16), then numerically integrated or computed, and the distributions are shown in Fig. 11, and parameters in Fig. 12.

A. A. Anis and E. H. Lloyd (1953) give the mean value of the range for finite small n as

$$\bar{R}_n = \sqrt{\frac{2}{\pi}} \sum_{i=1}^{n} i^{-1/2} \qquad (17)$$

with i integers from 1 to n.[1] As an example, for $n = 4$, $\bar{R}_4 = 2.22166$. The values $\bar{R}_i$ computed by equation (17) are given in Fig. 12, curve (3).

The comparison of the mean values of the range distribution for different small n is given for three types of values: (*a*) asymptotic values according to equation (12); (*b*) values obtained by numerical integration of exact distributions, equations (14), (15), (16) and similar; and (*c*) values obtained from analytical expression of equation (17). Though there are some departures among the curves (*b*) and (*c*), it could be assumed that equation (17) approximates closely the exact values given by curve (*b*) for very small n. The asymptotic values depart greatly from the exact values for very small n. For $n = 1$ the asymptotic value is double the exact value for the mean range.

DISTRIBUTION OF MAXIMUM RANGE OF EFFECTIVE ANNUAL PRECIPITATION FOR 14 RIVER GAUGING STATIONS OF THE UPPER COLORADO RIVER BASIN AND AROUND IT

Procedure

The cumulative curves of ΔY_i departures were plotted and the ranges for $n = 1, 2, 3, 4, 5, 7, 10, 15, 20, 25$ were determined for as many periods m of length n as they may be included in the total length N for each station, without overlapping of periods of length n. While the number m of R values were greater for R_1 (equal to

1. The authors (Anis and Lloyd, 1953) give the coefficient of equation (17) both as $\sqrt{2/\pi}$, and $1/\sqrt{2\pi}$, and A. A. Anis in two successive papers (*Biometrica*, vol. 42, 1955, p. 96-101, and vol. 43, 1956, p. 79-84) gives always the value of coefficient as $1/\sqrt{2\pi}$. The author of this paper has found out that to his approach the value of $\sqrt{2/\pi}$ of equation (17) was correct.

$N - 1$), the number m decreased with an increase of n, so that for R_{25} this number was either one ($N < 50$) or two ($N \geq 50$) for each station.

The values R_i were divided by the standard deviation of Y series of the corresponding station, so that all values $\frac{R}{s}$ for all stations refer to a unique standardized variable with the variance $s^2 = 1$. This procedure enabled the pulling together of values R for given n of all 14 stations in one large sample (size 646 for R_1, and size 28 for R_{25}).

Results

The distributions of ranges for 14 stations, with all corresponding values pulled together, are given in Fig. 13, and for the first five values of n (1, 2, 3, 4, 5) the distributions of ranges of random series (Fig. 11) are plotted also.

The computed values of mean, coefficient of variation and skew coefficient are plotted in Fig. 14. The corresponding statistical parameters for random series are plotted in this figure also, and specifically: (*a*) mean and coefficient of variation of R-distribution for asymptotic range values; (*b*) mean, coefficient of variation and skew coefficient for five values of n, computed by numerical integration of range distribution; and (*c*) the mean, computed by equation (17).

Comparison of Y series and random series

Fig. 13 shows that the distributions of ranges for 14 river gauging stations for small n are very close to distributions of ranges of random series.

Though the values m (sample sizes for R distributions) are large for R_1 to R_5, the sampling stability of range is, however, relatively small. This is mainly due to the fact that the concurrent values of Y series (values for the same water year) of 14 stations in the Upper Colorado River Basin and around, pulled together, are not independent among them.

It can also be seen from the comparison of distributions in Fig. 13, that both the mean and the standard deviation of range distributions of Y series increase constantly with an increase of n, as it is the case with a random series.

Taking into consideration the following factors: (*a*) regional sampling; (*b*) errors in the computation of carry-overs from one water year to another; and especially (*c*) non-homogeneity of data (created by man-made changes in river basins), it can be assumed here that the distributions of range of the effective annual precipitations in the Upper Colorado River Basin are very close to those of random time series.

The comparison of statistical parameters of range distributions of Y series for 14 river gauging stations in the Upper Colorado River Basin and around it, with the statistical parameters of range distributions of random series shows that the mean values of ranges of Y series are nearly identical with mean values of range of random series, because the curves (2) and (4) of Fig. 14 are very close, at least for values $n = 2 - 15$.

The asymptotic values of mean range, curve (1) in Fig. 16, are much larger than the values of the mean ranges of Y series. The mean ranges computed by equation (17) approximate well the computed mean ranges of Y series.

The comparison of the coefficients of variation of range distributions of Y series with those of random series shows that the departures between them are not great, curves (5) and (7), Fig. 14, while the asymptotic constant value, curve (6), is much smaller than the observed values.

The comparison of skew coefficients of range distributions of Y series with those of random time series shows, in the limits of the sampling instability of the third statistical moment of distributions of Y series, that the closeness of two curves, (7) and (8), Fig. 14, is sufficiently good to derive the conclusion that even the skew coefficients are very close for the two range distributions.

RANGE DISTRIBUTIONS FOR SEVEN LONG-RECORD RIVER STATIONS

Dependence factor

Assuming that only the coefficients b_0 through b_{m-1} (first m values) in equation (3) are significantly different from zero, then according to Cramer (1935)

$$r_k = \sum_{0}^{m-k} b_j b_{j+k} \Big/ \sum_{0}^{m-1} b_j^2 \tag{18}$$

The value

$$D = \left(1 : \sum_{0}^{m-1} b_j^2\right)^{1/2} \tag{19}$$

is defined here as the dependence factor of a time series. Then (Yevdjevich, in preparation)

$$D^2 = 1 + 2 \sum_{1}^{m-1} r_k \tag{20}$$

With $D = \sqrt{1 + 2r_1}$, when only r_1 is significantly different from zero, and approximately $D^2 = 1/(1 - r_1)$ when several other r_k values are significantly different from zero.

Dividing the mean range values, or other parameters of range distributions by D, the series of different dependence factors may be compared.

Comparison of parameters of range distribution for seven long-record stations with random series

Fig. 15 shows the mean relative range $\overline{R}$, divided by the product $D \times s$ (dependence factor of series multiplied by standard deviation of U or Y series), for seven

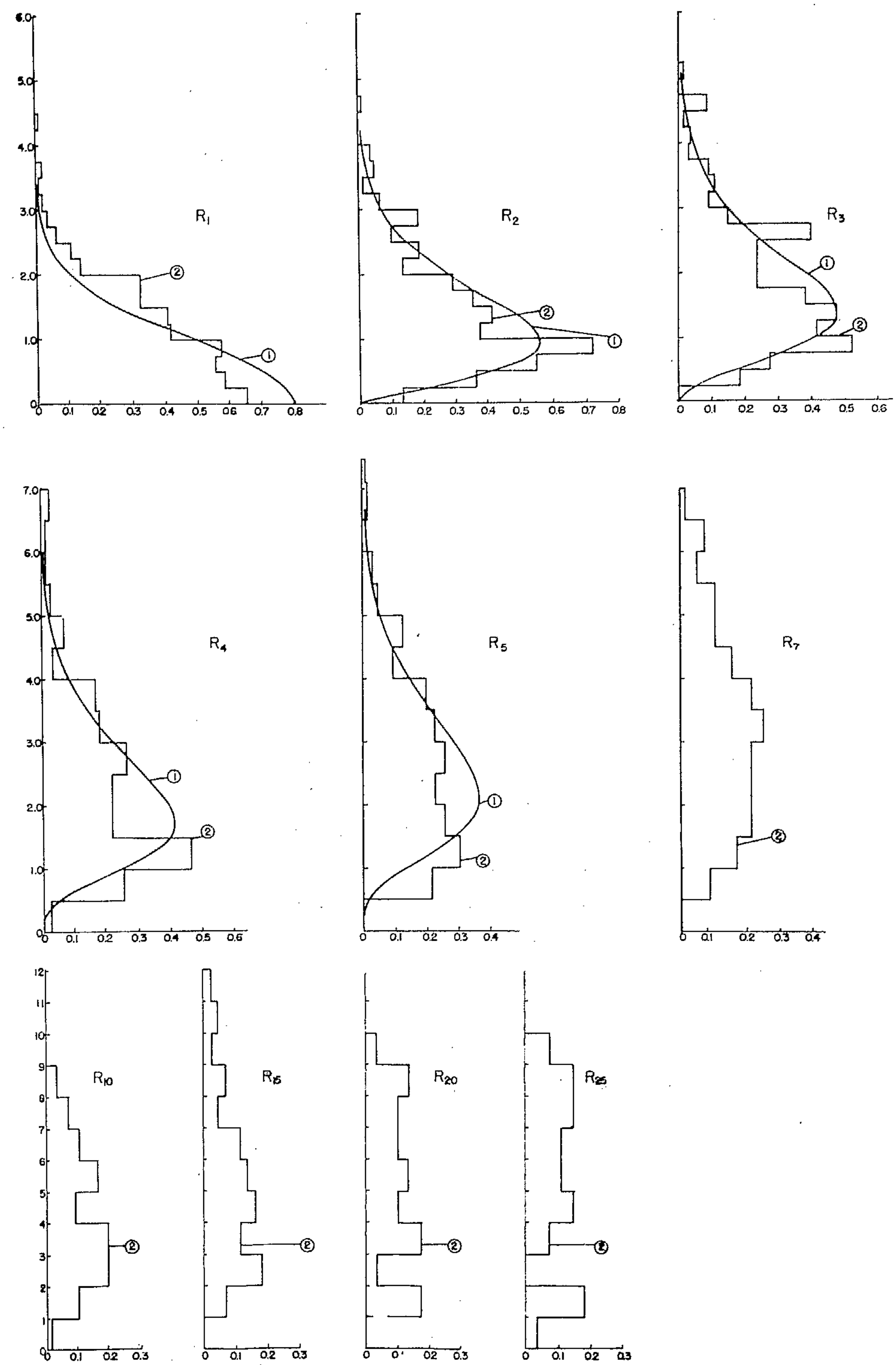

FIG. 13. Distributions of ranges for random time series (for $n = 1, 2, 3, 4, 5$), and for 14 river gauging stations from Upper Colorado River Basin and around it, for $n = 1, 2, 3, 4, 5, 7, 10, 15, 20$ and 25, for all 14 stations pulled together as a unique standardized variate of Y series (modular coefficients) of effective annual precipitations :
1. Random series.
2. Upper Colorado River Basin.

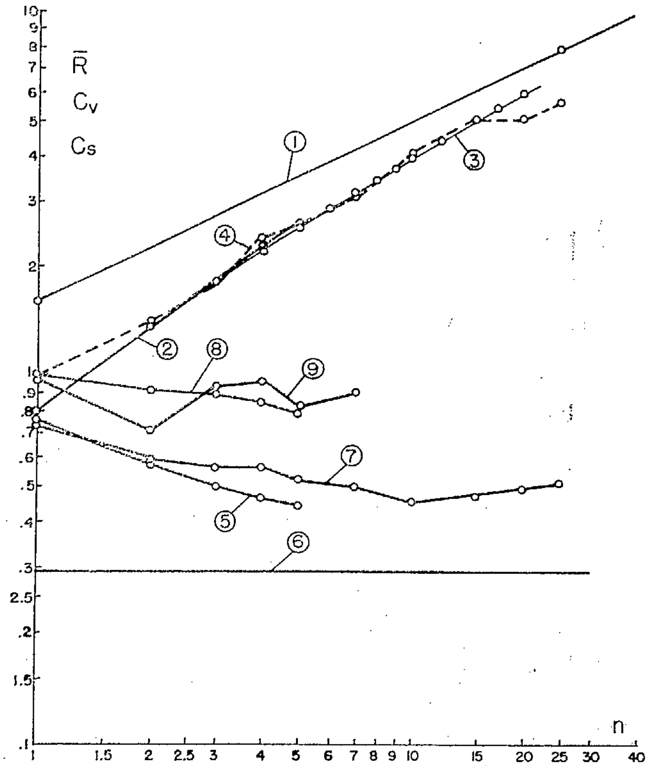

FIG. 14. Comparison of statistical parameters of range distributions for effective annual precipitations (Y series) of 14 river gauging stations in Upper Colorado River Basin and around it, with those of random time series :

1. Asymptotic values (1.6 *n*) of the expected mean of random series.
2. Exact values of means for random series.
3. Values of means for random series computed by equation (23).
4. Means of range distributions for 14 river gauging stations.
5. Exact values of coefficient of variation for random series.
6. Asymptotic constant value for coefficient of variation for random series.
7. Coefficient of variation of range distributions for 14 river gauging stations.
8. Exact values of skew coefficients for range distributions of random series.
9. Skew coefficients of range distributions for 14 river gauging stations.

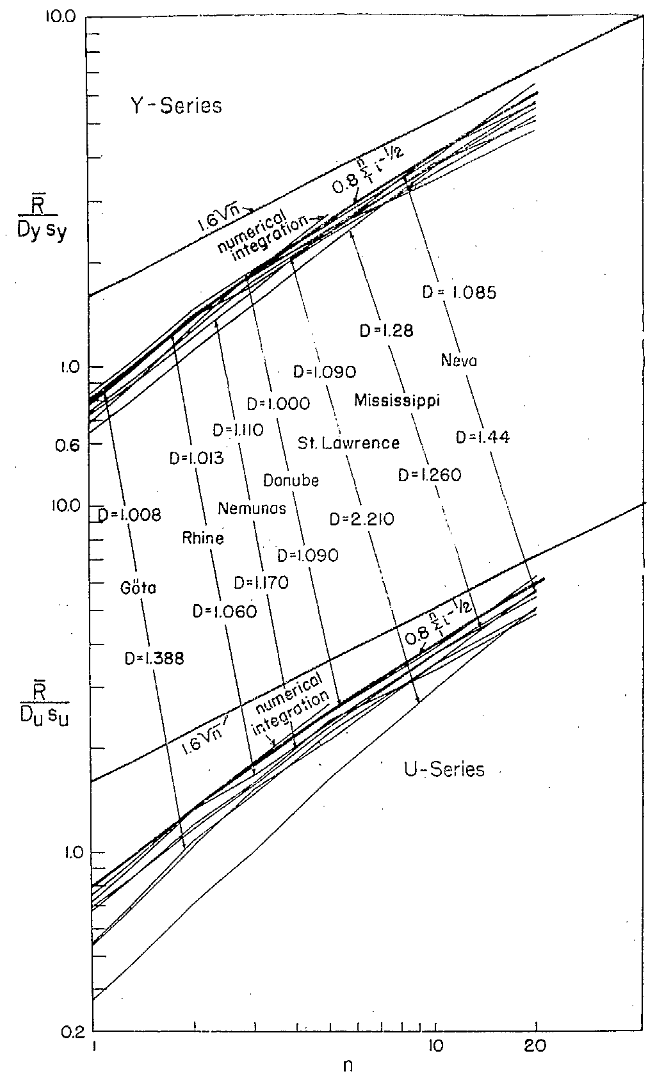

FIG. 15. Comparison of mean ranges divided by D × *s* (dependence factor multiplied by standard deviation) for seven rivers with long records, for both Y_i and U_i series, with the asymptotic mean values (Feller), mean values for small *n* (Anis-Lloyd), and for mean values determined by numerical integration of exact range distributions.

rivers in relation to *n*. The curves for these rivers are compared with series (D = 1): (*a*) asymptotic values of mean range, given by Feller; (*b*) mean ranges given by Anis-Lloyd formula, equation (17); and (*c*) mean ranges obtained by numerical integrations. The dependence factors are given for each river and U and Y series respectively.

The upper graph of Fig. 15, with relatively small D values (close to unity), clearly points out that the computed mean ranges for seven rivers are very close to the corresponding values of random time series for small *n*. For the Danube (120 years), the Göta (150 years), and the Rhine (150 years) it is difficult either to distinguish their mean ranges from the ranges of random series.

The lower graph shows that the greater is D (St. Lawrence) the greater is the departure of that series from the corresponding values of random series.

As distributions of U and Y series are skewed, the departures evidenced in Fig. 15 may be partly attributed to the skewness effect.

Fig. 16 shows a comparison between the coefficient of variation of range distributions, as function of *n*, with the same parameter of range distribution of random

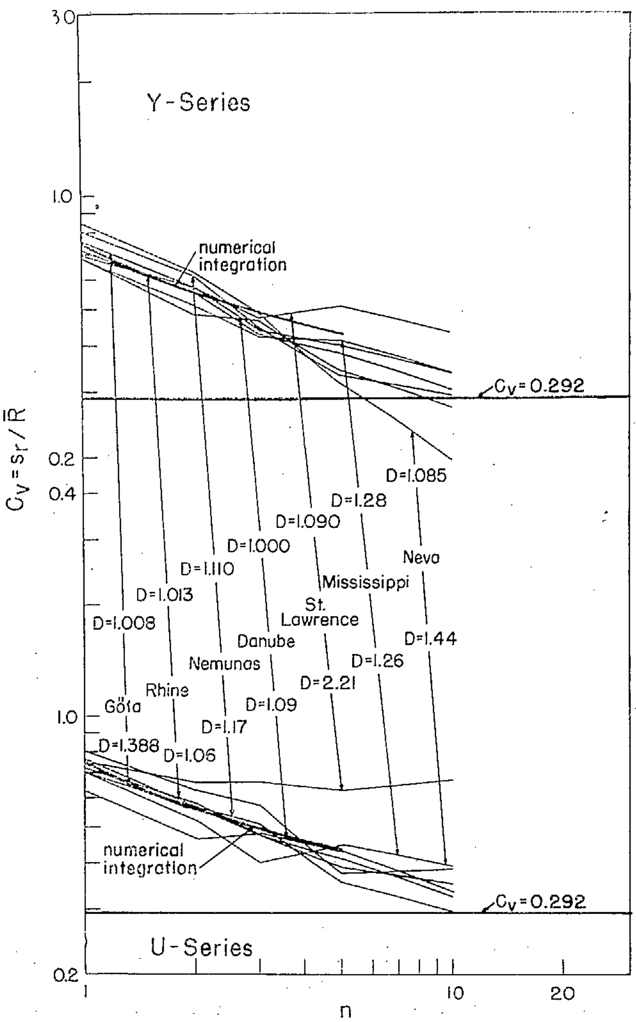

FIG. 16. Comparison of coefficient of variation of ranges for seven rivers with long records, for both Y_i and U_i series, with the asymptotic constant value $C_v = 0.292$ (Feller) and the coefficients of variation, determined by numerical integration of exact distribution of ranges.

series. There are two lines for random series: asymptotic constant value $C_v = 0.292$ of this coefficient, as given by Feller, and the values obtained by numerical integration of exact probability distribution functions. It points out that for small values of D the Y series approaches sufficiently close the random series.

GENERAL CONCLUSIONS

The analysis of hydrological characteristics in fluctuation of annual river flows and derived effective annual precipitations leads to the following conclusions:

1. Distribution of first serial correlation coefficient, correlogram analysis, and distribution of maximum range have shown that the sequence of effective annual precipitations is very close to random sequence.
2. Most of dependence between the successive values of annual flows can be explained: (*a*) by changing of water carry-over from one water year to another in the form of different water storage in a river basin; (*b*) by non-homogeneity in data; (*c*) by some systematic errors in compilation of annual flows; and (*d*) by error from regional sampling. After these factors are taken care of the room left for the causes of this linkage, which come either from the atmosphere or solar activities, remains small.
3. Dependence between successive values of effective annual precipitations can be explained: (*a*) by data inconsistency, data non-homogeneity, and error in computation of water carry-over in the corresponding river basin; (*b*) by an assumed complex relationship of evaporation and evapotranspiration to precipitation (non-linear relationship); (*c*) by a regression effect of stored moisture in atmosphere; (*d*) by regional sampling errors; and (*e*) by selection of the beginning of a water year.
4. There is no statistical evidence that the fluctuations of annual flows or effective annual precipitations may be composed of hidden periodicities, or of some regular patterns in the fluctuations, which can be extrapolated in the future with a reasonable expectancy that they would occur and would be verified by future flow records.
5. There is no evidence that the climatic factors as related to water resources have been changed significantly in the last 150 years.
6. Reliable forecasts of future annual flows (of order two to five years or more) by methods which are based on extrapolation or regular patterns in annual flow fluctuations (for instance, of hidden periodicities, or sun-spot cycles) do not seem possible.
7. Non-homogeneity (or inconsistency) in data of annual flows is an important hydrological characteristic of many river basins. It affects substantially the characteristics of available records of river flows, making the dependence of flows and effective precipitations greater than it would be without it. This is usually also the case with other series of climatic factors, related to water resources.
8. Carry-over of water from one water year to the next is an important hydrological characteristic of river basins, which greatly affects the linkage between the successive values of annual flows.

RÉSUMÉ

Étude des fluctuations climatiques au moyen des débits annuels et des précipitations annuelles effectives
(V. M. Yevdjevich)

La présente communication traite des fluctuations, dans les bassins fluviaux, tant des débits annuels que des précipitations effectives annuelles que l'on en déduit. Les valeurs des précipitations annuelles effectives (précipitation moins évapotranspiration) sont obtenues en corrigeant les débits annuels pour tenir compte des reports d'eau en fin d'année. Les données de base comprennent les valeurs des débits annuels enregistrés dans 140 stations fluviales de mesure situées dans de nombreuses régions du monde. Les caractéristiques statistiques des séries de débits annuels et des précipitations annuelles effectives sont rapprochées des caractéristiques de séries chronologiques aléatoires, ou de séries dérivées de séries chronologiques aléatoires. Les techniques appliquées consistent à établir des coefficients de corrélation, avec des corrélogrammes et les amplitudes des écarts accumulés à partir de la moyenne. La présente analyse indique qu'une partie importante de la différence qui apparaît entre les débits annuels observés et les séries chronologiques aléatoires peut s'expliquer par les effets de régression du report d'eau, de neige et de glace en fin d'année. Une autre partie de cette différence, en ce qui concerne les débits annuels et les précipitations annuelles effectives, peut être attribuée aux erreurs systématiques et au manque d'homogénéité des données et à des rapports complexes entre l'évaporation ou l'évapotranspiration et la précipitation. L'ensemble de ces facteurs explique en grande partie la différence constatée, un petit reste pouvant être considéré comme représentant l'effet d'autres facteurs qui peuvent influer sur la persistance des fluctuations climatiques. La suite des précipitations annuelles effectives est très proche des fluctuations aléatoires. Aucune donnée statistique ne montre que le climat, dans ses rapports avec les ressources hydrauliques disponibles, a changé d'une manière significative depuis cent cinquante ans, à en juger du moins par les fluctuations des débits fluviaux annuels.

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SECTION II

CHANGES DURING THE LATE GEOLOGICAL AND EARLY HISTORICAL RECORDS

CHANGEMENTS SURVENUS A LA FIN DES TEMPS GÉOLOGIQUES ET AU DÉBUT DES TEMPS HISTORIQUES

Chairman / Président: Dr. K. W. Butzer

CHANGES OF CLIMATE DURING THE LATE GEOLOGICAL RECORD

Introductory Remarks

by

K. W. Butzer

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During the some 250 million years that elapsed subsequent to the Permocarboniferous glaciations, planetary climates were surprisingly uniform and pronouncedly non-glacial in character. Lower Tertiary floras have been interpreted as evidence of mesothermal climates polewards of latitude 60°, while tropical and subtropical forests dominated middle latitudes. Although the Eocene isoflors are noticeably zonal in their arrangement, concentric with the modern North Pole, meridional temperature gradients must have been remarkably weak. This situation of complete deglaciation and reduced latitudinal differentiation is the essence of what the late C. E. P. Brooks described as the "normal climate of geological time".

A downward trend of mean temperatures is evidenced during the course of the Tertiary, European averages being lowered by 10° C. during a 20-million-year span since the later Oligocene. Some 2 million years ago according to recent potassium-argon dates, the planet entered the violent pulsations of climate characteristic for the Pleistocene. With higher latitudes sufficiently cool, a very delicate balance of heat exchange permitted frequent thermal aberrations that may have been due to primary lowering of planetary temperature or to the cumulative momentum of changes in latitudinal heat exchange, large-scale circulation patterns, albedo, reduction of ocean water surface in high latitudes, etc. Whatever the cause the resulting physical phenomena were momentous.

Geomorphologists and geologists have spent over a century analysing the full impact of successive glaciations on the world's surface. Biologists of different backgrounds have sought answers to numerous problems in evolution by studying the evidence of migrations and mutations within the spectrum of glacials and interglacials. And the study of early man has likewise turned back into the Villafranchian dark ages of African prehistory to consider gene flow and genetic drift of early populations in a complex of changing ecological niches on that continent.

Palaeoecological and palaeoclimatological research is no longer a matter of speculation and grandiose hypotheses. Each field of investigation has aimed at and partially succeeded in obtaining quantitative rather than qualitative estimates of fossil processes. Bodies of reliable information are slowly building up in the most varied institutions of learning. Techniques undreamt of two decades ago have revolutionized our thinking. One need only recall radio-carbon dating, whereby our notions of time scales in a 70,000-year span have become tangible even if not absolute. Or the recent advances in Pleistocene comprehension thanks to potassium-argon dating, tentative yet amazing. Palaeotemperature measurements of ocean surface waters are now known for a time span of several hundred thousand years. And the biological sciences have taken great strides in elucidating total ecology.

If I may take the liberty I shall outline some of the less spectacular but equally significant directions of specialized study in the field of geomorphology. Field students have realized that cataloguing phenomena or identifying materials without process analysis is unsatisfactory. The study does not merely consist of Pleistocene glaciers and normal fluviatile cycles. A great variety of cold-climate phenomena span most latitudes awaiting careful interpretation against actualistic observations in specific ecological environments. Fluviatile features are dismembered into sedimentary entities, susceptible to laboratory analysis or comparable with carefully observed actual data such as are outlined by Miller and Leopold in a later section. Wind deposits have been employed to reconstruct storm-wind circulation means and former *grosswetter* situations. Fossil pedogenetic processes have been more widely recognized in chronological context and at least qualitatively interpreted. With the revitalization of geomorphology in its climatic aspects, dynamical earth science aspects of the Pleistocene have hope to escape the dead burden of "classical" geological investigation in which the briefest units are measured as a factor of 1.10^6 years.

Perhaps the acceleration of innovation, perfection and application of methods, with resulting accumulation of data, has never been as great as now in the field of palaeoclimatology. An example may suffice, namely the revolutionary progress of solid scientific work in the east, central and south African Quaternary during the past few years.[1] The frustrating discussions of pluvial stratigraphy in equatorial latitudes have been terminated by radio-carbon-dated pollen-analytical studies locating the last major pluvial in the time span corresponding to the Early Würm period. Geomorphological studies have likewise shown the associations of pluvial river deposits with the advance of the central-east African glaciers. Soils work on the other hand has shown the humid-type red soils of the Sudan margins to extend in analogous form from the Equator to the Alps, and to be fossil or relict. The hue-and-cry of some authors for wholesale latitudinal migrations of climatic belts seems unwarranted in the face of ever-new empirical observations.

And here there is much room for climatological and meteorological application. At the moment it seems justified to suspect that first-order climatic changes of the later Pleistocene were changes in degree and not in kind. Intensification or slackening of existing phenomena, moderate frequency shifts of alternative dynamic patterns, these all appear to call for specific consideration and thought. The fundamental question, since probably first suggested by Sir George C. Simpson, is one of planetary radiation balance and thermal exchange. Meteorologists must tackle these problems with the "palaeo" view in mind. Without thought or willingness to communicate on the part of meteorologists, the earth scientist is condemned to interpretative stagnation or heretical deviation. I am confident that it is everyone's wish at this conference that a better and more balanced future lies in wait for interdisciplinary research on changes of climate.

1. See the publications (in press) of the Wenner-Gren symposium "African ecology and primate evolution ", Burg Wartenstein, Austria, July 9-22 1961.

LES CHANGEMENTS DE CLIMAT PENDANT LES ÈRES GÉOLOGIQUES LES PLUS RÉCENTES

Remarques préliminaires

par

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Pendant les quelque 250 millions d'années qui ont suivi les glaciations du permocarbonifère, les climats planétaires ont été étonnamment uniformes et de caractère nettement « non glaciaire ». On a déduit de l'étude des flores du tertiaire inférieur que des climats mésothermes régnaient dans les zones comprises entre le 60e degré de latitude et le pôle, tandis que des forêts de type tropical ou subtropical prédominaient aux latitudes moyennes. Bien que les isoflores de l'éocène présentent une disposition zonale marquée, centrée sur un point qui correspond à la position actuelle du pôle nord, les gradients méridiens de température devaient être remarquablement faibles. Cet état de complète déglaciation et de faible variation des températures selon la latitude caractérise ce que C. E. P. Brooks appelle « le climat normal des temps géologiques ».

Une tendance à l'abaissement des températures moyennes apparaît au cours du tertiaire, les moyennes européennes diminuant de 10 °C au cours des 20 millions d'années qui font suite à la période de l'oligocène supérieur. Il y a quelque 2 millions d'années (d'après les récents résultats de la datation au potassium-argon), la planète commença à connaître les brutaux changements de climat caractéristiques du pléistocène. Les latitudes élevées étant relativement froides, un bilan très critique d'échange de chaleur a permis de fréquentes fluctuations thermiques qui peuvent avoir été dues à un abaissement d'ensemble de la température planétaire ou aux effets accumulés de modifications intervenues dans les échanges thermiques latitudinaux, les systèmes de circulation atmosphérique à grande échelle, l'albedo, la réduction de la surface liquide des océans aux latitudes élevées, etc. Quelles qu'aient pu être les causes de ces fluctuations, les phénomènes physiques qui en sont résultés ont été très importants.

Les spécialistes de la géomorphologie et de la géologie ont passé plus d'un siècle à analyser les multiples effets des glaciations successives qu'a connues la surface du globe. Des biologistes travaillant dans des domaines différents ont cherché à préciser de nombreuses questions liées à l'évolution en étudiant les signes de migration et de mutations dans la gamme des glaciaires et interglaciaires. Dans l'étude de l'homme primitif, on s'est de même tourné vers les obscures époques « villafranchiennes » de la préhistoire africaine pour considérer les transformations et tendances génétiques des anciennes populations dans le cadre complexe des variations écologiques du milieu naturel africain.

Les recherches paléoécologiques et paléoclimatologiques ne sont plus faites aujourd'hui de simples spéculations ou de grandioses hypothèses. Dans chaque domaine, des efforts partiellement couronnés de succès ont été déployés en vue d'une appréciation plutôt quantitative que qualitative des processus paléontologiques. Peu à peu une documentation sûre est en train de se constituer dans les instituts scientifiques les plus divers. Des techniques auxquelles on ne songeait nullement il y a vingt ans ont révolutionné nos façons de penser. Il suffit de mentionner à ce propos la datation au carbone, grâce à laquelle nous disposons pour un laps de 70 000 années de repères chronologiques d'une précision remarquable, sinon absolue. On peut également signaler les récents progrès qui ont été accomplis dans la compréhension du pléistocène grâce à la datation au potassium-argon, qui, si elle en est encore au stade des essais, donne cependant déjà des résultats fort intéressants. On connaît maintenant pour un laps de temps qui s'étend sur plusieurs centaines de milliers d'années les paléotempératures des eaux superficielles des océans ; et les sciences biologiques ont fait de grands progrès en ce qui concerne l'élucidation de tous les facteurs écologiques.

Qu'il me soit permis de signaler quelques-unes des tendances, moins spectaculaires mais également très importantes, que l'on observe aujourd'hui dans le domaine de la géomorphologie. Les spécialistes qui opèrent sur le terrain se sont rendu compte que le travail qui consiste à cataloguer les phénomènes ou à identifier les matériaux sans analyser les processus est peu satisfaisant. Il ne suffit pas d'étudier les glaciers ou cycles fluviatiles normaux du pléistocène. Des phénomènes caractéristiques des climats froids se sont produits à toutes les latitudes et attendent d'être minutieusement interprétés à la lumière d'observations concrètes concernant les milieux écologiques. Les dépôts fluviatiles sont décomposés en sédiments susceptibles d'être analysés au laboratoire ou étudiés dans leurs rapports avec des observations précises telles que celles mentionnées plus loin par Miller et Léopold. L'étude des dépôts éoliens a souvent permis de reconstituer en moyenne les régimes des vents forts ou les types de temps des époques géologiques. Les processus pédogénétiques de ces époques ont pu être déterminés dans leurs grandes lignes à l'intérieur de leur contact chronologique et ils ont fait l'objet d'une interprétation au moins qualitative. Avec le nouvel essor qu'a pris, sous ses aspects climatiques, la géomorphologie, on peut espérer que, dans ses applications au pléistocène, la science de la dynamique des sols parviendra à se soustraire au poids mort de ces recherches géologiques de type classique pour lesquelles on a recours à des unités de temps dont les plus brèves se chiffrent par 1.10^6 années.

Peut-être n'y a-t-il jamais rien eu de comparable à ce qui se passe aujourd'hui dans le domaine de la paléoclimatologie en ce qui concerne le renouvellement des méthodes, leur perfectionnement, l'extension de leurs possibilités d'application et l'accumulation de données qui en résulte. Il suffit, pour être tenté de le croire, de songer aux progrès révolutionnaires qui ont été accomplis depuis quelques années dans l'étude scientifique du quaternaire en Afrique orientale, centrale et méridionale[1]. Les stériles débats auxquels avait donné lieu la stratigraphie pluviale des zones équatoriales ont pris fin avec des études qui, reposant sur des analyses de pollens avec datation au carbone, ont permis de préciser que la dernière grande période pluviale a coïncidé avec le début de la période Würm. Les études géomorphologiques ont de même mis en lumière la corrélation entre la formation des dépôts laissés par les cours d'eau de la période fluviale et l'avance des glaciers de l'Afrique centro-orientale. L'étude des sols a, de son côté, montré que les sols rouges de type humide que l'on trouve aux frontières du Soudan se rencontrent sous une forme analogue de l'équateur aux Alpes et ne représentent que des vestiges ou des sols fossiles. Les théories que défendent vigoureusement certains auteurs et selon lesquelles il y aurait eu de vastes déplacements latitudinaux des zones climatiques ne paraissent pas trouver de justifications dans les résultats des observations empiriques auxquelles on ne cesse aujourd'hui de se livrer.

Toutes ces constatations peuvent avoir de larges applications dans le domaine de la climatologie et de la météorologie. Pour le moment, on est, semble-t-il, en droit de penser que les principaux changements climatiques du pléistocène supérieur ont été des changements de degré, et non pas de nature. L'intensification ou l'amortissement de phénomènes qui existaient déjà, les variations relativement faibles de fréquence qui ont pu se produire dans l'alternance des types de circulation atmosphérique, tels sont les sujets qui méritent, semble-t-il, d'être particulièrement examinés et de susciter nos réflexions. La question essentielle, que sir George C. Simpson a probablement été le premier à mettre en lumière, est celle qui a trait au bilan radiatif planétaire et aux échanges thermiques. Les météorologistes doivent aborder ces problèmes dans l'optique de la paléométéorologie. Si les météorologistes ne songent pas — ou ne sont pas disposés — à se mettre en rapport avec les spécialistes des sciences de la terre, ceux-ci seront dans l'impossibilité de rénover leur interprétation des faits ou sombreront dans de regrettables erreurs. Je suis sûr que le vœu de tous ceux qui sont venus participer à la présente réunion est que les recherches sur les changements de climat puissent à l'avenir bénéficier de l'appui de différentes disciplines et se développer ainsi plus largement et de façon plus équilibrée que par le passé.

1. Voir la publication (sous presse) du Wenner-Gren symposium, *African ecology and primate evolution*, Burg Wartenstein, Austria, 9-22 juillet 1961.

PALEOSOILS AS INDICATORS OF PALEOCLIMATES

by

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Since the work of W. W. Dokutchaev (1879) and P. E. Müller (1879) the soil is regarded as a product of the parent material and the environmental conditions of a habitat. This can be verified particularly by comparative micromorphological investigations on soils in different latitudes and altitudes. Here the interrelations between the soil and the environmental conditions are surprisingly well established. The manifold varieties of the habitat correspond to the great variations of microscopic structure and are so closely connected with them that we can to a great extent relate a given *in situ* soil formation and its micromorphology to the environmental conditions under which it was produced. In addition, every decisive change in the environmental conditions becomes visible and can be recognized in the microscopic soil structure of the particular horizons of the soil profile. Pedology is in this way becoming an important auxiliary science of paleoclimatology and historical geology. Soil formations have already been widely used for studying the chronology and climatology of the Pleistocene. It is easy to predict that the same will occur with respect to the other geological periods and formations. Soil formations can be used also for the recognition of climatic changes during soil development. In an earlier publication, I tried to demonstrate the close interrelations between climate and micromorphology for Pleistocene soils on loess. In the present communication, I intend to point out the same interrelations from a general point of view, and to demonstrate the phenomena connected with them by a number of coloured slides of landscapes, soil profiles and thin section preparations which can only be shown in a lecture because of the high costs of reproduction in a printed paper.

In the region of the equatorial rain forest, we find today the formation of a highly weathered yellow- to ochre-coloured soil with dense unstable structure which we call *braunlehm*. However, without successive transformation, this soil exists only in low areas where water and temperature conditions remain more or less unchanged. In higher altitudes the soil is replaced by another formation in which iron hydroxide, although amorphous as in the typical *braunlehm*, becomes flocculated to a great extent. We call this soil, because of its loose and earthy appearance, earthy *braunlehm*. This mentioned genetic relation to altitude is particularly well established in case of all transitional formations in the various mountain zones of the Santa Isabel Peak of Fernando Po (Gulf of Guinea) or the Cameroon Mountain. This recent zonation of the soil cover serves as a basis for our comparative investigations on soil formations in other latitudes and altitudes.

In tropical climates with marked changes of wet and dry seasons, another typical but red-coloured non-lateritic soil formation which we call *rotlehm* is frequently observed. It generally occurs up to an altitude of about 600 metres (although the *rotlehm* limit varies greatly according to the local conditions and the parent material). On the Cape Verde Islands *rotlehm* was the common soil formation in the foot-hill region of the mountains. With higher altitudes the *rotlehm* was replaced by a brown-coloured, but also highly-weathered soil which we have called earthy *braunlehm*. Both soils were originally covered by forest vegetation. Today the general climate tendency is towards a great and continuous decrease of precipitation and an increase in the length and intensity of the dry seasons. On the island of São Tiago we still see the former *rotlehm* soil in the coastal region but the forest has entirely disappeared. The earthy *braunlehm* above 400-600 metres shows a transformation into a very loose and dusty variant with open thornbush vegetation and only over 1,500 metres do we see an unaltered *braunlehm* with an evergreen bush vegetation. The progress of the xeromorphic character of the soil formation is most advanced in the island of La Sal. All recent soils here are desert soils with very low weathering and complete absence of humus horizons. They are mainly produced from basic volcanic ash which under other conditions weathers very easily. The vegetation has disappeared almost completely; apart from fishing, the population depends almost entirely on imported food. It is evident that the main climatic change was produced in historical time by the influence of man, primarily as a result of intensive goat grazing.

In the Central Sahara the recent soil development is likewise produced without the formation of profiles and horizons. Relict soils and exposed fossil soils of former more favourable climates become entirely loose and are transformed into powdery masses. The limit of pulverization in the High Atakor (Hoggar) is about 2,000 metres. Above this line we find the Pleistocene soils well preserved throughout the mountains. These soils correspond to the recent earthy *braunlehm* of the Santa Isabel Peak and the Cameroon Mountain in the zone of the rain forest. They represent the soil formation of the last pluvial. This earthy *braunlehm* is formed on the highest and youngest basalt lava layer and can be followed downwards, although in more or less transformed variations, almost to the foot-hill zone. The older basalt layers show, with an upward altitudinal limit of about 1,000 metres, different fossil *rotlehm* formations of probably old Pleistocene age, and in the Valley of Tamanrasset remnants of *rotlehm* relicts of probably Tertiary origin are found. Both *rotlehm* formations correspond to the white horizon type which indicates climatic conditions with long dry seasons alternating with short wet seasons.

The two catenas of soil formations mentioned (the one beginning with typical *braunlehm*, the other beginning with *rotlehm* in the foot-hill region), are characteristic for all mountains of West Africa, and can be observed in different distribution according to climatic variations in the humid or seasonally humid areas. All secondary climatic changes in their region, particularly those which cause xeromorphic transformations, become clearly visible.

Of particular interest as indicators of paleoclimates are relict soils in southern Europe. We see similar earthy *braunlehm* remnants in altitudes up to 2,000 metres in the Sierra Central of Spain and *rotlehm* profiles in the foot-hill region. Both correspond to the recent formations in tropical Africa. They are mostly of Tertiary origin and could be dated repeatedly. Similar soil relicts are found in almost all parts of the Mediterranean including North Africa. Here *rotlehm* relicts of Pleistocene origin are more frequent than on the European side.

The relict soils in the Mediterranean countries are of particular value because the present soil-forming factors do not allow the development of soils with sufficient clay content and water-holding capacity. By the influence of man, and the grazing of sheep and goats and under the scanty garrigue vegetation, only very shallow soils are formed with little earth formation, poor soil life and low humus content. We call soils of this kind meridional *Braunerde*. The greatest loss of the former *braunlehm* and *rotlehm* relicts occurred during the time of the Roman colonization and its intensive land use. After the destruction of the *braunlehm* and *rotlehm* soils by erosion, the development of new soils in the form of meridional *Braunerde* set in. During the time of the Moors in Spain, great sections of the land were covered by grassland in the shade of Ballota oaks which had a good influence with regard to soil development. This can be studied in regions where this vegetation or parts of the former *Quercus ilex* forests are preserved. In recent times, a great part of those areas has been transformed into arable land again, with a resultant rapid increase of the xeromorphic properties of the soil and in some areas an almost complete loss of their productivity.

RÉSUMÉ

Les paléosols en tant qu'indicateurs de paléoclimats
(W. L. Kubiena)

L'auteur appuie la théorie suivant laquelle les sols proviennent de l'interaction entre la roche mère et les conditions du milieu. Cette affirmation peut être corroborée par l'étude micromorphologique des sols à des latitudes et des altitudes différentes. Une des conséquences de cette interaction du sol et de l'habitat est que la pédologie devient un auxiliaire important de la paléoclimatologie et de l'histoire géologique. Des exemples sont cités tels que l'île de Fernando-Po, les îles du Cap-Vert, le Sahara central, la Sierra Central en Espagne et les sols fossiles de la région méditerranéenne pour faire ressortir le rapport étroit entre climat et micromorphologie des sols du pléistocène; leur corrélation possible est également indiquée. Finalement la variation des sols par rapport à l'altitude est démontrée de manière assez détaillée.

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THE LAST "PLUVIAL" PHASE OF THE EURAFRICAN SUB-TROPICS

by

K. W. BUTZER

INTRODUCTION

One of the most important palaeoclimatic problems of the sub-tropics is the character and chronology of what have been described as "Mediterranean pluvials" (see Zeuner, 1953). There is little doubt on the part of specialists today that the poleward margins of the sub-tropical high pressure cells enjoyed extended periods of moister climate during parts of the Pleistocene. There is widespread agreement that these morphologically conspicuous phases of ameliorated hydrological balance were broadly associated with glacial episodes. Two fundamental problems have, however, received but incidental attention and no unanimity.

"Pluvial" periods have been defined as periods of wide-spread, long-term rainfall increase of sufficient duration and intensity to be of geomorphic significance. Basic phenomena employed to ascertain the presence of pluvials have usually been limited to high lake levels and greater fluviatile activity. Conceivably misunderstandings have resulted, and dissident opinions have been voiced whether or not a true rainfall increase is implied. Specifically it is argued that a zonal lowering of temperature by 4°-5° C. during various glacial phases would automatically reduce evaporation sufficiently so as to permit higher lake levels or greater stream discharge. Consequently it is argued that the term "pluvial" is inappropriate, and that such phases are little else than "fluvial" periods. Admittedly such arguments have been loosely used for distinct geographical regions, and they may be better founded in the case of inner-tropical or equatorial phenomena. Yet they have also been frequently employed to discredit truly rainy phases in northern Africa and the Mediterranean area.

Closely associated with this problem of physical geological interpretation is another of stratigraphical character. The precise chronological position of "pluvial" phenomena is absolutely essential if conclusive argumentation is to be attempted. It is climatologically quite unrealistic to assume or state that glacials and pluvials are contemporary or not. Classical stratigraphical methods, whereby periods of many million years are considered quite homogeneous, are disastrous when applied to the Pleistocene. Furthermore such long- and short-term fluctuations of climatic elements as are known from the instrumental and historical record are incredibly complex and incompatible with the oversimplification of sedimentary processes so often made by earth scientists.

A historical review of Upper Pleistocene climatic interpretation may be useful in actually defining the problems to be discussed here. After the existence of widespread glacial epochs had been conclusively proven during the later nineteenth century, many decades of argument were devoted to the problem of many versus one, single glaciation of Pleistocene date. Although A. Penck and E. Brückner's classical alpine study (1900) generally bore out the polyglacial interpretation, some so-called monoglacialists still publish today. But after 1920 the problem of immediate controversy shifted from the plurality of glaciations to the uniformity of each glacial epoch. Interstadial interruptions were recognized or disputed, exhumed or interred. With the successful application of radio-carbon dating, it has now become almost obvious that what was previously considered to be the Würm-Weichsel glaciation in Europe was interrupted by at least several warmer episodes.

With the realization that there were several and not only one Pleistocene glaciation, and that glaciations consisted of several and not one stadial phase, general opinion seems to have been susceptible to accept further complications. In 1950 J. Büdel, an apparent opponent of subdivided glaciations, and I. Schaefer, both outlined significant climatic phases recognizable in the sequence of interglacial-glacial. More precisely Büdel and Schaefer independently showed that major Pleistocene solifluction and river aggradation preceded the maximum extent of the glaciers, and that loess and sand deposition with linear erosion followed under drier conditions during the period of glacial standstill and ultimate dissipation.

Büdel consequently postulated a comparatively moist, cool glacial advance phase, a dry, cold glacial maximum and a dry, warmer glacial retreat. Despite some difficulties in interpretation, recent work, particularly in palynology, has well substantiated the distinction of moist early glacial and dry full (and late) glacial phases in middle latitude Eurasia (Frenzel, 1959, p. 130; 1960, p. 296, 331 *et seq.*).

Meteorological interpretation of Pleistocene general circulation soon gave consideration to this dichotomy of advance and full glacial periods, as the stimulating discussion of G. Viete (1951) and a study by H. Flohn (1953) indicate.

Several years ago the writer (Butzer, 1957, 1958) began to question the glacial homogeneity still insisted upon for the domain of subtropical pluvials. Wherever geological publications for the Near East were rendered in satisfactory detail it was obvious that no uniform pluvial phase spanned the 60,000 years of the Würm glaciation. In many cases it was possible to show that precisely the period of glacial advance, i.e., the incipient Würm regression of the Mediterranean Sea was the Würm pluvial *par excellence*. The later Upper Pleistocene was in fact quite dry. Consequently if subtropical pluvials show an early glacial maximum—at a time when the extent of the continental glaciers was quite limited—and if pluviation was minimal during the period of maximum world glaciation and retreat, then two conclusions must be drawn: (a) subtropical pluvials can not be genetically interpreted as secondary effects of the presence of continental ice sheets in higher latitudes; and (b) subtropical pluvials must be attributed to a primary change of the general circulation, presumably in immediate association with glacial advances in higher latitudes. This initial change is unlikely to have been a simple lowering of planetary or of higher latitude temperature but must be thought of in terms of complex circulation patterns and latitudinal heat exchange. P. Woldstedt (1958, p. 353-355) arrived at an identical conclusion.

Information is now available, however, requiring even further modification of the simple correlations of glacial-pluvial, interglacial-interpluvial. Pedological observations of the last 15 years or so and, particularly stratigraphic associations first noted by H. Klinge and A. Mella (1957) in Mallorca (see Butzer and Cuerda, 1961*a*, 1961*b*), leave no doubt that fossil or relict *terra rossa* soils date from warm, moist interglacial phases. The geomorphic equilibrium of moist and dry interglacial periods in the Mediterranean Basin was recently described by the writer (Butzer, 1961*a*). Such moist interglacial phases were characterized by a complete vegetative mat, no mechanical but intensive chemical weathering, a lack of erosion (apart from removal of dissolved carbonates) and little deposition. The perfect equilibrium required, presumably under a subtropical rain-forest vegetation, may perhaps be likened to what has been described as a state of biostasy (see Durand, 1959). Yet these warm, humid phases were not responsible for fluviatile erosion or aggradation, so that they were not "pluvial" episodes in the conventional sense.

PLUVIAL PHENOMENA OF EASTERN SPAIN

Throughout the Mediterranean (Csa) climate zone of the western Mediterranean Basin the initiation of the Last or Würm glacial was heralded by intensive sheet-flood erosion and deposition of a heterogeneous class of colluvial silts and alluvial gravels. The colluvial silts of this true "pluvial" phase are largely derived from reddish interglacial soils (*terra rossas* in limestone bedrock areas), hence the French technical term of *limons rouges*. One group of these sediments is located in caves, where C. Arambourg (1952) first outlined their stratigraphical peculiarity in association with a Levalloiso-Mousterian Industry and an Upper Pleistocene fauna of warm affinities. Another group is largely fluviatile, for example, the great spreads of red silts associated with last pluvial of Morocco, first analytically studied by G. Choubert (1948*a*, 1948*b*). More recently aeolian components have been recognized in Catalonia (Virgili and Zamarreno, 1957) and Tripolitania (Hey, 1961).

Colluvial silts are of considerable importance in the Balearic Islands, and to a lesser extent northern Catalonia. Analogous but sporadic phenomena can also be observed in the interior of Spain. The following generalizations are based on field and laboratory studies by the writer in these areas.

The morphology of the deposits is mainly one of relatively thin areal sheets (to 1 metre), attaining greater thicknesses only at the foot of slopes or in original topographic hollows (to 5 metres or more). Surface slopes seldom exceed 15 per cent, and characteristic examples can be cited from Mallorca where the bed-rock topography has slopes of 1-3 per cent. In drainage channels these beds grade laterally into alluvial fill.

Sedimentology is highly variable. Stratification of individual beds rather than individual coarse components is usual, sorting is less common. At the base of steep slopes beds may be detrital in character. The amount of coarse component over 2 mm. diameter is usually confined to coarse angular to subrounded gravel embedded in fine sediment. The granulometry of the fines shows a spectrum roughly proportioned among the clay, silt, fine, medium and coarse sand fractions. Often a moderate maximum may be found in the coarse silt and finer sand fraction. The writer knows of no granulometric spectra over 70 per cent in the 2-60 micron range however, so that typical loess deposits are not known. Semi-aeolian beds are not uncommon in association with regressional dunes, specifically aeolian materials bedded by water. Most frequently the granulometry is analogous to that of the source materials, namely soils and weathered aeolian beds.

Frequently the colluvial silts are interrupted by, interbedded with, or capped by tufaceous calcareous crusts. These particular crusts (*croûtes zonaires*) are due to sedimentation by lime-charged surface waters, and occasionally grade into true travertines. They are presumably associated with sheet-flooding of moderate intensity, i.e., with little or no accompanying erosion (Durand, 1959; Butzer, 1961). Such interbedded crusts help to illuminate the former climate associated with the sedimentation of colluvial silts.

The stratigraphy of the colluvial silts is well defined in the Mediterranean littoral regions (Butzer and Cuerda, 1961*a*, 1961*b*). The silts are often interbedded with marine beds of the Tyrrhenian III transgression and are gradually superseded by regressional dunes during the major negative movements of sea level accompanying the advance of the Würm glaciers. Terrestrial silt beds can be found to well below modern sea level, and laterally conformable alluvial fill shows abnormally steep gradients at the coast.

It may be further mentioned that two or three positive interruptions of the Würm regression were followed by colluviation and subsequently by renewed aeolian deposition. This leaves no doubt that several major oscillations of the continental glaciers in higher latitudes had direct repercussions in the Mediterranean area; the re-advances were associated with secondary maxima of the peculiar climatic régime responsible for silt colluviation.

On the flat terrain of parts of the Balearic Islands the colluvial silts represent an areal accumulation on horizontal bed-rock strata, locally grading into alluvial fill of drainage lines. In Catalonia, Aragon and Old Castille colluvial silts are laterally conformable with river terraces. In coastal areas such terraces were graded to a lower sea level and are locally overlain by consolidated regressional dunes. Geomorphologic interpretation must then explain the fact of intensive areal denudation of upland surfaces, with accompanying areal accumulation and valley alluviation.

The primary fact of greater water transporting capacity by streams is quantitatively confirmed by comparative morphometric gravel analysis. The index of pebble rounding devised by G. Lüttig (1956) proved to be the method capable of maximum and safest differentiation within the range of angular to subangular gravels. Statistical analyses of recent and Pleistocene gravels of varying age in various silt beds and valley successions (Table 3) indicated that the Würm pluvial was not the wettest pluvial, but certainly moister than the Postglacial period. Colluvial spreads on nearly flat surfaces indicated a fair degree of rolling of contained pebbles, more than in modern torrent beds. No assumption of perennial stream flow is possible for such torrents which now enjoy only episodic or seasonal water flow. But the periodic flash floods must have been more frequent or capable of carrying a load over greater distances.

Study of modern fluviatile processes and pedogenesis in particular topographic situations of eastern Spain (Butzer, 1961*a*) indicated that on terrain with gentle slope (under 8 per cent) practically nothing is happening today in the way of erosion, soil stripping or local sedimentation. Pedogenesis is limited to the development of rendzina type soils on limestone, meridional brown earths on acidic bed-rock (Kubiena, 1957; Klinge, 1958; Butzer, 1961*a*, 1961*b*). The vegetation cover under semi-natural conditions is almost never associated with a complete or grassy vegetative mat. Except at spring or ground-water localities the vegetative mat is either non-existent as under Mediterranean-type woodland, or consists of isolated shrubs, bunch grasses and dwarf scrub. An increase in aridity would not seriously increase the area of bare soil available to sheet-flood erosion or accelerated soil erosion. Yet such processes are not effective in terrain in gentle slope today. A peculiar set of climatic conditions, in particular of rainfall amount and intensity (but without change in seasonality), must have been responsible. The implied climatic change could not have been accompanied by a major change in the density of the vegetative mat, otherwise such areal erosion as occurred would not have been possible. Similarly the difference can therefore not be simply explained as one of run-off conditions.

Throughout the course of study particular attention was given to cold climate phenomena such as solifluction, cryoturbation, etc. Such features of Upper Pleistocene age were not found below 1,100 metres in the Province of Soria (Old Castille), or below 800 metres in Catalonia or (at least) 950 metres in the Balearic Islands. None of the colluvial silts studied lay within the high elevation ranges effected by cold climate transport, and none of the deposits was effected by so-called periglacial phenomena.[1]

The sole remaining interpretation is one of (a) greater rainfall intensity to enable such effective erosion, and (b) greater rainfall amount to permit such widespread transport or materials and the deposition of tufaceous crusts or travertine beds in semi-arid country with 400-550 mm. precipitation. A pronounced dry season must have persisted to account for the nature of the vegetative mat. Quantitative work of erosive capacity and sheet-flood level as proportional to amount of rainfall per unit time and size of raindrops (Barat, 1957) confirm this interpretation of the colluvial silts.

The colluvial silts of eastern Spain, which in local association with river aggradation were here singled out as most characteristic Mediterranean pluvial phenomena, are widespread. Associated with several Pleistocene phases they are not localized in the littorals of

1. The writer disagrees with the conclusions of G. Johnsson (1960) with respect to periglacial climates at an elevation of 200 metres in Aragon, and questions the validity of so-called ice wedges described. Solifluction phenomena found by Fränzle (1958) at lower elevations in Soria were not "dated" by that author and are presumably older.

the western Mediterranean Basin but also occur in western Morocco and have been described from Tripolitania, Israel and Syria.

LAST PLUVIAL AGGRADATION FEATURES OF EGYPT

Contemporary with the Early Würm pluvial phenomena described in the particular Mediterranean environment of eastern Spain are equally spectacular features of the northern African arid zone. Saharan pluvial phenomena can be observed in Egypt, from which example the essential description and interpretation of processes can be made (Butzer, 1959, 1961*c*, 1961*d*).

During the high Mediterranean sea level corresponding to the last interglacial, the lower Nile aggraded its bed to a rising sea level at a time of arid local climate. The Nile deposits in question show few sediments indicating lateral influx of water from local water-courses. The river waters were then presumably exotic as today, derived from more humid areas south of the Sahara. In fact, under present climatic conditions the dry stream beds or wadis of the interior are practically defunct. With a long-term annual rainfall mean of less than 10 mm. for the level country south of latitude 30° N., and a possible maximum of 20 mm. in the higher country of the Red Sea hills, little morphogenesis can be expected. Local cloudbursts produce localized spates which sweep some kilometres down the major wadis every few decades. In drainage systems with considerable gradients and strong convergence of tributary canyons considerable masses of local rubble may occasionally be removed and redeposited as an ungraded, crudely stratified and unsorted mass in the wadi channel. This is the exception rather than the rule, however. Most of the major wadis have at best succeeded in redepositing fine materials along the floor. Although the actively forming scree at wadi heads remains undisturbed by erosion, the net effect of these sporadic modern agencies over many millenia has been dissection of the Pleistocene fill, i.e., linear erosion. Smaller wadis with low-lying basins have remained defunct since the Middle Pleistocene in many cases.

Wadi activity capable of removing local rubble and depositing it over tens or hundreds of kilometres in regular, graded, stratified and moderately sorted deposits requires considerably greater quantities of water. Similarly soil development is non-existent today apart from the formation of thin powdery gypsum crusts (Sa horizons of 3 cm. or so underlying the pavement surface of finer Pleistocene beds, gypsum-yerma soils in the sense of Kubiena, 1953). The presence of fossil soils must likewise be interpreted as evidence of former humidity, without which the necessary biochemical activity would be impossible.

Returning to the Last Interglacial levels of the lowermost Nile, it is interesting to note a fossil soil developed upon these sandy beds. The pedogenesis involved achieved a rubefaction of the top 15 cm., whereby the calcareous component was appreciably weathered. This (B) horizon recalls an incipient *terra rossa* development (disregarding that the parent material consists of lime and quartz sands). This soil must belong to a moister interglacial phase, as it is older than the true pluvial deposits of the Upper Pleistocene.

These subsequent pluvial deposits consist of coarse flint and limestone gravels, with a little matrix of coarse sands. In Upper Egypt these coarse deposits were graded to a flood-plain some 4 metres higher than today. In Middle Egypt the wadi terraces are graded to a lower and degrading flood-plain, while further north yet the local water-courses functioned erosively in response to low base-levels induced by the glacial-eustatic regression of the Mediterranean Sea. Limestone pebbles, found in such terraces 2 or 3 kilometres from the head-waters of wadi basins, are already remarkably well rolled.

The only possible interpretation for these gravels with their Levalloisian industry is more frequent and more regular winter rainfall. The larger wadis with higher catchment areas may have achieved the status of seasonal (as opposed to episodic) streams during the maximum of the pluvial period. Yet smaller streams in the flat terrain of the western desert show little record of this pluvial, so that over-all climatic conditions were probably no moister than those of the modern Egyptian coastline today. But a change from lifeless desert with less than 10 mm. annual rainfall to semi-desert with 100 mm. or so would produce a tremendous change in geomorphic processes.

Judging by the thickness of wadi deposits, which seldom exceed 5 metres, the pluvial did not last more than a few millenia. Similarly it was not conspicuous in Nubia as good evidence is lacking south of about Aswan (24° N.). Gravel aggradation was first succeeded by soil development, a sierozem type soil with an Sa (gypsum) horizon. Conditions became progressively arid, and excepting a minor phase of gravel aggradation with a Late Palaeolithic industry, achieved full aridity well before the end of the Last Glaciation. Upper Egyptian wadis were no longer even capable of downcutting their beds to conform to a lower flood-plain level of the Nile at the close of the Pleistocene. Aeolian activity became very prominent in contrast. No absolute dating is yet available, but indirect association with the glacio-eustatic rhythm of the Mediterranean Sea via the Nile does give us a fair approximation on stratigraphic dating.

LATE PLEISTOCENE ARIDITY IN THE MEDITERRANEAN AREA

Dating from the maxima of the Mediterranean regression corresponding to the Würm glaciation are ubiquitous littoral dunes known as aeolianites (Butzer, 1962). These sediments are due to deflation of marine littoral beds of unconsolidated lime sand during progressive lowering of sea level. They are not necessarily indicative of local aridity. But when found blocking torrent mouths without intercalated fluviatile materials, or when found in interior locations with conspicuous bedding planes and without root drip, aeolianites were certainly deposited under comparatively dry conditions. Conspicuous bedding is impossible in coastal dunes under Mediterranean woodland today, so that a local tuft grass-xerophytic shrub vegetation is postulated as ideal for aeolianite expansion.

Deflation and deposition of aeolianites will continue as long as the regressive oscillation continues to expose fresh sediments (Wright, 1961). Therefore an aeolianite record is lacking for the late glacial interval of protracted retreat of the higher latitude ice sheets. The palaeoclimatic record is, however, covered by the soils developed upon the colluvial silts and aeolianites of the earlier Würm. These soils are practically identical in type and depth of profile with the climax soils on Holocene dunes, namely xerorendzinas. The soil profiles consist of 40-65 cm. A horizon of light brown colour, with a rendzina moder or mulliform moder humic type and fine granular structure. A Ca/C horizon of 10-40 cm. may underlie the A horizon. In other words climatic conditions since the glacial maximum have, with brief exception of the postglacial thermal maximum, generally been as dry as or drier than now.

Numerous other sequences of the Eurafrican subtropics correspond closely with the pattern of palaeoclimates outlined here (Table 1). Seen in a general way the Last Interglacial was largely warmer than at present on the basis of the molluskan fauna. The greater part was probably as dry as now. But several phases of it were moist and accompanied by *terra rossa* soil developments, in part succeeded by local deposition of colluvial silts. The Early Glacial was the Upper Pleistocene pluvial as is indicated by innumerable, well-studied sedimentary sections. Normal moisture conditions were dominant during the Full Glacial, as verified by minor soil development in the northern Sahara, aeolianite extension in the Mediterranean Basin. Some moister interruptions are recorded by colluvial silts and wadi gravels. Finally the Late Glacial was at least as dry as now in all areas, judging by semi-arid soil development in the Mediterranean Basin, aeolian activity and desert soils in northern Africa.

Two successions may be simply mentioned here, the palaeobotanical successions of the Final Interglacial to Würm from the Cueva del Toll (at 750 metres, in Catalonia) and the Basse Versilia (near sea level, Italy) (Donner and Kurtén, 1958; Blanc, de Vries and Follieri, 1957). Both profiles show an analogous pattern to that described here.

A major problem is raised by dominantly dry conditions in the Eurafrican sub-tropics during the Full and Late Glacial. Study of Full Glacial aeolianite directions on Mallorca (Butzer, 1961*a*; Butzer and Cuerda, 1961*b*) indicated a noticeable decline of cyclonic lows travelling route VIb into the Mediterranean zone, in favour of greater significance of route VII. This tends to confirm a southerly preference of cyclonic routes in certain latitudes at least, and questions the relation of associated aridity. The only explanation offered is

TABLE 1. Upper pleistocene palaeoclimates of Egypt and eastern Spain

<table>
<tr><th colspan="2">Egypt</th><th></th><th colspan="2">Eastern Spain</th><th rowspan="2">Higher latitude parallel</th></tr>
<tr><th>Climate</th><th>Phenomena</th><th></th><th>Climate</th><th>Phenomena</th></tr>
<tr><td>Warmer</td><td>Beaches with thermophile fauna</td><td></td><td>Warmer</td><td>Beaches with thermophile fauna</td><td>Early Interglacial</td></tr>
<tr><td rowspan="3">Warmer
Moister</td><td rowspan="3">Beaches with thermophile fauna</td><td rowspan="3">Red Soil development</td><td>Warm, humid</td><td>Terra rossa soil</td><td></td></tr>
<tr><td>Warmer</td><td>Beaches with thermophile fauna</td><td>Late Interglacial</td></tr>
<tr><td>Warm, humid</td><td>Terra rossa soil</td><td>Temporary Glacial advance (Earliest Würm?)</td></tr>
<tr><td>?</td><td>?</td><td></td><td>Warmer</td><td>Beaches with thermophile fauna</td><td>Final Interglacial or First Interstadial</td></tr>
<tr><td>Semi-arid, pluvial</td><td>Wadi gravels</td><td></td><td>Humid, pluvial</td><td>Colluvial silts, torrent gravels</td><td>Early Glacial</td></tr>
<tr><td>Drier</td><td>Erosion, sierozem soil</td><td></td><td>Semi-arid</td><td>Aeolianites</td><td>Full Glacial</td></tr>
<tr><td>Arid</td><td>Yerma soil, aeolian activity</td><td></td><td>Semi-arid</td><td>Xerorendzina soil</td><td>Late Glacial</td></tr>
</table>

reference to the notable reduction of evaporation over the rapidly cooling oceans, which Flohn (1953) estimates at over 25 per cent for lower middle latitudes. This reduction of the precipitation cycle would only have been effective after planetary lowering of temperatures was complete.

Inferred circulation conditions during the Late Glacial are more compatible with dry anomalies in the Eurafrican sub-tropics. H. Poser (1950) reconstructed the prevailing wind directions of central Europe during this period from the orientation of fossil aeolian deposits. In this manner the dominant pressure patterns of the warmer half-year, associated with moderate to strong winds (at least Beaufort 3), could be outlined. Applicable *Grosswetter* situations in the classification of Hess and Brezowsky (1952) are (a) high pressure centres or ridges over central Europe associated with types as HM, NW, and BM, and (b) westerly steering north of about 50° N., with higher pressures to the south (Wz, Wa, SW). The situations comprise almost the whole range of zonal or mixed type patterns. All of these types are unfavourable for precipitation development in the Mediterranean Basin (Butzer, 1960). Each involves below-average mP air advection into the western basin, with cyclone expectancy some 40 per cent below average. This could well explain local aridity even greater than at present.

CONCLUSIONS AND PROBLEMS

The Eurafrican sub-tropics have experienced all combinations of the four qualitative words: cold, warm, wet and dry. Interglacial episodes may be warmer and moister or warmer and drier. Similarly glacial episodes were in part comparatively cool and wet, in part cold and dry. The cool-wet combination coincides with those intensive morphogenetic phases that fully deserve the designation of subtropical pluvials. Semi-quantitative methods (Table 3) whereby relevant sediments unquestionably verify the existence of heavier rainfall were outlined. Rain must have been more frequent and heavier, although the dry season remained as conspicuous as now. To allow for the denudation evidenced, the vegetative mat must have been analogous to that of the present. During the remainder of the Last Glaciation, conditions were at least as arid as today. In conjunction with the brief outline here, and further data in an earlier publication (Butzer, 1961*a*), the following tabular representation (Table 2) outlines the major processes and inferred climates as evidenced in the Mediterranean Basin.

Viewed in their hypothetical palaeoclimatic interpretation these conclusions immediately beg meteorological problems well beyond those touched upon briefly by some of the preceding suggestions. Some of

TABLE 2. Upper pleistocene processes and palaeoclimates in lowland Mediterranean climates (with particular reference to eastern Spain)

	Moist Interglacial	Dry Interglacial	Pluvial Glacial	Dry Glacial
Weathering	Intense chemical	Little, mainly chemical	Moderate mechanical, weakly chemical	Intense mechanical
Climate	Quite warm, negligible frosts; humid winters, short intensive dry season	Warm; little frost; subhumid winter half-year, extended dry season (as today)	Temperate; moderate frosts; heavy, torrential rains, moderately extended dry season	Cool; frequent frosts; subhumid winters, extended dry season
Vegetation	Subtropical rain-forest	Subtropical dry forest and sclerophyll steppe (as today)	Subtropical dry forest and mixed woodland	Submediterranean mixed woodland and steppe
Pedogenesis on limestone	*Terra rossa*	Xerorendzina	(*Terra fusca*)	Erosion and leaching
Pedogenesis on acidic bed-rock	*Rotlehm* or *braunlehm*	Meridional *Braunerde*	(*Braunerde*)	Erosion and leaching
Degradation	Weak chemical denudation, some vertical erosion	Limited surface washing	Sheet-flood (areal), denudation and incision of valley margins	Vertical erosion
Aggradation	Local redeposition	Localized aggradation of valleys	Colluvial silts, fan deposition and valley alluviation	Limited aggradation

TABLE 3. Morphometric gravel analyses. Mean values of ρ (Lüttig's index of rounding), $2r/L$ (Cailleux's index of rounding), and $(1 + L)/2E$ (Cailleux's index of flattening)

Locality	Stratigraphy	Sample size	Mean ρ (%)	Percentage ρ ≦ 8%	Coefficient of variation of ρ (%)	Mean $2r/L$	Mean $(1 + L)/2E$
		Mallorca. Lithology: Limestone					
Sa Plana	Holocene bed	100	8.4	68	106.2	59.6	1.55
Sa Plana	Würm colluvium	100	14.0	52	104.7	79.3	1.65
Sa Plana	Riss colluvium	100	23.0	38	78.3	88.3	1.64
C. Figuera	Holocene bed	100	12.1	57	111.3	—	1.62
T. S'Avall	Würm terrace	50	42.1	2	34.6	104.4	1.78
T. S'Avall	Riss terrace	50	36.3	4	47.0	137.4	1.67
T. Son Veri	Holocene bed	50	11.9	54	103.8	—	1.68
T. Sa Riera	Riss terrace	100	57.6	0	36.5	—	1.50
T. Socorrada	Holocene fill	100	12.1	50	89.8	—	—
T. Socorrada	Würm colluvium	100	26.6	10	55.0	—	—
		Catalonia (Prov. Gerona). Lithology: Granite					
Riera Tossa	Holocene fill	50	37.7	16	63.7	—	—
Riera Tossa	Würm terrace	50	44.3	4	54.0	—	—
Riera Tossa	Riss terrace	100	45.8	0	34.0	—	—
		Castille (Prov. Soria). Lithology: Limestone					
Ambrona site	Würm terrace	100	10.9	55	95.3	—	1.44
Ambrona site	Mindel terrace	100	25.5	12	60.5	—	1.50

these problems and directions in which further thought and research are required may be outlined:

1. Although rains in the Mediterranean area are largely of brief duration, and comparatively great intensity today, their torrential character must have been much more strongly emphasized during the pluvials. How can an increase in rainfall intensity within the present circulatory arrangements be explained in terms of dynamic meteorology?
2. To what extent could primary changes of the general circulation produce a simultaneous advance of higher latitude glaciers and subtropical pluvials without recourse to an initial lowering of planetary temperatures?
3. Using various hypotheses, assumptions and known data on intensity of the general circulation and ocean surface temperatures during full glacials, what alternate possibilities and suggestions can be made today about the evaporation-precipitation cycle?
4. Given the existence of moist interglacial climates in subtropical latitudes, how can these be understood in view of the reduced meridional temperature gradient with attendant corollaries? We know that higher latitudes were warmer during such periods.

Possibly this symposium will directly or indirectly contribute towards formulating these and similar problems more precisely and offering possible explanations or circulation models. Conversely the meteorologist can also expect the earth scientist to attempt preciser analysis and interpretation of his data, so that more catalogued materials may be accessible to the meteorologist, preferably with labels of "reliable", "probable" and "possible". The meteorologist cannot, obviously, be expected to collect and evaluate the specialized data he is to analyse. This symposium will probably contribute substantially towards the kind of question-and-answer between disciplines of what particular information one group of specialists would require of another.

RÉSUMÉ

La dernière phase « pluviale » de la zone subtropicale eurafricaine (K. W. Butzer)

Lorsqu'on étudie, d'après les récents relevés géologiques, les climats qui ont été autrefois ceux des régions arides du monde, l'un des problèmes fondamentaux qu'on rencontre est celui des périodes « pluviales ». Aucune série d'anomalies climatiques n'a eu, sur les zones désertiques subtropicales et à leurs lisières, des effets comparables à ceux de plusieurs périodes d'humidité plus grande. La configuration terrestre du Sahara, du Proche-Orient et même des régions adjacentes telles que le bassin Méditerranéen est parsemée de particularités géomorphiques dues à des périodes anciennes de précipitations plus importantes. En fait, dans beaucoup de régions prédominent des fossiles caractéristiques de la période pluviale du pléistocène : on y trouve des sculptures fluviatiles impressionnantes, alors qu'il n'y pleut presque pas aujourd'hui.

En concentrant son attention sur une seule zone climatique, à savoir l'Afrique du Nord et la région méditerranéenne, et sur une seule période qui correspond *grosso modo* à la dernière glaciation, on peut dégager de cette étude plusieurs caractéristiques paléoclimatiques assez précises. Certains sédiments, trouvés associés à la plus ancienne oscillation régressive de la mer Méditerranée qui date de la glaciation de Würms, sont considérés comme l'indice de pluies violentes du type torrentiel. Ces dépôts comprennent les limons colluviaux du bassin Méditerranéen (dus à une érosion laminaire et à des dépôts locaux) et les graviers des oueds ou des torrents qu'on trouve tant dans la région méditerranéenne qu'en Afrique du Nord. La comparaison de ces dépôts d'alluvions avec les processus fluviatiles de l'époque actuelle montre sans aucun doute possible qu'il y a eu augmentation en valeur absolue de la quantité des précipitations, bien qu'une saison sèche d'intensité comparable ait dû persister. Des caractéristiques analogues sont associées à diverses oscillations du niveau de la mer dans le bassin Méditerranéen et, par conséquent, aux fluctuations des glaciers continentaux aux latitudes plus hautes.

Les périodes de régression maximale (correspondant à la pleine période de glaciation de Würms) et de transgressions ultérieures (correspondant à la dernière phase glaciaire) ont néanmoins été principalement sèches. Sur les côtes de la Méditerranée, le développement intensif des dunes entraînant la régression du littoral n'a été que faiblement empêché par la végétation, et l'activité fluviatile en Afrique du Nord s'est fortement réduite ou bien a complètement cessé. Il en résulte une succession d'initiales phases glaciaires humides avec des maximums d'humidité secondaires aux divers moments où les glaciers reprennent leur avance graduelle, et de phases glaciaires complètes ou tardives, mais sèches.

L'association que cela implique n'est évidemment pas fortuite : il doit y avoir un phénomène de circulation primaire qui explique l'avance simultanée des glaciers situés à de hautes latitudes et l'apparition des phases pluviales dans la zone subtropicale. Cela tend à montrer que ces périodes pluviales ne sont pas simplement des phénomènes secondaires résultant d'une déflexion mécanique des perturbations occidentales par les souches continentales existantes de glace. Du point de vue météorologique, la question se pose aussi de savoir comment les changements fondamentaux de la circulation et les formes d'équilibre et d'échanges thermiques latitudinaux se sont trouvés associés à l'abaissement général de la température dont témoigne la période glaciaire maximale.

DISCUSSION

L. B. Leopold. It is requested that Dr. Butzer explain by simple sketches or by a few sentences, what he means, in connexion with his Table 2, by "sheet-flood erosion", "limited surface washing", "incision of valley margins". Also, it would be valuable to the audience if he would explain briefly why he believes "vertical erosion" is associated with "cool, frequent frosts, subhumid winters, and extended dry season" (see Table 2), and further why "valley alluviation" is associated with "temperate, heavy torrential rains, moderately extended dry season".

K. W. Butzer. In a few words, what is meant by "sheet flood erosion" is areal denudation, particularly of irregular terrain or slopes, with mass transfer of soils and regolith on to lower slopes, into topographic hollows or drainage channels.

"Limited surface washing" should simply mean analogous processes of very limited intensity.

"Incision of valley margins" should mean linear erosion of lateral margins of existing torrents or canyons, with accumulation along the soles.

"Vertical erosion" associated with "cool, frequent frosts, etc." is meant in the sense that areal denudation had declined or ceased entirely during the Full Glacial. Various deposits present are of more local origin, and more angular, being derived from limited erosion of adjacent surfaces. These processes cannot compare with the wholesale denudation and alluviation or colluviation associated with preceding "pluvial" conditions of rather more frequent and intense torrential rains.

R. C. SUTCLIFFE. Does the kind of evidence described by Professor Butzer enable us to say whether the climate of the Mediterranean has remained "Mediterranean" in character, that is, whether in all phases the rainfall was mainly in the winter with relatively dry summers?

K. W. BUTZER. The seasonality of climate seems, from all available evidence, to have remained analogous to that of today. A dry season very probably persisted throughout the Pleistocene. The question of temperature, as defining the other statistical element employed to define a "Mediterranean" type climate, is different. A general lowering of temperature means by some 4°-5°C. can be safely assumed for glacial maxima from various lines of evidence. This would then reduce large parts of the Mediterranean Basin to "submediterranean" or "temperate" conditions in the thermal sense.

H. BOBEK. While congratulating Professor Butzer on his paper, I should like to make a warning remark against too early and too much generalization. All the phenomena involved are dependent not only on climate, but also on a host of other factors which certainly have to be taken into consideration and make generalization a very precarious thing.

As to quantification of controlling factors otherwise not determinable, the comparative method should, I feel, be much more used; e.g., the "sheet-flood erosion" was classified in Table 2 under "Pluvial Glacial" whereas "vertical erosion" should belong to the "Dry Glacial". Accordingly pediments, or *glacis d'érosion*, in the western Mediterranean have been attributed by many scholars to the Pluvial periods. However, in Persia (which I have known for years) the Central Plateau is certainly a region where sheet-flood erosion, i. e., pedimentation, is active today as it has been for ages, at a precipitation range of 100(50)-300 mm. Why, then, should one claim a still more humid pluvial in the western Mediterranean to explain the pediments there instead of a drier climate?

Aggradation and degradation have their specific place in a river system. They should not be labelled in terms of climate only without referring to their specific situations in the respective river systems, or to other important co-factors (tectonics, etc.). The same applies to the size and form of materials.

General statements of the type made in Table 2 may all too easily prove dangerous.

K. W. BUTZER. I would like to emphasize that in my paper I have attempted to single out very specific phenomena and outline these in such detail as is possible here. The tables presented were simply offered as a systematic organization of materials and suggestions, and to consider one column as reference to areal erosion as opposed to vertical erosion in another, is to misunderstand and misinterpret their purpose. Reference is made specifically to the phenomena discussed in the background paper.

So, for example, pedimentation, a phenomenon not typical of the "Mediterranean" climates of the Mediterranean Basin, was not considered, and is a topic on the genesis of which I offer no opinion. The sheet-flood erosion mentioned was specifically directed towards the genesis of colluvial silts. I then feel quantitative or semi-quantitative study of pediments to be decidedly more significant than general morphological study in palaeoclimatic interpretation.

Professor Bobek's statements about solifluction or cold climate phenomena being responsible for upstream aggradation do not apply to the areas described, namely the Mediterranean lowlands. I feel very strongly that cold climate transport hypotheses are unwarranted unless solifluction or cryoturbation features can be demonstrated in questionable pediments. Specific reference has already been made to the lower limits of cold climate ("periglacial") transport in the areas considered. The catchment basins studied were chosen to be free from such phenomena.

As regards localization of aggradation and erosion in a stream system, I believe that sufficient description is given in the background paper and in details given above in reply to Dr. Leopold. It was indicated that the contrast of pluvial and dry glacial or dry interglacial is fundamentally one of morphogenesis as opposed to quasi-equilibrium, excepting of course man-induced erosion. Furthermore the local catchment basins of the Mediterranean littorals are generally small so that particular longitudinal differentiation patterns do not occur other than already indicated. "Other factors" such as tectonics are insignificant as regards aggradation problems in Spain and Egypt for the Upper Pleistocene and Holocene.

H. FLOHN. Referring to the questions at the end of Professor Butzer's paper I would like to formulate, in a quite preliminary way, some suggestions from the viewpoint of a meteorologist.

1. It seems most likely that at the last glacial epoch the surface temperature of the Mediterranean sea was not lowered more than 4°-5°C. as compared with the recent value. The existence of the Alpine glaciation, however, indicates a larger decrease of the temperature in the middle troposphere which may be estimated to 7° or 8°C. in the area of a rather persistent upper-air trough. Under such conditions the average vertical lapse rate of temperature was substantially larger than it is today, frequently conditionally unstable, which favoured torrential cloudbursts. To support this there is evidence of an extremely rainy and cloudy climate of the French and Italian Riviera, near Genoa, during the last glaciation, where these conditions—due to the vicinity of the warm sea to the glaciated Alps—are expected to be most pronounced.

2. A predominance of "low latitude low index" circulation types (Willett, 1958) seem to coincide, from a geographical view point, with the distribution of high latitude glaciations and subtropical pluvials. However, these circulation types are nowadays apparently more or less related to lower temperatures, at least in middle latitudes.

3. Taking into account the fact that the heat content of the oceans is several orders of magnitude higher than that of the atmosphere, we have to expect a phase shift between the temperature of the oceans t_w and that of the air t_a. Thus, at the beginning of each glaciation, during a fairly long period t_w-t_a can be expected to remain substantially greater than today, accompanied by instable conditions in the lower atmospheric layers and by increased evaporation at the oceans. Vice versa, at the end of each glaciation t_w-t_a might be substantially smaller, largely negative, and therefore accompanied by stable conditions and decreased evaporation. It seems not unlikely that the total water-vapour content of the atmosphere may have varied largely during this cycle. Since the average residence time of a H_2O molecule in the atmosphere is not greater than 11 days, the global annual

precipitation amount must be equal to the annual evaporation, and this lag effect may have influenced markedly the global water budget.

4. If the coincidence of moist periods in subtropical latitudes with warm and dry climates in temperate latitudes is established beyond any doubt, we ought to consider how far equatorial disturbances may have extended to the north during the summer at least over the continents, as suggested by H. H. Lamb for the postglacial optimum.

During the war, in one case a cloud system from the equatorial summer rains reached the Mediterranean coast of Egypt, even producing some rain-drops (H. G. Koch). As quoted from C. E. P. Brooks, during the Roman era of Egypt, summer rains were nearly as frequent as winter rains. Thus it might be conceivable that during an Interglacial of the Postglacial optimum a semi-arid climatic type similar to that near Peshawar (northern Pakistan) may have governed large parts of the Near East, with two short (and weak) rainy seasons of 2-3 months each in winter and summer, and with two intermediate dry seasons.

K. W. BUTZER. I thank Professor Flohn for these stimulating and valuable remarks.

W. L. KUBIENA. I am very grateful to our chairman for his very valuable and detailed presentation of the subject and I am particularly grateful that he used paleosoils for his synthesis to such an extent. As to the question of the character of the humid interglacials, I would like to make a remark. We have tried to date *terra rossa* formations in Spain. Pleistocene and Tertiary formations were found but it has not been possible as yet to find a *terra rossa* which could be dated as a recent formation. This is very strange because the *terra rossa* has been regarded up to now as the most typical Mediterranean soil. We are still looking for the recent *terra rossa*. In this connexion I might mention that I prepared a soil map of Spain pointing out the possible recent *terra rossa* areas which, however, could not be proved up to now. It it turns out definitely that a recent *terra rossa* does not exist in the Mediterranean, it would mean that the present climate is different from that of the humid interglacials the latter having had perhaps a greater African influence with much warmer and much more humid winters.

M. KASSAS. 1. The stabilized sand dunes (Qoz) of Kurdufan (Sudan), may be taken to indicate a more arid climate in the time of formation as compared to the present-day climate which makes the growth of stabilizing vegetation possible.

2. On the plain at the base of the Qoz, extending to Omdurman, numerous fossil ant hills are found. These may be taken to indicate a wetter climate previous to the arid climate of the dune formation.

3. Concerning the gypsum layers in desert soils, one may refer to the presence of a surface layer of amorphous powder gypsum and a deeply seated layer (usually thicker) of crystalline gypsum. The former layer is formed by capillary rise and is typical of the present arid climate. The deeper bed may indicate a less arid climate where a water-table is developed.

4. The study of wadi development may provide evidence on the climatic change. There are two types of wadi cutting: downward cutting of long channels (wet climate) and backward cutting of gullies (arid climate). The pattern and interrelationships of the two types may bring the required evidence.

K. W. BUTZER. As regards the Qoz I do not claim any authority other than to confirm the existence of patterns such as Dr. Kassas described from most of the Sahelian belt. The younger Qoz presumably indicates phases of even drier climate than today, although the basic genesis of the Qoz appears very complex according to Professor Monod's work.

The two varieties of gypsum crusts so well observed by Dr. Kassas are familiar to me. I have not, however, found the latter in stratigraphic context. As to its interpretation, I would prefer to refer the issue to Professor Kubiena.

The wadis of Egypt are from all evidence Upper Miocene to Lower Pliocene, forming under moister conditions during the Tertiary. Presumably both agencies mentioned by Kassas are responsible. Although both headward erosion (on a very limited scale by talus development) and linear incision and gullying do occur today, the latter is more significant. It is, however, very localized indeed and confined to soft, fine sediments.

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SIMULTANEITY OF GLACIAL AND PLUVIAL EPISODES FROM C-14 CHRONOLOGY OF THE WISCONSIN GLACIATION[1]

by

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Radio-carbon dating supplies the chronological base for the past 40,000 years of climatic history, plus the possible extrapolations beyond the method's range. This paper summarizes briefly: (a) the chronology of the past 40,000 years for glaciated portions of North America and Europe; (b) the difficulties encountered in providing these dates, both in the laboratory and in the field; (c) some examples of correlations from the glaciated sections to nonglaciated areas; and (d) several new projects currently being explored.

Prior to the use of C-14 for dating, the accepted chronology of the last glacial stage for the continental

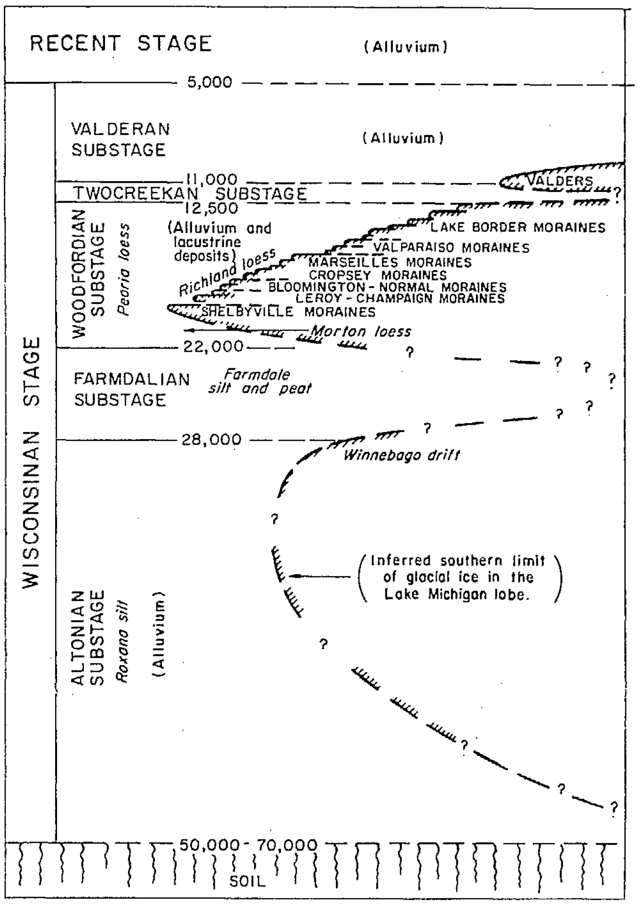


Fig. 1. Time stratigraphic sub-division of the Wisconsin Stage in the Lake Michigan glacial lobe. (After Frye and Willman, 1960.)

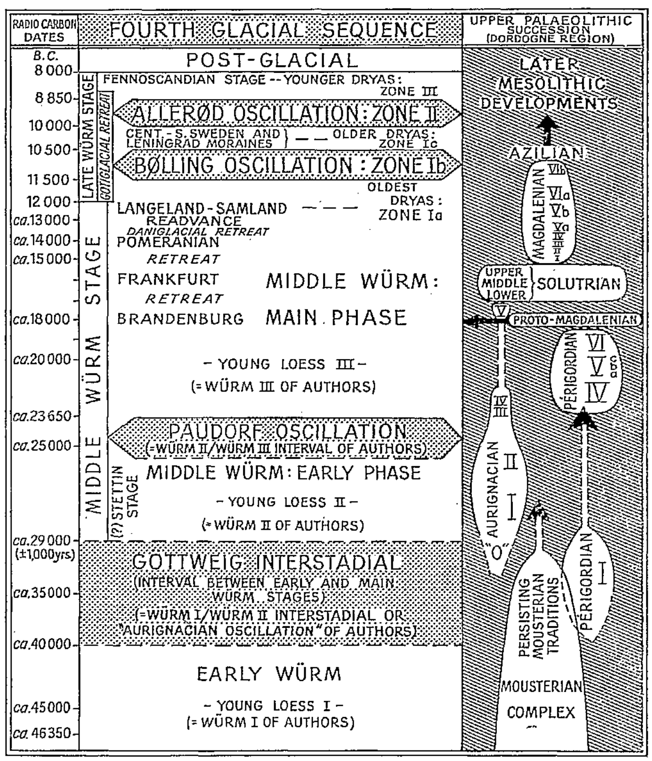


Fig. 2. Würm chronology and the upper paleolithic sequence in Western Europe. (After Movius, 1960.)

1. Publication authorized by the Director, United States Geological Survey.

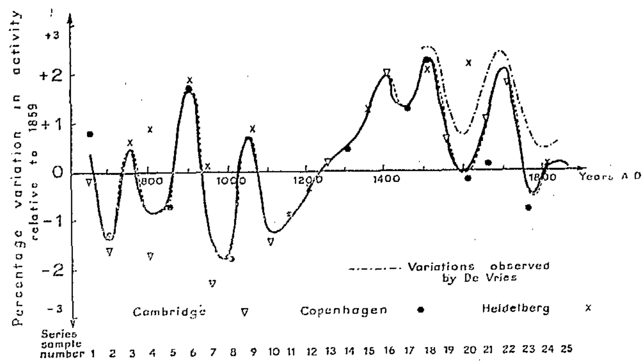


Fig. 3. Initial activities of 25 samples taken at 50-year intervals from a giant sequoia, represented as a percentage variation from the activity of the wood from the 1859 tree ring. (After Willis, Tauber and Münnich, 1960.)

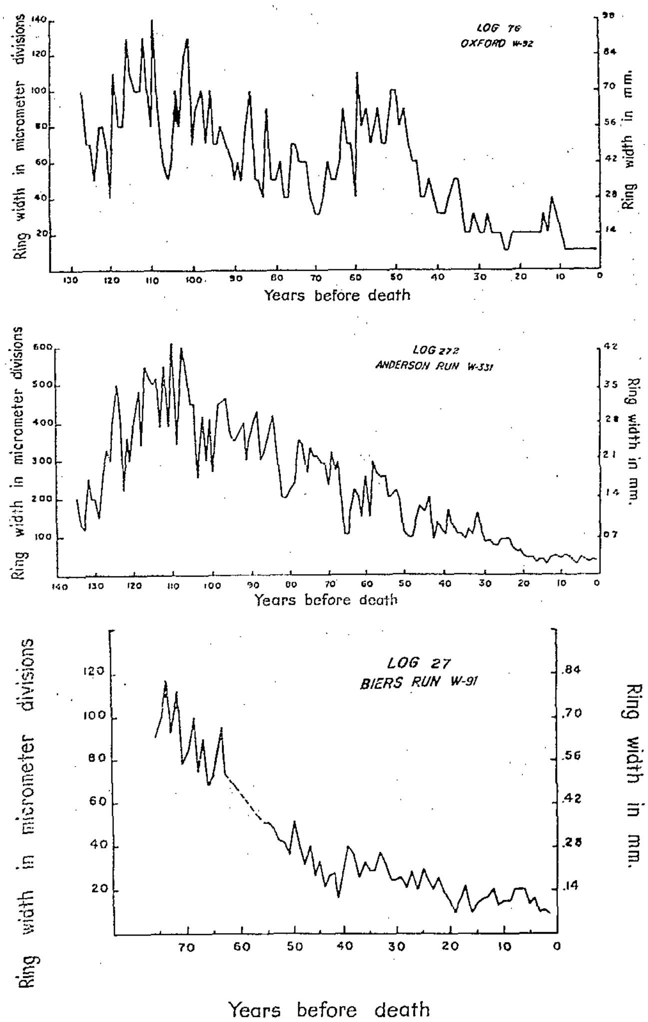


Fig. 4. Ring widths of dated trees from Ohio, showing growth diminution produced by the advancing ice front. (After Burns, 1958.)

glaciers of the United States consisted of five substages of the Wisconsin stage. These were the Mankato, Cary, Tazewell, Iowan, and Farmdale, from youngest to oldest. A newer classification with the ages determined by C-14 dating is that of Frye and Willman (1960) (Fig. 1) from the state of Illinois. This classification is not accepted by all American geologists, but does reflect the current trend toward combining several substages into one. Movius' chronology (1960) (Fig. 2) shows the European classification for the same C-14 time span.

Technical difficulties in determining these ages include the problem of the half-life of C-14. The half-life currently used by all laboratories is the Libby average of 5,568 $\pm$ 30 years. The National Bureau of Standards has made new measurements which indicate a half-life of about 5,700 years. Other workers are at present

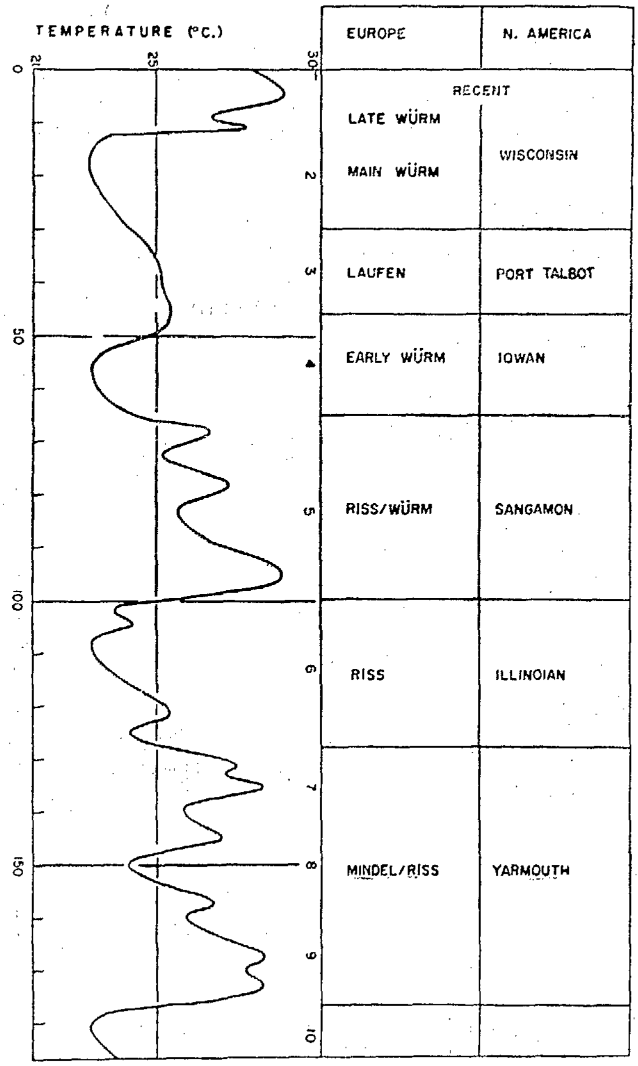


Fig. 5. Generalized temperature curve and absolute time scale (by extrapolation beyond 150,000 years B.P.). (After Rosholt *et al.*, 1961.)

engaged in this study and undoubtedly a new value will be accepted when all the data are available.

To date a sample accurately, the initial C-14 concentration must be known. One of the basic assumptions of the C-14 dating method was that the initial concentration was the same as in present-day living organic matter. Recent work has shown that this is not entirely true (Willis, Tauber and Münnich, 1960). The atmospheric C-14 concentration measured in tree-rings shows changes of ± 2 per cent, equal to a possible dating error of ± 160 years (Fig. 3). These variations have been measured for the past few thousand years and do not present an insurmountable problem. If the ancient concentration did not oscillate about a mean value, but instead continued in an increasing or decreasing trend, then radio-carbon years can differ considerably from absolute years.

In view of the many possible errors in the method, it is unrealistic to interpret radio-carbon dates more precisely than within 300 years in the range 0-1,000 years, within 500 years at 10,000 years, within 700 years at 20,000 years, and within about 2,000 years at 30,000 years. It is suggested that conservative use be made of dates of samples estimated at more than 42,000 years old.

Interpretive difficulties are frequently harder to assess. The sample may be dated, but its climatic significance must be interpreted. Does the wood found in a glacial deposit date the time when the ice reached that spot, or was it transported from a distant place, or was it incorporated from a much older, underlying deposit? Questions of this type must be answered for each sample dated. In Ohio, the glacial advance was indicated by the marked growth diminution of the outer rings on trees buried by the encroaching ice cap. An average net advance of the ice of about 38 feet per year is estimated by the growth pattern (Fig. 4) (Burns, 1958).

In nonglaciated areas, the interpretive problem is increased by the similarity of results produced by arid climates and cold climates. Many different materials have been used for dating in nonglaciated areas, the most successful being pollen. The type of pollen indicates the climate, and the organic matter at that horizon provides the material for the radio-carbon age. Stalactites have been used recently in attempts to date cave formations. Deep-sea sediments have been dated by the carbonate from shells of Foraminifera. The temperature of the water in which the Foraminifera lived is determined by the O^{16}/O^{18} ratio in the same carbonate. C-14 in caliche in soils has been measured, as well as in the bicarbonate in ground water.

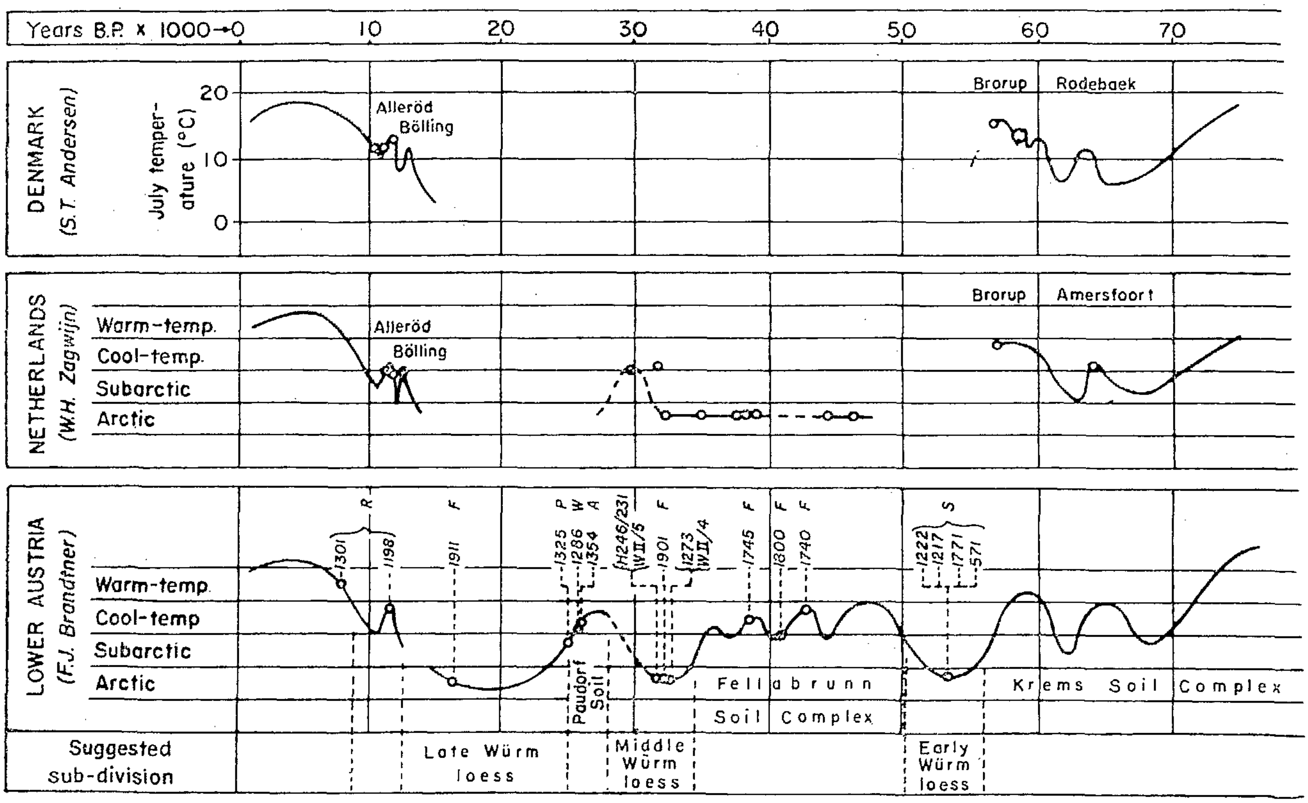


FIG. 6. Climatic variations within the last 70,000 years, inferred from terrestrial data. Circles show positions of C-14 dated samples. (After Flint and Brandtner, 1961.)

Using these various materials, chronologies in non-glaciated areas have been determined. Emiliani's deep-sea cores provide a good world temperature record for the past 200,000 years (Fig. 5) (Rosholt *et al.*, 1961). Flint and Brandtner (1961) show (Fig. 6) curves for past temperatures from the loess of lower Austria, from the Netherlands, and Denmark. Pollen studies (Fig. 7) show a somewhat similar pattern in Bogota (Colombia). A temperature curve for the Great Lakes-St. Lawrence region was derived from glacial material as well as from pollen analysis. A curve for Searles Lake area, California, has been interpreted from the petrologic characteristics of the deposits of the lake (Fig. 8). All show a major warm period at about 50,000-60,000 years, then a long cold period with some oscillations, then a return to the present warm climate beginning at 10,000-11,000 years. Greater detail is shown in this last postglacial time interval in Godwin's summary (1960) (Fig. 9) of the German and English pollen zones.

Recently, there has been an increased interest in dating sea-level changes that relate to climatic change. Many different attacks on this problem have been started, and sea-level time curves are beginning to appear in the literature. A general rise of sea level, correlated with the melting back of the world's ice caps beginning about 18,000 years ago, is the emerging picture.

Another new application of the dating tool is the dating of ground water by its CO_2 and HCO_3 content. As rain falls through the atmosphere, it picks up CO_2 and forms a weak acid. As it passes through the soil zone, more modern carbon is added. The weak acid then dissolves the carbonate in rock formations according to the equation: $CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca(HCO_3)_2$. Knowing the equilibrium point of the modern carbon in this system we can determine how long ago the water

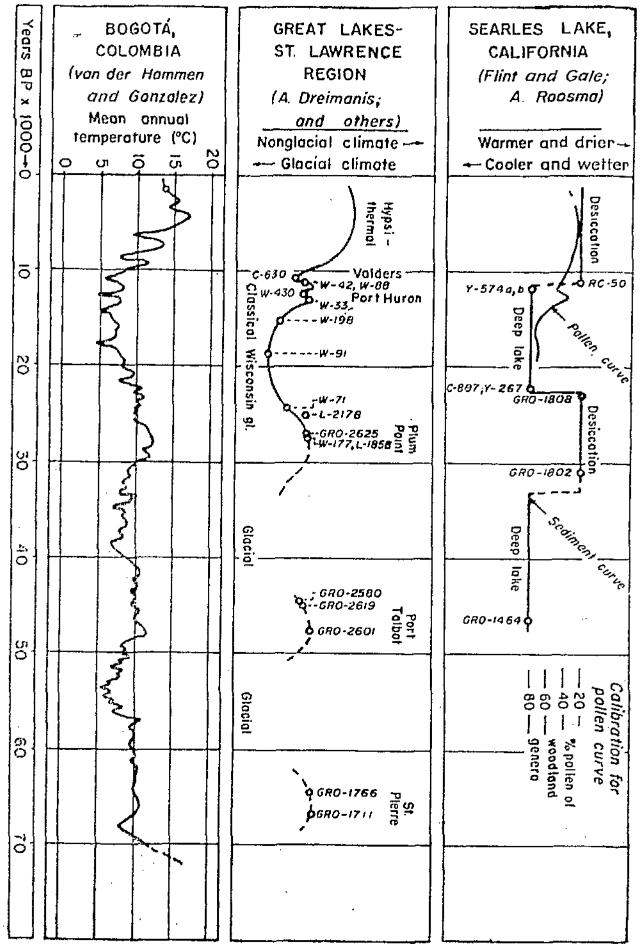


FIG. 7. Climatic variations within the last 70,000 years, from North and South America. (After Flint and Brandtner, 1961.)

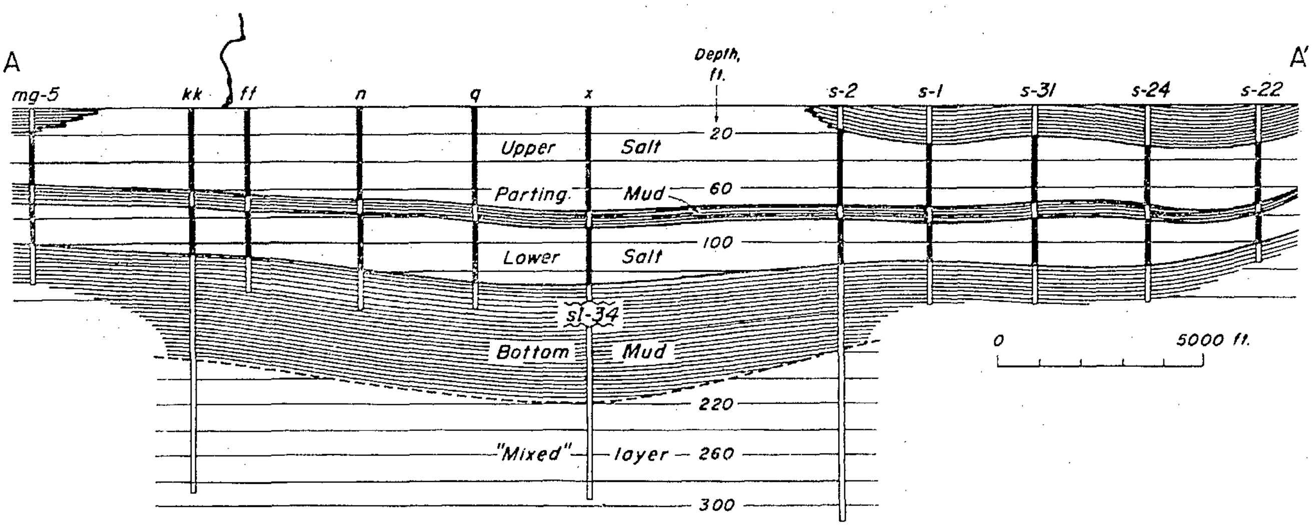
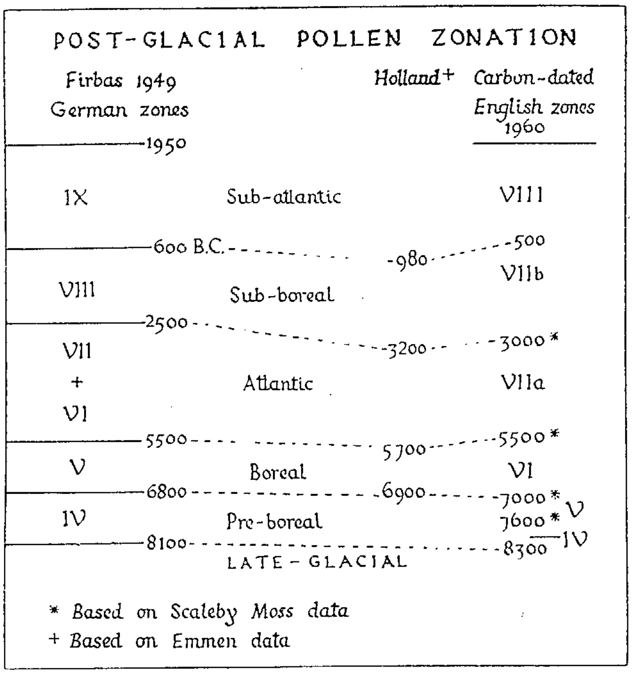


FIG. 8. Section from Searles Lake, constructed from core-drill logs to show stratigraphic units. Mud layers interpreted as representing fresh water phases of the lake; salt layers, desiccation. (After Flint and Gale, 1958.)



fell as rain by measuring the radio-carbon activity of the bicarbonate and dissolved carbon dioxide in the ground water. This has been done for waters in aquifers in Germany, Egypt, and Saudi Arabia. Results indicate that in certain arid regions, ground water is being "mined". The age of some waters in Saudi Arabia and Egypt is about 20,000-24,000 years. This corresponds to a time of maximum glaciation, when rainfall was more plentiful than today.

In conclusion, we see that a workable chronology of world climates for the past 40,000 years is emerging, in spite of the difficulties in both the dating techniques and the interpretation of sample source. Wider application of the method to carbonaceous material is to be expected, but what is needed most is a new dating method; an isotope whose geochemistry can be determined and which has a half-life of about 100,000-200,000 years.

FIG. 9. Schematic representation of dates attributed to West European pollen zone boundaries. (After Godwin, 1960.)

RÉSUMÉ

La simultanéité des épisodes glaciaires et pluviaux dans la glaciation du Wisconsin d'après la datation au moyen du carbone-14 (M. Rubin)

Grâce à différentes méthodes de datation, notamment au moyen du carbone-14, on a pu, dans le Wisconsin, établir avec suffisamment de précision la chronologie de la glaciation continentale nord-américaine, avec ses stades et ses périodes intermédiaires diversement désignés, pour permettre la confrontation des mouvements glaciaires avec l'évolution climatique de régions non glaciaires.

L'étude des épisodes marqués par la présence d'eau douce et par la persistance des hautes eaux dans les lacs de drainage intérieurs (lacs de Bonneville, Lahonton et Searles, par exemple) montre — pour autant qu'on peut se fier aux méthodes de datation — la simultanéité des périodes fluviales et des progressions extrêmes des glaciers continentaux. La même concordance ressort des courbes polliniques des fonds marécageux et des sédiments lacustres formés, d'après la datation au carbone-14, aux périodes de changement climatique. Enfin, les dates assignées aux grottes, aux couches sédimentaires successives et aux dépôts de lœss révèlent la même corrélation entre le froid et l'humidité.

La même technique de datation des eaux fossiles d'après la teneur en carbone-14 de leur bicarbonate et de leur gaz carbonique prouve que certaines périodes ont été marquées par d'importants afflux d'eau qui ont reconstitué les réserves souterraines. Or ces périodes de précipitations accrues semblent correspondre à des maximums de glaciation.

DISCUSSION

R. J. Braidwood. Could I ash Dr. Rubin for his impression of the present state of potassium-argon dating, in view of the recent determination which more than doubles the total duration conventionally suggested for the Pleistocene.

M. Rubin. The application of potassium-argon dating to very young ages is in its infancy and I am withholding any judgement until more dates have been run.

C. Voûte. I would like to comment upon the problem of dating ground water and probable causes of contamination. Dr. Rubin mentioned an example from Saudi Arabia where a sample of ground water showed an age of 20,000 years. Now I happened to have been to Saudi Arabia a few months ago to make a survey of the local ground-water conditions in the Buraida area. The sample mentioned came from the town of Buraida from a well which is 1,200 ft. deep, if I am well informed. I have found that, because of the drilling methods adopted, several aquifers have become interconnected in this area. This is particularly grave, as there are at least 200 flowing wells by which at least 4 different aquifers have become interconnected. The shallowest of these is only 200-400 ft. deep. This may have caused some mixing of waters and erroneous results as far as the age of the water is concerned.

M. Rubin. Thank you for this information.

J. Murray Mitchell. There are two small points raised at the beginning of this paper about which I should appreciate clarification. First, concerning the interpretation of the first figure, Dr. Rubin cited the example that a C-14 sample, actually dating from A. D. 1400, would appear to date from A. D. 1600, in view of a 2 per cent error in apparent age or a discrepancy of only about 10 years instead of 200 years. Do I, therefore, misinterpret the significance of this figure? Second, concerning the evidence from tree-ring thickness (in your second slide) for deteriorating climate in Ohio during the last glacial advance there, it is of course true that ring thickness in a constant climate also decreases with advancing age of the tree. Can you therefore verify that such inferences about climate were arrived at after correction for this inherency in tree growth?

M. Rubin. 1. Two per cent excess activity does not yield a correction of 2 per cent of the age derived, rather it means 160 years. This is from the decay equation.

2. The decrease in the tree ring size was greater than the normal decrease with age, therefore it was attributed to a deteriorating climate.

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MEAN SEA LEVEL RELATED TO SOLAR RADIATION DURING THE LAST 20,000 YEARS

by

R. W. Fairbridge

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INTRODUCTION

A correlation between sun-spot intensity and climatic change has often been suggested, though the causes are much contested. The relationship of these solar oscillations to mean sea level (m.s.l.) changes, as indicated by tide gauge records, has now been investigated, also disclosing a probable correlation. The details, however, are rather complex, and it has not yet been possible to apply sophisticated statistical analysis to the question.

Oscillations of mean sea level have long been recognized on a basis of tide gauge observations. The seasonal cycle was studied by Pattullo, Munk, Revelle and Strong (1955), who have shown that the recorded variations correspond closely to the sum of the departures due to steric and atmospheric causes. The major role in low latitudes (40°N. and S.) is played by the steric departures, defined as the seasonal fluctuation in specific volume controlled by salinity and thermal changes. In high latitudes the atmospheric pressure anomalies tend to make m.s.l. an "inverted barometer" (Lisitzin and Pattullo, 1961). Thus in the mid-latitudes there is a general seasonal trend by which in spring and summer of each hemisphere sea level is low (temperature and salinity low, pressure high), and in the summer and autumn sea level is high (temperature and salinity high, pressure low). In equatorial and marginal seas there are more complex oscillations.

We are now able to show that the well-marked two to three year oscillations of the annual mean sea level (Fairbridge and Krebs, 1961) are related to a climatic control by the so-called "Southern Oscillation" of Sir Gilbert Walker, recently re-examined by Berlage (1957) and by Berlage and de Boer (1959), a pressure control "steered" in all probability by the solar cycle.

Plotting long-term m.s.l. records discloses an extremely complex oscillation which, smoothed to five-year running means, approximately parallels a smoothing of the 11-year sun-spot "cycle". However, there are many departures, which may be possibly related to solar radiation and its meteorologic and hydrologic effects.

It follows that it might be possible to use the records of sea-level stands of the distant past, found in littoral and marine sediments (Fairbridge, 1958, 1960), as absolute indications of general climatic conditions and of solar activity. Although granting that a reasonable doubt still exists as to whether the demonstration of a short-range relationship is an acceptable criterion for a long-range deduction of this sort, there now seems to be a sufficient convergence of data obtained from multiple approaches to encourage this assumption as a working model. Readers are urged to bear in mind the very tentative nature of such conclusions.

If such correlations are established on a long-term basis, an analysis of past cyclicity might render it possible to predict sea level and therefore general climatic trends. For coastal engineers there is the prospect of predicting the future needs of harbour works and dikes, while meteorologists, agriculturists, and human geographers are concerned generally about the long-range prediction of climatic trends.

VARIABILITY OF SOLAR RADIATION

Owing to observed variations of considerable magnitude of the sun's corpuscular emissions, it has sometimes been hinted that the sun is practically a variable star (Öpik, 1953, 1958). However, the solar constant of 2 cal.cm.$^{-2}$ per minute is confirmed by recent satellite of observations, at least for short periods. For longer periods there is an infallible geological test: this is the "principle of biological continuity". Owing to the extremely narrow thermal range of organic metabolism (roughly 0°-50°C.), there could be no serious departures from the solar constant, except for very short periods, over the whole span of recorded organic life on earth, thus approximately 3×10^9 years.

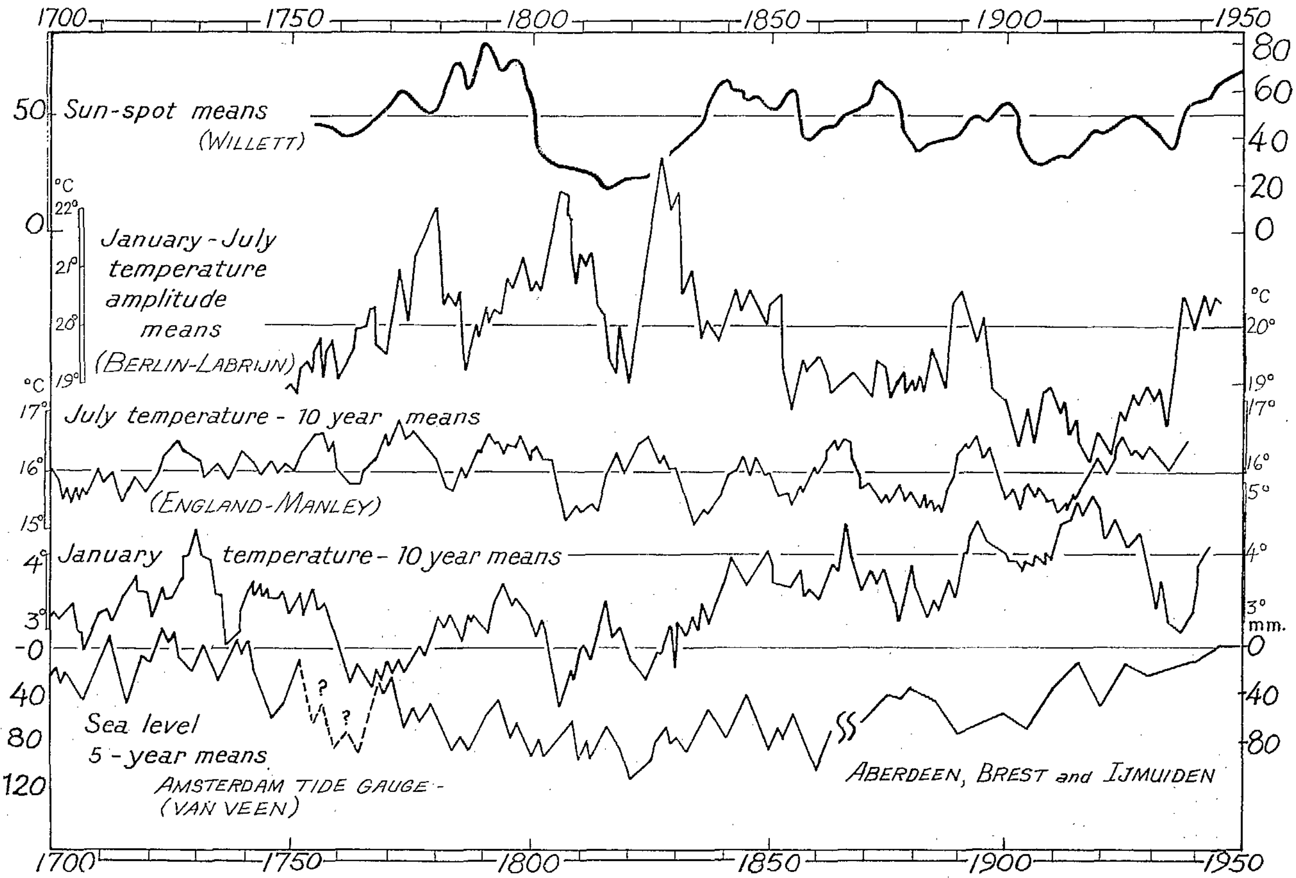

FIG. 1. Relationship of sun-spot cycle to selected climatic records and mean sea level. The 11-year sun-spot cycle, when smoothed, shows a great variation in peak values suggesting 22-40-80 year periods; note extreme low about 1805-25. A second curve shows winter-summer temperature amplitude means, an expression of continentality-maritime climate change; note extreme variations about 1805-25 with minimal oscillations 1900-30 (e.g., for Berlin, also true for all north European stations according to Labrijn). Third curve shows summer temperatures for central England (after Manley); note short-period variations and coldest summers about 1810 and 1835, but no significant secular change. Fourth curve is for winter temperature means (same area and source); note certain relationships to sun-spot oscillations and lowest peak in 1805. Fifth curve shows sea level, as recorded on the Amsterdam tide gauge since 1682, and, after interruption (dike construction), continued with an average of Aberdeen, Brest and Ijmuiden, three north-western European stations with long records; all stations are corrected for tectonic (isostatic) anomalies. Note the secular lowering of mean sea level to 1820-21 and since 1890 (about 1.2 mm. per year).

Examination of the geological data shows that "ice ages" (of relatively short duration) have periodically interrupted the normally mild to subtropical climatic record, but that those periods were widely scattered in geologic time (Fairbridge, 1960) and reflected certain extreme topographic conditions set up by geotectonic revolutions (Flint, 1957).

This generalization of solar constancy may, however, be slightly modified. For example, there are short-period variations of the solar spectrum, particularly in the ultra-violet range (below 2900 Å), of more than 200 per cent (Haurwitz, 1946) and of cosmic radiation of extremely complex nature. The ultra-violet departures are particularly significant since these control the earth's ozone screen, which plays the major role in the "greenhouse effect", cloudiness, meridional ocean currents, etc. Fifty years ago it was customary to relate short-term climatic variations simply to sun-spot "cycles". It is now becoming apparent that it would be more accurate to relate them (positively or negatively) to oscillations in solar emission, of which the Zürich sun-spot number is merely a convenient index, over and above which are many additional factors. For example, study of the C-14 in tree rings over the last 13 centuries suggests that the cosmic radiation intensity (responsible for C-14 production) may be inversely proportional to the mean sun-spot level (Stuiver, 1961).

The sun-spot "cycle" itself is simply a mathematical average of peak periods which range from 8 to 16 years. Classical records have given an approximation of the phenomenon back to 649 B. C. (Schove, 1955), from which Dewey (1958) drew a "forced" cycle of 11,094 years. Since the magnetization of the spots oscillates from the northern to the southern solar hemisphere with each cycle it is not surprising that a 22-year ("Hale") cycle is observed in many terrestrial events.

The connexion between sun-spots and the earth's weather is still a mystery. On a short-term basis there is no statistical validity to most local correlations, but on a global basis, and over long terms, a very striking coincidence emerges. According to Abbot (1960), the double sun-spot cycle should be expressed as a 273-month period, and consequently the peaks always fall at different seasons. The work of Willett (1949) and his collaborators showed that the 11-year cycle generally follows an alternating high-low pattern, with the low *corresponding to the southern orientation phase*. The world climatic anomalies introduced by the high maxima were notably in contrast to those associated with the low maxima (see Figs. 2 and 3). Anderson (1939) showed that the 22-year cycle could be usefully plotted as a curve above and below a line of zero concentration, corresponding to the migration of spots from the northern to southern solar hemisphere and back.

An important feature of the sun-spot record over the last two millenia that does not appear to have received much attention is that the amplitudes of the sun-spot peaks, in terms of annual averages, show a tremendous variability, *ranging from maxima of the order of 20-50* up to the recent peaks of over 200. Of the low periods, "the great sun-spot dearth" of 1660-1720 is well known, but there were still greater disturbance-free periods, in Roman times and in the ninth, fourteenth and sixteenth centuries. Each is known to correspond to periods of lowered temperatures in western Europe, glacier advances, and low sea levels. We have both historical and geological data that indicate m.s.l. in mid-Roman times to have been 2 metres below the present.

There has been some disagreement expressed as to the coincidence of various sun-spot conditions with climate trends. Here it is very important to recognize the scale involved. In long-term oscillations (40 years and more), the reaction seems to be uniformly positive, i.e., high mean sun-spots = higher world mean temperatures and vice versa.

In brief solar flares there seems to be no correlation at all. In the 11-year cycle, the reaction depends, as Willett showed, very much upon the sun-spot intensity and the regional influences. As Callendar (1961) recently brought out, the sun-spot peak maxima lead to lowered temperatures in the Tropics and regions geared in part to tropical influences (e.g., typical United States means). It seems to be that increased radiation leads to increased evaporation in the tropical oceanic regions, thus

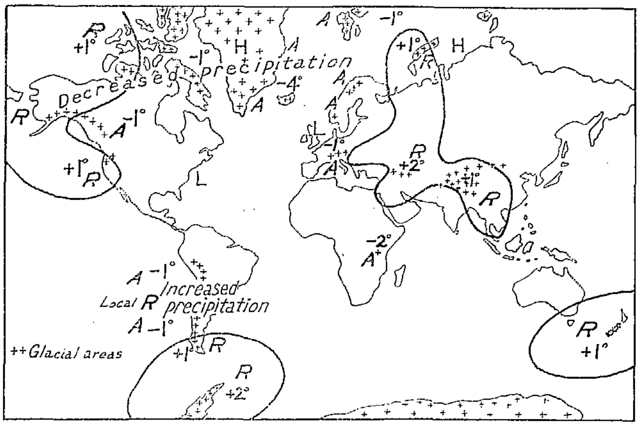

FIG. 2. World map illustrating mean winter temperature anomalies resulting from a change from a sun-spot minimum peak (after Willett, 1949). Probable glacier reactions have been added. Several sources of error are recognized: (a) the reaction of any particular glacier is subject to various delay mechanisms, dependent upon area/volume ratio, elevation, latitude, etc.; (b) the peak sun-spot condition is reached at different seasons, so that no two have an identical effect and a tendency may even be reversed; (c) glacier melting is controlled mainly by the length of the summer, i.e., warm spring and autumn temperatures, often indicated by a high winter mean, but not always. (Temperature departures expressed in °F., 1°F. = approx. 0.5°C.)

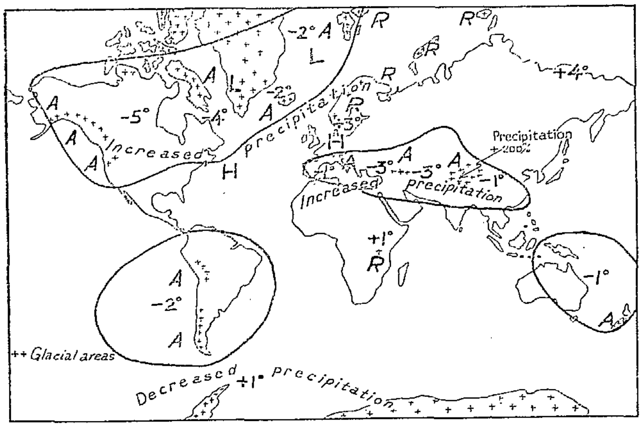

FIG. 3. World map illustrating mean winter temperature anomalies resulting from a change from a sun-spot minimum to a low-intensity peak (after Willett, 1949). As in Fig. 2, probable glacier reactions are indicated. By and large, if the net area of glaciers under advance exceeds that of those retreating, as is the case here, then sea level may be expected to fall. In the condition illustrated in Fig. 2, the opposite is generally true. Any of the above tendencies may be reversed owing to Willett's alternate high-low (22-year cycle) being superimposed in a more powerful oscillation of longer range. Note, for example, the anomalous high pressure over western Europe that replaces the low of sun-spot maxima will tend to depress sea level further in this region, more than the world pattern.

increased cloud and also monsoon rainfall; lowered surface temperatures occur in the cloud-covered areas, but in the desert regions the effect is reversed, and often also in temperate latitudes. However, associated with low sun-spot maxima, the Tropics are often warmer. There is clearly room for more sophisticated analysis in this field.

Fortunately, the long-term meteorologic trends that impinge upon the geological seem to be clearer than the short. In particular, the extended low mean periods correlate nicely with cold-climate records. Simultaneous reactions are reflected by glacier advances in Alaska (Lawrence, 1950; Lawrence and Elson, 1953), and in tree-ring data from the South-west (Douglass, 1936). During the last two centuries the 11-year harmonics (22-year and "double Hale" or 44-year cycles) tend to dominate the pattern.

Barta (1956) identifies this 44-year period as dominant in waves of the geomagnetic field (also in certain regions the half and quarter waves, of 22- and 11-year periods). Schove (1955) notes also traces of 77.5-78.0 and 160-170 year cycles. The former is regarded as an independent 80-year astronomic cycle by Gleissberg (1958). Sea levels, within the range of instrumental records, reflect each of the periodicities, most strikingly the 80- and 160-year oscillations on smoothed records.

The only part of the sun-spot oscillation that is strictly comparable with modern meteorologic and sea-level statistics is the last 250 years. Accordingly, a trial comparison of data was prepared (see Fig. 1). While the smoothed sun-spot record shows a series of distinct peaks, most striking is the sun-spot dearth that occurs in the period 1805-25. Coinciding with this is the maximum continental maritime alternation in western and central Europe (second curve). Little secular variation is seen in a typical summer temperature record (third curve); but a marked downward swing is seen in the winter means (fourth curve) about 1805-25. Finally (in the fifth curve) one sees mean sea level at its lowest at 1820-21.

At this same time there were minima in northern tree rings (as organic thermographs, not precipitation indicators as is the case farther south), records of freeze-ups in New York harbour, and other local data. Alpine glaciers demonstrate maximal advances. The Caspian Sea reached its highest level for many centuries in 1820; this reflects the increased pluvial activity engendered by the Mediterranean storm tracks. One might imagine a miniature Ice Age condition.

In the period 1825-1960 one notes a fairly high mean level of sun-spot activity, leading up to the crescendo of the last decade, matched by a striking rise of sea level (1.2 mm. annually from 1890 to 1950). Although fairly low sun-spot maxima are recognized (e.g., 1880-1930), the mean level was never below 25 and it is clear that a single sun-spot low is too brief to bring about a hydrologic withdrawal marked by more than a few millimetres of eustatic lowering.

CLIMATIC REACTIONS IN "SENSITIVE" AREAS

Sufficient climatic evidence over the last two centuries permits a more rigorous analysis. Willett (1949) has prepared world isobaric, temperature, and precipitation anomalies for two observed conditions of sun-spot variation: (a) the marked change from a minimum to a maximum, as seen at the double (22-year) peaks; and (b) the distinctive changes seen at the intermediate (11-year) high levels. In certain areas it is important to note that the orographic coincidences are such that locally greater or reversed climatic changes are established during the minor sun-spot maxima.

Il should be emphasized that the coincidence of modified isobaric patterns with orographic and oceanic "accidents" of the geographic pattern is the major factor in controlling appreciable changes in the world glacial budget today. The Northern Hemisphere assumes the major portion of this control. The reason is relatively simple: the belt mainly affected by anomalous pressure-temperature-precipitation conditions coincides with the bulk of the world's mountain glaciers. The Greenland area is included, although it contains both ice-cap and mountain-type glaciers. Antarctica, on the other hand, seems to represent a rather passive element, except perhaps for Grahamland (Palmer Peninsula). The smaller a glacier is, and the smaller its volume/surface area ratio, the more sensitive it is to small changes in temperature or precipitation. The "sensitive" areas of temperate latitude glaciers are mainly distributed, according to data by Flint (1957), in the Northern Hemisphere; indeed there is nearly 95 per cent greater area of mountain ice here than in the Southern Hemisphere.

Ahlmann's studies of a series of small glaciers in the North Atlantic area (Ahlmann and Lindblad, 1940; Ahlmann, 1940*a*, *b*, 1948*b*) show a remarkable correlation with divergences of 1-1.5°C. from the mean temperature patterns, with approximately 3- 5-year delays, both in advances and retreats. The delay factor tends to smooth the glacier reactions so as to give 5- 11-year oscillations of the ice front, although the temperature oscillations are, of course, annual. Note that precipitation variability plays a minor role.

For a typical retreat stage in one of the small Norwegian glaciers (Ahlmann, 1940*a*) the melt water liberated represents 6.0×10^5 m.^{3} km.$^{-2}$yr.$^{-1}$, corresponding to approximately 0.5°C. annual temperature rise. Current melting of a small glacier on Mt. Kenya (Charnley, 1959) is at the rate of 8.0×10^5 m.^{3}km.$^{-2}$yr.$^{-1}$. Since it would require 0.36×10^{12} m.^{3} of water to raise the sea level 1 mm. in a year, the world area of ablation from similar types of glaciers to produce this response would be 2.4×10^5km.^{2}. This figure is compatible with the available areas of most "sensitive" middle latitude mountain glaciers (4.84×10^5km.^{2}). Confirmation of the same trend comes from many areas (Ahlmann, 1948*a*, 1953).

Naturally the sea-level change only represents a summation or average of all climatic changes in both glacial and nonglacial areas, so that the empirical deduction of expected change is not simple. It depends upon the absolute areas involved, the volume/surface area ratios of the glaciers, cloudiness and precipitation/evaporation ratios, as well as the temperature changes.

All other climatic data, of course, are also useful in testing the method. The long-period January-July temperature means for Sweden (Ångström, 1939), Holland (Labrijn, 1945), central Europe (Baur, 1948) and the British Isles (Manley, 1953) are most helpful. The records of the rise and fall of the great interior lake basins are particularly impressive, notably the Caspian Sea (Berg, 1940) and the Great Salt Lake (Brooks, 1951). Naturally, these are local records, but many reflect regional trends. Even more local are tree rings; Schulman (1945) pointed out that sub-Arctic trees are local thermographs, while trees in semi-arid lands are local raingauges (see also Glock, 1945; Schove, 1954; Hustich, 1949, 1956).

GLACIER RESPONSE TO SOLAR ACTIVITY

Two maps have been constructed, illustrating the effects of the two dissimilar climatic changes in the 22-year cycle obtained by Willett (1949). If the change is expected to favour glacial advance, the area is marked with a big A, and likewise retreat with a big R. The surface area and latitude of the glaciers involved gives the relative importance of the reaction.

PERIOD OF MAJOR SUN-SPOT ACTIVITY

The period of major sun-spot activity is reflected by two possible climatic effects in temperate to cool latitudes (changes in polar and tropical belts do not greatly affect nivation):

1. Increase of mean winter temperature (by 0.5° to 1.5°C.) occurs in Alaska, California, eastern Europe, Caucasus, Middle East, Patagonia, Grahamland, south-west Australia and New Zealand. These localities include many of the world's smaller (and therefore most sensitive) glaciers. Therefore, we predict an earlier seasonal melting and a sea-level rise, partly immediate and partly subject to some delay owing to retardation (due to glacier volume/area ratio, latent heat principle, etc.).
2. Decrease of mean winter temperature (0.5°-2°C.) occurs in continental North America, Greenland, Iceland, Scandinavia, western Europe and northern Asia. Increased nivation in these areas would be possible only if there were increase in cloudiness and circulation. However, observations show that there is a steep rise in atmospheric pressure over Canada, Greenland, Iceland, and northern Asia; anomalously, Scandinavia shows a slight decrease. The net effect, however, will be decrease in winter snow precipitation in all the "sensitive" areas, including Scandinavia (Willett, 1949, Fig. 3). This will also favour the positive sea-level trend mentioned above.

PERIOD OF MODERATE SUN-SPOT ACTIVITY

According to Willett (1949), a period marked by minor peaks of sun-spottedness (peaks about 50, means about 25) results in a modified displacement of pressure systems. The anticyclonic centres of Greenland and northern Asia occur farther south and move laterally, so that they now pass over western Europe and (to a lesser extent) eastern North America. The contrast is exceptionally great in western Europe where there is an astonishing swing from maximal low to maximal high pressure depending upon the extent of rise of sun-spot activity.

Increase of mean winter temperature occurs in Scandinavia, Iceland, northern and eastern Asia, the eastern United States, and western Australia. High pressure systems cluster along the 45° latitudes of the North Atlantic, western Europe and South Pacific, while the lows form over Greenland and the north of Scandinavia. Precipitation increases in Scandinavia, the United States, southern Alaska, central Asia, south-eastern Australia and New Zealand but decreases in western Australia. One may predict increased nivation and glacier advance in most "sensitive" areas, so that an immediate fall of sea level will occur (no retardation effect).

Decrease of mean winter temperature occurs in Canada, Greenland, Mediterranean and Middle East, South America and eastern Australia, where it is matched by decreased precipitation in higher latitudes (high pressure) but increases in the monsoon-affected areas (low pressure). Higher snowfall in the Himalayas and Tibet will contribute to the lowering of sea level predicted above, but the loss of precipitation in the other areas is of little significance owing to general absence of glaciers.

The retardation factor is a very important one. There is a curious anomaly: a lowered annual mean temperature normally brings a shorter summer, which causes an immediate decrease in the summer melting. Conversely a raised annual mean temperature should immediately increase the melting rate, but this is not so. The latent heat of freezing is only one-seventh the latent heat of vaporization; further, snow crystals are formed omnidirectionally and at any elevation, while ablation from the snow glacier surface is only from a single plane and at a lower elevation than the snow clouds. A serious delay or retardation is involved.

In very small glaciers that show annual advances and retreats the delay may be of a few months; retardation of the 11-year cycle may be three to five years, and in the largest known type of oscillation, such as the late

Wisconsin (approximately a 40,000-year cycle) the retardation of the North American-Eurasian continental ice melting was about 10,000 years.

This phenomenon will therefore cause a bias in favour of the preservation of a glacier (or a glacial age) but will not delay the beginning of a new one. The greater the ice mass is, the greater will be the delay; this Antarctica is still essentially intact after 10,000 years of a world-wide warm climatic phase. Small glaciers, especially in middle latitudes, may disappear very quickly. The retardation phenomenon thus tends to bridge over the peaks of short-period climatic oscillations, but with longer cycles (80-year, 160-year, etc.) the reaction is clearly seen in the m.s.l. records.

MEAN SEA-LEVEL REACTIONS

The record of useful tide gauge data is all too short, but the 80-year pattern is suggestive (Fig. 4). Prior to 1860 only a few stations are available preventing a statistically valid rate to be determined at this time. Only the Amsterdam gauge goes back to 1682 (van Veen, 1957).

POSITIVE EUSTATIC REACTION

This occurs from a sun-spot condition where there is a progressive increase from minimum peaks to a maximum marked by glacier melting (partially retarded) in many of the temperate-cool belts, and was noted at the following times during the last three centuries:

Occurrence	Maximum rate of rise of m.s.l. per year (in mm.)	Increase in mean sun-spot peaks	Maximum sun-spots
About 1780-95 (high for eighteenth century)	10.0	40-75	150
About 1860-78 (high for nineteenth century)	10.0	30-65	140
About 1946-60 (maximum observed m.s.l. rise)	12.0	35-70	200

The maximum eustatic rise is based on 5-year means in order to eliminate steric and pressure anomalies. It is recognized that the technique of moving means may introduce spurious oscillations but the broad trends emerge satisfactorily. The average rates of rise for such periods are 2-3 mm.yr.$^{-1}$. Although within each of these events there were temporary reversals, glacier melting was such that 3 to 4 $\times 10^{12}$ metric tons of fresh water could be added to the ocean annually for several years at a time. However, this is not an excessive figure, since at several times in the early Holocene (after 10,000 B.P.) the excess melt water was averaging 18×10^{12} metric tons annually for periods of a century and more.

NEGATIVE EUSTATIC REACTION

Since there should be little or no retardation any sudden or secular drop in sun-spots (11, 22, 40 or 80-year cycle), marked by lowered temperatures or increased snow accumulation, causes a drop in sea level. This reaction is seen strikingly at the following times during the last three centuries (without any retardation):

Years	Average rate of fall of m.s.l. per year (in mm.)	Variation in mean sun-spot peaks	Western Europe: mean winter temperature anomaly (10-year means)
1740-65	3.0	20-50	—2.5
1790-1820	1.2	20-30	—2.0
1878-92	3.0	30-50	—1.0

A maximum annual rate of fall can only be derived for the last period, and this is 12.0 mm.yr.$^{-1}$, thus comparable with the positive eustatic rate (mentioned above).

Owing to the climatic change of the oscillated, often reaching further last half century, the high pressure systems associated with the Tropics have migrated poleward, the equatorial region has received slightly less precipitation, and the westerlies have been strengthened so as to warm the sub-polar regions, especially in winter, resulting in widespread deglaciation. The central Sahara Desert and other subtropical arid regions have mostly become drier, but some of the monsoon areas have become wetter.

To recapitulate, the following perturbations to mean sea level with periods in excess of 12 months appear to be instrumentally identifiable:

1. The two- to three-year "Southern Oscillation", an atmospheric pressure effect, related by Berlage to solar sources. With high pressure the sea level falls, and with low pressure it rises. This barometric oscillation also drives a dependent series of steric reactions in the same sense.
2. The 11-year "standard sun-spot cycle" with possible sub-components. The world annual m.s.l. often shows coinciding peaks, but it is difficult to distinguish how much of the effect is steric, driven ultimately by the same solar causes.
3. The 22-year "Hale cycle" of major and minor sun-spot peaks, associated by Willett with regional atmospheric pattern changes, and further correlated by us with glacier variations. A minor sun-spot peak often causes temporary cooling in critical areas so that sea level drops, reversing the last pattern.

4. The 40-44 year "double Hale cycle", a harmonic development of the above systems of some climatic significance, with glacial and eustatic reactions.
5. The 78-80 year "Gleissberg cycle" and the 160-170 year "Schove cycle" represent further developments that play the greatest role in glacier and sea-level changes.

Thus precise prediction of a sea-level reaction is not a simple matter. Regardless of local or regional changes there may be world tendencies that represent cumulative products of the above trends or they may be out of phase and reversed.

ADDITIONAL CONTROLS OF THE HYDROLOGIC BUDGET

Glaciers are the most obvious water-holding reservoirs which can affect the hydrologic cycle and thus create sea-level changes. But there are many other areas where a small climatic change can control the turnover rate of the hydrologic cycle.

In temperate and tropical forest-covered areas where ground water approaches saturation and the evaporation/precipitation ratio is not high, small climatic changes will not have great effects upon the water

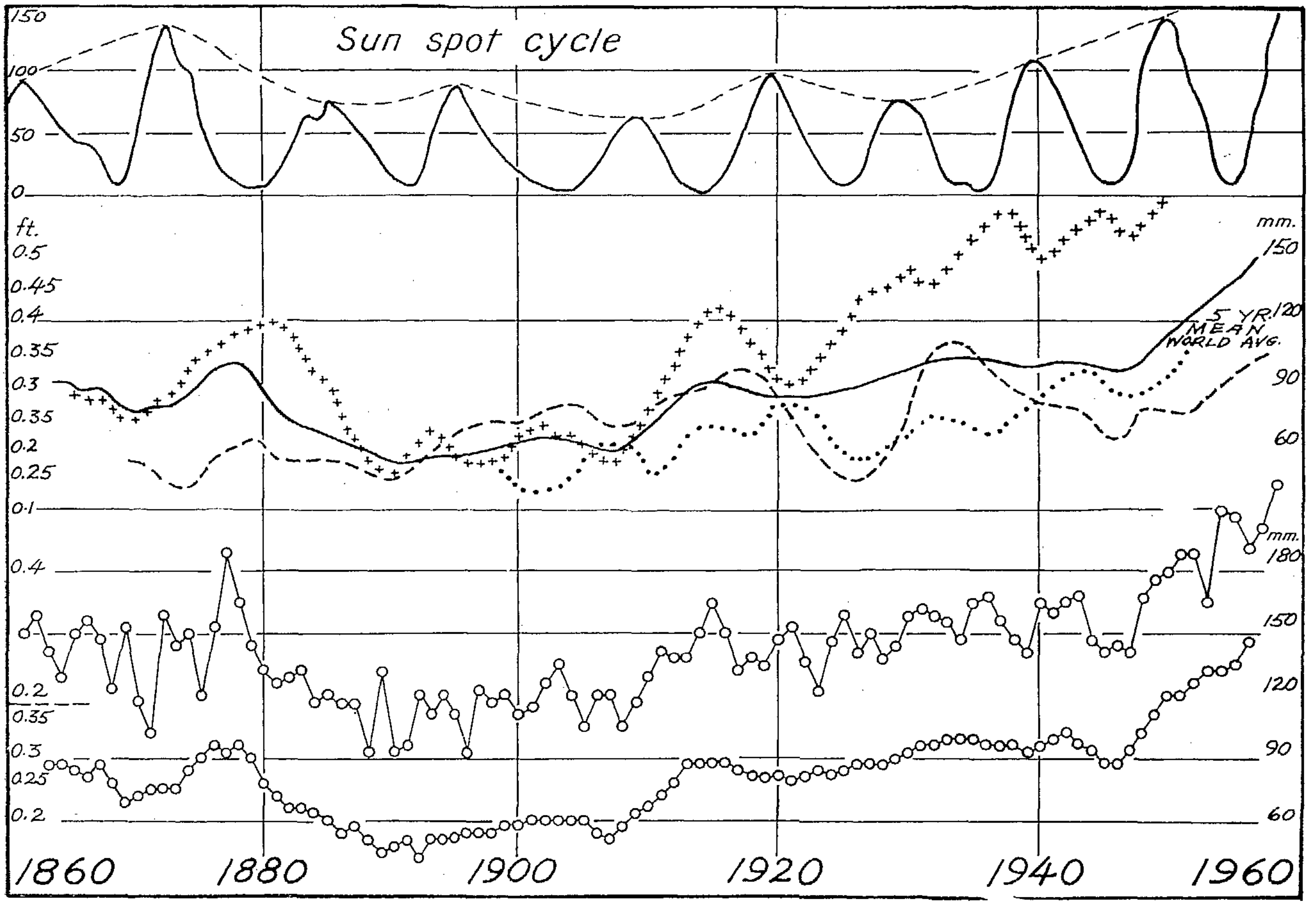

FIG. 4. World sea-level averages. The upper curves illustrate (solid) the 11-year sun-spot cycle (after Schove), with (broken line) the variation of the sun-spot peaks. The *middle curves show five-year mean sea levels for the world, the Atlantic,* Pacific and Indian Oceans. Sea-level records were selected upon the basis of the four longest and most widely distributed gauges for each ocean. For the Indian Ocean (Karachi, Bombay, Aden, Port Balir), however, for 1870-87 only Karachi was available; for 1921-36 only Bombay was suitable. For the Pacific Ocean (Honolulu, Seattle, Sydney and Balboa) care was taken to omit volcanic and mobile-island arc stations. For the Atlantic Ocean (Aberdeen, Ijmuiden, Brest, New York) care was taken to omit glacial rebound areas, partly closed basins (Mediterranean, etc.) as well as tectonically *active areas. The lower curves compare the world five-year sea-level means and the world annual averages. In comparing* the sea-level changes with sun-spot cycles, note that at sun-spot peak maxima a low pressure anomaly exists over the North Atlantic (especially north-western Europe) and at the lower peaks this is replaced by a high pressure anomaly, according to Willett (1949). No very great long-term pressure anomalies occur in the other oceans. In the world annual average curve, the effects of the two to three year cycle of atmospheric pressure are well displayed (the "Southern Oscillation").

retention. However, arid regions can play a role (admittedly minor) analogous to that of the glaciers of the cool and temperate highlands.

It is most difficult to gauge ground-water conditions on a world-wide scale; however, the interior basins of semi-arid continental regions present ready hydrologic markers in the form of endorheic lakes. Thus the largest of these, the Caspian Sea, is particularly susceptible to changes in regional climatic patterns. As first shown by Eckhardt (1909), during the last glacial stage (Wisconsin or Würm) the isobaric high which lay over the northern European ice sheet tended to force the westerly storm tracks to the south, so that they crossed the entire length of the Mediterranean to reach the Caucasus, the Caspean and western Siberia. The Caspian was therefore extremely high, the so-called "pluvial" condition. With postglacial ice removal the former condition ceased.

Even with present conditions sun-spot variations are reflected by this interior sea. Given a major increase of sun-spots, Willett (1949) indicated precipitation in the Caspian area down by 23 per cent and temperature up 1.5°C. Such conditions with record low lake levels occurred about 1840, 1900 and 1950. With the low sun-spot condition, in contrast, pluviality gains ascendancy, precipitation increases on the average 39 per cent and temperature decreases 1.5°C.; maximum level of the Caspian was in 1820 with smaller rises about 1860-70 and 1910. In the eighteenth century sun-spot low, the sea reached 8.5 metres above the 1925 datum (Berg, 1940).

The Great Salt Lake of Utah is also interesting and rather different in this respect. Its maximum level came in 1875, after the sun-spot high of 1871 (the peak of an 80-year cycle), a condition repeated about 1958, while its lowest level came in 1937, after more than 50 years with no sun-spot maximum over 100.

LONG-TERM SOLAR CONTROLS

If we should try to explain long-period eustatic oscillations and climatic changes by the observed short-period variations of solar activity, we are discouraged by the relatively small amplitude of the effects, both eustatic and thermal. Relatively small thermal changes can, however, if extended over much longer periods, have profound effects, mainly by the operation of feed-back mechanisms.

This is explained by two basic climatic laws. The first, as worded by Faegri (1950): "The shorter the duration of a climatic fluctuation, the smaller is the area similarly affected; the longer the cycle, the greater the area within which it is felt in the same way".

In the second law Faegri (1950, p. 194) observes that "the longer the period, the more complete is the reaction of all indicators".

From these considerations emerges an extremely important deduction, clearly recognized by Faegri. In order to establish the extreme climatic conditions of the ice-age maxima, it may only be necessary to have variations in solar radiations of approximately the present amplitudes, provided that the condition was maintained over a considerable period.

It would seem, as Ewing and Donn (1956, 1958) have suggested, that, within the range of the meteorologic patterns recorded within the last 100 years, it is only necessary to establish a topographic-meteorologic condition favourable to high latitude continental ice accumulation, and maintain it for an adequate period, to initiate a glacial condition which, in turn, tends to promulgate a chain reaction that greatly extends the normal period of oscillation.

Let us take the available instrumental records to prepare a rough generalization on glacio-eustasy. Over the last 100 years the mean annual temperature of the mid-latitudes (temperate climatic belts) has risen about 1°C. and sea level at about 1 mm. per year. Paleobotanical evidence of Wisconsin/Würm periglacial areas suggests about 10°C. lower mean temperatures, at a time about 10,000 years before the post-glacial "Climatic Optimum", when sea level was about 100 metres below present. These movements would be compatible with a formula: 1°C.yr. = 1 mm. Not only is this a generalization, but also it has limitations, following the Faegri Law and the Retardation Principle; thus it cannot be applied to very short periods. There are obviously also upper limits, so that the curve must be sinusoidal.

THE GEOLOGICAL RECORD

The nature of the geological record of sea-level changes over the last 20,000 years is complex, and difficult to unravel. What is now presented can only be regarded as an approximation, considerable refinement and improvement being urgently needed. A detailed review and full bibliography is provided in another paper recently published (Fairbridge, 1961).

The evidence is found in three distinctive structural provinces:

1. More or less stable coastlines of ancient continents and long-established islands. Evidence of events prior to the 6,000 year B. P. is limited to data gathered from the continental shelf (where old beach-lines, reefs, etc., are often still uncovered because of slow sedimentation or strong bottom currents), or from borings in estuarine deposits (which have filled in rapidly with the rising sea level). The first type of record is highly discontinuous and, owing to submarine exploration difficulties, is still exceptionally sparse. The recent development of the sub-bottom depth recorder that reflects the nature of the Sub-Holocene unconformity is the most promising development in this field (Beckmann *et al.*, 1959). The second type of evidence is much more commonly

available, and with the development of palynology and C-14 dating, gives considerable promise. Many engineering and water bores near harbour mouths contain a record of alternating marine clays (transgressive stages), intertidal and fresh-water peats, and fluvial sands (regressive stages). A careful and world-wide analysis of this data would solve many of the eustatic climatic problems of the period 20,000-6,000 years B.P.

2. Subsiding delta and active geosynclinal areas of nonglaciated latitudes. The best known of such areas is the Mississippi delta, where an exceptionally large number of bores for oil (and water) have given an approximate picture of the confusing stratigraphy. Radio-carbon dating has gone a long way towards the development of a time scale. However, a simple plot of depths and dates, without proper allowance for subsidence, compaction, biofacies, etc., produces a curve that is crudely generalized and systematically lower than it should be (see for example, models offered by Shepard and Suess, 1956; Jelgersma and Pannekoek, 1960). There is a complex interplay in such regions of eustatic oscillations, differential tectonic subsidence, and local factors, which make the problem fraught with difficulties. Borings in other delta regions, the Rhine, the Rhone, the Po, the Danube, the Nile, are bringing more light to the questions, but suffer from similar complicating factors.
3. Isostatically active areas, that were formerly glaciated began to rise ("rebound") as soon as the ice load began to lighten. At the same time peripheral areas began to subside, owing to the collapse of the "marginal bulge" (of Daly) and further downwarping tendencies. As the locus of the ice front retreated inland, so the "zero isobase" (the fulcrum between uplift and subsidence) would migrate inland. At the same time the ice melting would produce a rising sea level, superficially modified by brief negative eustatic oscillations that reflected short-term cold phases. On such coasts the time of the maximum and secondary transgression phases depends on the relative rate of uplift to eustatic rise; since this varies both in time and geographically, the complexity of the picture is quite challenging (see, for example, Bloom, 1960).

In my preparation of a "standard" eustatic curve (Fairbridge, 1961) I could not rely entirely upon stable coast data, but was aided by certain indications from both the delta type and glacial isostatic rebound coasts; deductions drawn from the stratigraphic data were most helpful.

For example, in a slowly subsiding delta, there is a negative secular tectonic trend that never suffers short-term, positive reversals. When superimposed by eustatic oscillations, a characteristic sequence of facies develops. When eustatic rise is fast, there is a marine transgression, marine clays on river sands or coastal peats. When there is a eustatic reversal, the fluvial and continental deposits march out over the marine; this is the stratigraphic principle of "on-lap" and "off-lap".

On the glacial rebound coasts, there are numerous traces of transgressive but emerged marine deposits in patches, here and there. But if the eustatic trend is briefly reversed, a strand line will be left to mark precisely that moment in history. In favoured areas the continued uplift will carry that "raised beach" above the limit of the next transgressive wave, so that it is preserved subaerially for a considerable time. In Scandinavia the dating of such beaches has not yet received adequate attention by radio-carbon chronology, but the sequence and distribution are well established and the varve chronology is generally reliable (de Geer, 1940). It has been found that radio-carbon dating of eustatic events in relatively stable regions, such as Australia and the Pacific islands, finds a close correlation with the varve-dated raised beaches of Scandinavia.

THE HOLOCENE BOUNDARY

There is evidence that in the late Wisconsin (Würm) sea level dropped to at least —100 metres, and that a progressive but oscillatory ice retreat extended from about 16,000 to 6,000 years B.P. (the "Flandrian Transgression"). Somewhat beyond the half-way mark on this curve (11,000-10,000 B.P.) there was an exceptionally large oscillation = the warm Alleröd (Two Creeks) stage about 11,000 B.P., when sea level reached —30 metres, and the following cold, readvance stage of the Salpausselkä (Valders), when the sea level dropped again to about —40 metres.

The beginning of the next great warming phase and associated transgression (on a world-wide basis) was between 10,000 and 10,500 B.P. It is suggested that this should be regarded as the beginning of the Holocene. About this time there was a notable change in all deep-sea "Globigerina Ooze" sediments (Broecker *et al.*, 1960; Ericson *et al.*, 1961) and in Scandinavia it was the beginning of the Finiglacial retreat (Danish Pollen Zone IV).

Accepted procedures of stratigraphy require that geological stages be erected on the basis of identifiable type sections, and these can be recognized excellently both in the deep-sea core material, and in the isostatically emerged "raised beach" sections.

The related climatological data are more confusing. On the basis of large numbers of paleobotanical observations a fairly accurate curve of mean annual temperatures has been worked out for temperate latitudes over the last 20,000 years. This curve crosses the present mean about 10,000 to 9,000 years B.P. It reached the "Climatic Optimum" about 7,000 to 6,000 years B.P. Thus the Holocene can be defined climatologically as that period that has elapsed since the mean temperatures reached or passed the present level after the Würm (Wisconsin) glacial stage.

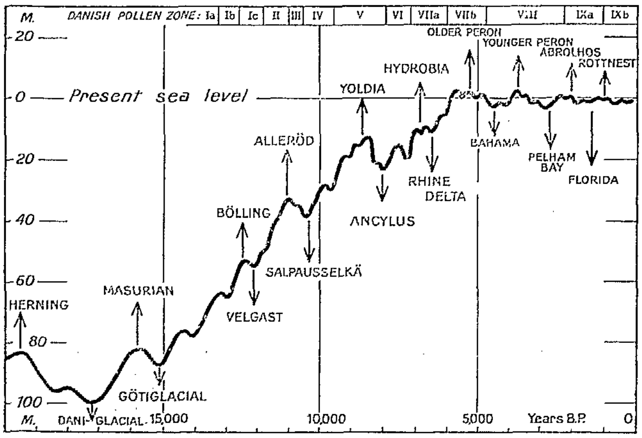

FIG. 5. "Standard" eustatic curve for the last 20,000 years (Fairbridge, 1960), derived by synthesis from depths of terraces on stable continental shelves, facies changes in estuarine formations, periodicity of raised strandlines on isostatically uplifted coasts; all dated wherever possible by C-14, varve chronology and various methods of stratigraphic and geomorphological correlation. (This must only be regarded as a working model because C-14 dates may be up to 500 years in error toward the left of the diagram and facies also require interpretation with errors of ± 2 metres.)

If we consider the Milankovitch calculations of solar radiation it is apparent that the last minimum was about 25,000 years B.P. and that the latest maximum was at 10,000 years B.P. Many critics have argued that the timing of the "Climatic Optimum" is wrong, if it is to be explained in the terms of Milankovitch. However, this is not really true; the period during the Holocene when temperatures were consistently well above the present ran from about 9,500 to 4,500 years B.P. One would not expect the middle latitude temperatures to follow the solar radiation with exact symmetry. We saw that the eustatic level did not reach the present until 4,000 years after the mean temperatures. The latter in turn did not reach the present until 6,000 years after the radiation.

There is thus an approximately 10,000-year eustatic retardation delay behind solar radiation, assuming the Milankovitch timing to be approximately correct. Independent consideration of the delays to be expected owing to the latent heat principle, the area/volume ratio glaciers, the effects of isostatic rebound, and so on, just about require a delay of this magnitude. In this writer's opinion, therefore, the timing of the retardation offers strong independent support for the Milankovitch calculations.

ASTRONOMIC CYCLES

The well-known series of astronomic variables that were used by Milankovitch fell into an integration of 21,000/40,000/92,000 years. We do not find that this cyclicity is out of harmony with the record of Quaternary climatic events. But we do find that correlations, either to make the "Long Pleistocene" (of Soergel) or the "Short Pleistocene" (of Emiliani), are entirely hypothetical, and to this day do not contain any really convincing landmarks.

A sequence of smaller cycles in celestial mechanics have long been known, thanks to the work of Pettersson (1914), and more recently Karlstrom (1961).

A period of 567 years is a cycle when the orbits of the earth, moon, and sun vary from being most nearly in one plane to their maximum departures. Pettersson argued that maximum perigee tidal ranges would mark these culminations. Climatic events at such times should reflect the particular characteristics of insolation produced by the attitude of earth and sun. The last such year was A. D. 1433, when historical records from western Europe and radio-carbon data from elsewhere suggest that m.s.l. was at least 1-2 metres below the present ("Paria Emergence") and climatic records suggest one of the coldest centuries in the last 2,000 years.

This might be just a coincidence but a recurrent oscillation of the order of 550 years over the last 10,000 years has been noted by many observers in Europe and North America (Pearson, 1901; Gillette, 1938; Bennema, 1954; Bakker, 1958). Some researchers have worked out a series of harmonics (1,133 years, 1,668 years, approx. 3,400 years), all converging on a "zero check year" at A. D. 1433 according to Clyde Stacey (personal communication).

It seems hardly a coincidence that the 567-year period is a 1/12 harmonic of the 20,400-year precession cycle and a 1/6 harmonic of Karlstrom's 3,400-year "substage" cycle. While any discussion of geological cycles is fraught with difficulties owing to imprecision in our dating methods, there is no doubt that there is room for much intriguing investigation in this area.

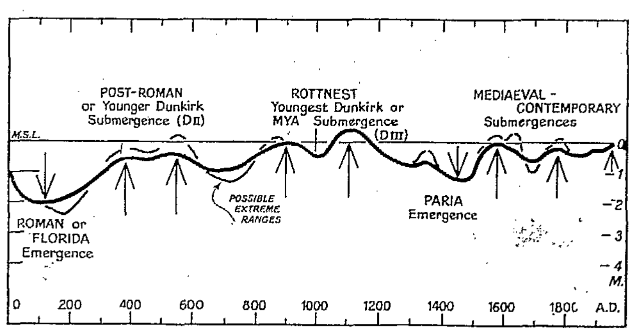

FIG. 6. Eustatic curve for the last 2,000 years, derived by synthesis from historical data, climatic records, C-14 dated stratigraphy, etc. (Owing to imperfect records, this curve is only a working model, subject to correction of numerous small errors.)

A SUMMARY OF THE SOLAR-EUSTATIC DATA

We believe we have established certain fundamental relationships that have some bearing on ice-age theory. These are:

1. Short-term changes of solar activity, as indicated by sun-spots in 11-22 year and longer cycles, are reflected by changes in the atmospheric circulation patterns that result in climatic variations of a systematic nature.
2. Glaciers represent temporary storage reservoirs in the world hydrologic cycle. Glacier régimes depend more upon mean temperatures than upon precipitation (as shown by Ahlmann, Faegri and others); therefore, abnormal temperatures in critical glacial areas control advance and retreat of the ice, and thus the net withdrawal and return to the world oceans.
3. Glacier régimes are sensitive to climatic change in inverse proportion to their dimensions and proximity of the poles. The Greenland and Antarctic ice caps play a minor role in present-day oscillations. Indeed, for several thousand years there must have been a general stability of the major ice sheets, since there has been no sea-level change in the last 6,000 years that exceeded ± 3 metres above or below the present m.s.l. (Fairbridge, 1958).
4. About 95 per cent (by area) of the world's mountain glaciers lie in middle latitudes of the Northern Hemisphere. Therefore, the world hydrologic balance is governed by climatic events in the "sensitive" northern mid-latitudes.
5. Therefore the location of mountainous topographic "accidents" in the mid-latitudes is essential for short-term eustatic control. While some of these glaciers advance as others retreat, it is only the net effect that has world-wide significance.
6. Major peaks of sun-spots correlate with glacial melting and retreat in the majority of areas. Lack of sun-spots generally matches cooling in mid- and high-latitudes. Such effects, however, may augment or reverse certain long-range and regional trends, Various factors (volume/surface area, etc.) control the reaction rate in glaciers; varying degrees of retardation are observed.
7. Annual mean sea level records of nearly 300 years reflect the predicted changes in the world hydrologic balance. Local factors, such as Postglacial isostatic uplift, geosynclinal downwarp, and irregular tectonic perturbations can be removed from the curves on the basis of the local evidence. During the last 70 years world m.s.l. has shown a mean rise of about 1.2 mm. annually, that is a secular excess of melting over withdrawal; this is a relatively short-term trend, however, and may be soon reversed if we are now entering a new 80-year cycle of lower sun-spot activity. There is no evidence to suggest that the recent upward swing is not merely a normal but a short-period climatic fluctuation; it has been claimed that it is uniquely caused by industrial CO_2 in the atmosphere absorbing infra-red radiation by the "greenhouse" effect (Plass, 1956, 1959). However, the role of CO_2 has still not been precisely determined owing to doubts about the rate of interchange with sea water and equilibrium re-establishment (Revelle and Fairbridge, 1957; Revelle and Suess, 1957).
8. The lowest point of sea level in the last three centuries occurred about 1820, coinciding with the lowest point of the sun-spot means; this low solar peak occurred in an 80-year oscillation. Another long period of low sun-spots is reflected by a sea-level low in 1660-1715. Such extended sun-spot lows occurred in 160-year or longer oscillations over two millennia. The longer and deeper the sun-spot low, the lower the sea level; historical records over the last two millennia indicate one of the longest sun-spot lows in Roman times, when sea level seems to have dropped to about 2 metres below the present level.
9. Earlier sea-level oscillations are not instrumentally recorded, but are identified by C-14 and stratigraphic dating of beach shells or peats used as intertidal markers (Fairbridge, 1958, 1961). The maximum sea-level oscillation during the last 6,000 years, of about ± 3 metres above or below present m.s.l. appears to reflect mean annual temperature departures in mid-latitudes of approximately 1°-1.5°C. of many centuries duration.
10. Confirmation is added thus to the Faegri Law that the longer the period of a climatic cycle, the more complete is the reaction of all indicators.

ACKNOWLEDGEMENTS

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RÉSUMÉ

Le niveau moyen des mers et le rayonnement solaire au cours des 20 000 dernières années (R. W. Fairbridge)

Le réchauffement du climat qui s'est produit pendant la première moitié de notre siècle a été suivi d'une élévation frappante du niveau moyen des mers, qui s'est poursuivie jusque vers 1950, et qui a confirmé l'exactitude des travaux de Thorarinsson (1940) et de Gutenberg (1941). Le volume d'eau qui s'est ainsi ajouté aux océans a été, en moyenne, de 400×10^9 m^3 années^{-1}. Ce chiffre est compatible avec celui que l'on a obtenu après avoir mesuré le taux de recul des glaciers sous les latitudes de moyennes « sensibles à la température » ; aucune tendance séculaire générale n'est signalée en ce qui concerne l'Antarctique ou le Groenland. C'est la première preuve géophysique qui soit ainsi apportée, à l'aide de données instrumentales récentes, à l'appui de la théorie géologique de l'eustatisme.

Une équation de caractère général est proposée, en ce qui concerne les variations, sous les latitudes moyennes, de la température moyenne annuelle de l'air : 1 °C année^{-1} = 1 mm (de variation eustatique). Les données historiques confirment qu'une variation d'environ 1 °C, échelonnée sur 100 ans, se traduit par une variation du niveau de la mer d'environ 10 cm et les données géologiques montrent qu'une variation de 10 °C en 10 000 années produit une variation eustatique d'environ 100 m. Cependant, étant donné qu'il y a des limites au volume de la glace qui peut fondre et à la formation de glaciers continentaux en direction de l'équateur, la courbe complète du niveau moyen des mers (élévation eustatique) en fonction de la température et du temps est sinusoïdale.

Les variations du niveau moyen des mers qui se produisent pendant des périodes moyennes (1 à 10 ans) sont, dans plus de 90 % des cas, d'origine spatiale ou atmosphérique, tandis que les variations astronomiques régulières qui surviennent au cours d'une année ou d'une période plus courte disparaissent sous l'effet du nivellement. Seuls, les relevés portant sur une longue période permettent de discerner les tendances climatiques séculaires, mais il est sans doute possible de déterminer l'« oscillation méridionale » — échelonnée sur 2 ou 3 ans — de la pression atmosphérique, les oscillations de 11 à 22 ans dues aux taches solaires et les cycles géomagnétiques.

Jusqu'en 1682, il n'existait pas de données instrumentales relatives au niveau moyen des mers ; mais les données que fournissent l'histoire, l'archéologie et la géologie, jointes aux données de la courbe des variations des taches solaires pendant 2 000 ans (courbe de Schove), semblent indiquer qu'il existe, à long terme, une relation entre le niveau de la mer et le rayonnement solaire. La datation, à l'aide de carbone-14, de coquillages de CO^3Ca provenant d'anciennes plages et de tourbe provenant de marais côtiers permet d'obtenir des données eustatiques qui remontent à plus de 20 000 ans. Au cours de cette période, le niveau moyen des mers s'est élevé, par oscillations, de plus de 100 m et il a atteint sa cote actuelle il y a environ 6 000 ans. Le milieu de cette courbe, qui se situe aux environs de l'année 10500 av. J.-C. et qui est le point où la courbe présente sa plus forte pente, correspond à une période de changements prononcés dans le dépôt des sédiments marins, de transgression très étendue et de discordances géologiques ; il est donc logique de situer en ce point la démarcation entre le pléistocène et l'holocène.

Une comparaison avec les données paléobotaniques et la formation des carbonates marins indique que l'augmentation de la température de l'air et de l'eau des mers s'est produite bien avant l'élévation du niveau de la mer. En outre, la courbe astronomique de l'insolation (courbe de Milankovitch) était en avance sur celle de l'augmentation de la température. Il semble qu'il y ait eu un retard eustatique global de 10 000 ans.

A la courbe eustatoclimatique générale des 20 000 dernières années viennent se superposer d'importantes oscillations secondaires dont la plus marquée, qui semble avoir une période d'environ 550 ans, s'accompagne, sous les latitudes moyennes, de variations à long terme de la température moyenne annuelle de l'ordre de 2 à 3 °C et se manifeste dans les oscillations eustatiques (3 à 4 mm), dans les transgressions marines et la submersion des côtes (notamment aux Pays-Bas), dans les horizons intermédiaires des tourbières (Grandlund), dans les dépôts stratifiés des lacs glaciaires (de Geer), etc.

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DE L'APPLICATION DE TECHNIQUES PALYNOLOGIQUES A UN TERRITOIRE DÉSERTIQUE. PALÉOCLIMATOLOGIE DU QUATERNAIRE RÉCENT AU SAHARA

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Si la découverte des premiers grains de pollens fossiles dans des sédiments géologiques remonte à peine à l'orée du XX[e] siècle (Fruh, 1885; Weber, 1896), c'est à von Post (1897) que revient le mérite d'avoir établi le premier des diagrammes polliniques, et d'avoir tiré de ces constatations les premiers enseignements paléontologiques et stratigraphiques relatifs au quaternaire. C'est, par la suite, la gloire de l'école scandinave d'avoir montré la richesse et la fidélité des renseignements susceptibles d'être livrés par cette méthode, notamment dans l'étude du pléistocène.

Mais le champ des investigations s'est rapidement étendu, à toute l'Europe continentale et à l'Amérique du Nord en particulier. Toutefois, jusqu'à une date très récente, le choix du matériel étudié était resté pratiquement limité aux tourbes. Dès 1936 cependant, Firbas et Braihan publiaient des résultats obtenus dans les couches humifères d'horizons podzoliques, ensuite Erdtman (1943) et Sittler (1955) dans des passées sableuses; enfin, divers horizons pédologiques, humus alpin en particulier, s'avéraient également fertiles.

L'utilisation de la méthode paraissait donc être bien plus large qu'on ne le soupçonnait au début. Toutefois, l'opinion prévalait que le matériel sporopollinique pouvait seulement se fossiliser et subsister en milieu pauvre en oxygène et fortement réducteur. C'est ainsi qu'à notre connaissance, aucun résultat relatif aux zones arides et à plus forte raison désertiques n'avait été publié avant 1950.

Aussi bien, les recherches que nous avons entreprises avec A. Pons à partir de 1954 (Pons et Quézel, 1954) et C. Martinez à partir de 1956 (Quézel et Martinez, 1961), l'ont-elles été sans grand espoir. Notre but était essentiellement de chercher à vérifier grâce à des techniques dûment établies les conclusions biogéographiques et paléoclimatologiques auxquelles nous amenaient inévitablement les études botaniques poursuivies par nous au Sahara depuis une dizaine d'années.

RÉSULTATS OBTENUS PAR LES ÉTUDES PALYNOLOGIQUES EN PALÉOCLIMATOLOGIE ET EN PALÉOBIOGÉOGRAPHIE SAHARIENNES

L'exploration préhistorique botanique, zoologique et géomorphologique du Sahara a en effet accumulé toute une série d'arguments tendant à prouver le dessèchement très récent de tout le Sahara. L'épanouissement des industries humaines dans les zones hyper-arides est impensable sous le climat actuel; or la multiplicité des gisements atériens et surtout néolithiques stigmatisés par de très nombreux vestiges d'industrie et par des gravures ou des peintures rupestres présentes presque partout, mais plus spécialement en bordure des massifs montagneux (Tefedest, Hoggar, Tassili, Tibesti), confirme l'abondance du peuplement humain de toute cette région quelques millénaires seulement avant l'ère chrétienne. De même, la presque totalité des animaux représentés (éléphants, chevaux, girafes, lions, en particulier), malgré les réserves émises par quelques préhistoriens qui ne verraient là que des souvenirs de voyage ou de chasses lointaines, ne sauraient exister au Sahara dans la phase d'aridité actuelle. Les géomorphologistes enfin, depuis quelques années, ont mis en évidence au Sahara des phases d'érosion fluviatile importantes, deux, semble-t-il, en particulier au Sahara central, dont la plus récente doit se situer tout près de nous. Une mise au point de P. Dutil (1959) ainsi que les travaux poursuivis au Hoggar actuellement par P. Rognon concourent tous à affirmer l'existence de deux seules phases d'accumulation fluviatile dans le Sahara central. Cette constatation ne manque pas d'intérêt car les choses sont loin d'être aussi nettes dans les vallées sahariennes alimentées par de grands fleuves trouvant leur origine en dehors des zones désertiques: Saoura (Alimen, 1955) et Nil en particulier (Butzer, 1959), mais il s'agit là évidemment de cas très particuliers qui ne sauraient fournir de lois générales sur la paléoclimatologie du Sahara proprement dit.

Toutes ces considérations nous ont amené à rechercher, dans des techniques nouvelles, une confirmation absolue de tout ce faisceau d'arguments, confirmation qui permettrait, en particulier par la reconstitution de la flore du quaternaire récent saharien, de préciser les conditions bioclimatiques du Sahara néolithique en particulier.

Dès 1954, avec notre collègue Pons, nous entreprîmes les premiers essais; ils furent tentés sur des paléosols noirâtres relativement riches en matériel organique, paléosols déjà signalés par Bordet au Sahara central, et qui semblent en général correspondre à des bas-fonds marécageux édifiés pendant la dernière phase pluviale saharienne. Après de laborieux essais de mise au point des techniques, les premiers résultats positifs furent obtenus. Depuis cette date les investigations se sont poursuivies et, à l'heure actuelle, plus de cent échantillons ont été étudiés. Il s'agit d'ailleurs non seulement de paléosols, mais de sédiments de remplissage d'abris sous roche, de guano, de diatomites, de tufs et même de sédiments éoliens. Dans plus de la moitié des cas, des pollens ont été rencontrés.

Bien qu'encore très fragmentaires pour l'ensemble du pléistocène, les résultats obtenus permettent toutefois de se faire déjà une idée des modifications floristiques et des vicissitudes climatiques qui ont intéressé le Sahara durant toute cette période.

Pour ce qui est du premier pluvial l'étude de rares sédiments fertiles et indiscutablement datés, soit par des industries humaines en place (*Pebble-culture* et acheuléen), soit par des critères géomorphologiques précis, montre indiscutablement l'extension, sur tout le Sahara central, d'une flore typiquement méditerranéenne à base, en montagne, de conifères (pins, cèdres) et de cupulifères (chênes). Malheureusement il est encore trop tôt pour serrer de plus près le problème; la seule certitude est actuellement la présence d'une flore méditerranéenne dans les terrasses alluviales correspondant à ce pluvial. L'âge de ce pluvial ne peut être pour l'instant précisé, si ce n'est par l'existence à son niveau d'un paléolithique inférieur indiscutable.

Un très important hiatus de sédimentation sépare le pluvial ancien, qui a accumulé des terrasses de 20 à 30 mètres d'épaisseur dans de nombreux points, du pluvial récent, dont les terrasses n'excèdent que rarement 4 à 5 mètres. Ce n'est qu'en de rares localités (bassins importants de sédimentation) qu'apparaissent des horizons sablonneux de quelque importance, toujours dépourvus, semble-t-il, de croûtes ferrugineuses.

Tout laisse donc supposer qu'une longue phase aride très accusée s'est étendue au Sahara pendant cet interpluvial. C'est d'ailleurs ce que semble confirmer l'absence presque totale dans ces régions des industries humaines du paléolithique supérieur.

Les sédiments appartenant à la terrasse récente sont très homogènes et ne présentent quelque variété que dans les bassins lacustres d'ailleurs assez fréquents au Sahara central et méridional. Les études polliniques stratigraphiques poursuivies dans plusieurs localités offrent des résultats très homogènes.

A la base, uniquement des pollens de salsolacées, de composées (armoises) et de graminées traduisant indiscutablement l'existence d'une végétation steppique sèche ou très sèche.

Ensuite apparaissent diverses essences méditerranéennes sylvatiques: cèdres, chênes divers. Peu à peu, cette flore s'enrichit et bientôt apparaissent les chênes caducifoliés nord-africains, les érables, les pistachiers (*Pistacia lentiscus*), la bruyère en arbre, le frêne dimorphe, et même le noyer, le tilleul et l'aulne. Le maximum d'extension de cette flore de chênaie caducifoliée correspond à l'épanouissement des industries atériennes dans tout le Sahara.

Avec l'apparition du néolithique, la flore reste toujours méditerranéenne, mais de tendance nettement plus xérophile avec, surtout, le pin d'Alep, les genévriers, le cyprès de Duprez, le micocoulier et l'olivier de Laperrine.

Ensuite, avec les industries rupestres du Hoggar et du Tassili des Ajjer, la dégradation de la flore et du climat s'accuse. Seuls persistent les éléments les plus xérophiles: cyprès, genévriers, oliviers. Le pin d'Alep a pratiquement disparu.

On assiste, par la suite, à une invasion brutale de tout le Sahara par les éléments saheliens (*Acacia*, *Salvadora*, *Balanites*) qui semblent bien coloniser la totalité des zones de basse altitude et s'étendre pratiquement jusqu'à l'Atlas saharien; seuls quelques vestiges méditerranéens arrivent à subsister sur les sommets montagneux.

La désertification fait peu à peu son œuvre, et c'est par l'appauvrissement de la végétation précédente que se mettent en place les paysages végétaux actuels de tout le Sahara.

Tels sont les faits que nous livre la palynologie saharienne. Quelques problèmes restent évidemment à discuter. Ce sont: les limites de l'extension méditerranéenne durant le dernier pluvial; l'âge au moins relatif de ces phénomènes; les modifications climatiques qu'ils stigmatisent; les rapports des phases pluviales sahariennes avec les glaciations européennes et africaines.

LIMITES DE L'EXTENSION DES FLORES MÉDITERRANÉENNES DURANT LE DERNIER PLUVIAL SAHARIEN

Elles peuvent dès à présent être précisées avec certitude au moins dans certaines régions (fig. 1). C'est ainsi que, vers le sud, l'Aïr, le Tibesti et le Borkou ont été atteints par la végétation méditerranéenne. L'Ennedi paraît être par contre resté à la limite de ces influences. Tous les massifs montagneux du Sahara central ont été recouverts par la forêt. Au Sahara septentrional, il en a été de même pour tout ce qui n'était pas ennoyé par les sables. Nous ne savons rien de la végétation des ergs, mais leur base, à peu près partout, a baigné dans

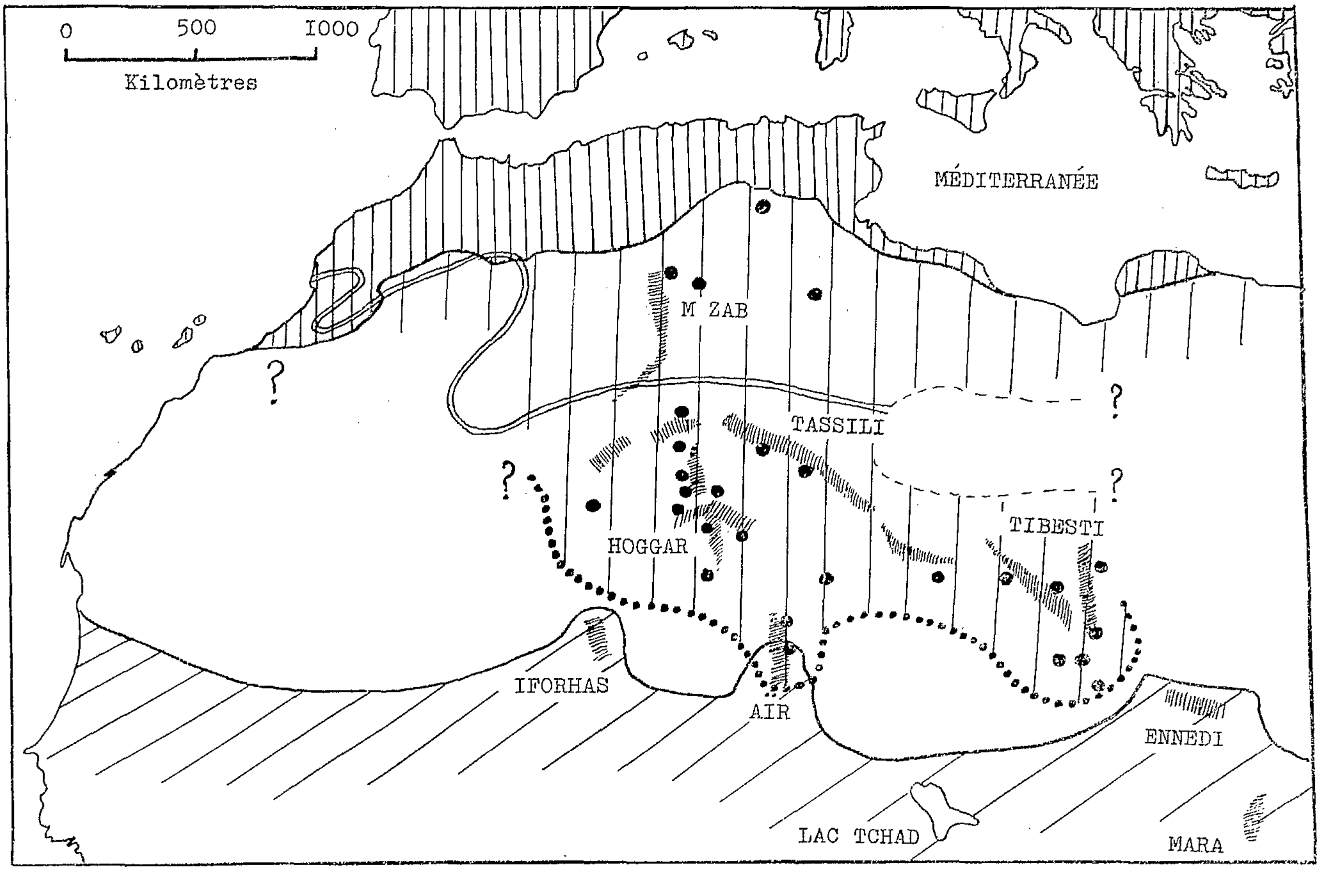

FIG. 1. Limites de l'extension des flores méditerranéennes durant le dernier pluvial saharien.
En traits verticaux denses: extension actuelle de la région méditerranéenne en Afrique du Nord.
En traits verticaux lâches, et limités vers le sud par une ligne de pointillés : extension des flores méditerranéennes pendant le pluvial récent saharien.
En traits obliques: limite nord de la région afro-tropicale.
En traits doublés: limite septentrionale actuelle des influences tropicales au Sahara (peuplement d'*Acacia*).
Les grisés indiquent les principaux massifs montagneux. Les points noirs indiquent les principaux points où des pollens méditerranéens ont été mis en évidence dans des sédiments atériens ou néolithiques.

des lacs ou des sebkhas au moins temporairement inondées. Au Sahara occidental, nos résultats sont encore trop fragmentaires pour entraîner une certitude.

AGE DE CES PHÉNOMÈNES

Les données à invoquer sont de deux ordres : *a*) une chronologie relative fournie par les vestiges *in situ* des industries humaines, et les données géomorphologiques ; *b*) une chronologie absolue fournie par les datations au carbone-14.

Le pluvial ancien est, nous l'avons vu, contemporain, au moins en partie, des toutes premières industries humaines : *Pebble-culture* et acheuléen. C'est donc très loin de nous, dans la première partie du quaternaire, qu'il doit être placé.

Le pluvial récent, au contraire, peut être daté avec beaucoup plus de précisions. Il est contemporain au Sahara des industries atériennes et néolithiques, et son début ne doit guère dépasser (période steppique) une vingtaine de millénaires avant l'ère chrétienne. L'extension maximum des influences méditerranéennes correspond aux industries atériennes, que les préhistoriens sont unanimes pour situer au Sahara, au plus tôt vers le 12^{e} millénaire avant le Christ, et probablement nettement après. Pour le néolithique, des dates peuvent être avancées avec certitude. Quatre datations sont ici à notre disposition. Son maximum de développement ne dépasse pas le 4^{e} millénaire, et sa terminaison se situe aux environs de la fin du troisième. Les industries rupestres lui ont immédiatement succédé (3000 av. J.-C.). Nous avons même montré que c'est aux environs de 2700 av. J.-C. que peut se situer la fin de la phase typiquement méditerranéenne au Hoggar. La phase sahélienne enfin, actuellement à l'étude, s'est certainement étendue jusqu'à l'orée de l'ère chrétienne.

MODIFICATIONS CLIMATIQUES CORRÉLATIVES A CES DONNÉES FLORISTIQUES

Il est encore trop tôt pour parler ici du premier pluvial, mais les quelques données que nous possédons semblent montrer que le schéma retenu pour le pluvial récent peut sans doute lui être appliqué. L'importance bien plus grande des phénomènes géomorphologiques qui l'accompagnent permet toutefois de penser que les modifications climatiques y ont revêtu une plus grande acuité.

Pour le dernier pluvial, tout paraît débuter par une période à climat contrasté et sec correspondant à la phase de végétation steppique signalée plus haut. Ensuite, sans doute à partir du 15e millénaire, se développe un climat tempéré et humide, assurément de type méditerranéen humide ou subhumide, qui voit l'invasion de tout le Sahara central par les espèces forestières méditerranéennes (cèdre, pin d'Alep, chêne vert) et même par des éléments de la chênaie caducifoliée (tilleul, érable, aulne, etc.).

La partie moyenne de ce même interpluvial, et ce jusqu'à la fin de l'optimum climatique, assiste à une dégradation progressive du climat qui se réchauffe et s'assèche en restant toutefois de type méditerranéen, comme le prouve la flore correspondant au néolithique saharien où se rencontrent encore le pin d'Alep et le chêne vert, mais à côté d'éléments nettement plus xérophiles (olivier, cyprès, genévriers, etc.).

Ensuite, le réchauffement se poursuit ainsi que l'aridification du climat ; après une période où les peuplements d'*Acacia* de type sahélien sec ont envahi la quasi-totalité du Sahara, s'installe la flore désertique actuelle.

Ainsi donc en quelques millénaires, depuis le début de l'ère historique, les modifications de la végétation au Sahara ont accusé une importance jusqu'à ce jour insoupçonnée. La forêt ou la garrigue méditerranéenne ont cédé la place au désert. Depuis 4 000 ans, la région méditerranéenne, dans les zones montagneuses du Sahara tout au moins, a reculé de plus de 1 500 km.

RAPPORTS DES PHASES PLUVIALES SAHARIENNES AVEC LES GLACIATIONS EUROPÉENNES ET AFRICAINES

C'est ici l'un des points les plus délicats à établir. Si nous envisageons tout d'abord le dernier pluvial saharien, pour lequel nous possédons de nombreuses données, il est indiscutable qu'il peut se superposer au moins en partie au würmien. Mais si l'on cherche à serrer de plus près le problème, on est amené avec Trevisan (1950) et Chiarugi (1950) à distinguer dans chaque glaciation une période anaglaciaire à climat peu contrasté avec pluies abondantes de type, semble-t-il, océanique et une phase cataglaciaire de type continental accusé assistant progressivement à la diminution des précipitations et à l'élévation des températures. Au Sahara on assiste à un décalage très net dans le temps de ces phénomènes. La phase anaglaciaire européenne du würmien ne semble pas se stigmatiser par des phénomènes géomorphologiques et botaniques importants. Les sédiments fins qui s'y rapportent sont rares et ne contiennent qu'une flore de type steppique. Elle a donc dû correspondre à une simple augmentation des précipitations, augmentation progressive qui a d'ailleurs permis vers le 15e millénaire av. J.-C., c'est-à-dire précisément vers sa période terminale en Europe, la migration vers le sud de la flore méditerranéenne. La période cataglaciaire européenne correspond, au contraire, au maximum d'extension de cette flore concomitante à l'installation au Sahara d'un climat méditerranéen humide ou subhumide qui se dégrade progressivement jusqu'à l'épisode épiglaciaire, l'extension sahélienne vers le nord lui faisant immédiatement suite et correspondant peut-être à l'oscillation de Buhl.

Tels sont les faits. Ils stigmatisent donc un décalage très net dans le temps des phénomènes pluviatiles au fur et à mesure que l'on descend vers le sud. Notons au passage que les préhistoriens arrivent à des conclusions analogues en étudiant en Afrique du Nord et au Sahara le développement de la plupart des industries humaines.

Un autre point paraît actuellement acquis : c'est l'augmentation simultanée sur les marges nord et sud du Sahara des précipitations. Des critères floristiques et palynologiques permettent en effet d'affirmer que le dernier pluvial saharien a entraîné un effacement généralisé de la zone désertique, la végétation méditerranéenne entrant en contact sur sa frange méridionale avec la végétation sahélienne. Il semble donc bien qu'en Afrique tropicale les choses se soient passées sensiblement de même façon qu'en Afrique méditerranéenne, le cataglaciaire assistant à un reflux vers le nord des zones influencées par les précipitations tropicales. Si les rapports chronologiques existant entre la glaciation würmienne et la glaciation makalienne sont encore discutés, leurs conséquences dans la région qui nous intéresse paraissent bien être synchrones ou presque synchrones.

Un problème irritant est l'existence au Sahara, non influencé par le climat de ses marges, de deux phases pluviales alors que le nombre des glaciations européennes et africaines est bien supérieur. S'il est encore trop tôt pour chercher à résoudre cette question, il semble toutefois peu probable que les pluviaux sahariens et singulièrement centro-sahariens puissent être augmentés, ou alors leur importance a dû être pratiquement négligeable.

Nous nous garderons d'aborder ici en détail le problème du pluvial ancien saharien. Si tout laisse penser que les choses se sont passées de la même façon que pour le pluvial récent, il est impossible pour le moment de le rattacher avec certitude à une phase glaciaire européenne connue. Est-il contemporain de Guntz ou de Mindel, ou des deux à la fois, rien ne permet de l'affirmer, pas plus d'ailleurs que ses rapports avec les glaciations kiesegienne et kamasienne.

Chronologie	Phases postglacières en Europe	Europe septentrionale — Végétation	Europe septentrionale — Climat	Sahara central — Industries préhistoriques et datations au C-14	Sahara central — Végétation	Sahara central — Paléosols	Sahara central — Climats
—10000	Würm supérieur	Glaciers	Glacial	?	Steppes. Végétation méditerranéenne très fragmentaire possible	Alluvions	Climat aride de type steppique
— 8000	Période subarctique Oscillation d'Allered	Dryas, bouleau nain, saules polaires	De toundra	Industries Moustère atériennes (au Sahara)	Forêt mixte de cèdres et de chênes divers, aulne-tilleul, érable en montagne, pin d'Alep à basse altitude	Diatomites, paléosols de type forestier + sols de marais	Climat tempéré et humide avec sécheresse estivale déjà marquée, surtout à basse altitude (méditerranéen subhumide-humide)
— 6000	Période préboréale	Bouleau, tremble, apparition du pin sylvestre et du noisetier	Froid et humide				
— 5000	Période boréale	Pin sylvestre, noisetier, apparition de l'ormeau du tilleul et du chêne pédoncule	Réchauffement progressif. Climat encore continental	Néolithique saharien —5000	Pin d'Alep, olivier, genévrier, cyprès, micocoulier ; avec, en montagne, cèdre, chênes divers, noyers, lentisques, bruyères	Diatomites	Climat chaud et sec (méditerranéen semi-aride)
— 2800	Période atlantique (optimum climatique)		Réchauffement marqué. Climat doux et humide de type atlantique	Rupestres bovidiens —3500		Sols de marais	Encore assez arrosé en montagne
— 500	Période subboréale	Chêne sessiliflore, hêtre, charme, pin sylvestre	Nouveau refroidissement. Climat plus froid et contrasté	—2700 Rupestres lybico-berbères	Disparition presque totale de la flore méditerranéenne, invasion de la forêt d'acacia sur tout le Sahara	Pas de paléosol	Remplacement du du climat de type méditerranéen sec par un climat sahélien
	Période subboréale	Disparition progressive du chêne sessiliflore	Climat humide et froid		Désertification progressive et rapide du Sahara	Pas de paléosol	Climat désertique

Ainsi donc, en moins de cinquante ans, la palynologie paraît être devenue une des techniques capitales dans toute recherche paléontologique et paléoclimatique. Ses limitations se sont étendues dans des proportions considérables et, nous venons de le voir, elle est susceptible de fournir dans les zones arides et désertiques des indications qui ne le cèdent en rien en importance à celles qu'on était habitué à lui voir livrer dans les zones boréales, tempérées et, depuis moins longtemps, tropicales.

Certes, sous climat aride ou désertique, le choix des sédiments à étudier reste délicat, mais, dans plus de la moitié des cas, les sédiments lacustres, les croûtes calcaires, les diatomites et les paléosols nous ont fourni des résultats positifs. Un matériel de choix, mais malheureusement rare, est constitué par les guanos et les excréments fossiles d'herbivores. Sauf dans ce dernier cas, le matériel sporo-pollinique mis en évidence est relativement rare, et beaucoup de patience est nécessaire dans l'étude microscopique des échantillons. Toutefois, nous disposons maintenant là d'une méthode de toute première valeur qui ne saurait être négligée en aucun cas.

En effet, de toutes les techniques scientifiques mises depuis peu à la disposition des géographes et des climatologistes : géomorphologie, paléopédologie, paléozoologie, chronodendrologie, paléotempératures, la palynologie reste à notre avis, une des plus significatives. C'est d'ailleurs par une exploration combinée de ces méthodes, et sans doute en zone aride plus que nulle part ailleurs, que des résultats complets et significatifs pourront être obtenus, et nous n'hésitons pas à dire que c'est grâce à des travaux poursuivis en commun avec nos collègues géomorphologistes, pédologistes et préhistoriens, que les résultats analysés plus haut ont été obtenus.

Il n'en reste pas moins que, pour le quaternaire du moins, la reconstitution d'un environnement végétal constitue la façon la plus simple et la plus sûre de représenter les caractères climatiques généraux contemporains de la flore mise en évidence.

Tout est loin d'être dit, un chapitre vient seulement de s'ouvrir mais tout laisse supposer qu'il contribuera largement à étendre nos connaissances sur l'un des problèmes les plus angoissants de l'histoire de la planète, celui de l'extension des zones arides et désertiques depuis le début de l'époque historique.

SUMMARY

Palynology of the Recent Quaternary in the arid and desert zone of northern Africa and its paleoclimatic effects (P. Quézel)

Following the results of botanical and climatological studies on the Recent Quaternary era in Europe and North America, similar research has been carried out over the past five years in North Africa. Findings, confirmed by radio-active carbon dating, indicate that during the last 20,000 years or so a considerable humid current affected the major part of the Sahara and was accompanied by the migration southwards for over 1,250 miles of a mediterranean type of flora, and the almost total disappearance of the desert zone

The maximum precipitation, at the time of the Aterian industries, did not extend beyond 10,000 B.C. It facilitated the extension to Hoggar and Tibesti of oak and cedar forests.

Progressive drying led to the appearance in Neolithic times (5,000 B.C.) first of a xerophilous flora of mediterranean type: Jerusalem pine, juniper, cypress, olive; later of savannah land with acacias; finally only eremophytes remained, except in certain favoured places where a few of the mediterranean relics have been able to subsist until present times.

DISCUSSION

K. W. Butzer. Professor Quezel's contribution underlines how our increasing pollen analytical information for arid zones adds meat to the primitive sketches provided indirectly by geomorphic evidence. To avoid confusion, I must point out that the term "last pluvial" in Professor Quézel's and my own paper is used differently : I have referred it exclusively to the particular conditions associated with the Early Würm in the Mediterranean Basin and Egypt. In the eastern Sahara evidence for a moist Neolithic phase (subpluvial) is present although very much less significant than the last Pleistocene moist phase. This raises an interesting problem as to why the western Sahara should be dominated by a young phase of postglacial date. Of equal interest is the remarkable accentuation of the western and central Saharan highlands as moist, moderately wooded islands of moisture, above the persisting aridity of the plains—there interconnected by water-courses deriving their water from higher altitudes.

P. Quézel. L'extension des analyses polliniques en Égypte et dans tout le Proche-Orient aride et désertique est éminemment souhaitable, et permettra de faire la part exacte de cette phase pluviale (ou subpluviale) dans ces zones.

J. Tixeront. La pluviosité du Sahara à l'époque néolithique a dû s'accompagner d'écoulements d'eau susceptibles de créer de vastes lacs, dans la région des chotts entre le Sahara et l'Atlas algéro-tunisien.

1. Avez-vous étendu vos investigations au Sud algéro-tunisien, et y a-t-on constaté des augmentations de pluviosité du même ordre ?
2. Compte tenu des conditions d'évapotranspiration dans le Sud algéro-tunisien, l'existence d'un lac comparable au lac Tchad, dans la région des chotts supposerait un taux d'écoulement de l'ordre de 40 mm correspondant à une pluviosité de l'ordre de celle déduite de la palynologie. A-t-on fait des constatations à ce sujet dans la région des chotts ?

P. Quézel

1. Des variations du même type, quoique moins spectaculaires, ont été trouvées dans le Sud algéro-tunisien, traduisant dans les zones basses et en dehors des ergs une pluviosité dépassant sans doute 600 mm. Toutefois d'autres analyses restent nécessaires pour saisir clairement leur importance. En particulier, la permanence de zones arides ou subdésertiques est certaine.
2. Aucune étude géomorphologique n'a été faite à ma connaissance dans cette région que je connais très mal. Toutefois, il est nécessaire de se souvenir que le Grand Erg oriental coupait le lit des cours d'eau descendant du Sahara central et il est peu probable que l'Irharhar par exemple ait pu atteindre alors la dépression des chotts.

Mlle E. Léopold. Has the speaker considered the possibility that at least some of the pollen from the Mediterranean forms might be re-worked or redeposited in the Holocene from sediments of older age, say from Late Tertiary deposits ?

P. Quézel. Je n'ai pas fait ici la critique de la méthode, mais tous les pollens mis en évidence ou à peu près tous sont contemporains de la phase pluviale étudiée. La conformation la plus remarquable est fournie par l'étude des excréments d'herbivores toujours très riches en pollen et qui peuvent facilement être datés par le C-14.

M. A. Kassas. Within the Egyptian eastern desert and also the Sudan Red Sea coastal land, the tropical and Mediterranean floral elements are associated together within the mountain ranges. This may mean that these mountains acted as refugial sites for both floral elements within the zonal migration northward (tropical) and southward (Mediterranean). These residual mixtures may be taken as indicative of the zonal migration of the floras in the way Professor Quézel shows.

P. Quézel. Il s'agit là certainement, comme au Tibet ou en Abyssinie, des vestiges de migration végétale conformes à l'opinion du professeur Kassas. Cette flore est actuellement réfugiée sur les montagnes où les conditions climatiques sont plus favorables et les microclimats plus nombreux. Au Sahara central, par exemple, deux séries au moins de migrations, respectivement des flores septentrionale et tropicale, peuvent être discernées en étudiant les endémiques. La flore septentrionale, ne l'oublions pas, a même atteint les hauts sommets de l'Afrique centrale.

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SUMMARY OF PREHISTORIC INVESTIGATIONS IN KURDISTAN IN RELATION TO CLIMATIC CHANGE

by

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Since 1948, a series of prehistoric archaeological investigations have been undertaken along the Kurdish hill flanks of Iraq and Iran. In particular, those investigations undertaken by the Prehistoric Project of the Oriental Institute of the University of Chicago[1] have been concerned with reclamation of evidence as to how an effective level of food production (through the domestication of plants and animals) was achieved, and of what were the cultural consequences of this achievement. In other words, the Prehistoric Project's central focus of problem has been: how did man first arrive at a village-farming community way of life, and what were the socio-cultural characteristics of this new life way?

The proposition is put in the above manner to emphasize that the archaeologist's business and training is primarily with the reclamation and interpretation of the material evidence for the cultural activities of ancient man. Nevertheless, this particular problem focus being what it is, understandings of the cultural-environmental linkage of the pertinent ranges of time and of the geographical region are of course important. Hence, the Prehistoric Project has been fortunate in being able to put a team of natural scientists into the field along with its prehistoric archaeologists (Braidwood, Howe and Reed, 1961). Two other field efforts also call for mention; the Smithsonian Institution-Columbia University expedition under Ralph Solecki (1960) at the Shanidar cave and the Zawi Chemi Shanidar open site in the valley of the Greater Zab river, and the several intensive surveys for ancient sites in alluvial Mesopotamia and Khuzestan and their relationship to increasing salination undertaken by the Oriental Institute, under Robert M. Adams (Jacobsen and Adams, 1958; Adams, s.d.)

A portion of the locale of the Prehistoric Project's field work is also covered in the paper by Voûte and Wedman in the next section of this volume. On both ethnographic and paleoethnographic grounds, we would suggest three sub-units (rather than two) for Voûte and Wedman's unit I, i.e:, I*a* : high central ridges of the Zagros; I*b* : intermontane valleys with separating ridges; and I*c* : a foothill-piedmont zone; as concerns the Zagros flanks of Kurdistan in general.

Our interest in this Zagros flanks unit or zone depends on the ever-increasing likelihood (as the evidence mounts) that this zone formed an important part of a still-undefined general zone in south-western Asia which included the natural habitats of the potential domesticates. These potential domesticates were wheat and barley, certain legumes, sheep, goat, pig, cattle, dog and ass (Helbaek, 1959; Reed, 1959; both these authors in Braidwood, Howe *et al.*, 1960). It is not, of course, suggested that all items in this constellation necessarily flourished together in any one restricted niche at one moment of time, in their natural state. It is considered likely that the boundaries of this general natural habitat zone included the eastern Mediterranean littoral as far south as southern Palestine, certainly parts of Turkey and the south-east extensions of the Zagros as far as Shiraz in Iran, but its boundary especially to the north (the Caucasus?) and north-west (Thrace?) is still very uncertain.

A traverse from the alluvium of classic southern Mesopotamia or Susiana (Khuzestan) would pass from the fertile alluvium bordering the lower reaches of the rivers Euphrates, Tigris, Karkeh or Karun to a relatively restricted arid-steppe piedmont, thence to a succession of intermontane valleys with their intervening ridges and trellised drainage systems, and finally to the high alpine ridges of the Zagros. North of Baghdad, the alluvium is restricted to the narrow valley bottoms of the rivers proper, and the intervening Jezerih steppe has poor gypsum soils until the piedmont is approached

1. The Oriental Institute's Prehistoric Projects have been joint efforts with the Baghdad School of the American Schools of Oriental Research, and have benefited by grants from the Department of Anthropology of the University of Chicago, the National Science Foundation, the Penrose Fund of the American Philosophical Society, the United States Public Health Service, and the Wenner-Gren Foundation for Anthropological Research. In 1959-60, the Project was also joined by the Institute of Archaeology of the University of Teheran.

—either to the east of the Tigris or just south of the present Syro-Turkish border in the north. In fact, north of about 35°, the piedmont becomes an increasingly broad and grassy downland, once the "bread-basket" of the Assyrian empire. The system of successively higher intermontane valleys is also well expressed in the north.

In a generalizing sense, the cultural level of literate urban civilization first appeared in the lower alluvium and at about 3250 B.C. (to the nearest quarter millennium), and the level of effective village-farming communities seems first to have appeared in the lower valleys of the intermontane valley zone (and perhaps along its border with the piedmont) at about 7000 B.C. Whether an intermediate level of market towns with small temples first appeared on the grassy piedmont downland at approximately 5000 B.C. still remains to be investigated, but the general trend of the locale of greatest cultural potential does appear to have been down-slope as time proceeded. Before the level of the earliest effective village-farming communities (as now known, the Jarmoan phase), the intermontane valley zone—and perhaps also the upper piedmont—was the scene of a level of incipience of cultivation and animal domestication. At least one phase of this level of incipience is now known, the Karim Shahirian, with somewhat variant but allied inventories at M'lefaat, Zawi Chemi Shanidar and Asiab. The probable time range of this general level must have been about 9,000 to 7,000 B.C. Before this lay—again predominantly in the intermontane valley zone, as our evidence now goes—the terminal level of late pleistocene food-collectors or "upper paleolithic", of which the general industry for this region is known as the Zarzian. Pre-Zarzian (i.e., Baradostian) levels are also known, and even earlier levels with flint industries of generalized Mousterian and Acheulean types.

Now it is important to note that we are not sure of a direct typological-technological continuity in this ascending sequence of flint industries and later artifactual inventories. At Shanidar, Solecki suspects discontinuity between his Mousterian and Baradostian horizons and between the Baradostian and Zarzian horizons as well. On the basis of a field assessment alone, Howe sensed a general continuity of development at the Warwasi cave near Kermanshah (Iran), but these meterials await Howe's further laboratory processing. It is not clear that the Karim Shahir phase developed directly out of the Zarzian, nor that the Jarmo phase developed directly out of the Karim Shahirian.

It is also important to note that each of these sites (and a few others not named here) lie in the intermontane valley zone or along the upper slopes of the piedmont. Further, the sites so far examined are relatively few, and the processing of their excavated materials is still incomplete. They lie within one niche or another within the subregional diversity of the intermontane valley zone. It thus remains an open question whether the suspected gaps in the continuity of the available sequence will eventually be filled in at slightly lower or slightly higher elevations than those of the phases now manifested by excavated materials. In other words, there could have been minor up-slope or down-slope environmental readjustments, in response to slight climatic fluctuations, which our evidence does not yet allow us to see because it is still incomplete and is available from only a relatively few sites.

Bearing this in mind what brief generalizations may we make now which are pertinent to the history of climate along the slopes of the Zagros? Most of the points below are discussed in greater detail in Braidwood, Howe *et al.* (1960).

1. Certainly as regards larger mammals, an essentially modern fauna was established by about 40,000 B.C. and was manifested at each point in the available sequence since then.
2. Certain species of land snails were an important element in the diets of the peoples of the Karim Shahir and Jarmo phases, and the same species inhabit the general area today.[1]
3. The traces of grasses and trees, as preserved at Karim Shahir and Jarmo are again essentially those of species available in the region today (or, better, along the crests of the flanking ridges).
4. There are increasing hints of evidence for "niche adaptation", even within the available sites of the Zarzian-Karim Shahirian-Jarmoan range. Onagers appear to have been hunted by the people of sites on or immediately overlooking the valley floors, while the bones of sheep and goats bulk largest in the sites along the ridges.

The above generalizations appear to lie in the direction of no great climatic change from the approximate level of the Mousterian (*c.* 40,000 B.C.) onwards. But there are also some hints which *may* point in the opposite direction:

5. Wright observed traces of a considerably lowered Pleistocene snow line at several points along the higher Zagros range.
6. Solecki (personal communication) has received identifications of date palm pollen from samples taken in his Mousterian horizon at Shanidar; the site lies well north and at a higher elevation than dates mature today.
7. Van Zeist (personal communication) in a preliminary analysis of pollen cores taken by Wright at the Marivan Lake (between Sulimaniyah and Kermanshah, in the higher Zagros), noted a marked increase in oak at a point suggested so far only by a single radiocarbon determination at about 3500 B.C. or later.

1. That they do not appear importantly before and especially after the Karim Shahir-Jarmo phases may simply be due to what Reed (Braidwood and Reed, 1957, 23, no. 12) has called the "culture filter"—i.e., that there may have been some culturally determined reason why snails were not favoured as food and hence that we archaeologists do not find traces of them. The implications of the principle of the "culture filter" are too often overlooked in making interpretations on the basis of excavated archaeological materials. No self-respecting Moslem in the area today would dream of eating the snails!

It is not, of course, completely impossible that the two last generalizations need interpretation with respect to the "culture filter" (see (1) above) effect, as well as directly.

As of the present moment, however, and with respect to the still very incomplete state of our knowledge, the natural scientists of the Prehistoric Project's staff are in essential agreement that: (*a*) during the Karim Shahirian and Jarmoan phases on the Zagros hill flanks, essentially the same environmental situation obtained as does today, save for slightly more forest cover, and (*b*) the domestication of plants and animals proceeded from cultural and not natural causes.

The general spirit of this paper has been to suggest the types of evidence which may be recovered by teams of archaeologists and natural historians working in the field together, and of how this evidence—when there is much more of it—may be very pertinent to the history of climate and climatic change. Unfortunately, even the slender amount of primary evidence suggested here is available for almost no other sub-region or time range in Near Eastern prehistory or early history. For this reason, the author permits himself to offer the following good counsel to colleagues in the symposium who might be inclined to search the archaeological literature on their own for hints of climatic history or climatic change:

1. There have been innumerable differing systems of chronological reckoning applied by archaeologists in the last half century, with little consistency from one system to the next. "Dates" offered, especially in generalizing secondary sources earlier than the middle 1950s, should be viewed with suspicion.
2. Generalization offered by archaeologists bearing on their own identifications or interpretations of natural phenomena are to be viewed with suspicion (see Dyson, 1960).
3. A very great quantity of primary evidence was overlooked (or tossed on the dump heaps) by the old fashioned tradition of fine arts museum oriented archaeology.
4. Archaeologists tend to think in terms of simple regional bar-diagram successions; the possibility that differently adapted inventories in different sub-regions may have in fact been contemporary is often not imagined.

RÉSUMÉ

Exposé sommaire des résultats de recherches préhistoriques faites au Kurdistan relativement aux modifications du climat (R. J. Braidwood)

De recherches menées conjointement par des spécialistes de l'archéologie préhistorique et des sciences naturelles il semble résulter qu'en Asie du Sud-Ouest, les lieux où l'homme a commencé de produire sa nourriture se situent principalement dans une « zone d'habitat naturel » comprenant les vallées intérieures et les plaines de piedmont des contreforts montagneux, du Zagros au Taurus. L'auteur indique quelles sont actuellement les conditions mésologiques dans cette zone, ce qu'elles étaient selon toute vraisemblance peu après la fin du pléistocène et quelles en étaient les manifestations préhistoriques. Il est peu probable, d'après ce que l'on sait, que les conditions climatiques ou mésologiques se soient profondément modifiées pendant la période de temps considérée, et l'apparition d'une véritable production de denrées alimentaires semble due à des causes d'ordre culturel. L'auteur termine par des conseils aux spécialistes des sciences naturelles qui seraient tentés d'utiliser les données déjà élaborées qui se trouvent dans des travaux relativement anciens d'archéologie et d'histoire des civilisations.

DISCUSSION

H. Bobek. At what height exactly is Lake Marivan, about 700-800 metres ?

Did you think of a possible oscillation of the lower limit of the oak forest ?

R. J. Braidwood. 1. The Marivan Lake lies at about 1,300 metres.

2. This is certainly one of the factors which Wright and Van Zeist are considering. I should emphasize again that the Marivan cores are to be seen only as a bare beginning of pollen analytical studies along the Zagros. Now that we know the material is available, an effort to secure more and longer cores is being planned.

J. Tixeront. A quel point de la colonne des stations de vallées montagneuses avez-vous commencé à trouver trace de la culture des céréales? Zarzini? Jarmo?

R. J. Braidwood. The cereals *T. dococcum*, *T. monococcum* and *H. distichum* are first available in the range of the site of Jarmo ((*c.* 6750 B.C.)

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RECENT ADVANCES IN DENDROCHRONOLOGY IN AMERICA WITH REFERENCE TO THE SIGNIFICANCE OF CLIMATIC CHANGE

by

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INTRODUCTION

Trees maintain a record of many significant events occurring during their span of life. They are products of their heredity and environment as they influence the processes in the individual throughout its life. Whenever one or more factors become limiting to a chemical process in the tree, morphological, anatomical or physiological phenomena related to the process may exhibit a change corresponding to the variation in the environment.

Growth-rings are an anatomical response which provide unique evidence for yearly climatic variation. A tree occupies the same site throughout its life and may live for centuries generally laying down one growth-ring per year. This ring may be large if the tree has: (*a*) adequate soil moisture to offset transpirational losses; (*b*) adequate sunlight for the photosynthetic production of basic food materials; (*c*) sufficient leaf area so that photosynthesis can support its food-using tissues; (*d*) sufficiently high temperatures for rapid respiration rates; and (*e*) adequate minerals for its assimilation needs. If one or more of these factors are limiting for a prolonged period during the growing season, the tree-ring will be small.

In the drier regions trees can be selected for which sunlight, competition, exposure, and soil factors remain essentially constant throughout their lives. Therefore, the growth-ring width becomes primarily a function of the limiting environmental factors, moisture and temperature. Soil moisture has been found to be the major factor in south-western United States (Schulman, 1956), but other factors, especially temperature and humidity, may counteract or accentuate the limiting effects of soil moisture.

The systematic study of the relationship of tree-ring growth to environmental factors and the use of the information so derived to accurately determine the age of trees and of living or dead parts, constitutes one of the basic phases of dendrochronology. The reverse order of this, wherein a tree section of known age is studied to determine what information it may yield as to the year by year environment of the tree, may have wide application in the evaluation of weather and stream-flow conditions during the life of the tree. It is the intent of this paper to discuss recent developments in the field of dendrochronology and to point out the growing potential for climatic interpretation. The author wishes to acknowledge the contributions and suggestions of his colleagues at the University of Arizona : Dr. W. G. McGinnies, Mr. T. L. Smiley, Dr. B. Bannister, Mr. M. A. Stokes, Dr. N. Matalas and Dr. C. W. Ferguson.

ADVANCES IN TECHNIQUES AND APPROACHES TO THE STUDY OF TREE-RINGS AND ENVIRONMENT

Many of the concepts and techniques now being employed in the field of dendrochronology originated from the work of A. E. Douglass and his colleagues at the University of Arizona Laboratory of Tree-ring Research. The first major efforts were applied to the study of sun-spot cycles (Douglass, 1919, 1928) and to the dating of archaeological sites. More recently, through the work of Edmund Schulman (1938, 1945, 1947, 1951, 1953, 1956), the tree-ring technique was extended to the problem of evaluating climatic fluctuations in precipitation and run-off. He established regional dendroclimatic series by : (*a*) sampling and measuring the rings of old-age conifers from semi-arid sites; (*b*) fitting trend lines to his data and dividing the ring value by the trend line value to obtain an index; (*c*) averaging indices from large numbers of trees; and (*d*) extending the indices beyond the age of the oldest trees by using crossdated archaeological specimens. His search for old-age trees culminated in the discovery of the 4,000yearold *Pinus aristata* Engelm. Because of his untimely death, the work on this species has not been completed. The reactivation of this project is anticipated in the near future.

Archaeological tree-ring work is being continued throughout south-western United States and at the Casas Grandes site in northern Chihuahua (Mexico) by the Laboratory of Tree-ring Research (Bannister, 1959; Smiley, 1961). Dating is now being attempted on tree-ring collections from Turkey and Egypt. Although there is less emphasis at the present time on chronology building, many of the existing chronologies are being extended through archaeological specimens, and a new chronology has been established for the Continental Divide of the south-western United States (Smiley, 1961). A new project is under way at the University of Arizona for extensive sampling and analysis of the tree-ring sequences represented by tress from different sites at Mesa Verde National Park in south-eastern Colorado. It is hoped that these studies will make possible a more detailed and accurate approximation of the weather conditions under which the cliff dwellers lived.

Considerable effort is also being expended in the search for new species which are satisfactory for dendrochronological purposes. Current emphasis is on arid land shrubs and small trees (Ferguson, 1959*a*, 1959*b*), While the greater portion of these are not dateable due to multiplicity or to indistinct ring structure (Glock *et al.*, 1960), some at higher elevations near the lower forest border exhibit chronologies which correlate with the rings of dateable coniferous trees. Ring patterns which may prove to be annual in nature are even apparent in some xerophytic succulents, such as *Cereus giganteus* Engelm.

The application of ring counts to age determination of trees and the minimum age of their substrata continues to find widespread use. The study by Sigafoos and Hendricks of the United States Geological Survey (1961) is of special significance to the problem of climatic change. They use tree ages to date the recent maximum advances of three glaciers on Mount Rainier, Washington.

The current trends in dendrochronology are toward increased emphasis on basic studies dealing with the statistical model represented by tree-ring series and the physiology of tree growth and tree-ring formation. The recent work of Matalas (1962) represents an important contribution to the understanding of tree-ring statistics. He points out that the population of tree-ring widths along a given radius can be described by means of several parameters. The largest rings are usually near the tree centre with the ring size gradually diminishing with distance from the centre so that the growth can be represented by $\overline{Y}_{i+1} = \overline{Y}_1 e^{-mi}$ where $\overline{Y}_1$ is the Y intercept at year one and m is the slope of log Y on ring number from centre i which represents time. The expected value of growth during any year is shown to be proportional to the standard deviation of the growth, so that the coefficient of variation, K, given by $K = \frac{Y_i}{S_i}$ can be used as a measure of the degree of sensitivity or complacency of tree growth. Unlike the variance of the ring widths, K is independent of the time sequence i. Matalas shows that for probability distributions which seem to apply to tree-ring data, the standard deviation cannot exceed the mean, and that a "purely sensitive sequence" would have a value of $\frac{1}{K}$ and a "purely complacent sequence" a value of 0. He demonstrates that the usual procedure of converting the ring width Y_i to an index W_i

$$W_i = \frac{Y_i}{\overline{\overline{Y}}_i}$$

performs the same function so that the variance of W, $V(W_i)$, is equal to $\frac{1}{K^2}$.

The tree-ring indices are not randomly distributed with respect to time but are significantly serially correlated with first order correlation coefficients ranging from 0.28 to 0.73 for individual cores. The sequence within a core was divided into 50-year intervals, and their serial correlation coefficients ranged between 0.21 and 0.72 for a *Pinus flexilis* and between 0.38 and 0.78 for a *Cupressus* sp.

Another approach to the problem of the growth function in young trees is presented by Duff and Nolan (1953). Young *Pinus resinosa* Ait. trees were dissected and the rings measured at every node. The growth function and patterns associated with differences in environment are analysed along three sequences: (*a*) the ring widths for a given year but at successive internodes down the tree; (*b*) the ring widths at a given internode (as commonly used in dendrochronology) progressing from the inside to the outside ring; and (*c*) the ring width at a fixed ring number from the pith progressing from internode to internode down the tree. Duff and Nolan demonstrate that while types (*a*) and (*b*) have a pronounced growth function, type (*c*) is unpatterned by the growth function as "... all the rings of a given sequence were laid down in their respective internodes when those internodes and cambia were of uniform age". Random variations associated with the environment are manifest in types (*b*) and (*c*) sequences. The unpatterned type (*c*) sequence would be ideal for dendroclimatological work, except that it would be practically impossible to sample every internode of a 500-year-old tree. However, some very important principles of tree growth have been derived through the Duff and Nolan approach.

Since dendrochronological work must deal with the type (*b*) sequence, a computer programme has been developed at the University of Arizona for objectively calculating the growth function, converting measurements to indices, and calculating parameters such as standard deviation, serial correlation, and mean sensitivity. The programme accumulates yearly indices and at the end of the analysis computes a composite index from the indices of all cores and calculates their standard errors, mean squares, and mean sensitivities. We believe this will not only facilitate our computational work, but will eliminate the subjectivity that might arise in fitting the growth function by eye.

Another major development which promises to facilitate tree-ring studies is the rapid advancement in new, more high-powered statistical techniques. The simple correlation method which has generally been used assumes that (*a*) tree-ring widths are randomly distributed with respect to time and (*b*) relative tree-ring widths can be expressed as a function of a single environmental variable. It is evident from the preceding discussion that the first assumption does not apply, and more evidence is accumulating (Fritts, 1960*b*, 1961, 1962; Larson, 1957) which indicates that in many cases the second assumption may also be inappropriate. Multiple regression, analysis of variance, and similar techniques assume a multiplicity of interacting causal factors and have been used in tree-ring studies with marked success (Fritts, 1961; Larson, 1957). An exception to this is the study by Tryon *et al.* (1957) in which a multiple regression model was assumed, but only one variable proved significant.

Serial correlation can be handled through the multiple regression method by including in the analysis as variables the width of the several preceding rings (Fritts, 1961, 1962). The use of covariance and variance power spectra, correlograms, and truncated correlation may also apply. Matalas (1962) suggests that multiple regression can appropriately be used to predict a regional phenomenon such as stream flow, for if each individual tree is used as a separate independent variable, rather than averaging all of them into one, more variance in the dependent variable should be explained.

Some of the recent work has given more emphasis to the components within the ring such as early-wood, late-wood, density, and cell size. Larson (1957) analysed the percentage of late-wood in *Pinus elliottii* Engelm. by multiple regression techniques. He found "the percentage of summer-wood . . . tended to be highest in those areas favoured by a low pre-season and high mid-season rainfall and on sites with a low moisture holding capacity in the B-horizon and/or a deep-lying fine textured horizon". He was able to account for 55 per cent variance in his analysis ($R = 0.74$).

Tree-ring workers are beginning to look to other climatic parameters besides the traditional precipitation and temperature. Evapotranspiration deficit (Fritts, 1961, 1962), soil water deficit (Clark and Barter, 1958; Smith and Wilsie, 1961) and vapour pressure deficit (Fritts, 1959, 1960*a*) have been employed in tree-growth analysis. Smith and Wilsie (1961) studied the early-wood and late-wood in *Pinus taeda* L. by the Duff and Nolan technique (1953). The percentage of late-wood in the "adult wood" of the type (*c*) sequence was found to be inversely related to soil water deficits from June to October, while in "juvenile wood" it was positively related. Thus ". . . an annual increment produced during a year of low water deficit is characterized by a low percentage of summer-wood at the apex of the increment and a high percentage of summer-wood at the base of the increment, whereas in years of greater water deficits, the trend becomes less pronounced".

The physiology of tree-rings has frequently been approached through studies of cambial activity and radial increase throughout the growing season. The author has been especially concerned with this type of work through the use of a recently developed dendrograph (Fritts and Fritts, 1955) which can measure the growth for each day (Fritts, 1958, 1960*b*). I would like to present briefly a few of these results along with some tree-ring analyses which, I believe, illustrate the significance of many of the points discussed previously in this paper. The data presented are largely unpublished, although portions of the total study are in print (Fritts, 1959, 1960*a*, 1960*b*).

The results represent three years of daily growth and environmental data for one of two white oaks (*Quercus alba* L.) which were measured with dendrographs (Fritts and Fritts, 1955). The tree was growing on the lower portion of a south-facing slope of a forested ravine located in the prairie border region of the deciduous forest in Illinois. Twenty-eight independent variables were used in a stepwise multiple regression routine (Ralston, 1960) to analyse daily growth. These included the following environmental variables : average day and night temperatures, solar radiation, rainfall, average vapour pressure deficit, and soil moisture. Powers of the variables were included so that curves could be fitted; day number and year number were employed to account for growth factors associated with time; the growth for the two preceding days was used to account for serial correlation; and the product of vapour pressure deficit and soil moisture was employed to allow for interaction between the two variables.

Since one of the objectives of the analysis was to evaluate the relative effects of different variables on radial growth during different portions of the growing season, the data were divided into four problems representing different periods of the growing season : (*a*) the first 30 days of growth which starts early in April coinciding with the first day of growth and lasting until leaves were half expanded, the approximate time when photosynthesis and transpiration become significant; (*b*) 39 days slightly overlapping with period (*a*) and starting on approximately 1 May; (*c*) 39 days following period (*b*) starting approximately 9 June; and (*d*) 39 days following period (*c*) starting approximately 19 July and ending 29 August. The actual date for the start of each period was adjusted so that all three years of data would represent comparable phenological stages in the tree. A stepwise multiple

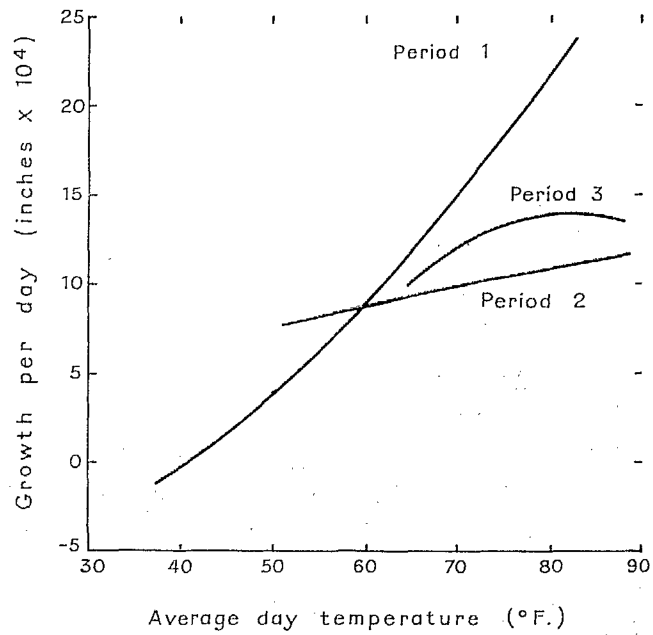

FIG. 1. The growth on day temperature relationships for a white oak growing on a lower south-facing slope in Illinois.

curvilinear regression analysis was employed which selects one at a time those variables which are most significantly correlated with the dependent variable and calculates the corresponding multiple regression equation (Ralston, 1960).

Fig. 1 illustrates some of the most significant temperature relationships obtained for the white oak. Each curve represents the growth-day temperature relationships calculated from the last step of each analysis (i.e., where the greatest number of significant variables were included in the equation). The curves are drawn for two standard deviations of the independent variable. The absence of a curve indicates the variable was of so little significance that it was not included in the calculated equation. The multiple correlation coefficients for these problems ranged between 0.906 and 0.915.

Daily radial growth in white oak during period (*a*) exhibits a large and significant variation with day temperature (0.001 level), but as the season progresses (last three periods) this direct relationship becomes less significant (0.05 level) with the coefficients becoming so low in period (*d*) that they were not computed. On the other hand night temperatures exhibit a similar direct relationship with daily growth that during period (*a*) there is no significant relationship, but in period (*b*) to (*a*) the relationship becomes significant (0.01 level).

When day temperatures are high, they become inversely related to growth as they influence the vapour pressure deficit of the air and hence its evaporating power. Thus, vapour pressure deficit is inversely related to growth and its influence is dependent upon availability of soil moisture. The curves in Fig. 2 represent these relationships. Each set of curves represents the calculated growth-soil moisture relationships at three levels of vapour pressure deficit. No curve was calculated for period (*a*) since transpiration was insignificant, but in period (*b*) vapour pressure deficit is significantly related (0.01 level) although the soil moisture relationship is insignificant. During period (*c*) more growth variation occurs with differences in soil moisture, but the relationship is most markedly an inverse one where periods of high moisture and low soil aeration are most limiting. Vapour pressure deficits, however, are more influential in reducing growth when soil moisture is low. Both variables are significant at the 0.05 level. During

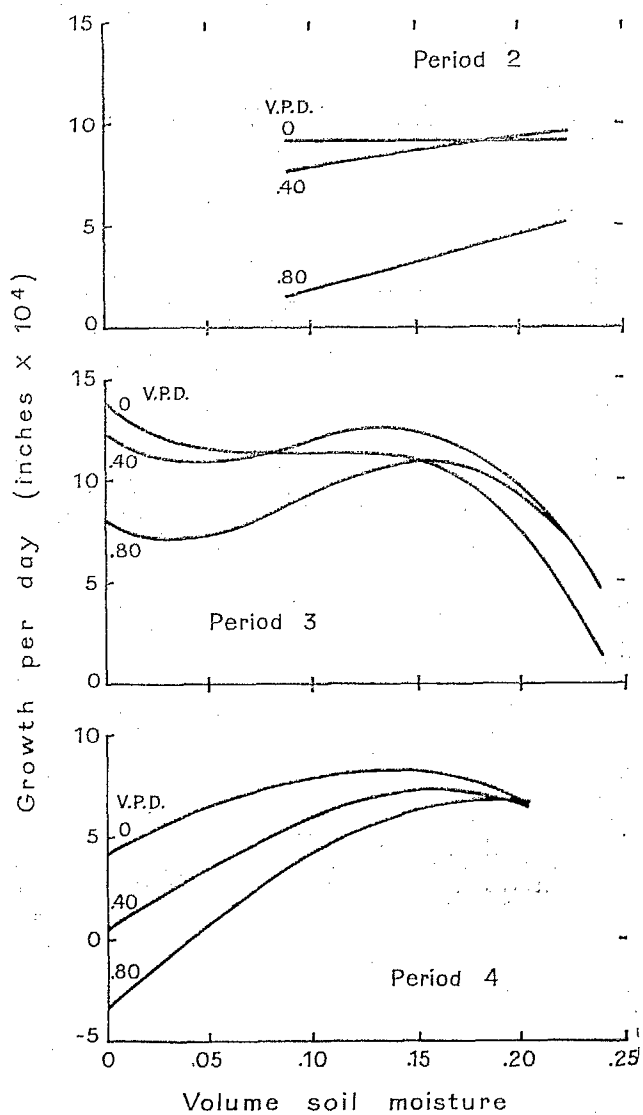

FIG. 2. The growth on soil moisture relationships (3 inch depth) at several levels of average vapour pressure deficit for a white oak growing on a lower south-facing slope in Illinois.

period (*d*) growth is largely limited by low soil moisture, especially when vapour pressure deficit is high (significance 0.001 and 0.01 levels respectively).

Daily growth was also found to be highly serially correlated (significant at the 0.001 level) with the previous day's growth and to a gradually changing function of time. These are thought to be a result of internal factors such as food reserves and hormone content which change with time. A second more-open-grown white oak higher on the slope exhibited similar relationships except that growth appeared less limited by periods of high soil moisture as the soil was better drained.

It would thus appear that there is physiological basis for a direct relationship between temperature and growth early in the season or at night when temperatures are low. However, when temperatures are high they are inversely related, especially when soil moisture is low. The inverse temperature effect appears most pronounced during mid-June through August and the direct soil moisture effect most pronounced during late-July and August.

If the dendrograph approach is to be usable in dendrochronology, then the daily growth measure must be equated to the tree-ring width. In order to check this, increment cores were extracted from the radii measured equated to the tree-ring width. In order to check this, increment cores were extracted from the radii measured by seven dendrographs, two placed on *Quercus rubra* L., two on *Acer saccharum* Marsh., and three on the two white oaks. The width of the early-wood and late-wood, as well as their sum, total ring width, were measured for the three study years and total ring width correlated with the total increment as measured by the dendrograph. The two measurements of the year's growth were highly related with a correlation of 0.96 and a regression coefficient for ring increment on dendrograph measure of 0.97 (Fritts, 1961). No significant difference was noted between species.

Since the two measures are so closely related, the early-wood increment and dendrograph record were used to date the approximate time when the early-wood to late-wood transition took place. The date for white oak was 24 May ± 8 days (Fritts, 1961). Since the radial increment represents both cell division and cell enlargement, the transition date is rather arbitrary as there was most certainly some differentiation of late-wood cells prior to the date and a corresponding increment due to enlargement of early-wood cells after the date. It is evident from these data that period (*a*) corresponds to the period of early-wood growth while periods (*c*) and (*d*) correspond to late-wood growth. The growth during period (*b*) represents the production of both types of cells.

The next step was to consider the tree-ring and environmental relationships. Increment cores were extracted along 15 radii for five white oaks on the same south-facing slope represented in the daily growth study. The widths of early-wood, late-wood, and the total ring were analysed by the same multiple regression techniques (Ralston, 1960) using 59 years of monthly climatic data obtained from a weather station two miles from the study area. This study will soon be published (Fritts, 1962), so it will be only briefly summarized here. Average monthly precipitation and temperature for the season concurrent with growth as well as for the season preceding growth were used as possible predictors of ring width. Other analyses were run using calculated soil moisture and monthly evapotranspiration deficits in place of precipitation. Evapotranspiration deficit was thought to be a relatively good measure of drought conditions when high vapour pressure deficits and low soil moisture are limiting to growth.

The results substantiate Matalas's findings (Matalas, 1962) in that each growth layer is very highly serially correlated with the immediate preceding one. The thickness of the early-wood is less variable than late-wood and is inversely related to the evapotranspiration deficits of the preceding September, as well as directly related to the late-wood of the previous ring. The temperature during April, instead of being directly, is inversely related to the thickness of early-wood. Evapotranspiration deficits during the current June also exhibit an inverse relationship. The late-wood thickness is directly related to the early-wood increment and inversely related to the temperatures in June and to the evapotranspiration deficits in July.

The daily-growth and ring-growth studies indicate that the growth-environmental relationships of white oak are not simple ones. While low temperatures in April may delay growth initiation and limit its growth rate, it does not reduce the increment of the early-wood. The fact that the early-wood layer is related to the climate of the previous September and inversely related to April temperature suggests that total early-wood growth is largely a function of stored food reserves which may be more efficiently utilized in cell production when early-season temperatures are low. High evapotranspiration deficits in June may reduce the total early-wood increment through their influence on water relationships and subsequent enlargement of the last formed early-wood cells.

The late-wood increment, since it is essentially a continuation of the same cycle of growth, is potentially directly related to the early-wood width except when the internal water balance of the tree is inadequate. Since high moisture as well as low moisture may limit growth, the calculated June evapotranspiration deficit does not fit the relationship. June temperature correlates with limiting vapour pressure deficits and thus is the best fitting June variable. By the end of July, soil aeration is rarely limiting so that high vapour pressure deficits and low soil moisture are the primary limiting conditions, and these are best estimated by the July evapotranspiration deficit.

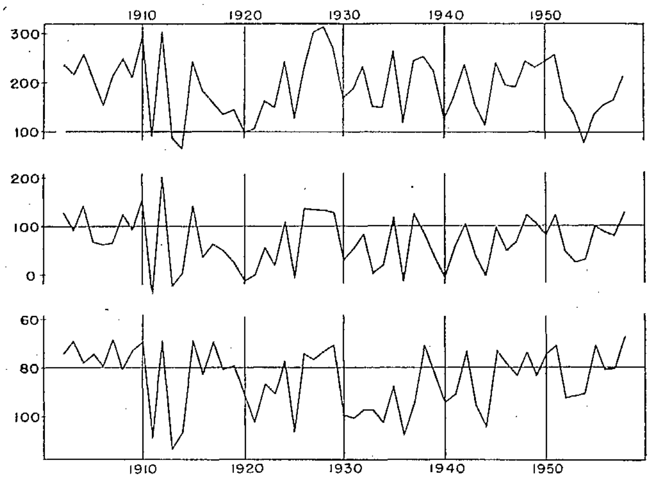

FIG. 3. Late-wood increment for 1902-58 (upper graph), calculated dendroclimatic index (middle graph), and the sum of temperature in June and evapotranspiration deficit in July (lower graph) for five white oaks growing on a south-facing slope in Illinois.

These data suggest that the late-wood in white oak could be used for dendroclimatic evaluation. It is highly inversely related to drought conditions represented by high temperatures in June and high evapotranspiration deficits in July. It is also related to the early-wood increment, but by using the multiple regression equation it is possible to calculate the relation to early-wood, subtract it from the late-wood value, and thus calculate a more precise dendroclimatic index of the limiting climatic factors. This procedure is illustrated in Fig. 3. The top graph represents the actual late-wood widths for the average of the five white oaks. The middle graph is the dendroclimatic index of temperature in June and evapotranspiration deficit in July calculated from the late-wood and early-wood values. The lower line represents the sum of the two environmental variables inverted for comparison with the indices. The similarity of the two lower graphs is sufficient evidence for the success of the technique. The multiple correlation was 0.855 and standard error of estimate, 0.032 inch. Studies are now under way for similar evaluation of the growth-environmental relationships of the conifers which are commonly used in dendrochronology.

TREE-RINGS AND THE SIGNIFICANCE OF CLIMATIC CHANGE

Edmund Schulman's *Dendroclimatic Changes in Semi-arid America* (1956) which brought together a great amount of information covering western North America, is the major American treatise on tree-rings as indicators of climatic change. Schulman constructs dendroclimatic series based on about one-third of a million annual rings in selected, drought-sensitive trees from semi-arid sites. All of his series are based on a number of individuals sufficient to give stability for 500 years and three series represent stable sequences for 2,009 years.

Although his work does not incorporate many of the recent refinements discussed in this paper, Schulman recognized a greater portion of the limitations to his method such as the error arising from serial correlation and lag, the problems inherent in the growth function, and the difficulties in making inferences from correlations of growth with rainfall occurring at distant stations. He states that his indices are not a precise absolute measure of rainfall, but they are a first approximation of the relative changes from year to year.

He approaches the problem of statistical instability by (*a*) selecting old-age, drought-sensitive trees for which the growth function was removed or negligible and (*b*) averaging data from a number of areas to provide an index which was representative of the regional variations but relatively free of the random fluctuations within the individual cores. He recognizes that his growth-rainfall correlation coefficients of 0.7 to 0.8 are not especially high. However, he points out that the growth series are perhaps more representative of rainfall in montane forests than the gauge records which are located mostly in towns and valleys. He achieves his highest correlation when he uses the average of rings from 84 trees distributed over a wide area and the average of rainfall from nine weather stations. When he selects old-age trees, he is careful to avoid the sequences which exhibit release due to fire, cutting or grazing. He also recognizes that, in the early portions of his chronologies where he uses short-term archaeological pieces, long-term climatic trends would not appear. This is why he placed so much emphasis on the value of long-lived over-aged trees.

On the basis of these analyses, he presents strong evidence for a great 200-year wave in rainfall and run-off in the Colorado River Basin, 1215-99 being extraordinarily dry and 1300-96 being extraordinarily wet with both extremes exceeding the intensity of those recorded in modern times. He also describes a tendency in southern California for long-term "swings" on either side of the mean value which occur from the thirteenth to the seventeenth century and which are followed by "swings" of shorter duration extending to the present time. In the Missouri River Basin, the indices show a reverse in this tendency.

He points out that a period of high growth and inferred high rainfall occurred at Banff, Alberta (Canada) (1897-1904) while other areas of the Colorado River Basin and southern California were experiencing severe drought. Recent climatic trends represented in the Colorado River Basin chronology (central and southern United States west of the Continental Divide but east of the Sierra Mountains) indicates a period of rainfall deficits between 1870-1904 followed by a period of high rainfall lasting until 1930. This was followed by another period of drought which is still manifest in the area. The departure from the mean during 1905-30 was equal in magnitude and in some years greater than the departure during the great wet period of 1300-96. The present drought for the entire Colorado region was on the average less severe than in the period 1871-1904, but in the portion represented by southwestern Arizona, the drought started earlier (1921) and is represented by the greatest deviation since the late 1200s. He points out that the total deficiency by 1955 was greater than the total excess during the interval 1905-20, a period which was probably one of the wettest in many centuries. Schulman states that he *could not find any steady underlying change* in climate over the total period of ring record.

Edmund Schulman's major contribution to the problem of climatic change, I believe, does not lie in any particular sequence or index value, but rather in his demonstration of climatic shifts from region to region, such as the differences in marked deviations among southern California, Alberta, and the Missouri Basin, and the varying intensity of the recent drought from north to south in the Colorado Basin. He also illustrates that the regional indices from widely separated latitudes may have decade-long intervals which are negatively or positively correlated, and which may be followed by a reverse in the correlation sign or a period of no correlation.

It would appear that such data would have considerable application to the problems of general shifting in atmospheric circulation and regional variation in climatic change, especially if the dendroclimatic network could be expanded to new areas, the index be more precisely determined, and the climatic parameter which the index represents be more specifically defined.

Schulman's simple linear correlation coefficients for growth and the rainfall interval July-July indicate that from 28 to 50 per cent of the variance is still unaccounted for. At the present time we are finding that serial correlations in the same type of sequence average around 0.50. If this value is the same in his tree-ring series, then it is very probable that a multiple regression analysis which includes the width of the previous ring as an added variable may provide us with better correlation results. A further consideration of the physiological basis for tree growth, of evapotranspiration as a climatic factor, and of the parameters lying in early- and late-wood should increase the precision of the ring index as a climatic measure. Other arid and semi-arid lands should also yield new drought-sensitive species and new opportunities for the application of the tree-ring technique.

At this session we are concerned with the significance of climatic change. We might ask what influence it has had on the organism. We may examine much evidence from plant and animal distributions, successional patterns, population shifts, and evolutionary change. But the tree, which lays down a permanent ring record, provides perhaps the most direct measure of favourable or unfavourable growing conditions that have occurred since its establishment. The question is no longer: "Can the tree furnish the measure?" but rather: "How can we decipher the measure in terms of its environment?"

RÉSUMÉ

Progrès récents en matière de dendroclimatologie en Amérique (H. C. Fritts)

L'auteur expose quelques-uns des résultats les plus intéressants des travaux effectués au cours des cinq dernières années. Il a été démontré que les chronologies fondées sur les cercles annuels du *Pinus aristata* vivant dans la région situées à l'est de la Californie s'étendent sur 4 200 années et plus et fournissent des données qui correspondent à celles qui proviennent d'espèces plus connues de la région. Des recherches sur des arbustes feuillus des régions désertiques dans le sud-ouest des États-Unis et en Argentine indiquent que quelques-unes de ces espèces (par exemple *l'Artemisa tridentata*) fournissent des indices sensibles et sûrs des variations de la pluviosité.

Des chronologies nouvelles sont en train de se dégager pour la région de Casas Grandes dans le Mexique septentrional et pour le versant continental sud des États-Unis. Des examens de cercles annuels en provenance d'Égypte et de Turquie laissent prévoir des possibilités intéressantes de datation.

Des études en cours du type stochastique sur les cercles annuels contribuent à l'établissement d'une base mathématique pour les paramètres de la sensibilité des cercles annuels, des variations avec l'âge, et de l'autocorrélation entre les cercles annuels. On a également appliqué des techniques de régression multiple à l'établissement des principales variables associées aux variations des cercles annuels et de l'équation la plus appropriée pour déduire les conditions ambiantes, les variations avec l'âge et l'autocorrélation restant constante.

Des recherches dendrographiques portant sur la croissance radiale quotidienne, en fonction des conditions du milieu, montrent l'importance relative de la température, de l'humidité, des radiations solaires, de l'humidité des sols et de la pluviosité à différentes périodes de l'année. Des études physiologiques et des analyses statistiques récentes de bois au début et en fin de saison fournissent une base plus solide à des indices dendroclimatiques plus précis. On a sensiblement amélioré les analyses en utilisant la température et le déficit d'évaporation et de transpiration plutôt que la précipitation comme variable indépendante unique. On s'attache aussi davantage aux études des cercles annuels et au débit des cours d'eau.

DISCUSSION

L. B. Leopold. This excellent new work offers the possibility, at some time, to use the tree-ring record to extend hydrologic records. I would ask Dr. Fritts if he might mention which parameters he hopes to use when analysing the ring width in an arid rather than a humid climate.

H. C. Fritts. I think that in Arizona we might look at several-month, rather than monthly intervals, representing winter and summer rainfall; also spring, summer and autumn temperature. We might consider some estimate of evapotranspiration deficit. Of course we also need to evaluate the relationship to the widths of the preceding rings, that is, the serial correlation.

J. Namias. The multiple regression techniques described for use with problems of tree-ring growth are also used in long-range weather specification and prediction. The method is called the "screening procedure".

There is also a very high serial correlation between monthly and seasonal values of meteorological elements over Arizona—in fact, higher than elsewhere in the United States. This may explain part of the serial correlation found in the annual tree rings.

H. C. Fritts. I am very pleased to hear this as it has been pointed out to the Tree-ring Laboratory that precipitation is essentially random. Temperature as it influences soil moisture loss would certainly affect tree growth in arid lands. Thus, if it is serially correlated, it would be expected to produce serially correlated tree-ring widths. However, I believe that botanical mechanisms are probably more important in producing this type of model for we find this serial correlation in different climates. We expect such relationships.

V. M. Yevdjevich. It is very useful to have more results of the biological character as it concerns the tree-rings. In this aspect the study presented by Mr. Fritts is very interesting.

Mr. Fritts stressed that the tree-ring series is greatly serially correlated. Though the annual precipitation series are very close to random time series, the storage of water in the soil (ground water, soil moisture) makes the annually available water for the trees serially correlated. The storage of food in trees makes the serial correlation still greater.

The use of multiple correlation and regression analysis by the step-up method (selecting variables of significant effect one after another) is to be studied as of its applicability, due to the fact that many variables (considered in multiple regression as independent variables) are not independent among them.

L. A. Ramdas. All dry matter produced by the growing tree is the result of photosynthesis, which in turn needs carbon dioxide. Carbon dioxide concentration is a variable factor within a plant community. So, in the detailed instrumental approach to study how exactly the tree builds its annual rings, I believe that the carbon dioxide concentration and its time and height variations should find a place.

H. C. Fritts. I agree with Dr. Ramdas and we hope soon to initiate microclimatic and physiologic measurements of such parameters. It does take rather expensive equipment which has not been available to the past studies. However, in Arizona the trees are widely spaced and there are commonly rather high winds so that it would appear that atmospheric carbon dioxide may not be as limited to photosynthesis as stomatal closure due to dehydration from excess transpiration. In the denser more mesic forests this may be a significant factor.

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SOME CLIMATIC INDICATORS IN THE PERIOD A.D. 1200-1400 IN NEW MEXICO

by

L. B. Leopold[1], E. B. Leopold[2] and F. Wendorf[3]

GENERAL STATEMENT

Three centuries before Columbus landed in America, the alluvial valleys of the south-western United States teemed with activity. The indigenous peoples had been building for 300 years a culture centred around community life based on flood-water farming and on hunting. A large number of pueblos had developed on sites earlier occupied by pit-house people. Community organization had brought advances in the ceramic and decorative arts, and changes in these artistic activities were sufficiently rapid that accurate chronologies have become available through the work of archaeologists during the twentieth century.

These chronologies were at first unrelated to absolute dates, but the excavations of the 1920s at Chaco Canyon (New Mexico) provided the materials through which absolute dates could be established. This was accomplished by matching the changes in tree-ring width backward in time from living trees through successively older samples. Trees overlapping in age provided, by unique successions of distinctive tree-ring widths, a calendar by which individual logs could be dated. Beams found in the excavations at Chaco Canyon gave the first material by which the cultural developments culminating about A.D. 1300 could be dated.

As a result of the time sequence provided by the tree-ring calendar, the dates within which different pottery types were developed could be accurately established. The dates of pottery types have been checked at a sufficiently large number of sites throughout the south-western United States that absolute dating of a large number of distinctive patterns can be considered unassailable.

The sequence of tree-ring widths gives some climatic indications of great interest both to archaeologists and to climatologists. A relatively large number of logs spanning the period from A.D. 1200 to 1300 and, in particular, the years between 1276 and 1299, indicate that this period was generally characterized by smaller tree-ring widths than in the centuries immediately before and after. As a first approximation, the hundred years of narrow tree-ring widths were interpreted as a time of relative aridity, and have been referred to as the "Pueblo Drought".

More recent studies of tree-ring widths using sophisticated statistical techniques have thrown some doubts on any direct correlation of tree-ring widths with rainfall. Such doubts have been put forward before by Glock (1955) whose studies have been aimed at separating the various effects of seasonal occurrence of precipitation, the amount falling in various seasons, and other climatic factors in their relative influence on tree-ring widths. At present, then, tree-ring widths may be considered more satisfactory for reading chronology than for reading climate.

It is this concern about direct correlation of tree-ring width with climate that led to initiation of the present study. This work is a preliminary attempt to obtain independent evidence from pollen concerning the probable nature of the vegetation and thus the climate in a period known to be characterized by narrow tree rings.

CORRELATIVE EVENTS

The indication of relative aridity during the period A.D. 1200-1300 provided a generalized explanation of a marked change in cultural patterns which took place about the same time. Flourishing pueblos were rapidly abandoned; communities centred in cliff dwellings similarly declined.

Correlative geologic work indicated that the time of pueblo abandonment coincided with the development of trench-like arroyos that gutted many alluvial valleys through the south-west. From the dating available

1. United States Geological Survey, Washington, D.C.
2. United States Geological Survey, Denver, Colorado
3. Museum of New Mexico, Division of Anthropology, Santa Fé, New Mexico.

through the use of potsherds, it is believed that the arroyo-cutting episode was relatively brief. Though not all alluvial valleys were so eroded, there were a sufficient number to justify the geological interpretation that the period A.D. 1200-1400 was characterized by a change in the rainfall-run-off relations (Hack, 1942). Subsequent to the trenching of alluvial valleys, there began in most areas a much longer period of aggradation during which the trenches became alluviated, and by the middle of the nineteenth century most alluvial valleys were characterized by flat floors only occasionally interrupted by discontinuous gullies. There followed a period, centred about 1880, of another epicycle of valley trenching, this time complicated by the effects of intensive grazing accompanying the development of western lands under the American flag.

THE PROBLEM OF CLIMATIC INTERPRETATION

The general simultaneity of arroyo cutting, the abandonment of pueblos, the decline of Pueblo civilization, and the two centuries of narrow tree-ring width made it plausible to interpret these phenomena as interrelated and as indicative of two centuries of relative drought. With regard to the geologic evidence, however, it remains difficult to prove by any available observations the exact nature of the change in rainfall-run-off relations which would be necessary to cause the observed epicycle of erosion in alluvial valleys.

It would be not only of hydrologic interest but also of concern to archaeologists and climatologists to be able to identify what climatic parameters must have changed, and in what degree, in order to reverse a trend of valley alluviation and replace it by valley degradation. It would be logical to suppose that indications of the type and degree of climatic change required for this could be ascertained from a study of the more recent epicycle of erosion centred around the year 1880. However, this later epicycle has been interpreted by many to be the result of man's activities alone—that is, the effect of grazing. In such a view it is not necessary to call on any change in climatic factors to explain the period of arroyo trenching that characterized the end of the nineteenth century. There were others (Bryan, 1941) who interpreted the erosion epicycle of the nineteenth century to be similar in cause to that of immediately pre-Columbian times, and to be related primarily to variations in climatic factors. An intermediate view (Leopold, 1951) is probably more generally accepted now. He provides evidence that there was a change in the intensity of heavy rains during the period of the recent erosion epicycle. This view emphasizes the importance of both grazing use and the simultaneous change in effective climatic parameters.

This brief review emphasizes, then, both the importance and the difficulty of finding ways of separating the individual effects of climatic change from the varying effects of man's activities on the land. The simultaneity of these two factors, both of which would tend in the same direction, reduces the usefulness of observations on the epicycle of erosion in the nineteenth century in ascertaining the individual effects of a changing climate uncomplicated by the effects of man.

Indeed, changes at present observed in the position and form of river channels, in the amount and types of sediment load, and in species and density of native vegetation cannot be clearly ascribed only to the effects of man's use. Meteorological evidence indicates that there has been in much of the Northern Hemisphere a tendency toward greater aridity throughout the first part of the twentieth century. So, the problem of ascertaining the effects of climatic change alone on the hydrologic cycle and on rainfall-run-off relations stands as one of the salient problems in both hydrology and in climatology.

POLLEN AS AN INDEPENDENT CLIMATIC INDICATOR

There is an inherent importance, therefore, of making use of whatever independent evidence can be brought to bear on the question of the nature of the supposed climatic variation occurring in the period A.D. 1200-1400. One possibility for the accumulation of independent evidence is the pollen associated with deposits which can be dated through pottery types stratigraphically associated. With this in mind, the authors collected soil materials in stratigraphic sections containing identifiable pottery types, in the hope that changes in pollen composition would add some information on the nature of vegetation and thus, indirectly, the climate characterizing a span of centuries, including the supposed drought.

The stratigraphic sections are of two general types. The Pueblo Indians characteristically made circular rooms known as kivas, mostly underground, roofed with timbers and soil, which were used as ceremonial rooms. The roofs of these kivas often collapsed, either through abandonment of the structures or lack of maintenance, leaving holes in the earth adjacent to the village. Such holes would logically be used as trash pits by the local inhabitants. The bulk of the trash was composed of soil materials, presumably from deteriorated house walls and from sweepings, including broken pottery, ashes, bones, and other debris. Natural run-off also washed alluvial materials into these holes and tended to fill them up gradually.

Because of the admixture of pottery, stratigraphic lines in earth materials accumulated in kivas can be dated accurately. A sequence of samples obtained at different depths within such kivas constituted one of the sources of the pollen which was analysed. A similar stratigraphic deposit was provided by material that filled pit-houses, early forms of habitation prior to the construction of the more complicated community apartments. Alluvial materials filling pit-houses are, therefore, analogous to those in kivas.

The second main type of deposit from which pollen was obtained is the alluvial valley fill. Owing to the arroyo trenching of the nineteenth century, there are unending miles of vertical arroyo walls in which the stratigraphic sections of alluvial deposits can easily be seen. It is not uncommon, then, that the sections exposed in the sides of the valley trenches provide artifacts, hearths, charcoal lenses, bones, and other evidence by which dating may be accomplished.

THE SITES AND THEIR INCORPORATED POLLEN

The present paper presents the pollen evidence from a limited number of kivas, pit-houses, and alluvial sections in the vicinity of Santa Fé (New Mexico). Owing to the small number of sites sampled and the restricted geographic area of their occurrence, the evidence presented must be considered preliminary in character and indicative rather than conclusive. Three pit-houses, one kiva, and one alluvial section in an arroyo bank occur in the vicinity of Tesuque (New Mexico) along a 5-mile reach of the valley of Rio Tesuque, elevation 6,500 feet. A kiva was investigated on an unexcavated pueblo site standing on a high ridge at elevation 7,000 feet, one-half mile due north of the village of Chupadero. In contrast to the alluvial section, the pueblo and pit-house sites all have the advantage of being topographically isolated from any possible source of pollen carried from the mountains by streamflow.

Both the Chupadero site and the sites in the Tesuque Valley are located on remnant outliers of unconsolidated sand and gravel of Miocene age, the Santa Fé formation, and extend well above the valley floor. The alluvial deposits of the Tesuque Valley are derived primarily from the weathering of the same Santa Fé formation, but were deposited principally during the period from about 250 B.C. to about A.D. 1300 (Miller and Wendorf, 1958).

The area near Tesuque is presently characterized by a woodland association dominated by piñon pine (*Pinus edulis*) and juniper (*Juniperus utahensis*). These woodland types represent a crown density of perhaps 10 per cent. Grasses and shrubs, including various species of grama (*Bouteloua*), snake weed (*Gutierrezia*), mountain mahogany (*Cercocarpus montanus*), characterize the hills and slopes. The same grasses and shrubs occur in the alluvial valley flats but there, in addition, grow cottonwood (*Populus* sp.), willow (*Salix* sp.), and some salt bush (*Atriplex conescens*).

The dates indicated in Fig. 2 for the pit-houses and kivas include the probable time ranges of the group of pottery types found in the structures. There is no way of determining, however, whether these deposits accumulated during most of the indicated time range.

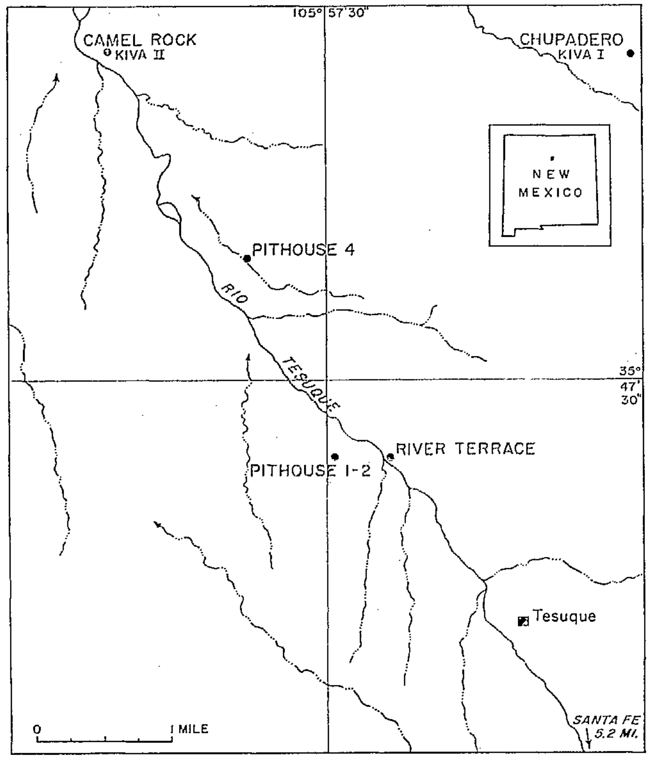

FIG. 1. Location of sampling sites, New Mexico.

The kiva may have filled rapidly, and thus would record only a comparatively brief span within this interval.

DESCRIPTION OF POLLEN DATA

Pollen data are arranged in the diagram (Fig. 2) according to percentage-total pollen and with amounts of *Pinus* and other trees on the left, shrubs in the middle, and herbaceous and cultivated forms on the right. The total number of pollen grains in each count is shown on the far right. The chief forms in the pollen samples and the ones that show the primary variation here are *Pinus*, Chenopodiaceae, and Compositae. The family Chenopodiaceae in the south-western United States is represented mainly by small salt-tolerant shrub genera adapted to arid conditions, such as *Sarcobatus*, *Atriplex*, and *Allenrottea*. Except for *Sarcobatus*, these Chenopodiaceone genera cannot be distinguished by their pollen, unfortunately. The family Compositae, of which the shrub genus sage or *Artemisia* is noted here, is considered to represent either woody or herbaceous forms in the present assemblage, and cannot otherwise be identified by pollen to genera.

The six sections are arranged on the diagram according to their inferred archaeologic age, the youngest at the top.

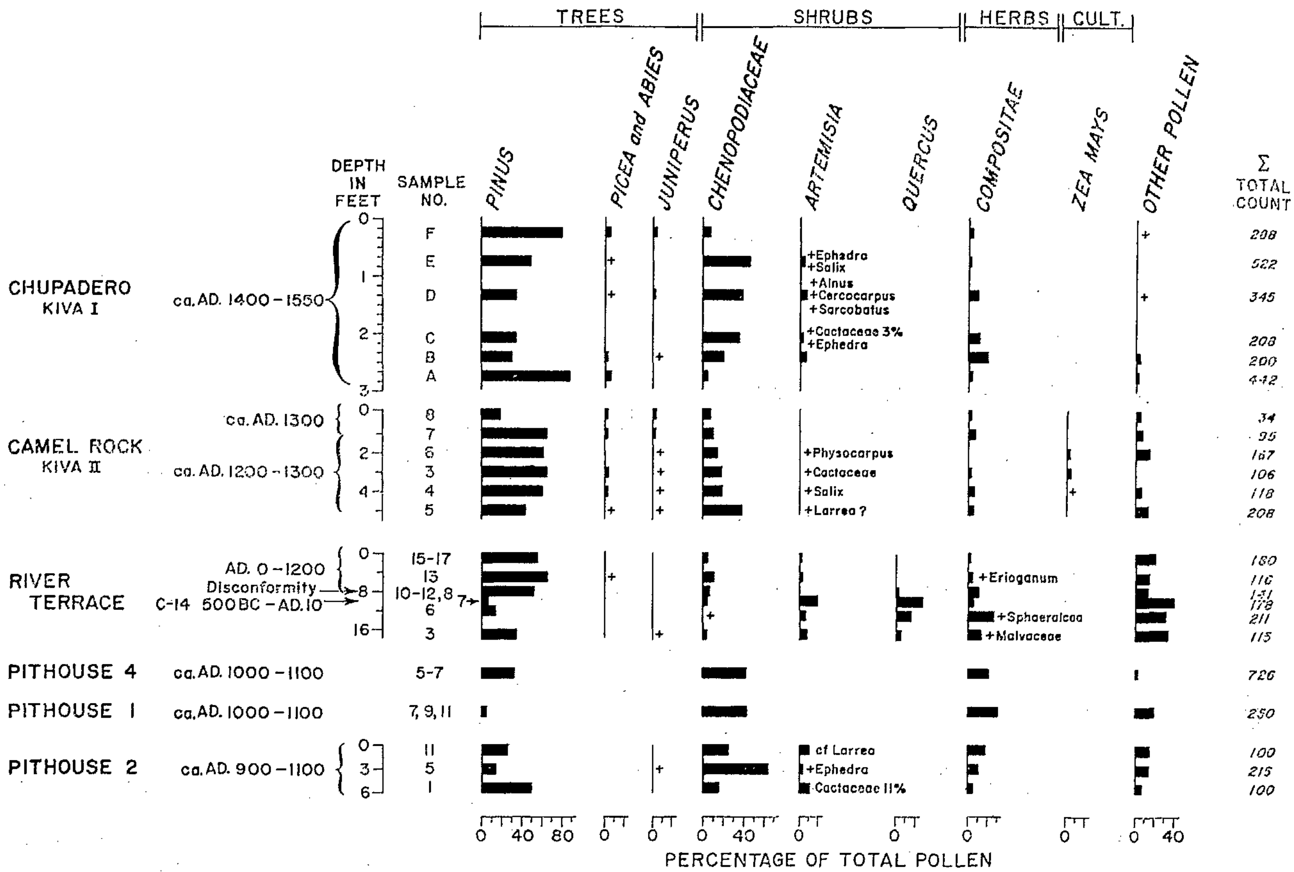

FIG. 2. Pollen diagram of sites near Santa Fé, New Mexico.

It should be noted first of all that the older sections at the bottom of the diagram, including pit-houses 2, 1, 4, and the lower part of the river terrace, are all thought to be older than A.D. 1100, and are as a whole comparatively poor in tree pollen. They contain, instead, various amounts of Chenopodiaceae, Compositae, *Quercus* (which will be scrub oak in New Mexico) and other non-tree forms.

On the other hand, the younger materials dating from A.D. 1200-1300, as in the Camel Rock kiva, contain comparatively large amounts of tree pollen, mainly *Pinus*, and with small amounts of *Picea* and *Abies*.

A section which cannot be dated very well because it contains little archaeologic evidence, and is mainly dated by correlation with other fluvial sequences, is the top part of the river terrace. By inference, it is thought to represent fluvial deposition some time between A. D. 0 and 1200. It contains relatively large amounts of tree pollen and is therefore like the samples from Camel Rock rather than the older materials that are known to be pre-A. D. 1100.

The youngest section, the kiva from Chupadero ridge (top part of Fig. 2) contains pottery that suggests deposition during the general interval of A.D. 1400-1550. This section is very rich in pollen and permitted larger tallies of pollen than the other less polleniferous sections. Within this 3-foot section there appears an oscillation in the percentage values of *Pinus* pollen. While *Pinus* varies from high to low to high values, there is a concomitant rise and fall of Chenopodiaceae and Compositae pollen.

DISCUSSION OF THE POLLEN AND OTHER DATA

Of stratigraphic interest are the low values of pine in all the pre-A.D. 1100 pit-house samples. The contrast between these and the younger Camel Rock kiva materials is considerable. The difference between the older and younger samples in abundance of tree pollen may reflect changes in pollen rain in the valley during the early part of the Christian era. Assuming that the sequences do reflect changes in pollen rain, we can take two possible interpretations of the pollen percentages. The simplest one is that the more prominent representation of tree pollen in the samples may reflect the occurrence of factors that favour the blooming and propagation of pine pollen, perhaps years of higher than average rainfall during the growing season.

It should be emphasized that there are no data by which one may know whether more rainfall in New Mexico results in more prolific blooming of pine.

The other empirical interpretation of the data might be to suppose that some climatic factor such as low values of precipitation might have inhibited the blooming and propagation of non-tree pollen while pine pollen production and dispersal remained unaffected. Under this interpretation, pine pollen is well represented only because of the failure of the non-tree elements to bloom prolifically.

The logical conclusion of the first hypothesis would contradict the generally held concept of relative aridity in the two centuries of arroyo cutting and pueblo abandonment. The samples that are rich in tree pollen are between A.D. 1100 and 1400 in age.

The other empirical interpretation permits us to suggest that unfavourable rainfall might be inferred during the same interval.

As in the case of the other data concerning this interval in New Mexico, pollen analysis provides evidence that something happened to the climatic environment between A.D. 1100 and 1200 that affected the internal composition of the pollen rain in the Tesuque Valley (New Mexico).

The question of what exactly happened remains at this moment still unanswered. However, there is hope that studies now being carried out will result in better understanding of the factors affecting pollen rain in this arid region. There is, further, the possibility of studying the annual modern pollen rain for several years in the valley and comparing it to the contemporaneous changes in seasonal rainfall. It is already known that in modern pollen rain over short time intervals, absolute numbers of tree pollen may remain constant while absolute numbers of non-tree pollen may increase, thus effecting an apparent percentage decrease in tree pollen in the samples. Because of this possibility and because the interpretation of the whole of the post-pluvial pollen chronology from this area is an important question, we think that modern pollen rain studies must be undertaken in the area in order for some of these questions to be answered.

The relation of geographic distance from dominant vegetation to pollen catch is inadequately known. Recent work (Davis and Goodlett, 1960) sheds further doubt on the usual assumption that pollen catch in any locality is predominantly related to the principal vegetation in the same locality.

Further work must also be done on the differential effects of variation in winter and summer precipitation, in particular as this relates to the growth of trees and the production of pollen. As Martin *et al.* (1961, p. 89) have recently pointed out, the so-called "Pueblo Drought" may have been a period when the winter precipitation was different, but the summer rainfall was increased.

CONCLUSIONS

The principal conclusion of the present preliminary investigation is that climatology and hydrology vitally need whatever new tools can be provided by palaeontology and a more sophisticated study of the dendrochronologic record. The actual findings of the pollen itself must be considered more tentative. These findings indicate that the period A.D. 1200-1300 had more pine pollen and less of the Compositae and Chenopods than in the preceding and succeeding centuries. This finding brings into question the supposition that this period was one of relative aridity. We are not the first to raise this doubt (Martin *et al.*, 1961, pp. 82-94).

All kinds of new independent evidence are needed to help separate the effects of climatic change and the effects of man's activities. The authors hope that this challenge will be increasingly recognized and aggressively accepted.

RÉSUMÉ

La sécheresse de 1200 à 1400 apr. J.-C. dans le sud-ouest des États-Unis (L. B. Leopold, E. B. Leopold et F. Wendorf)

Des études de cercles annuels portant sur des séries d'échantillons dans le Nouveau-Mexique et le Colorado indiquent une période de sécheresse prolongée s'étendant approximativement de 1200 à 1400 apr. J.-C. Cette conclusion, formulée il y a plus de vingt ans, a été utilisée à plusieurs reprises par des savants de différentes disciplines pour expliquer d'autres faits connus. Des études dendrochronologiques ultérieures ont montré l'interdépendance complexe des facteurs qui détermine l'épaisseur des cercles annuels ; il est donc nécessaire d'obtenir des preuves nouvelles et objectives pour confirmer la théorie généralement admise selon laquelle une longue suite de cercles annuels étroits indique une période de sécheresse.

Dans la présente étude, des échantillons prélevés dans des couches qui pouvaient être datées avec précision au moyen de tessons et d'objets façonnés ont été analysés pour rechercher le pollen qu'ils contenaient

dans l'espoir que l'on pourrait comparer le pollen découvert dans ces couches datées avec des dépôts de pollen moderne dans la même région. Bien que les données soient quelque peu contradictoires et qu'il se pose des problèmes d'interprétation, certains des échantillons montrent que la végétation associée avec la période de sécheresse supposée était en fait d'un type plus xérophyte que la végétation existant actuellement dans la même région. Les auteurs présentent et commentent certaines données ainsi que les problèmes d'interprétation qu'elles posent.

DISCUSSION

J. NAMIAS. Drought over the south-west is now known to be associated with a fairly definite pattern of large-scale wind and moisture flow. It is probable that on the basis of studies with recent (30 years) upper air data, meteorologists could suggest areas which had quite opposite (very wet) conditions. Would such predictions of simultaneous abnormalities of climate be of help in suggesting places in which pollen analysts, dendrochronologists, etc., might look for clues for long-term climatic fluctuations?

L. B. LEOPOLD. This is a sound suggestion. The knowledge of places where one might expect either similar or opposite anomalies might spur the archaeologist and other scientists to seek confirmatory evidence. The difficulty we envisage is that a combination of dating tools and climate indicators are unique in the south-western United States, owing particularly to the chronology developed by use of tree rings to date unique pottery decorations. Despite the present lack of these tools, Dr. Namias' suggestion that evidence be sought should be kept in mind.

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SOME REMARKS ON THE LAST CLIMATE FLUCTUATION IN THE ARCTIC REGIONS AND IN CENTRAL EUROPE

by

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After the intensive regression which occurred during the well-known warming period, ablation and recession of glaciers in recent years was somewhat retarded while, in some regions, transgression even occurred.

I had an opportunity to prove such facts on Spitsbergen by means of geodetical and photogrammetrical surveys and by means of ablation-stakes measurements carried out during my glaciological and meteorological investigation for the IGY and IGC (1957, 1958, 1959 and 1960) especially on the Werenskjold Glacier and Hans Glacier in south-west Spitsbergen.

In these four years the Hans Glacier showed distinctive dynamization and even advance of its terminal margin into Hornsund. The Werenskjold Glacier showed an increase of accumulation in the upper firn part, dynamization in the medial part while decrease of ablation in the terminal part was still negative.

The decrease in thickness of the end part of the Werenskjold Glacier in these four years amounted to about 2 metres per year and recession was 5 metres per year.

During the 40 years of intensive ablation (1915-57) the Werenskjold Glacier in its terminal part lost about 120 metres in thickness, i.e., a yearly decrease of 3.3 metres; and recession was 1,230 metres, i.e., a yearly recession of 29 metres.

Some of these relations are illustrated in detail in a publication of the Wrocław University entitled *Polish IGY Spitsbergen Expedition in* 1957, 1958, 1959, 1960, by A. Kosiba.

Geodetic and ablation stakes are established on these two glaciers in Spitsbergen and more surveying will be carried out in the future.

Similar glacial changes were found in other regions of the Arctic.

It is at present difficult to estimate how far these changes of the Hans and the Werenskjold glaciers were the effect of local actinogenic and thermogenic conditions and how far the effect of external factors (such as advection of air masses, etc.) since the surveying results are at present still being evaluated and need comparable analysis on a broad synoptical and climatological basis.

I would also like to stress here that significant variations of climate from year to year occurred in Spitsbergen from 1957 to 1960. In 1957, the summer was foggy, wet and windy; in 1958 it was rather sunny and less windy; in 1959 it was again foggy and wet; in 1960 it was partly sunny, partly foggy and wet. During that period strong contrasts also appeared in the summer climate of south and of north Spitsbergen.

I also wish to mention here that during these four years of investigations in south-west Spitsbergen the frequency of east and north-east circulation of the lower atmosphere largely prevailed. It was mainly connected with frequent cyclone complexes, namely with the northern part of cyclones originating from the Barents Sea or the Atlantic. This circulation would bring the strongest winds, intensive snow-drifts on the glaciers, and most intensive and heavy rainfalls highly exceeding the normal rate of precipitation in polar regions. Maximum daily totals registered in 1957-60 were over 55 mm. in 1957 and 62 mm. in 1959.

I also wish to emphasize here the important role of dust as a climatic factor in Spitsbergen. Dust is blown off in large quantities from numerous nunataks which are subjected to intensive weathering e.g., in the area of the Heckla-Hook Formation which became exposed from the firn and ice cover when it suffered intensive ablation during the last 40-50 years of climatic warming.

Better understanding of these processes will make it easier to explain some difficult paleoclimatic problems in south-east Europe where similar conditions—intensive advection of wet air masses from the south and great pollution during the Pleistocene glaciations—were present.

In central Europe rapid cooling occurred after the known warming period. It was marked by the concentration of extremely severe winters beginning with the series of three sequential severe winters of 1940, 1941 and 1942, a precedent of which is found in the eighteenth century during the period of the so-called "Little Glacial". The following severe winters which followed were those of 1946-47, 1953-54 and 1955-56. This constitutes the greatest concentration of severe winters in Wrocław in the last 150 years.

Having recently filled the gaps in climatological data for Wrocław winters during the war, I have been able to show a rate of 109 severe winters since 1851. This rate was determined according to that measure of severity which is the most representative criterion of winter, namely the mean daily temperature for the winter months : December (TXII), January (TI), February (TII), and for the whole winter (TXII, I, II). The six severe winters mentioned above are represented among the 20 most severe of 109 winters in the period 1851-1960 (see Table 1). I would like to add that, as far as the severity of winters is concerned Wrocław is consistent with all other parts of central Europe.

In Wrocław extremely severe winters indicate a great correlation with Wolf Numbers. They occur most frequently 0.5 to 1 year before maximum of W.N. or 0.5 to 1 year post-maximum W.N. But extremely severe winters in central Europe synchronize, on the average, with extremely warm winters in the Arctic and vice versa.

These relations are illustrated in Table 2, giving the examples of Wrocław in central Europe, of Upernavik and Myggbukta in Greenland, and of Isfjord Radio Station in Spitsbergen.

These regional contrasts of extremely severe winters make it very difficult to investigate the problems of climate oscillations and their relation to solar activity. Therefore, some scientists who based their estimations mainly on means-data, integrated from larger areas regardless of the climatological coherence, came to a conclusion that there is no relation at all between climatological variation and the solar activity. But yet in some regions, this relation is very distinctive. However, it requires very detailed regional investigations establishing the limits of climatological coherence and establishing comparable criteria and methods of analysis.

Finally, I wish to stress some peculiarities of climate oscillation in central Europe during the last warming period, particularly in the decades 1901-40.

During this period, warming was most intense in winter months (average temperatures), summer temperatures did not reveal any distinct trend.

Warming of winters was particularly marked in the region bordering on the Sudeten and Carpathian mountains and in the nearby Silesian and Great Poland lowlands and in the central European lowlands. Simultaneously there was an acute water deficiency, known in literature as the "steppization process". This process seems to be paradoxical in view of the fact that drying was distinctly marked and acute in the western part of the Polish lowlands nearer to the Atlantic but not in the eastern part. Precipitation did not show any considerable variation in this period.

Now, we should consider the main cause of drying to be the "foehnization" of air masses at the barriers of the Sudeten and Carpathian mountains, occurring with an increase of frequency of circulation south-west, east and south in the warming period and an increase of cyclone frequency, whose eastern parts often reach

TABLE 1. Severity ratio (N) of the mean daily temperature (in °C.) of the winter months (T XII, T I, T II) and of the whole winter (T XII, T I, T II).

N	T XII		T I		T II		T XII, I, II	
1	—7,8	1879	—11,2	*1940*	—13,3	1929	—7,1	1928/29
2	—7,1	1855	—9,0	1893	—11,9	*1956*	—7,1	1946/47
3	—6,7	1870	—9,0	*1942*	—10,2	*1947*	—7,0	1939/40
4	—6,7	1890	—7,4	*1947*	—9,0	1855	—5,6	1870/71
5	—5,3	1933	—7,2	*1941*	—8,8	1870	—4,5	*1941/42*
6	—5,1	1853	—7,0	1871	—8,1	*1940*	—4,5	*1953/54*
7	—5,0	1864	—7,0	1929	—7,5	1858	—4,2	1890/91
8	—4,6	1927	—6,7	1861	—7,3	*1954*	—4,1	1864/65
9	—4,1	1871	—6,3	1864	—6,7	1865	—4,0	1923/24
10	—4,0	1899	—6,3	*1954*	—6,6	1895	—3,7	*1940/41*
11	—3,9	1875	—5,8	1881	—6,1	1875	—3,6	1854/55
12	—3,8	*1946*	—5,8	1933	—5,5	*1942*	—3,5	1879/80
13	—3,7	*1940*	—5,2	1922	—4,9	1924	—3,2	1857/58
14	—3,6	1902	—4,9	1876	—4,7	1917	—3,2	1892/93
15	—3,3	1958	—4,5	1891	—4,4	1901	—3,2	*1955/56*
16	—3,0	1867	—4,4	1924	—4,1	1886	—3,1	1869/70
17	—2,7	1906	—4,3	*1945*	—3,6	1909	—3,1	1894/95
18	—2,6	1923	—4,3	1912	—3,4	1888	—3,0	1921/22
19	—2,4	1860	—4,2	1889	—3,3	1932	—2,6	1853/54
20	—2,0	1862	—4,2	1937	—3,0	1922	—2,6	1875/76

TABLE 2. Departures of mean daily temperature of some extreme winters severe or mild (T_W XII, I, II) from the many years winter temperature (T_W XII, I, II).

Winters	Europe Wrocław	W. Greenland Upernavik	E. Greenland Myggbukta	W. Spitsbergen Isfjord Radio
1916/17	—0,3	+9,1		
1923/24	—3,1	+3,4		
1924/25	+3,2	—1,9		
1928/29	—6,2	+12,4		
1939/40	—6,1	+9,6		—0,3
1940/41	—2,8	+10,0		—1,7
1941/42	—3,6	+2,8		
1946/47	—6,2	+13,1	+4,5	+4,2
1953/54	—3,6	(.)	+2,2	+2,3
1955/56	—2,3	(.)	+1,6	+0,2

the region of the Polish lowlands and there decay. The air masses in advection from the south-west, south and, in the Sudeten mountains, also from the west, which are strongly "foehnized", dry and turbulent, cause intensive evaporation especially in the eastern part of cyclone complexes whose turbulence has a large vertical component.

Moving first north-eastward, then northward, they gradually absorb moisture againfrom the Polish low lands.

The "foehnization" of air masses in the Sudeten and Carpathian mountains, chiefly in the west part, being most frequent and most intensive in winter, often causes melting and disappearance of snow cover without yielding water to the ground.

The winter of 1950-51 may serve as a typical example of this sort of situation when over 50 foehn-days occurred in the Sudeten and Carpathian mountains which caused the complete disappearance of snow cover. That winter was followed by one of the most acute drought disasters in the Polish lowlands.

The evaporation in the foehnization area of the Silesian lowland often largely exceeds the total of precipitation. Therefore, measurements of evaporation, which is a more continuous and more general process than precipitation, should be taken into consideration in the meteorological network, at least to the same extent as precipitation is, this especially in the districts of strong foehnization.

In standard measurements of evaporation the instruments and methods used should be unified.

SIXTH INQUA CONGRESS HELD IN POLAND, AUGUST-SEPTEMBER 1961

I would like here to point out those papers included in the Paleoclimate Section of the INQUA (International Association for the Study of the Quaternary) Congress which correlate with the programme of the Unesco/WMO symposium on changes of climate:

"Introductory paper to the Paleoclimate Section", by A. Kosiba (Poland), chairman of the section.

"Atmospheric circulation and climatic changes in Europe since A.D. 800", by H. H. Lamb (Great Britain).

"Climatic oscillations in some regions of the Arctic and Europe", by A. Kosiba (Poland).

"Glacier fluctuations in Holocene time in Julianehaab district, south-west Greenland", by A. H. Weidick.

"Pleistocene glaciation in Kurdistan", by H. E. Wright (United States).

"Les changements des climats quaternaires dans les Alpes occidentales", by J. Corbel (France).

"An attempt at detailed classification of cold climates in glaciated mountains, on the example of Pamir", by M. Hess (Poland).

"Some aspects of the changes of climate in the period from the final phases of the last glaciation to the time of disappearance of the ice relicts in the north European lowland", by W. Okolowcz (Poland).

"Les fossiles de l'holocène dans les dunes", by J. Kobendzina (Poland).

"Late Pleistocene climates of arid and tropical America", by P. S. Martin (United States).

"Les variations de la fréquence des directions du vent à Poznan pendant la période de 1879 à 1956", by S. Schneigert (Poland).

Problems of paleoclimate were also covered in the sections related to stratigraphy, geomorphology, periglacial phenomena, paleobotany, paleozoology, archaeology and anthropology; by various commissions (Quaternary shorelines; Neotectonics; Origin and lithology of Quaternary deposits; Absolute age of Quaternary deposits); by symposia (Loess; Marginal glacial deposits) and by excursions. (The material will be reported in a suitable publication of the INQUA Congress.)

RÉSUMÉ

Remarques sur la dernière fluctuation climatique enregistrée dans les régions arctiques et en Europe centrale (A. Kosiba)

L'auteur soutient que le recul rapide des glaciers observé au cours de la dernière période de réchauffement s'est ralenti et a même été remplacé, dans certaines régions, par une progression du front des glaces. Il présente à l'appui de sa thèse différents exemples de reprise de l'activité glaciaire au Spitzberg, et il décrit les changements climatiques correspondants survenus dans cette région à une époque récente. Il trouve des preuves similaires d'un refroidissement récent dans les relevés climatiques concernant la partie orientale de l'Europe centrale, et il en déduit qu'il existe une relation spécifique entre l'activité solaire et les variations climatiques.

Il analyse enfin certaines particularités des oscillations climatiques observées durant la dernière période de réchauffement en Europe centrale, et il établit une relation causale entre les progrès de la steppe dans l'est de l'Europe centrale et le phénomène de "foehnisation" des masses d'air en bordure des barrières montagneuses voisines.

SECTION III

THEORIES OF CHANGES OF CLIMATE

THÉORIES DES CHANGEMENTS DE CLIMAT

Chairman / Président: Dr. R. C. SUTCLIFFE

THEORIES OF RECENT CHANGES OF CLIMATE

Introductory remarks

by

R. C. Sutcliffe

President, Commission for Aerology, WMO;
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When some time ago this joint symposium of Unesco and WMO was mooted it was natural to ask if it could usefully be held consecutively with some other meeting of meteorologists in order to reduce the amount of travelling. The most obvious meeting was that of the WMO Commission for Climatology but this had already been arranged at a date too early for the symposium and I, as President of the Commission for Aerology, was asked if I would be in favour of associating the symposium with the session of my commission. I was enthusiastic and so it has happened; the session of the Commission for Aerology ended on the day the symposium opened. Perhaps I may explain briefly why I was enthusiastic. The main function of the Commission for Aerology is to review and promote research in the physics and dynamics of the atmosphere and under this banner we have given attention to a wide diversity of topics from the micrometeorology of the air near the ground to the uses of rockets and artificial satellites, from electronic computing to atmospheric electricity, but we have not yet ventured into problems of climatic variations. These have been left to the climatologists to explore and have been shunned by the physicist and dynamicist because, frankly, they were too complicated and theoreticians do not like complicated problems. I recall a time not very long ago, not twenty years ago, when weather forecasting was also regarded as too complicated for the attention of mathematical physicists. Indeed, academic meteorologists would sometimes go out of their way to disclaim any connexion with forecasting—an activity of dubious scientific standing. But the position has changed rapidly. After millions of pounds and dollars and other currencies had been spent on exploring the atmosphere in three dimensions, a few theoreticians began to see the light and now weather prediction by calculation is not only academically respectable, it is almost staid, and the time is at last ripe for dynamical meteorologists to turn more of their attention to the most comprehensive problem of their science, the problem of the climate of the earth.

In the past the climatologist has been rather scorned by his colleagues in meteorology as a collector of tabulated data and a dabbler in statistics but this phase is happily passing into history and all the best meteorologists are now becoming climatologists.

By restricting the study to recent variations in climate we have the dual advantage of studying changes on a time-scale which is of practical economic interest and of eliminating many long-term variables, geophysical and astronomical, which complicate the problem enormously. We must welcome the restriction partly because there is merit in studying subjects which are of practical interest to mankind and partly, as I have said, because the theoretical meteorologist does not like complicated problems. The climate of the last few thousand years was probably at all times sufficiently like that of the present to be regarded as variations on a theme and largely explicable in terms which are used to explain present-day climates. The challenge is one which the theoretical meteorologist may well accept.

The problems of climatic change have, however, been specially unattractive to theoreticians on several counts. In the first place the basic theory of world climate or of the general circulation of the atmosphere is rudimentary. Starting with any reasonable basic assumptions about the distribution of land and sea, the composition of the atmosphere and the radiation from the sun, assumptions which do not beg the main question, it has not yet been shown that the climate of the earth should be distributed as it is, even as regards the broad climatic zones. In very recent years two or three theoreticians in America have made important progress in deducing certain broad features of the general circulation on a symmetrical earth without apparently begging the question but it is a long way yet before the theoretician can put limits to the range of possibilities and without a quantitative theory of climate the discussion of variability is necessarily conjectural and inconclusive, unsuited to the precision tools of the mathematical physicist. The attractiveness of the problem is further weakened by the inadequacy of the data. It is not perhaps always appreciated that the basic terms in the average annual energy budget of the earth's surface —radiation exchange, evaporation and precipitation, conduction—are not known within 10 per cent and some authorities would put the uncertainty at a higher figure, for there is no absolute standard and what we know about the ocean-covered area is almost entirely the outcome of estimates based on insecure theory. With theory so rudimentary and the data so incomplete it is understandable that the subject has largely been left as a topic for armchair speculation.

I believe that it was intended that the task of the chairman would be that of reviewing the state of knowledge as a background for the other contributions but I shall not attempt this, for a very good reason. There has so far been only limited progress beyond the level of speculation and of that limited amount much has been contributed by those who are to speak after me. I shall therefore leave the experts to speak for themselves and be content with a few general remarks on the nature of the problem.

Ideally the theorician would I suppose approach the problem by developing a theory of world climate on such reasonable basic assumptions as I have mentioned and would then consider how the solution would be affected by modifications in the assumptions, but so far this ideal has not been attained. Nevertheless we may explore the theory intelligently and in various complementary ways. One approach is to consider such variable extraneous factors as may seem relevant and to estimate, if only roughly, the magnitude of their effects. Among these are solar radiation, either total energy or spectral distribution, ozone in the high atmosphere, carbon dioxide increased by the burning of fossil fuels, volcanic dust or cosmic dust acting either as a radiation screen or as sources of condensation nuclei. Much has been written on these topics and we shall have further contributions in this meeting.

Another approach which has received less attention although it has not been ignored is to study the mechanism of world climate and the way in which variability in the behaviour of the mechanism may arise. I shall say a little about this.

In the first place we note that the concept of climate is empirical, a summary statement of the weather conditions over a period of years, and the definition of climatic change is so arbitrary that it has little theoretical interest. The problem is that of the behaviour of the atmosphere, a thermodynamical system defined by a number of properties—perhaps a dozen—which vary on all space-scales from the microscopic to the world-wide and on all time-scales without limit to the very short or the very long. It is of no great moment where we draw the line and decide to describe the variations as climatic; the meteorologist's task is to analyse the complicated behaviour, to reduce the chaos to some sort of logical order and so reveal the remarkable wealth of atmospheric science as each scale of behaviour is identified as a distinct physical problem. The large class of variations which we choose to call climate presents not one problem by many.

This kind of complicated behaviour on all possible scales of space and time is not something peculiar to weather and climate but is typical of complex natural systems whether physical, biological or sociological. Such systems exist in a state of constant commotion with a multitude of sub-systems more or less interdependent and have variations on many scales of space and time built into the system, especially certain kinds of instabilities and irreversible pseudo-periodic oscillations, booms and slumps, gluts and famines. Examples from biology or economics may spring to mind but I am safer with meteorology. In certain circumstances the atmosphere trends to vertical instability followed by an outbreak of showers more or less periodic. In some circumstances horizontal temperature gradients build up and are relieved by the development of cyclonic and anticyclonic disturbances. The index cycle is another illustration of an irreversible cyclic trend in the planetary circulation passing through a phase of breakdown and recovering in due course with an irregular pseudo-period of a few weeks. Again it is characteristic that different scales of trend and variation interact in such a way that one scale of variation may be completely inhibited at some stage in another, as showers do not develop in anticyclones and baroclinic developments are inhibited at the recovery phase of the index cycle, but the properties and the scales of time and space are characteristic of the system, not of external variables.

Mathematically such systems may be represented by sets of differential equations, generally non-linear in many time-dependent variables, and not solvable explicitly. In some long-term statistical sense there may be a steady state but constant change is the essential feature. It is meaningful and important then to inquire whether or not the variability which we call climatic can be explained as the built-in characteristics of the system, rendering it unnecessary to seek the cause in some extraneous factor, solar radiation, volcanic action or the like.

Taking the atmospheric system alone and ignoring any related changes in the land or oceans, it seems evident that fluctuations would be limited to time-scales of a few weeks superimposed on the annual cycle. The working of the thermodynamic system is rapid and in the turbulent troposphere, the seat of weather and climate, a few weeks is about right. Fluctuations on this scale certainly exist and we do not need to look for an extraneous cause but there is also the variation in seasonal weather from year to year, one of the most remarkable facts of climate: does this need a cause? The question is vital for our understanding of long-range forecasting and critical in deciding what methods are likely to prove most profitable. From the internal evidence, especially the large magnitude of the year-to-year variations and the relatively small magnitude of any likely extraneous disturbances, I suspect that the year-to-year variations are indeed built-in characteristics of the system. As the annual cycle advances, the whole structure of the general circulation of the atmosphere appropriate to the season must be created anew each year and, being subject at all times to large-scale synoptic variations with a period covering some weeks, the evolving circulation pattern might very reasonably choose in successive years quite diverse characteristics with forecasting then dependent wholly upon our ability to predict the sequential evolution: extraneous factors, whether sun-spots or sea temperatures, need have no controlling significance.

The inter-annual variations of weather may be excluded from the problem of climatic change by definition but the same kind of question arises and it is because these pronounced year-to-year variations exist that climatic change must be established over a considerable number of years sufficient to define a statistical trend which is not explainable as the result of random sampling from a population of individual years. About ten years is the minimum sampling period and there seems no possible reason why the atmosphere alone should tend to vary its behaviour appreciably over a time-scale of that length.

The thermodynamical system of climate must, however, comprise the earth below and especially the ice sheets and the oceans which control the lower boundary conditions of the atmosphere and by far the greater part of the energy input to the atmosphere, and which by feed-back mechanisms have physical properties closely dependent on the climatic conditions above. The atmospheric heat engine carries along with itself an oceanic flywheel with 1,000 times its own heat capacity and a much slower rate of internal working. Natural fluctuations over periods of hundreds of years have been suggested for the oceans and mechanisms covering tens of thousands of years at least may be imagined for permanent ice-sheets.

The feed-back mechanisms are such that variations of really large amplitudes are readily envisaged. Climate taken over a short period of years would be completely defined and "steady" if the oceanic conditions, especially the ocean surface temperatures, were defined but the energy gains and losses by the oceans, in totals and in seasonal and geographical distributions, are predominantly a function of climate. The energy accepted by the ocean and fed into the atmosphere to control the climate is short-wave solar radiation and an amount equal to that which is received by the ocean in this way is actually lost by reflection from clouds. Since any significant change in climate must imply a variation in the geographical distribution of cloudiness, it is evident that the feed-back mechanism has potentialities for variations in energy input, and in the geographical distribution of energy input, of a magnitude larger than anything which has been envisaged for solar radiation itself.

Later speakers will, I believe, put new flesh to the dry bones that I have put before you. In particular, Dr. Godson will discuss radiation, Dr. Flohn the general problem of energy input and output, Professor Bjerknes the ocean-atmosphere relationships, and Mr. Namias a specific example of feed-back in operation. My remarks then merely stress the obvious potentialities for variation without the need to introduce extraneous factors. Evidently if such variations are to become part of established theory the specific mechanisms must be studied and understood and little can be expected from a superficial examination of the climatic evidence alone. There is, however, one indicator which might be used in certain cases. If a variation of climate is essentially the direct response to a single extraneous variable—such as solar radiation of volcanic dust—we may reasonably expect the climatic pattern to be a single-valued function of the controlling factor varying about a mean. If, on the other hand, the intrinsic variability of the system is the controlling factor, the rate of change of the climatic pattern will be defined by the pattern itself and the variability about the mean will be a cyclic and irreversible process. Efforts have been made by a number of authors to present all climatic variations as essentially of the same kind, variations between weak and vigorous circulation, but my impression is that the evidence needs considerable forcing to meet this simple concept and that the complex trends, sudden jumps and lack of simple correspondence between temperature and precipitation anomalies is more suggestive of a system controlling its own evolution.

It would seen impossible on the face of it for the internal variability of the atmosphere-ocean system to account for the return of permanent ice-fields when these had been absent for millions of years and other factors, terrestrial or extraterrestrial, must then be introduced. But it may well be that the smaller period variations in which we are specially interested on this occasion require no extraneous cause and may even be to some degree predictable by extrapolation from atmospheric-oceanographic data alone. If this were so it would be a matter of real economic importance.

I am sure that the only effective way to disentangle the phenomena and diagnose their causes is, however, by careful studies of geographical structure and physical mechanisms and by the measurement of the obviously important physical quantities. We must therefore especially welcome the greater interest now being accorded to the two boundaries of climate, the ocean below and space above. There is nothing more obvious than that meteorology and oceanography are inextricably mixed in any study of climatic change and the advance of physical oceanography is absolutely essential to us. Perhaps less easy to use will be the evidence from space but the geographical distribution of terrestrial radiation and reflected solar radiation measured by satellites will I believe prove more helpful to meteorologists than the variation in solar energy itself.

The problems of climatic change are numerous and difficult and must be separated, as far as possible isolated, by systematic filtering processes and not all mixed together. There is an open field for all kinds of climatologists whether statisticians, synoptic analysts or mathematical theorists, and I confidently look for more attention to be given to the subject.

THÉORIES RELATIVES AUX CHANGEMENTS DE CLIMAT RÉCENTS

Observations préliminaires

par

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Lorsque, il y a quelque temps, a été lancée l'idée de ce colloque mixte de l'Unesco et de l'OMM, il était naturel de se demander s'il ne pourrait pas utilement se tenir à la suite d'une autre réunion de météorologues, ce qui réduirait le nombre de leurs déplacements. La réunion la plus indiquée à cet égard était celle de la Commission de climatologie de l'OMM, mais elle avait été prévue à une date trop proche pour que l'on pût organiser le colloque; aussi m'a-t-on demandé, en ma qualité de président de la Commission d'aérologie, s'il ne serait pas possible d'associer le colloque à la session de ma propre commission. L'idée m'a séduit et c'est ce qui s'est passé : le colloque s'est ouvert le jour où la session de la Commission d'aérologie se terminait. Je voudrais expliquer brièvement pourquoi ce projet m'avait séduit. La principale tâche de la Commission d'aérologie est de suivre et d'encourager les recherches sur la physique et la dynamique de l'atmosphère, et à ce titre nous nous sommes intéressés à toute une série de questions — allant de la microméteorologie de l'air près du sol aux utilisations des fusées et des satellites artificiels, du calcul électronique à l'électricité atmosphérique — mais nous n'avons pas encore abordé les problèmes posés par les variations climatiques. Cette question a été laissée aux climatologues par les physiciens et les dynamiciens parce que, à vrai dire, elle était trop compliquée et que les théoriciens n'aiment pas les problèmes compliqués. Je me souviens d'une époque encore récente — il y a moins de vingt ans — où la prévision météorologique était également considérée comme trop compliquée pour intéresser les physiciens mathématiciens. En fait, les météorologues classiques prenaient parfois la peine de préciser qu'ils ne s'occupaient pas de prévoir le temps, activité d'une réputation douteuse chez les savants. Mais la situation a changé rapidement. Après que des millions de livres, de dollars et d'autres devises eurent été dépensés pour l'exploration de l'atmosphère dans ses trois dimensions, quelques théoriciens ont commencé à se convertir et, maintenant, la prévision météorologique fondée sur des calculs n'est pas seulement admise dans les milieux scientifiques mais devient presque une science établie; le moment est donc enfin venu pour des météorologues à l'esprit dynamique de consacrer une plus grande partie de leurs efforts au problème le plus général de leur science: le problème du climat de la terre.

Dans le passé, les climatologues étaient assez mal vus de leurs collègues de la météorologie, qui ne les considéraient guère que comme des collectionneurs de données mises en tableaux et des amateurs de la statistique, mais cette attitude est, heureusement, en train de devenir un souvenir historique et les meilleurs météorologues deviennent tous maintenant des climatologues.

La limitation de cette étude aux récentes variations de climat présente deux avantages: elle permet d'étudier les changements sur une période présentant un intérêt économique d'ordre pratique et d'éliminer de nombreuses variables à long terme, géophysiques et astronomiques, qui compliquent énormément le problème. Nous devons nous réjouir de cette limitation, en partie parce qu'il est méritoire d'étudier des questions qui présentent un intérêt pratique pour l'humanité et en partie, comme je l'ai dit, parce que les tenants de la météorologie théorique n'aiment pas les problèmes compliqués. Le climat des quelques derniers millénaires a probablement toujours été assez semblable au climat actuel pour pouvoir être considéré comme une suite de variations sur un même thème et être en grande partie explicable comme le sont les climats actuels. Il y a là pour les météorologues théoriciens un défi qu'ils peuvent bien accepter.

Cependant les problèmes posés par les changements de climat ont été jugés particulièrement ingrats par les théoriciens, pour plusieurs raisons. D'abord, la théorie fondamentale du climat mondial ou de la circulation générale de l'atmosphère est rudimentaire. En partant d'hypothèses raisonnables de base concernant la répartition des terres et des mers, la composition de l'atmosphère et la radiation solaire, hypothèses qui ne supposent pas résolue la question posée, on n'a pas encore réussi à démontrer que la répartition des climats de la terre doive être ce qu'elle est, même en ce qui concerne les grandes zones climatiques. Dans les toutes dernières années, deux ou trois théoriciens d'Amérique ont fait des progrès importants en définissant par déduction certains caractères de la circulation générale sur une terre symétrique sans faire apparemment de pétition de principe, mais il reste encore beaucoup à faire avant que les théoriciens puissent limiter la série des possibilités et, en l'absence d'une théorie quantitative du climat, la discussion de sa variabilité est nécessairement conjecturale, peu concluante et inadaptée aux instruments de précision du physicien mathématicien. L'attrait du problème est encore réduit par l'insuffisance des données. On ne se rend peut-être pas toujours compte que les éléments fondamentaux du bilan énergétique moyen, par année, de la surface terrestre — échanges de radiation, d'évaporation et précipitation, conduction — ne sont pas connus à 10 % près ; certains spécialistes estiment même que l'élément d'incertitude est encore plus grand, car il n'existe pas d'étalon absolu et ce que nous savons sur les étendues océaniques résulte presque entièrement d'estimations fondées sur des théories incertaines. Avec des théories aussi rudimentaires et des données aussi incomplètes, il est compréhensible que la question soit restée en grande partie un sujet de spéculations en chambre.

Il était prévu, je crois, que le président aurait comme tâche de passer en revue l'état des connaissances, à titre d'introduction aux autres communications, mais j'ai une très bonne raison de ne pas le faire. Les progrès réalisés au-delà du domaine de la conjecture n'ont été jusqu'à présent que très limités et beaucoup de ces progrès limités sont l'œuvre de ceux qui vont parler après moi. Je laisserai donc les experts s'expliquer eux-mêmes en me contentant de faire quelques observations générales sur la nature du problème.

L'idéal serait probablement que le théoricien aborde le problème en formulant une théorie du climat mondial fondée sur des hypothèses raisonnables comme celles que j'ai mentionnées, et examine ensuite comment des modifications de ces hypothèses influeraient sur la solution, mais cet idéal n'a pas encore été atteint. Nous pouvons néanmoins explorer la théorie intelligemment et de différentes manières complémentaires. Une méthode consiste à envisager certains facteurs extérieurs variables pouvant paraître pertinents et à estimer même grossièrement l'ampleur de leurs effets. Parmi ces facteurs, il y a la radiation solaire — son énergie totale, ou sa distribution spectrale — l'ozone de la haute atmosphère, l'augmentation de la teneur en anhydride carbonique du fait de l'utilisation de combustibles fossiles, la poussière volcanique ou cosmique agissant soit comme écran devant la radiation, soit comme source de noyaux de condensation. On a beaucoup écrit sur ces questions et il en sera reparlé au cours de la présente réunion.

Une autre méthode à laquelle on s'est moins intéressé, encore qu'on l'ait parfois envisagée, consiste à étudier le mécanisme du climat mondial et la façon dont la variabilité peut s'introduire dans le comportement de ce mécanisme. Je vais m'étendre un peu sur cette question.

En premier lieu, constatons que la notion de climat est empirique, car c'est en fait une description sommaire des conditions météorologiques pendant une série d'années ; quant à la définition du changement de climat, elle est si arbitraire qu'elle présente peu d'intérêt théorique. Le problème est celui du comportement de l'atmosphère, système thermodynamique défini par un certain nombre de propriétés, une douzaine peut-être, dont les variations s'étendent, dans l'espace d'une zone microscopique, au monde entier, et, dans le temps, du très bref au très long. Le choix de la limite à partir de laquelle il sera décidé de décrire ces variations comme étant climatiques ne présente pas grande importance ; la tâche du météorologue est d'analyser ce comportement complexe, de réduire le chaos à quelque ordre logique et révéler ainsi la richesse remarquable de la science atmosphérique à mesure que chaque type de comportement est identifié comme un problème physique distinct. La grande classe de variations que nous intitulons climatiques ne pose pas seulement un problème, mais de nombreux problèmes.

Cette espèce de comportement complexe dans toutes les coordonnées possibles d'espace et de temps n'est pas particulière à la météorologie et à la climatologie ; elle est typique des systèmes complexes, qu'ils soient physiques, biologiques ou sociologiques. Ces systèmes sont dans un état d'agitation permanente, comprennent une multitude de sous-systèmes plus ou moins interdépendants, et présentent des variations dans de nombreuses quantités d'espace et de temps propres au système, en particulier des sortes d'instabilités et d'oscillations pseudo-périodiques qui sont irréversibles, des expansions et des effondrements, des pléthores et des pénuries. Des exemples tirés de la biologie ou de la science économique peuvent venir à l'esprit, mais je me sens plus en sécurité avec la météorologie. En certaines circonstances, l'atmosphère tend à une instabilité verticale, suivie par de soudaines averses plus ou moins périodiques. Dans quelques cas, il y a un relèvement du gradient horizontal de température, que vient modifier le développement de perturbations cycloniques et anticycloniques. Le cycle type (*index cycle*) est une autre illustration d'une tendance cyclique irréversible de la circulation planétaire, passant par une phase d'arrêt et se reformant éventuellement au cours d'une pseudo-période irrégulière de quelques semaines. Il est également caractéristique que des degrés différents de tendance et de variation réagissent réciproquement, de sorte qu'un degré de variation peut être complètement annulé à quelque moment par un autre ; ainsi, les averses ne se produisent pas dans les anticyclones et l'évolution baroclinique est suspendue pendant la phase d'expansion du cycle type, mais les propriétés et les quantités de temps et d'espace sont caractéristiques du système et non de variables externes.

Des systèmes de ce genre peuvent être représentés mathématiquement par des séries d'équations différentielles, généralement non linéaires, à de nombreuses variables dépendant du temps, et qui sont insolubles explicitement. Du point de vue de la statistique à long terme, on peut dire qu'il existe un état stable, mais c'est le changement constant qui est la caractéristique essentielle. Il est donc aussi intéressant qu'important de se demander si la variabilité que nous appelons climatique peut ou ne peut pas être expliquée comme étant une caractéristique propre du système, auquel cas il serait inutile d'en chercher la cause dans un facteur externe, comme la radiation solaire, l'action volcanique, etc.

Si l'on envisage séparément le système atmosphérique en laissant de côté tous les changements connexes qui intéressent la terre ou les océans, il paraît évident que les fluctuations seront limitées à des périodes de quelques semaines surimposées au cycle annuel. Le fonctionnement du système thermodynamique est rapide et, dans notre troposphère turbulente, siège du temps et du climat, quelques semaines semblent être une durée normale. Il existe certainement des fluctuations de cette amplitude, auxquelles nous n'avons pas à chercher une cause extérieure, mais il existe aussi la variation du temps saisonnier d'une année à l'autre, qui est un des éléments les plus remarquables du climat. Cette variation a-t-elle besoin d'une cause ? La question est capitale pour la compréhension des prévisions à long terme et d'une importance décisive quant au choix des méthodes qui se révéleront vraisemblablement le plus profitables. D'après des indices internes, en particulier la grande amplitude des variations d'une année à l'autre et l'amplitude relativement faible des perturbations extérieures probables, je présume que les variations d'une année à l'autre sont bien des caractéristiques internes du système. A mesure que se déroule le cycle annuel, toute la structure de la circulation générale de l'atmosphère correspondant à la saison doit se recréer chaque année; et comme la structure circulatoire en cours d'élaboration est toujours soumise à d'importantes variations synoptiques de quelques semaines, elle pourrait fort bien prendre chaque année des caractéristiques très diverses; la prévision dépendrait alors entièrement de notre capacité à prédire l'évolution subséquente, sans qu'il soit nécessaire d'attribuer à des facteurs externes, comme les taches solaires ou les températures de la mer, un rôle déterminant.

Les variations du temps d'une année à l'autre peuvent être exclues par définition du problème des changements de climat, mais il se pose alors une question du même genre, et c'est parce qu'il existe des variations prononcées d'une année à l'autre que les changements de climat doivent être vérifiés sur un nombre considérable d'années, suffisant pour définir une tendance statistique qui ne soit pas explicable comme étant le résultat d'un échantillonnage aléatoire pris dans un groupe d'années séparées. La période minimum d'échantillonnage est d'une dizaine d'années et il ne semble pas y avoir de raison pour que seul le comportement de l'atmosphère ait tendance à varier appréciablement pendant une période de cette durée.

Le système thermodynamique du climat doit toutefois comprendre la terre et en particulier les nappes de glace et les océans qui régissent les conditions climatiques au bas de l'atmosphère ainsi que la plus grande partie — de loin — des apports d'énergie à l'atmosphère, et qui, par l'effet de mécanismes de rétroaction, ont des propriétés physiques dépendant étroitement des conditions climatiques dans les couches d'air qui les recouvrent. Le grand « moteur thermique » qu'est l'atmosphère a un « volant océanique » dont la capacité de chaleur est mille fois supérieure à la sienne et le rythme de « fonctionnement intérieur » beaucoup plus lent. On a suggéré pour ce qui est des océans qu'il pourrait exister des fluctuations naturelles s'étendant sur plusieurs siècles et, pour ce qui est des nappes de glace permanentes, on pourrait imaginer de même des mécanismes durant des dizaines de milliers d'années au moins.

Les mécanismes de rétroaction sont si importants que l'on peut envisager facilement des variations de vraiment grande amplitude. Le climat observé pendant une période de quelques années serait complètement défini et « stable » si les conditions océaniques, en particulier la température de l'eau superficielle, étaient elles-mêmes définies, mais les gains et les pertes d'énergie par les océans, pour ce qui est de leur total et de leur répartition saisonnière et géographique, dépendent avant tout du climat. L'énergie absorbée par l'océan et rendue à l'atmosphère pour régir le climat provient de la radiation solaire à ondes courtes, et une quantité égale à celle qu'a reçue ainsi l'océan est en fait perdue par réflexion sur les nuages. Étant donné que tout changement notable du climat doit entraîner une variation de la répartition géographique des nuages, il est évident que le mécanisme de rétroaction peut entraîner des variations de l'apport d'énergie et de la répartition géographique de cet apport, d'un ordre de grandeur plus considérable que tout ce que l'on a imaginé pour la radiation solaire elle-même.

D'autres orateurs, j'en suis sûr, vont étoffer le simple schéma que je viens de vous soumettre. Notamment le D[r] Godson traitera de la radiation, le D[r] Flohn du problème général des apports et des pertes d'énergie, le professeur Bjerknes des rapports océan-atmosphère et M. Namias présentera un exemple précis de rétroaction en fonctionnement. Mes observations ne tendent donc qu'à souligner l'existence évidente de facteurs internes de variation qui excluent la nécessité de faire intervenir des facteurs externes. Bien entendu, si des variations de ce genre doivent être incorporées à la théorie traditionnelle, il faut que leurs mécanismes spécifiques soient bien étudiés et compris et l'on ne peut attendre grand-chose d'un examen superficiel des seuls indices climatiques. Il est cependant un indicateur qui pourrait être utilisé dans certains cas. Si une variation climatique est essentiellement la réaction directe à une seule variable extérieure, comme la radiation solaire ou la poussière volcanique, on peut raisonnablement s'attendre que l'évolution du climat soit une fonction simple du facteur qui la régit, variant autour d'une moyenne. Si au contraire la variabilité intrinsèque du système est le facteur déterminant, le rythme de changement de l'ensemble climatique sera défini par cet ensemble lui-même, et la variabilité par rapport à la moyenne sera un processus cyclique et irréversible. Un certain nombre d'auteurs se sont attachés à présenter toutes les variations climatiques comme étant essentiellement du même type — des variations entre une circulation faible et une circulation active — mais j'ai l'impression qu'il faut beaucoup solliciter les faits pour les adapter à ce concept simple et que les tendances complexes, les variations brusques et l'absence d'une correspondance simple entre les anomalies de la température et celles des précipitations indiquent plutôt qu'il s'agit d'un système déterminant sa propre évolution.

Il semblerait impossible que la variabilité interne du système atmosphère-océan puisse rendre compte de la réapparition de champs de glace permanents alors que ceux-ci avaient disparu pendant des millions d'années; il faudrait donc faire intervenir d'autres facteurs, terrestres ou extraterrestres. Mais il se peut fort bien que les variations de plus courte période qui nous intéressent particulièrement dans la présente réunion n'aient pas à être expliquées par des causes extérieures et puissent même être prévisibles dans une certaine mesure par l'extrapolation de données uniquement atmosphériques et océanographiques. Si tel était le cas, ce serait là une question d'une réelle importance économique.

Je suis certain, cependant, que la seule manière efficace de désenchevêtrer les phénomènes et d'établir leurs causes consiste à étudier de près les structures géographiques et les mécanismes physiques pour mesurer les quantités physiques manifestement importantes. On doit donc se réjouir tout particulièrement de l'intérêt plus grand qui est porté maintenant aux deux frontières du climat: l'océan, frontière intérieure, et l'espace, frontière supérieure. Il est parfaitement évident que la météorologie et l'océanographie sont inextricablement mêlées dans toute étude des changements de climat et que le progrès de l'océanographie physique est absolument essentiel en ce qui nous concerne. Il sera peut-être moins facile d'exploiter les données tirées de l'espace, mais la répartition géographique de la radiation terrestre et de la radiation solaire réfléchie que les satellites permettront de mesurer sera, je crois, plus utile aux météorologues que les variations de l'énergie solaire elle-même.

Les problèmes posés par les changements de climat sont nombreux et difficiles; il faut les séparer et autant que possible les isoler au moyen de procédés systématiques de filtrage et ne pas tous les mélanger. Il y a là un champ librement ouvert aux climatologues de toutes spécialités, qu'ils soient des statisticiens, des analystes synoptiques ou des théoriciens mathématiciens, et je suis sûr que ce sujet va désormais susciter plus d'intérêt.

FLUCTUATIONS OF GENERAL CIRCULATION OF THE ATMOSPHERE AND CLIMATE IN THE TWENTIETH CENTURY

by

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INTRODUCTION

In my opinion, the main laws of fluctuations of climate and general circulation of the atmosphere are best of all elucidated when they are treated dynamically by way of the combined analysis of long-period changes of climatic indices and circulation characteristics.

As the variations, or "departures", of values of climatic elements for shorter periods from climatic mean values are fluctuating, the climatic and circulation data that we use to attain our goal must provide the possibility of correct statistical analysis. This leads to the necessity of securing a long enough series of meteorological observations of an extensive network of stations and general circulation characteristics over a vast territory, which excludes breaks in natural processes caused by artificial boundaries. Therefore the term "general circulation of the atmosphere" should be understood in its genuine sense, as a denomination not of separate atmospheric processes, but of their interacting unity, embracing at least one hemisphere.

Disregard of these principles has frequently led to unreliable and controversial conclusions. There were attempts to explain them by "unlike reaction" of different geographical zones to the same changes in the solar activity. In fact, in these cases there was observed the effect—which is different at various places—of the same type of general circulation of the entire atmosphere, which leads to simultaneous emergence of different weather types in different areas of the hemisphere and, when repeated frequently over a long period, to climatic differences between these areas.

Daily weather maps are available only for the period since the beginning of the twentieth century, so we had to use the data covering this period.

The characteristics of atmospheric circulation over the Northern Hemisphere were obtained in accordance with 13 types of circulation processes over the Northern Hemisphere, defined by my co-workers and me. These types give more detailed representation of four main groups of circulation processes (Fig. 1):

1. Well formed Polar anticyclone; zonal circulation[1] in high latitudes; two to three intrusions of southern cyclones from low to high latitudes. Over the greater part of the hemisphere the zonal transfers are preserved.
2. "Violation of zonality"—a single intrusion of Arctic air masses over a hemisphere; zonal flows are preserved in all other sectors.
3. Two to four simultaneous intrusions over a hemisphere; this is the group of meridional circulation types.
4. Development of cyclonic activity in high latitudes and over the Arctic Ocean. Inflows of "southern cyclones" reach far to the north and often cross the North Pole region.

The numerous and diversified synoptic processes are well distributed among the determined circulation types. The transition from one process to another is rapid, and it is usually easy enough to type circulation on two border-line days. Untyped transitional conditions occupy 2-2.5 per cent of the time.

The principles of typing seasonal variability of circulation, its long-period frequency, etc., are treated in detail in some previously published papers (see Bibliography).

We have to mention here that the circulation and climatic data available in *World Weather Records* were analysed by us for 36 years (1899-1954) and that, to draw more detailed conclusions, the calculations were carried out in two variants for the entire hemisphere and, separately, for each of its six sectors. As there was an additional sector, overlapping the boundaries of the initial ones, all the calculations of the circulation

1. The term "*zonal circulation*" is used to define latitudinal (or close to this direction) tracks of cyclones and anticyclones. The term "meridional" is used when the tracks are close to north-south direction. This rather closely reflects the direction of principal flows on 700 mb. surface (and, frequently enough, on 500 mb. surface).

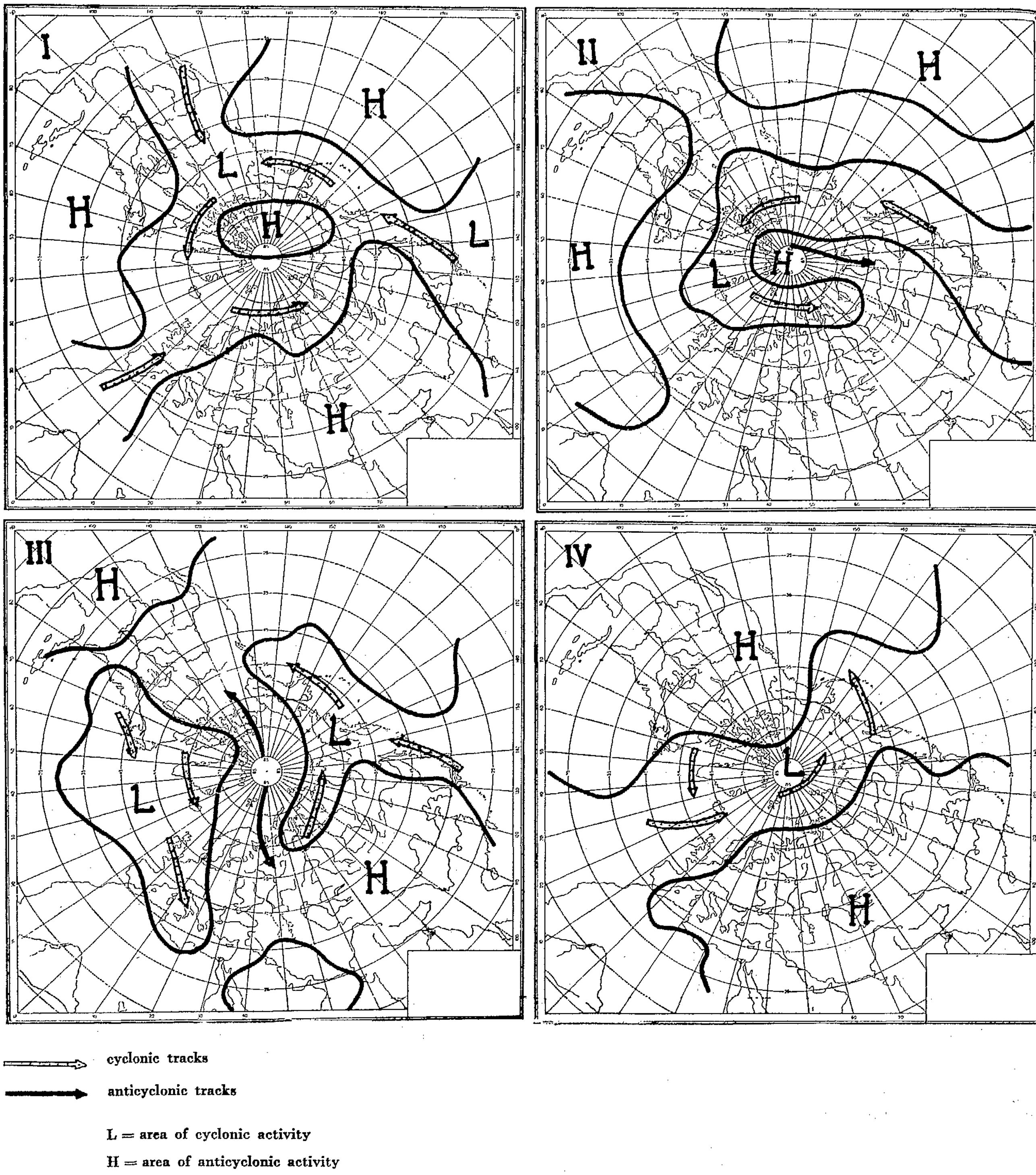

FIG. 1. Four main groups of atmospheric processes over the Northern Hemisphere taken as the basis for B. L. Dzerdzeevskii's typing (details in text).

data were repeated nine times. The work was performed on computers.

Only climatic data were calculated for the Southern Hemisphere.

The task of the paper is to report on the methods of research and to show, in certain examples, some of the results obtained.

DISCUSSION OF DATA

Integral (cumulative) or overlapping running curves are widely used to study long-period climatic fluctuations. Overlapping curves, in most cases, are plotted on the basis of 10-year sums or means.

Both types of curves have been repeatedly investigated with great care, for in certain cases they are apt to produce artificial—actually non-existent—fluctuations of the analysed value. It is especially characteristic of the integral curves method; the curves of this type show in points of change of dependence sharp turns which create an illusion of peaks or ridges on well-expressed waves or rhythms.

However, overlapping curves must be also used with certain care. Therefore it is useful to plot such curves for several periods. We have adopted 5, 10 and 20-year periods of summing. Although such triple calculations increase considerably the amount of work, the results obtained prove to be much more valid.

On the basis of such calculations we have constructed curves of long-period change of each of the analysed indices. The comparison of overlapping, and in some cases of integral, curves of change of climatic indices for separate stations with the characteristics of circulation over the entire hemisphere has shown good agreement. The correlation coefficients vary from 0.59 to 0.92, the prevailing value being above $0.75 \pm 0.03\text{-}0.04$.[1]

Thus, the connexion of change of climatic indices in different parts of the hemisphere with the general circulation of the atmosphere over the entire hemisphere is confirmed.

Referring to the investigations of Soviet heliophysicists A. Bezrukova (1950, 1954, 1960) and B. Rubashev (1957, 1958, 1959*a*, 1959*b*, 1960*a*, 1960*b*), who had shown good reaction of the general circulation in the entire earth's atmosphere to the solar activity fluctuations, we shall be able to explain the differences of climatic indices even for adjacent stations, as well as the controversial conclusions based on direct comparison of meteorological observations at these stations with the solar activity.

The next step, logically, should be the comparison of change of climatic elements in different parts of the hemisphere and determination of zones with synchronous or asynchronous climatic fluctuations in connexion with the general circulation of the atmosphere. In other words, the problem of "world-wide connexions" should be considered.

The long-period change of temperature in Portland and New York [Fig. 2 (*a* and *b*)] tends to be, in general, inverse in January and July. As the distance between these points is comparatively short, the fact may be explained both by their location on the opposite coasts of the continent and by circulation patterns. Comparing the change of temperature with the change of different circulation types, let us analyse Type 95—northern intrusion within the American sector.[2] In January the change of circulation is in direct correlation with the change of temperature in Portland, and in inverse correlation in New York; in July the character of dependence in both cases changes.

This means that the increase of number and duration of Arctic intrusions over the American sector in January is accompanied by lowering of temperature in New York and its rise in Portland; the development of analogous circulation patterns in July is accompanied by an inverse effect in both places.

These data are cited here to confirm the fact of sharply differing effects of one and the same process upon weather and climate even in adjacent areas.

In the given case the difference is determined by seasonal migration of tracks of Arctic intrusions and by change in direction of inflows (from the continent or from the ocean) connected with it and in the characteristics of warm air on the east and west sides of intrusions.

The differences in long-term changes of temperature and precipitation at Stykkisholm and Greenwich stations [Fig. 2 (*c*)] are, to all appearance, also explained best of all by the geographical location of the stations. It is worthy of notice that one observes at Stykkisholm considerably more expressed variability of climatic elements—with noticeable decrease in temperature and precipitation in the second decade of the twentieth century—which preceded widely known sharp warming of the Arctic. The variability of climatic elements at Greenwich is not so apparent, and the change of precipitation shows inverse correlation, which is weakly expressed, but agrees well in time.

The curves for climatic elements agree satisfactorily with the curves of zonal circulation types at Greenwich and with those of meridional types at Stykkisholm. However, at the beginning of the century the violation of zonality agrees better with Greenwich data; after a sharp increase in violation of zonality Stykkisholm showed better agreement. But the violation of zonality

1. Some of the obtained data have been already published, see Bibliography.
2. The first figure in the code system adopted here denotes the territory, taken as a basis for statistical calculations of circulation characteristics: 1 and 2, two variants of calculations for the entire hemisphere; 3, Atlantic sector; 4, European sector; 5, east European and west Siberian sector; 6, middle and east Siberian sector; 7, Far Eastern sector; 8, Pacific sector; 9, American sector.

The second figure denotes circulation characteristics: 1, western zonal; 2, eastern zonal; 3, northern meridional; 4, southern meridional; 5, violation of zonality (one northern intrusion); 6, stationary type.

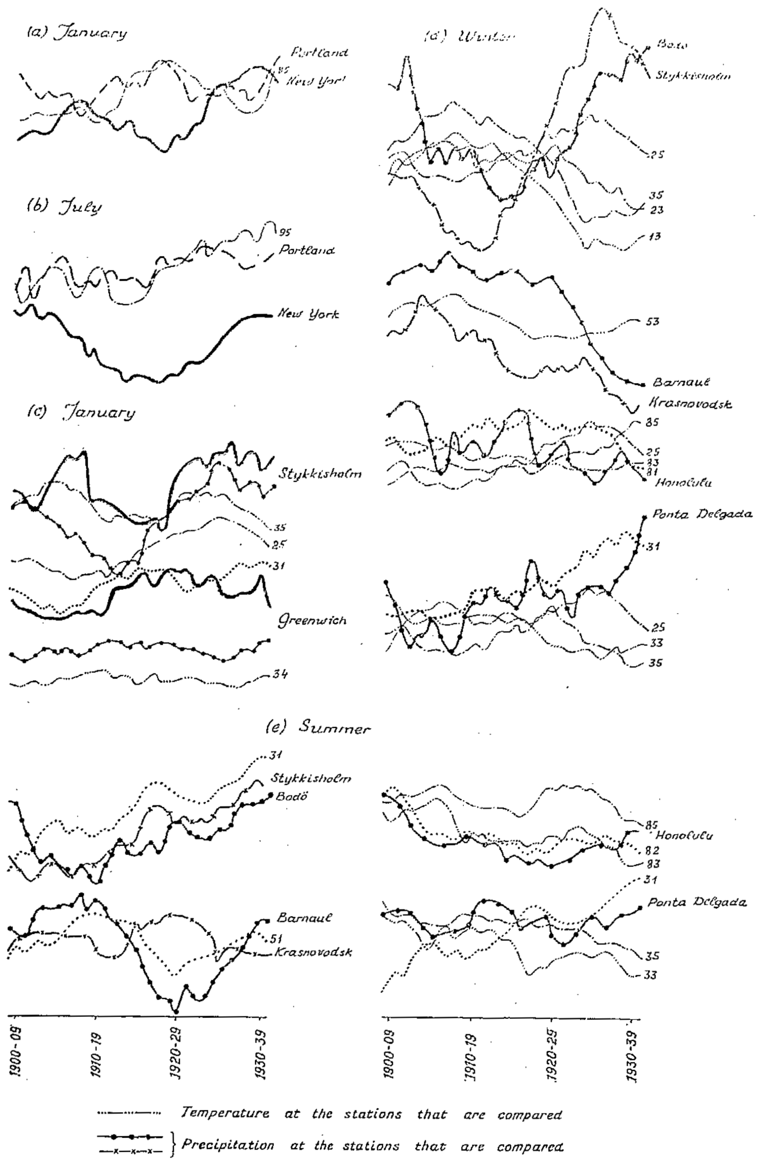

FIG. 2. Curves of long-period change of temperature, precipitation and different circulation types over the Northern Hemisphere at different stations. For code of circulation curves see note 2 on page 287.

over a hemisphere means that zonal circulation is preserved over the major part of the hemisphere; to zonal circulation are related also the processes of cyclogenesis in the Arctic Ocean. The intensification of these processes caused warming.

The series of curves for long-term changes in precipitation at Stykkisholm, Bodö (Norway), Barnaul, Krasnovodsk (U.S.S.R.), Honolulu (Hawaii) and Ponta Delgada stations—all located in ocean and continental areas of the hemisphere [Fig. 2 (*d*)]—is also of interest. In winter good agreement of change in precipitation with zonal types of circulation is observed in Stykkisholm, Bodö, Barnaul and Honolulu, while Krasnovodsk shows inverse correlation. Apart stands Ponta Delgada, where the connexion with zonal circulation is absent. One observes here the connexion with two patterns of meridional circulation.

In summer [Fig. 2 (*e*)] all these correlations change and the links become more complex, with different types of northern meridional circulation in high and middle latitudes.

In Stykkisholm and Bodö the correlation is inverse, in Barnaul and Krasnovodsk it is direct. In Honolulu and especially in Ponta Delgada connexions with zonal circulation types are well preserved also.

Such a variety of links during a season is easily explained by the geographical location of all these stations. Increasing intensity and duration of intrusions of Arctic air in high latitudes lead to a general decrease in precipitation in these latitudes and to its increase in Siberia. The variety of processes in low tropical latitudes over the oceans increases; this fact explains the complication of the curve for a long-period trend in precipitation and its closing with several types of circulation. In these latitudes the direct connexion with blocking meridional circulation types is feebly felt and east-west zonal motions are of importance here.

A good link of temperature changes with general motion is observed in low latitudes [Fig. 3 (*a*)]. This is

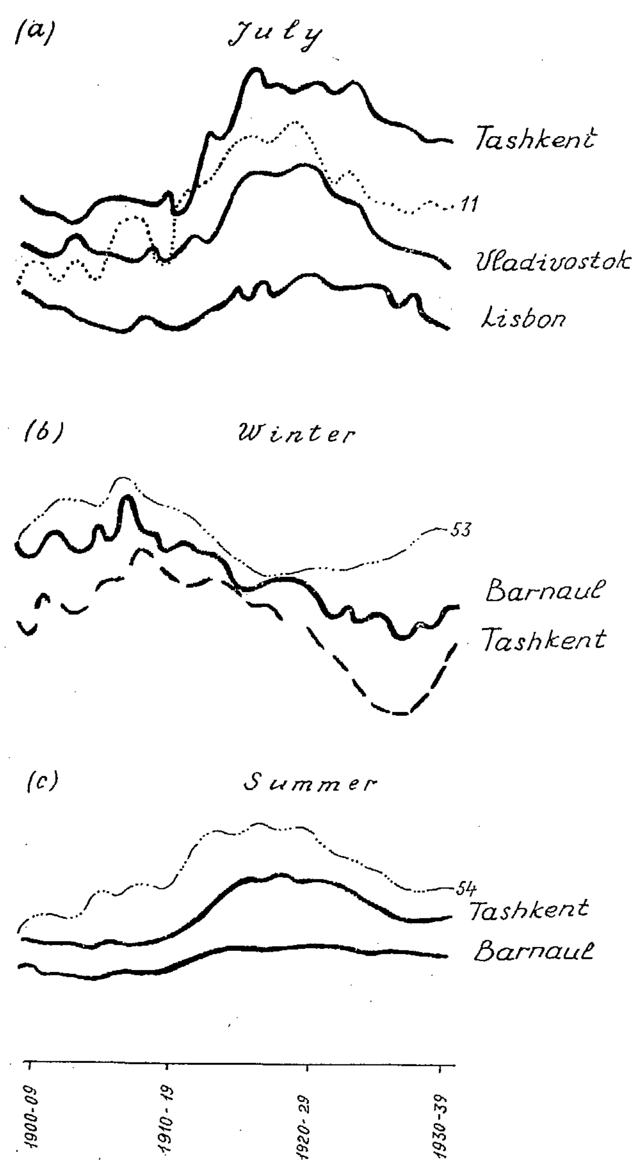

FIG. 3. Curves of long-period change of temperature, precipitation and different circulation types over the Northern Hemisphere at different stations.

confirmed by correlated temperature curves for Lisbon (Portugal), Tashkent and Vladivostok (U.S.S.R.) and the curve of change of the 11th circulation type (western zonal circulation, general for the entire hemisphere). It is interesting to note that the amplitude of temperature fluctuations increases from Lisbon to Tashkent. This fact may be connected with their location on the mainland of Eurasia and with the degree of remoteness from the oceans.

The curves of long-period change of temperature in Barnaul and Tashkent [Fig. 3 (*b* and *c*)] are interesting not only from the point of view of their similitude, but also from the point of view of their connexion with the change of the same circulation type in this sector. It is northern meridional circulation in winter and southern meridional in summer. In the first case the connexion is better expressed in winter in Barnaul, and in the second case in summer in Tashkent. However, in both cases it is quite noticeable on the other of the two stations.

It is especially interesting in relation to Barnaul. In July, temperature is influenced mainly by the general hemisphere zonal motions [see Fig. 3 (*a*)]. Preserving the connexion with southern meridional circulation during the entire summer testifies to the fact that in the warm season this circulation type plays an important part here.

Having plotted on the map all the points of meteorological observations with direct or inverse correlation of long-term changes of temperature and precipitation, we obtained a clear enough, though extremely complicated, picture of general "links"—fluctuations of main climatic elements. It goes without saying that here we have in mind their connexions with general circulation which stipulates the correlation of fluctuations in different points sometimes extremely remote from each other. Over the hemisphere as a whole, the correlation of long-period curves for stations in subtropical and tropical latitudes is preserved all the year round. In middle and high latitudes the "connexions" change, or are completely deformed, from season to season.

As these changes depend on the general circulation of the atmosphere, it is useful to analyse the circulation in order to find out the causes of these changes. Table 1 presents calculations of mean duration of action for 56 years of main groups of circulation types for all six sectors. The essential changes in the character of circulation are obvious. It is sufficient to compare the figures in the first line (northern meridional circulation). They are of similar value only in the Siberian sector, while in all other sectors they differ from summer to winter. The same applies to all other groups of circulation.

Analogous information is presented in somewhat different form in Fig. 4. For the sake of comparison the circulation structure of the entire year is also given here.

For the hemisphere as a whole both forms of zonal circulation (western and eastern) comprise 22 per cent

TABLE 1. Mean duration of action of different circulation patterns in summer and winter over six sectors of the Northern hemisphere (1899-1954)[1]

	Summer (June-August)												Winter (December-February)											
	Atlantic		European		Siberian		Far Eastern		Pacific		American		Atlantic		European		Siberian		Far Eastern		Pacific		American	
	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%
Northern meridional circulation	19.4	21.1	34.2	37.2	21.3	23.2	6.9	7.5	23.1	25.1	11.1	12.1	10.8	12.0	6.8	7.6	19.4	21.6	58.5	65.0	3.7	4.2	58.9	65.6
Violation of zonality	16.1	17.5	19.3	21.0	36.7	39.9	37.6	40.9	8.0	8.7	33.4	36.3	31.8	35.3	23.4	26.0	8.2	9.1	14.3	15.9	10.7	11.9	5.5	6.1
Western zonal circulation	50.3	54.8	15.0	16.3	25.1	27.3	5.0	5.4	20.8	22.6	5.7	6.2	36.6	40.7	28.8	32.0	6.8	7.6	—	—	73.3	81.3	15.5	17.2
Eastern zonal circulation	—	—	0.1	0.1	—	—	—	—	—	—	—	—	—	—	22.4	24.9	—	—	—	—	—	—	—	—
Meridional southern circulation	4.7	5.1	10.8	11.7	—	—	35.1	38.2	—	—	40.1	43.6	8.6	9.6	6.4	7.1	—	—	0.1	0.1	—	—	5.3	5.9
Stationary type	—	—	10.8	11.7	7.2	7.8	5.7	6.2	38.5	41.8	—	—	—	—	—	—	53.6	59.5	15.0	16.7	—	—	2.5	2.8
Untypified circulation	1.5	1.5	1.8	2.0	1.7	1.8	1.7	1.8	1.6	1.8	1.7	1.8	2.2	2.4	2.2	2.4	2.0	2.2	2.1	2.3	2.3	2.6	2.3	2.5

1. To ease the comparison of our data with the usual monthly data, the limits of seasons are synchronized with calendar months.

in summer and 34 per cent in winter, the corresponding figures for all forms of meridional circulation (northern, southern and violation of zonality) being 65 per cent and 50 per cent. It is caused mainly by a sharp decrease in the southern meridional circulation group in winter.

The predominance of the stationary type in the Siberian sector (59.5 per cent of time in winter) is also worthy of notice. Adding here pre-winter and pre-spring seasons we find that this circulation type covers 51.5 per cent of the duration of the cold half-year.

The diagram for the entire year shows predominance of zonal circulation over the Atlantic and Pacific. The correlation of values shows little change if the summary duration of meridional circulation and if violation of zonality is taken (it is quite justified for calculations within a sector, as was indicated above).

In the Far Eastern sector zonal circulation in its pure form is met extremely rarely; nor is it rather frequent over northern America. In these two sectors meridional intrusions are predominant. If taken with violation of zonality, they cover 65-66 per cent of the time.

It is rather interesting that southern meridional circulation is not met over the Siberian and Pacific sectors, although in the second case it may be connected —at least, in part—with the insufficiency of ship-borne observations.

Analogous calculations were carried out for years, seasons, months, climatic epochs. Thus, we have a kind of "climatology of general circulation of the atmosphere" over the Northern Hemisphere which determines the climatic régime of all its regions.

The established connexions do not always preserve close correlation as well as the type of dependence during the analysed semisecular period. The analysis of data from this point of view has only begun. However, the fact that violation of a former connexion is usually accompanied by its transformation into another circulation type leads to the conclusion that the main role in the change of activity of the circulation is played by displacement in space of the circulation as a whole (or, at least, of its major parts). In this process a point may be subject to predominant influence of other components of circulation which may be very often strengthened or weakened by moving over the underlying surface of another character.

The above may be confirmed by Fig. 5, showing the position of the centres of the Icelandic cyclone and the Atlantic anticyclone during extremely cold or warm months of December and January. During all cold months the Icelandic cyclone is displaced to the west, while the Atlantic anticyclone is displaced to the east; during all warm months both circulation cells are displaced in opposite directions. It is only natural that this is accompanied by change in direction and qualities of warm and cold flows.

Earlier I had compared the directions and distances of displacement of all main "centres of action of the

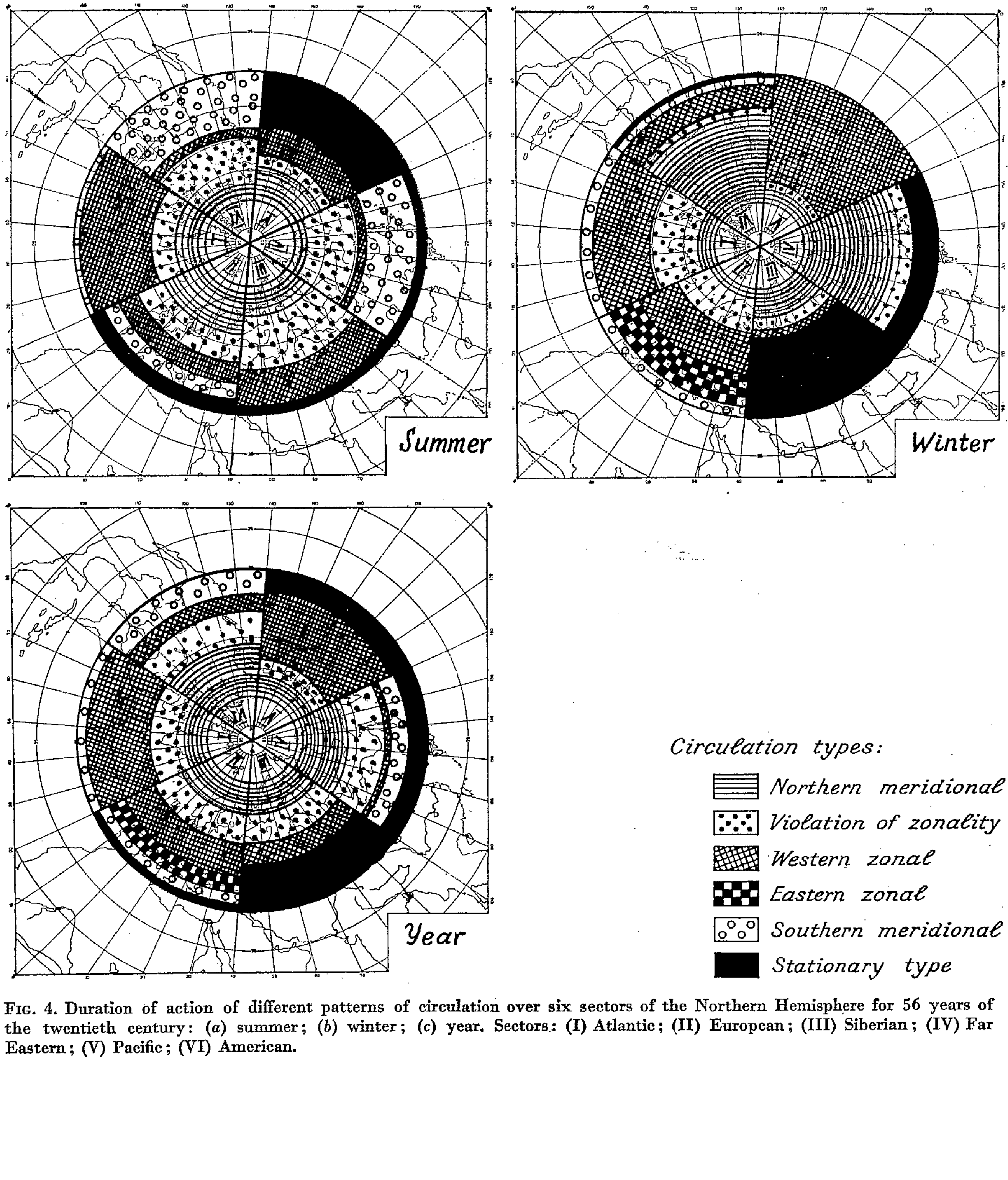

FIG. 4. Duration of action of different patterns of circulation over six sectors of the Northern Hemisphere for 56 years of the twentieth century: (*a*) summer; (*b*) winter; (*c*) year. Sectors: (I) Atlantic; (II) European; (III) Siberian; (IV) Far Eastern; (V) Pacific; (VI) American.

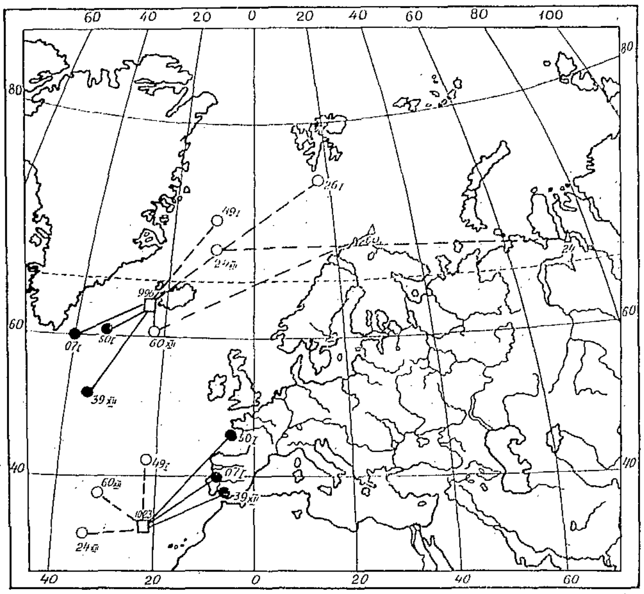

Fig. 5. Displacements of the Icelandic cyclone and of the Atlantic anticyclone in extremely warm and cold months of different years. (Figures at circles and triangles represent the month and the year. Squares indicate long-period positions of the centre. Figures at squares indicate mean pressure.)

atmosphere' over an 80-year period. Vectors of displacement for four seasons of 1933 and 1934 are shown in Fig. 6. Those years differed essentially in high latitudes. Here again one may note the opposite direction of displacement of neighbouring circulation cells.

It would not be an exaggeration to say that the study of climatic fluctuations in arid zones may be of greater practical importance than in many of humid zones. This is because unfavourably directed climatic fluctuations in arid zones mean in almost all cases the transgression of the lower—untolerable—limit. Although arid zones are located mainly in lower latitudes, where circulation is much more stable and less zonal than in moderate and high latitudes, the agreement of fluctuations of climatic indices with circulation in these zones is quite satisfactory. For example, in Khartoum and Aden summer links with southern meridional circulation types are replaced in winter by links with northern meridional circulation types, while during both seasons the links with zonal circulation types—general for the entire hemisphere—are preserved.

If we take the general circulation of the atmosphere for the basis of studying climatic fluctuations, we may apply this method of research to arid zones as well, although its use in low latitudes is connected with certain additional difficulties.

Prospectively, the main objective of such investigations should be the formulation and development of the problem of a climatic, i.e., basic, long-range forecast for the next circulation "epoch". The premises for formulating this extraordinarily complicated task may be found in the successfully developing research of reactions of the earth's atmosphere to the fluctuations of solar activity and probably of the magnetic field of the earth which serves as the intermediate agent.

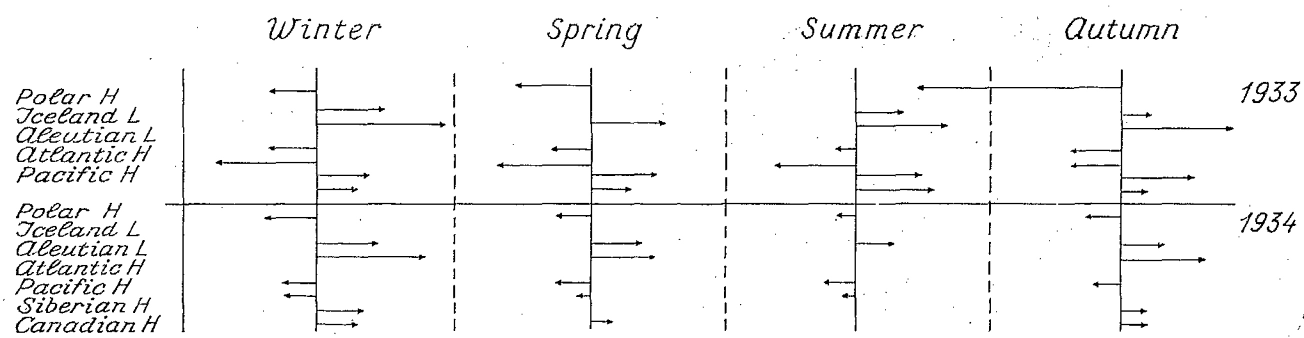

Fig. 6. Displacement of main components of the general circulation of the atmosphere in 1933 and 1934 (four seasons).

RÉSUMÉ

*Les fluctuations de la circulation générale de l'atmosphère et du climat au XX*e *siècle* (B. L. Dzerdzeevskii)

1. L'auteur a étudié les fluctuations à long terme (variations) des données relatives aux précipitations et à la température recueillies par un réseau mondial de stations météorologiques. Il a comparé et analysé les données relatives aux hémisphères nord et sud.
2. Il a fait une analyse combinée des données en certains points déterminés et des variations de la circulation générale de l'hémisphère dans son ensemble. Il a tenu compte du rapport des composantes zonales et

méridionales qui constituent les caractéristiques principales des phénomènes de circulation. A cette fin, il a analysé les cartes synoptiques de l'hémisphère nord depuis le début du xx^e siècle.
3. Cette analyse a permis de déterminer les causes principales des variations climatiques observées au xx^e siècle. L'auteur signale les relations entre les fluctuations des mêmes phénomènes de circulation et les variations de l'activité solaire.
4. Il confirme l'existence au cours de la première moitié du xx^e siècle de deux « époques » différentes du point de vue de la circulation et des caractéristiques climatiques. La comparaison entre les fluctuations des valeurs moyennes annuelles et les valeurs moyennes pour chaque « époque », d'après les observations de certaines stations météorologiques situées dans les zones arides, fait l'objet d'une analyse.
5. L'auteur examine enfin l'importance théorique et pratique des résultats obtenus pour les recherches sur les zones arides.

DISCUSSION

H. H. Lamb. Having myself tried and largely failed to define circulation types applicable to the Northern Hemisphere as a whole, I was filled with admiration for the suitability of the types defined by Dr. Dzerdzeevskii and what has been learnt from them. May I ask whether he knows if these same types are applicable also to the Southern Hemisphere or whether he has tried defining other types specially for the Southern Hemisphere.

B. Dzerdzeevskii. I believe these or similar types were recognizable in the Southern Hemisphere. This belief is encouraged by inspection of the synoptic charts by Astapenko at Little America.

J. Namias. In addition to the interesting studies relating to types of the general circulation to local or regional temperatures, has the speaker investigated any tendency to sequential development or to other lag effects in the forms of the general circulation?

B. Dzerdzeevskii. Yes, we have made such investigations. The values in several cases can reach 0.54-0.56; the prevailing value being above 0.3-0.4. This is for the individual circulation types. For the group of types the figures are higher.

J. S. Sawyer. Is it Professor Dzerdzeevskii's opinion that all important changes in temperature and precipitation can be associated with changes in frequency of large-scale circulation types? Alternatively are there any long-term weather changes which might be associated with overall changes in the structure and intensity of the general circulation not so expressed or with changes in the characteristic temperature or rainfall of individual circulation types?

B. Dzerdzeevskii. Yes. I think that all changes in temperature and precipitation—if they are taken (observed) for long enough periods—are connected with changes in frequency and duration of large-scale circulation patterns.

E. L. Deacon. Professor Dzerdzeevskii in his concluding sentences referred to the magnetic field of the earth. I take it that he here refers to solar particle effects.

B. Dzerdzeevskii. The Soviet heliophycist Dr. Rubashev compared the violations of the magnetic field with the trend of my circulation types. He established that the zonal circulation types and Arctic intrusions within the Pacific sector are observed near magnetically calm days, while intrusions within the Atlantic and European sectors occur near magnetically perturbed days. He showed also that the positive "anomalies" of meridional circulation types are connected with the minima of solar activity. These results were obtained from statistical calculations.

Dr. Rubashev investigated also the physical sense of these connexions.

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CLIMATIC CHANGE
AS AN OCEAN-ATMOSPHERE PROBLEM

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ORIENTATION FOR METEOROLOGICAL READERS ON SOME NORTH ATLANTIC HYDROGRAPHIC FEATURES

Fig. 1, published by A. Defant in 1941, and still valid in its major features, represents the available knowledge about the topography of the sea level of the North Atlantic Ocean. Hence it also represents an approximation to the geostrophic streamlines immediately under a shallow wind drift layer. Only near the jet-like currents like the Gulf Stream near America or the coastal currents past southern Greenland, do the simple geostrophic rules require corrections for lateral eddy friction and convective accelerations.

The general shape of the geostrophic streamlines satisfies the principle enounced by Sverdrup (1947) that in order to maintain at each locality a constant ocean level, poleward geostrophic flow, with its inherent horizontal convergence, must occur where the integrated transport of the drift current shows horizontal divergence, and equatorward flow with geostrophic divergence must occur under a drift current with mass transport convergence. Consequently, the proper place for poleward flow is under the cyclonic wind systems in the north where the "Ekman drift", 90° to the right of the wind direction, provides for surface divergence, and for equatorward flow under the anticyclonic wind system in lower latitudes, where the corresponding Ekman drift is convergent.

This Sverdrup principle, later amplified by Munk (1950), Stommel (1957), and Fofonoff (1960-61) is strictly valid only where the geostrophic current vanishes well above the bottom of the ocean. The bottom topography introduces additional constraints on the deep geostrophic currents all the way up to the surface, such as are seen in the sharp bends at the "Tail" of the Newfoundland Banks, at Flemish Cap (47° N., 45° W.), and at the mid-Atlantic Ridge from Iceland to the Azores.

The Sverdrup principle explains satisfactorily the important branching process of the Gulf Stream beginning at the Tail of the Grand Banks. All of the branches flowing north of the Azores will be referred to collectively as the North Atlantic Current [Iselin's (1936) terminology]. The northernmost branch flows along the oceanic Polar Front, which can be followed from the Tail of the Grand Banks in a general north-eastward and then eastward direction to the Mid-Atlantic Ridge at 51° N. Its continuation northward toward Iceland is less sharply defined, but in principle it would follow along the left flank of the farthest left branch of the North Atlantic Current, known under the name of the Irminger Current.

On approaching east Greenland the Irminger Current reaches the oceanic Arctic Front beyond which the East Greenland Current flows south-westward to Cape Farewell. The Irminger Current divides into one branch leading to the north coast of Iceland and another paralleling the East Greenland Current to Cape Farewell. The Arctic water of the East Greenland Current, although much colder than the Atlantic water of the Irminger Current, is less dense due to its low salinity and is confined to the Greenland shelf. West of Cape Farewell both Arctic and Atlantic water are represented in the north-westward-flowing West Greenland Current. Most of the Atlantic water, while progressively sinking, branches to the left toward the Labrador coast where it turns south parallel to the Arctic outflow from Baffin Bay. The Arctic water is also here lighter than the adjacent Atlantic water and does not descend from the Labrador shelf. What is normally called the Labrador Current thus consists both of Arctic and Atlantic water. The Arctic core of the Labrador current can be followed past Newfoundland and along the eastern edge of the Grand Banks to the Tail at 43° N. At that place part of it submerges while the rest makes a sharp turn into a north-eastward direction parallel to the swift North Atlantic Current. Intensive meandering of the two currents on that stretch gradually raises the temperature and salinity of the water from the Labrador Current toward that of the adjacent Atlantic water.

The cyclonic current system described above receives from the outside the warm, salty, water masses of the Irminger Current and the cold, much less salty ones,

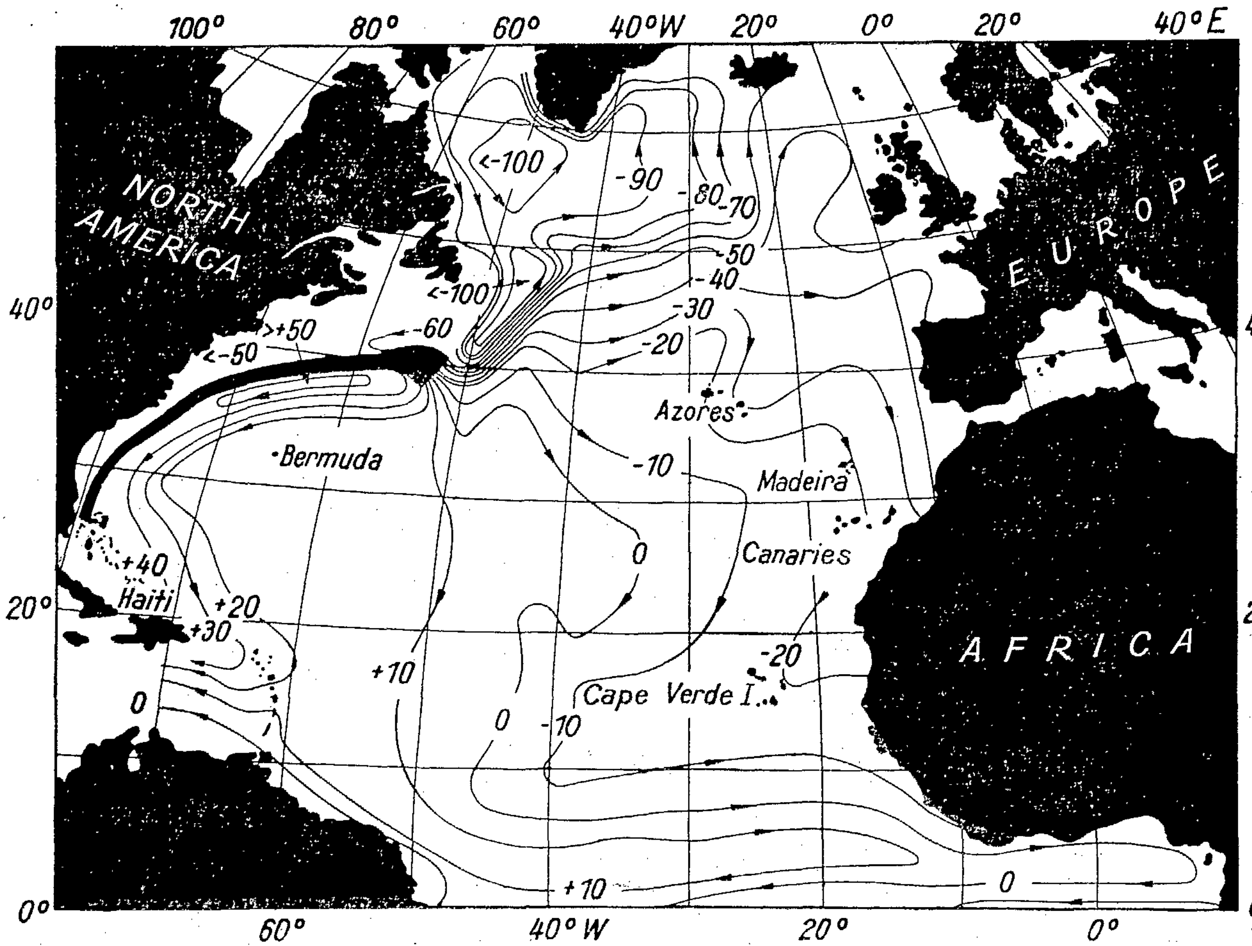

Fig. 1. Topography in dyn. cm. of the surface of the North Atlantic Ocean. (From A. Defant, 1941.)

from the East Greenland and the Labrador Currents. The excess of inflow at the surface must sink, as already described for part of the Irminger-Atlantic water, and feed a southward outflow of deep-water, estimated by Smith, Soule, and Mosby (1937) to an annual average of 1.9 million cubic metres per second. The same authors have, through their study of oceanographic profiles, been able to localize the most likely region for vertical convection from the winter-chilled surface water after elimination of the thermocline stability. It coincides with the trough of the ocean level off south-west Greenland on Defant's map in Fig. 1. According to the findings of the *Meteor* expedition in March 1935, the ocean stratification permitted sinking to about 2,000 metres depth also due south of Cape Farewell, between 57° and 55° N. and possibly continuing along the trough in the ocean level parallel to the south-east coast of Greenland.

The downwelling area coincides in location and shape with the average Iceland cyclone and its trough extension to the northern Labrador Sea (Fig. 2), in other words, it coincides with a region of Ekman divergence of the surface water. That systematic wind effect tends to keep the thermocline shallow at the centre of the oceanic vortex and it tends to maintain the observed dome shape of the deep-water isopycnals at the core of the vortex.

Atmospheric variability from day to day and month to month will interfere with the smooth performance of the dynamic linkage outlined above. In particular, it is likely that an atmospherically dictated temporary change from Ekman divergence to Ekman convergence is the trigger that releases the annual large-scale convection in late winter, which, once started, may run by conversion of potential into kinetic energy within the deep water.

The wind drift, which superposes itself on the geostrophic currents of Fig. 1, will also influence the sea-surface temperature through warm or cold water advection. A brief survey of the wind drift mechanism is therefore in order at this stage. Ekman's classical model of the drift current, reproduced in Fig. 3, contains

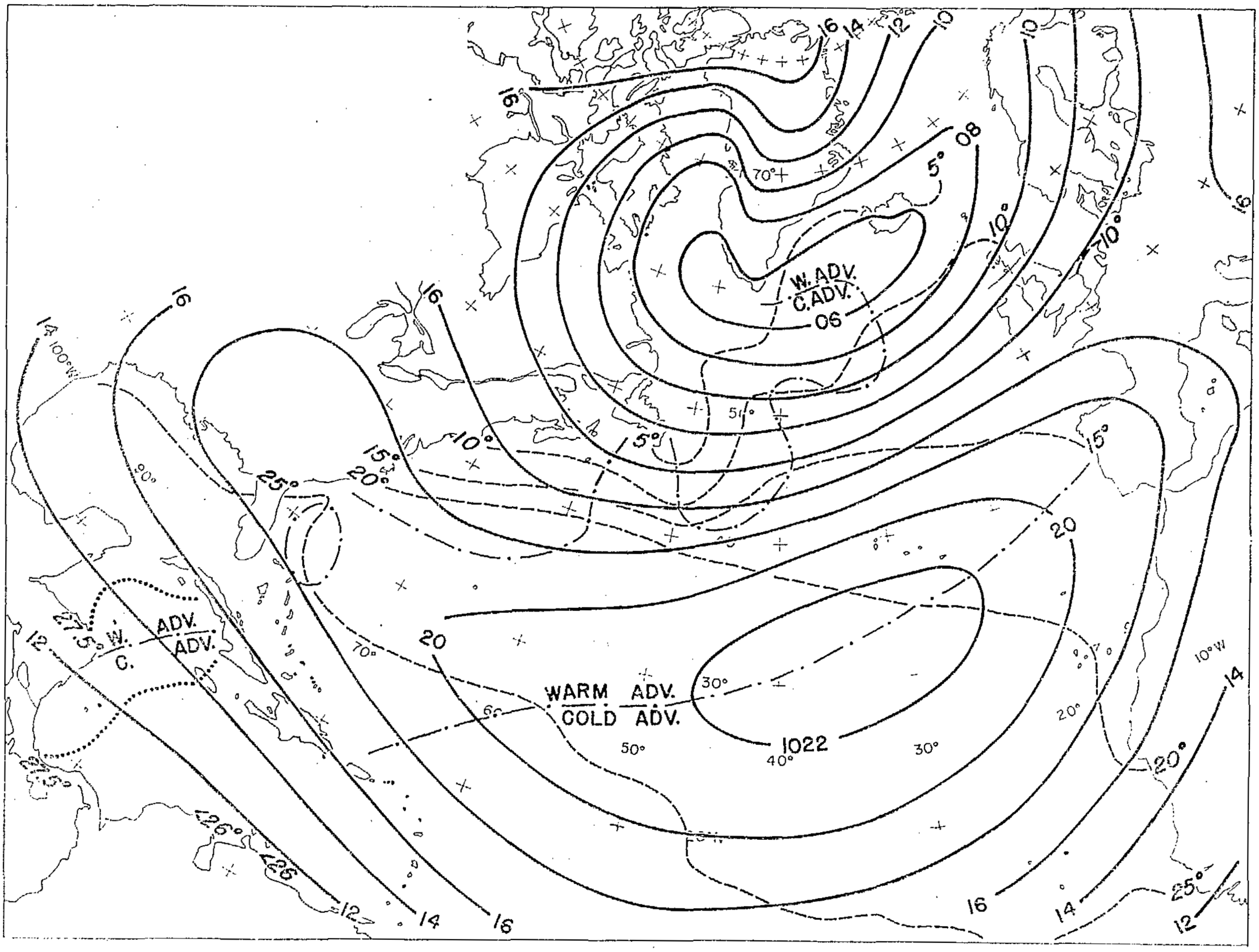

FIG. 2. Average annual isobars (solid), annual sea surface isotherms (dashed), and approximate prevailing limits (dotted) between warm and cold advection in the surface water.

all the necessary basic information: the pure wind drift at the surface of a homogeneous ocean deviates 45° to the right of the wind direction (assumed not to change with time) and turns with increasing depth more and more to the right (Northern Hemisphere) while decreasing in speed at such a rate that, in the hodograph shown at the base of the model, the arrow point of the wind vectors describes a logarithmic spiral with its centre at the common vector origin. After having turned with depth to the direction opposite to the wind drift at the surface the drift vector has decreased to $e^{-\pi} = 1/23$ times its scalar value at the surface. For practical purposes the depth where the wind drift has turned around 180° has been defined as the depth of frictional influence. That depth is known to be of the order 50 metres in the Iceland region and increases at given wind velocity as $1/\sqrt{\sin\varphi}$ toward the Equator. The "friction layer" above that depth has in the Northern Hemisphere an integrated mass transport directed 90° to the right of the wind direction. This is the "Ekman drift" already referred to:

$$T_y = -\frac{\tau_x}{\rho\, 2\omega \sin\varphi}$$

where the x direction runs along the wind direction, τ_x stands for the wind stress and ρ for water density, while $2\,\omega \sin\varphi$ is the Coriolis factor.

In our applications the atmospheric isobar is a more convenient co-ordinate axis than the wind direction. In the isobaric co-ordinate system the Ekman drift has a slight component forward along the geostrophic wind in addition to the cross-isobaric component, which is still the stronger of the two. At the ocean surface, instead of the equality of drift current components along and across the wind direction, we get in the isobaric system a greater component along than across the isobar.

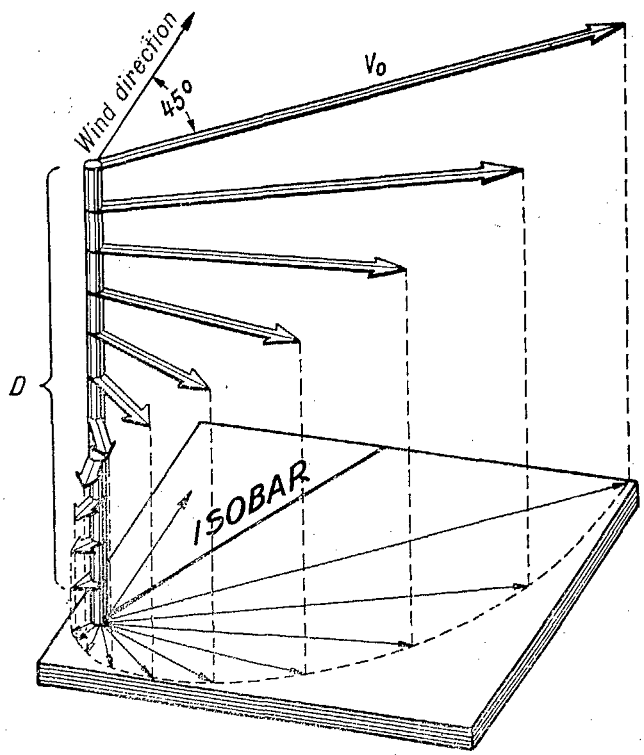

FIG. 3. Model of the pure wind drift current. (From Ekman, 1905.)

The empirical formula

$$v = \frac{0.0127\ \mathrm{W}}{\sqrt{\sin \varphi}}$$

relates the surface speeds of the pure drift current v to the wind velocity W. As a rule of thumb, which is good enough in our estimates, the average water drift in middle latitudes is only 1.5 per cent of the vectorially averaged wind.

As can be seen from Fig. 2, the long time average of the drift current is very weak in the western Atlantic, due to the small vectorial resultant wind, while from Newfoundland to north-west Europe it must be stronger, with a maximum west of Ireland. At the same time the geostrophic part of the water motion (Fig. 1) is strong, up to 150 cm./sec., in the Gulf Stream off the American coast, tapering off to speeds comparable with the drift current near Europe and Iceland. Hence, the vector sum of the geostrophic and the drift current is dominated by the former in the western Atlantic, whereas eastward from Newfoundland the meteorologically dominated drift current must become an increasingly important part of the total surface current.

Between Newfoundland, Iceland and the British Isles the geostrophic component of the surface current heads on the average a little farther northward than the average geostrophic motion in the atmosphere, while the pure drift component, in accordance with theory, deviates to the right of the atmospheric isobars (but less than 45°). Therefore we do not go far wrong by approximating the direction of the total surface current with that of the atmospheric isobars.

With the above general justification we have introduced in Fig. 2, in addition to the annual average sea isotherms, also the boundaries between warm and cold advection of surface water obtained under the approximate assumption of water motion parallel to the annual atmospheric isobars. With analogous justification the approximate picture of the time change of water advection at the ocean surface has been derived in Figs. 14 and 19 from the time change of the atmospheric circulation. It should, however, be clearly understood that the zero advection lines are merely entered as an orientation for locating the large-scale geographical changes in surface water advection, and are not an expression for precise physical theory.

One specific reason for minimizing the estimate of thermal advection in the ocean crosswise to the right of the geostrophic wind applies to the belt of westerlies. The cross-isobar component of the surface drift current goes there toward warmer and lighter water, and part of the surface water is apt to submerge wherever a baroclinic zone is encountered. With the North Atlantic Current splitting, as it does, into many branches, such baroclinic barriers would exist in great numbers and would count against the general cooling effect of the cross-isobaric advection.

In the end it is, of course, observations that must give the proper estimates of the water advection and we hope that the observations organised into the maps following later in this paper will give a little information in that respect.

In the low latitude belt in Fig. 1, the geostrophic flow in the ocean deviates systematically equatorward relative to the geostrophic flow in the atmosphere. The forces moving the water particles at the ocean surface are shown in their typical orientation in the vector diagram in Fig. 4 (from Defant, 1941). The pressure gradient force points "downhill" toward the south-east, the skin friction points south-westward parallel to the surface wind, and the Coriolis force, in order to establish balance, must point somewhere near northwards. The stronger the wind at a given ocean pressure gradient, the more the Coriolis force must point east of north to establish zero acceleration. Such a set of forces must operate in order to maintain the surface drift which in the North Equatorial Current is observed to point a little north of westward, while below the friction layer the geostrophic flow points definitely south of westward.

What is important for our problem is to know whether an increase of the trade wind will cool or warm the ocean surface. The verdict of the observations, presented by Bullig (1954) and long before him by Liepe (1911), is definitely in the sense that an increasing trade wind does cool the ocean. Recently performed spectral

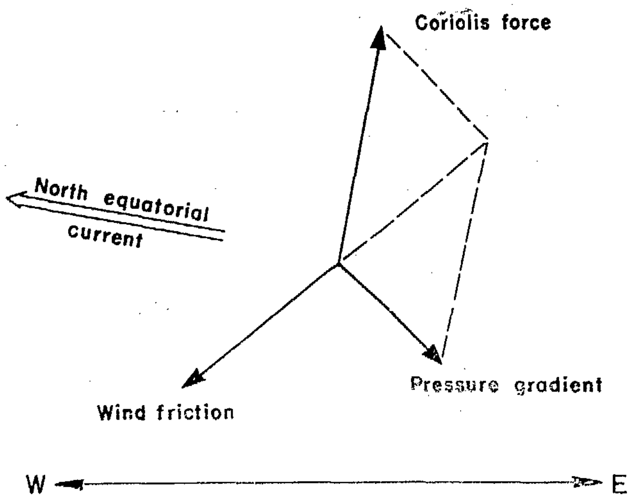

FIG. 4. Balance of forces for unaccelerated particles at the surface in the North Equatorial Current. (From Defant, 1941.)

analysis of Bullig's data by Roden (1961) confirms this result.

Despite these concordant findings, the suspicion might still remain that Liepe's and Bullig's sea temperature data on the Europe to South America shipping lane could be locally influenced by upwelling water from the African coast, and more so the stronger the north-east trade wind. The statistics by Neumann and Pandolfo (1958) for a test field between 16° and 20° N. and 34° to 36° W., settles the question for the mid-ocean trade-wind region, because also there the sea temperature and the strength of the trade wind are negatively correlated.

Three processes apparently join to firmly establish that relationship: the evaporation, the transfer of sensible heat, and the cold advection by the North Equatorial Current all tend to produce local cooling of the sea surface and more so the stronger the trade wind. The opposite advective effect of the surface component of current away from the equator, shown in Fig. 4, is evidently overcompensated.

Reference will be made in the following text to the Sverdrup-Jacobs (1942) map of the annual radiative heat surplus of the North Atlantic Ocean, and those of the net heat transfer of that ocean to the atmosphere. The maps are easily available in several oceanographic textbooks and will not be reproduced here.

TIME SERIES OF SEA TEMPERATURE IN A PROFILE ICELAND-AZORES

Fig. 5 gives an orientation concerning the fluctuations of sea surface temperature in six selected ocean test fields centred around longitude 27.5° W. and extending from western Iceland, 61.5° N. to the Azores 37.5° N. The fluctuations in the strength of the middle latitude westerlies are represented on the same time scale by the annual mean sea level pressure at Vestmannaeyar

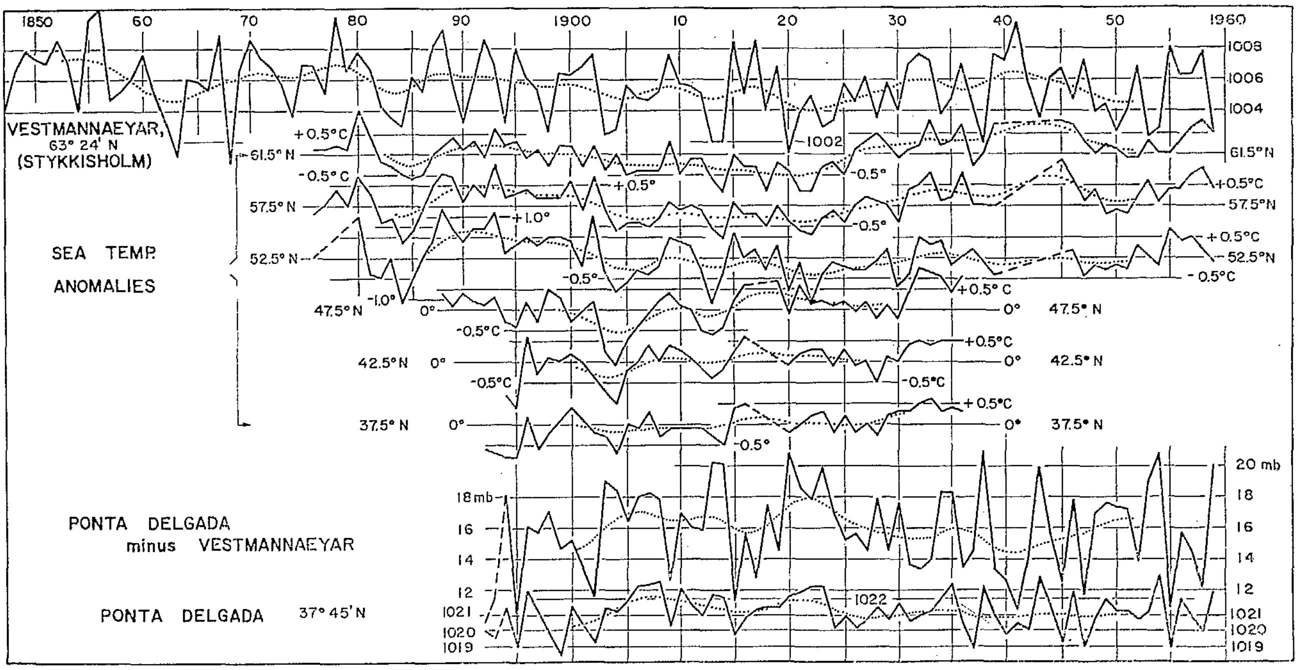

FIG. 5. Time series of annual sea temperatures in a profile Iceland-Azores. Top curve: Time series of annual sea level pressure for Vestmannaeyar (extrapolation before 1881 based on Stykkisholm). Bottom curves: Time series of annual Ponta Delgada minus Vestmannaeyar sea level pressure (zonal index), and time series of annual sea level pressure for Ponta Delgada.

(south-west Iceland) and Ponta Delgada (Azores) and supplemented by the curve of Ponta Delgada minus Vestmannaeyar pressure. In order to facilitate the visual identification of the long trends a 19-year binomial smoothing of all curves has been entered in dotted lines.

If we define the long trends by the dotted lines, we see that the epochs of weak Iceland cyclone (maxima in the Iceland pressure curve) occurred in the middle 1850s, in the late 1870s and again in the late 1880s.

Thereafter came a long trend of intensification of the Iceland low leading to the lowest pressures of the whole record in the early 1920s. Then a relatively steep pressure rise set in leading to the weakness of the Iceland low in the early 1930s, and even more so in the early 1940s. The latter maximum in the Iceland pressure curve practically equalled that in the late 1880s, but was a little less pronounced than the maxima in the late 1870s and the middle 1850s.

The sea temperature record in the ocean fields centred 61.5° and 57.5° N. started in 1876 and that of the next field to the south (52.5° N.) became continuous four years later. The smoothed curves for those three fields show a fair resemblance to the smoothed Iceland pressure curve in all major features. In particular, the long falling trend before 1922 and the subsequent rise[1] are unmistakably parallel features in sea temperature and Iceland pressure.

The correlation coefficients between the smoothed Iceland pressure curve and each of the correspondingly smoothed sea temperature curves are shown in Table 1.

TABLE 1. Sea temperature versus Vestmannaeyar pressure, both identically smoothed

Period	Test field	Coefficient
1882-1939	61.5° N.	0.66
1882-1939	57.5° N.	0.79
1882-1939	52.5° N.	0.80
1894-1928	47.5° N.	0.18

The closest correlation, about +0.8, is found between the Iceland pressure and the sea temperature in the belt of westerlies between 60° and 50° N. South of 50° N. the sea temperature correlates only slightly with the Iceland pressure. All the correlation coefficients are positive, hence indicating a warmer ocean surface when the Iceland cyclone has less than normal depth.

The conditions at the centre of the Iceland low are represented by the field marked 61.5° N. There the correlation between pressure and sea temperature is a little less firm than in the adjacent belt of prevailing cold advection westerlies.

The identification of a possible lag between the intensity changes of the Iceland low and the resulting change of the sea temperature would be of considerable interest. At this stage we will only point out as an example that the sea temperature minimum at 61.5° N. in 1885 and the maxima in 1889 and 1893 lag one year behind the corresponding extremes in the Iceland pressure curve, whereas the sea temperatures in the two adjacent fields to the south show no lag.

The test of long-trend relationships between Ponta Delgada pressure and the sea temperature in the adjacent fields to the north (all identically smoothed) gives the result shown in Table 2. The correlations are small

TABLE 2. Sea temperature versus Ponta Delgada pressure, both identically smoothed

Period	Test field	Correlation coefficient
1900-28	52.5° N.	—0.45
1900-28	47.5° N.	0.08
1900-28	42.5° N.	0.11
1900-28	37.5° N.	—0.22

and of varying sign, quite different from what was found in Table 1.

The correlations of the smoothed sea surface temperature anomalies near the line Vestmannaeyar-Ponta Delgada with the smoothed pressure differences between these two points are given in Table 3.

TABLE 3. Sea temperature versus pressure difference Ponta Delgada minus Vestmannaeyar, all data identically smoothed

Period	Test field	Correlation coefficient
1900-28	61.5° N.	—0.34
1900-28	57.5° N.	—0.82
1900-28	52.5° N.	—0.82
1900-28	47.5° N.	0.18
1900-28	42.5° N.	0.33
1900-28	37.5° N.	—0.37

The high negative correlations at 57.5° and 52.5° N. express the same dependence of sea temperature on the strength of the westerlies as do the high positive correlations for those same fields in Table 1, because the variations with time of the Azores minus Iceland pressure difference are mainly decided by the great variability of the Iceland pressure.

The northernmost field (61.5° N.) shows, as could be expected, definitely less dependence of sea temperature on the strength of the westerlies than do the neighbouring fields to the south. It is also worthy of note that the sea temperature of the northernmost field does depend on the depth of the Iceland cyclone, as shown in Table 1, whereas it depends much less on the Azores to Iceland pressure gradient.

1. For further statistical evidence of these long trends in sea temperature see also Neumann and Pandolfo (1958).

The fields south of 50° N., according to Table 3, do not follow the rule established north of that latitude. The fields 47.5° N. and 42.5° N. even show a faint tendency for warmer water when the westerlies, as defined by the Azores to Iceland pressure gradient, are stronger than normal.

So far, all the correlations discussed have been obtained from the binomially smoothed (dotted) curves in Fig. 5. As a final test of ocean-atmosphere correlations in the Iceland-Azores profile we now eliminate the long trends and correlate the shorter period residuals of sea temperature to the corresponding residuals in the Azores minus Iceland pressure change. The result is shown in Table 4.

TABLE 4. Short period residuals of sea temperature versus short periods of pressure difference Ponta Delgada minus Vestmannaeyar

Period	Test field	Correlation coefficient
1900-28	61.5° N.	—0.48
1900-28	57.5° N.	—0.64
1900-28	52.5° N.	—0.72
1900-28	47.5° N.	—0.65
1900-28	42.5° N.	—0.45
1900-28	37.5° N.	—0.45

All fields now show the tendency for negative sea temperature anomaly during years of positive anomaly of the westerly winds, and most strongly so in the field centred at 52.5° N.

Tables 3 and 4, considered jointly, present us with the question: why is the sea temperature between 50° and 40° N. correlated positively with the long-trend variations and negatively with the short-term variations of the westerlies? We will return to that question later.

Our next problem is to determine the main physical processes in ocean and atmosphere whose operation through the years leads to the statistical relationships contained in Tables 1 to 4. In the choice of method for this search the present author has been guided by his study of the monumental investigation by Helland-Hansen and Nansen (1917). These great pioneers gained their results concerning the causes of fluctuations in sea temperature from a thorough analysis of time series similar to those in Fig. 5, painstakingly compiled for the years 1898 to 1910 mainly from the shipping lane New York-English Channel.

Their conclusion was that very little evidence could be found of positive and negative sea temperature anomalies being transported along the Gulf Stream System at the speed of the water motion. Much greater temperature anomalies of the ocean surface were found to be produced by wind anomalies and to appear, and later disappear, over large sections of the North Atlantic almost simultaneously. The wind anomalies were represented in the statistical treatment by the monthly component of geostrophic wind transverse to the direction of the long-term average geostrophic wind for the same month. This method thus mainly correlates the sea temperature changes to the anomalous occurrence of north and south components of wind in the belt of average westerlies, whereby the cooling of the ocean by northerly and warming by southerly wind components clearly shows up.

The present much smaller investigation will be based on synoptic maps of (*a*) the sea temperature anomalies in selected years, or groups of years, representing extreme conditions and (*b*) the corresponding synoptic pressure fields in the atmosphere. Maps of changes of sea temperature, during selected one-way "trends" in that element, will also be used, together with the isallobaric maps describing the change in atmospheric circulation from beginning to end of the trend under consideration.

Despite the difference in tools, I feel that the present investigation is a direct follow-up of that of Helland-Hansen and Nansen 44 years ago. Its justification lies not in any revolutionizing of their ideas on ocean-atmosphere interaction, but in the utilizing of longer records of basic data.

SYNOPTIC PRESENTATIONS OF THE TRENDS IN SEA TEMPERATURE

THE SHORT TRENDS OF TWO TO FIVE YEARS

It can be expected that the simplest synoptic patterns of sea temperature change will result in the case of trends which are almost in phase all the way from Iceland to the Azores such as shown in Table 4. Moreover, the amplitudes involved in these short trends of two to five years are so great that their cause should not be too difficult to find. We have selected from the chronology diagram, Fig. 5, the years 1902, 1909 and 1915 to represent the warm, and 1904, 1913, and 1920 to represent the cold extreme in the short-period system. The successive cooling and warming trends are represented synoptically in Figs. 6 to 10 by dashed isallotherms of annual sea temperature. On the same maps the isallobars of annual pressure are shown in fully drawn lines. Reference to the long-term average annual fields of pressure and sea temperature can be obtained in Fig. 2.

The maps in Figs. 6 to 10 are strikingly similar in their major features. The isallobars show the extreme pressure changes in the Iceland-southern Greenland area, and in each case there is a centre of opposite pressure change west of the Azores. An extreme change of sea temperature is always found between the two poles of opposite pressure change, the average location of the isallotherm extreme being near 35° W. and a little north of 50° N. The sign of the sea temperature change is

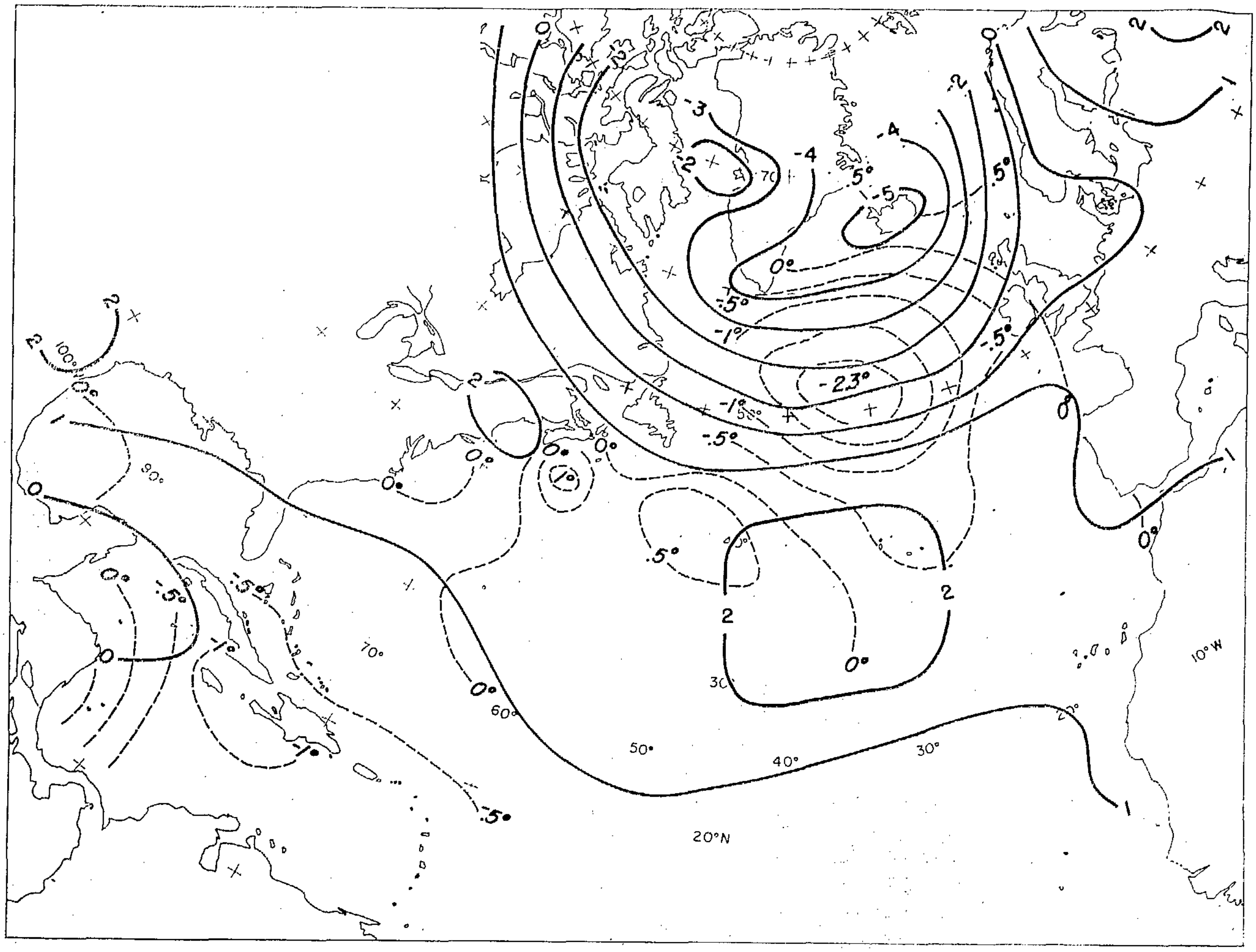

FIG. 6. Change of annual pressure and of sea temperature from 1902 to 1904.

always negative while the Iceland low intensifies, and positive while the Iceland low weakens.

Fig. 11 illustrates the average conditions for the three years of weak westerlies (low index) and Fig. 12 the three years of much stronger westerlies (high index). The dashed lines, indicating the field of sea temperature anomaly, again show the positive anomaly in the belt of westerlies to occur in low index years and the negative anomalies in high index years.

The difference in pressure and sea temperature between the average high index year and the average low index year is shown in Fig. 13. The isallobars define a belt of rise extending from the United States to southern Europe, with a maximum exceeding 3 mb. west of the Azores. The simultaneous pressure fall covers the Atlantic north of 50 °N. and exceeds —6 mb. in the Iceland to southern Greenland area. The maximum drop in sea temperature exceeds —1.5° C. and is located a little north of 50° N., near the latitude of strongest isallobaric gradient. The average extent of the area of cooling (respectively warming from high index to low index years) is defined by two nodal lines, the eastern one running from Iceland by way of Ireland to north-western Spain and the western one running from Newfoundland south-eastward, keeping west of the Azores. These nodal lines can be identified in almost fixed positions also on the individual difference maps in Figs. 6 to 10.

Altogether the maps in Figs. 6 to 13 corroborate Helland-Hansen's and Nansen's findings from before 1910 and add the information that the ocean-atmosphere system shows a distinctive tendency to repeat its geographic pattern of change although varying the rate of change from the one trend to the other.

The maximum range in sea temperature, 1.7° C., between low and high index years is almost one-third of the normal seasonal range at the same location. Hence, there must be considerable unbalance in the

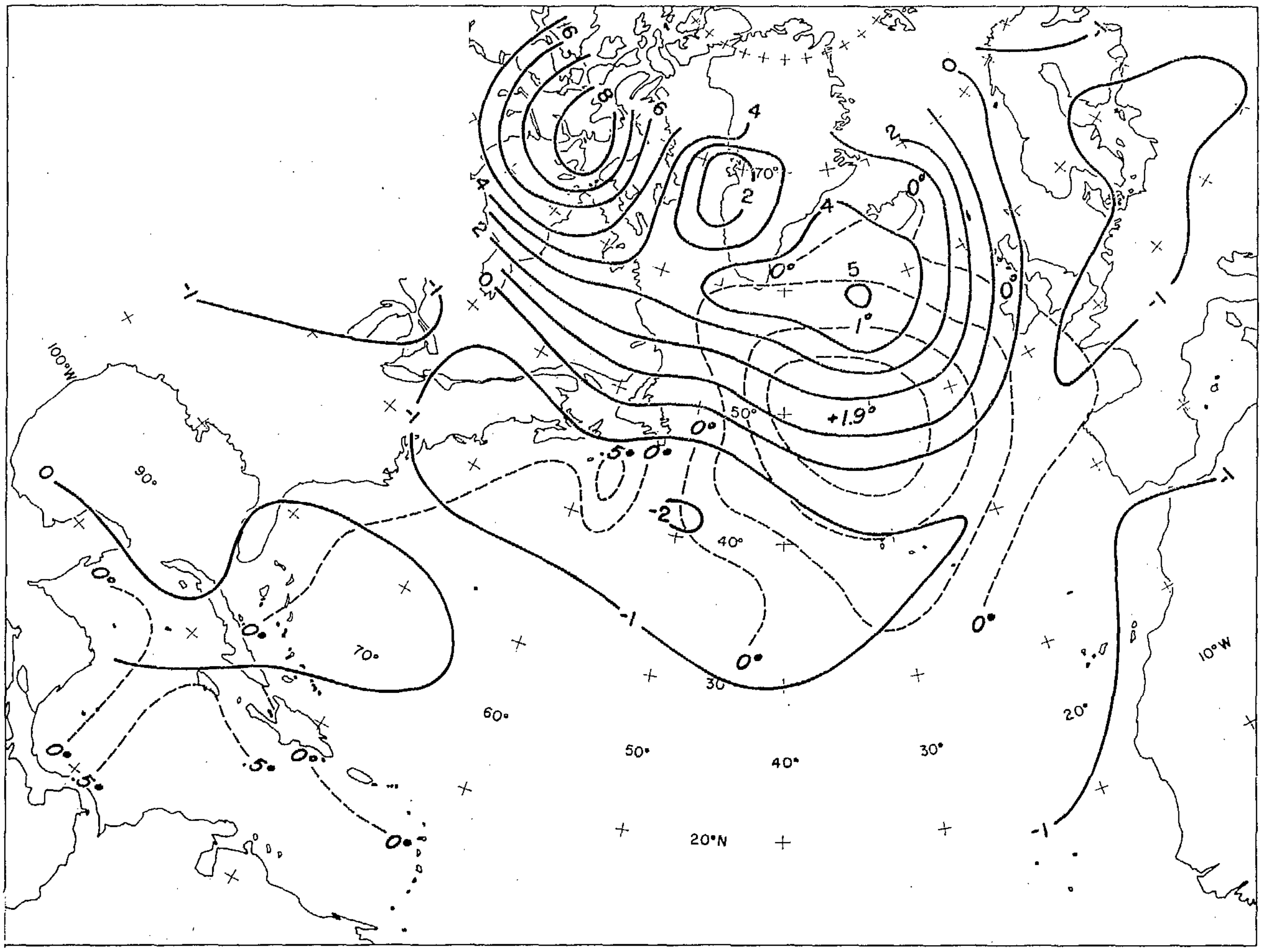

Fig. 7. Change of annual pressure and of sea temperature from 1904 to 1909.

heat budget of the sea-surface layer during the up- and down-trends in the short period system, especially so during the two-year fall 1902-04 and two-year rise 1913-15.

In seeking the physical processes most likely to be responsible for the unbalance of the heat budget we will apply the equation

$$c\int_o^{\text{year}} \frac{\delta T_w}{\delta t}\, dt = \int_o^{\text{year}} Q_r dt - \int_o^{\text{year}} Q_a dt + \int_o^{\text{year}} Q_v dt,$$

which expresses the fact that the year-to-year change of sea-surface temperature T_w of a fixed unit volume (cm.^{3}) results from: Q_r, the integrated radiation surplus of the surface water, minus Q_a, the integrated heat supply (latent and sensible) from ocean to atmosphere, plus Q_v, the integrated effect of heat advection, that is, the convergence of heat flux by ocean currents. If we think of the "surface water" as comprising the whole thickness z_o of the water layer with an appreciable annual temperature change, the heat budget is also influenced by the large and small scale vertical flux of heat Q_{z_o} through the surface $z = z_o$. In that case $\frac{\delta T_w}{\delta t}$ must be depth averaged:

$$\frac{c}{z_o}\int_o^{\text{year}}\int_o^{z_o} \frac{\delta T_w}{\delta t}\, dt dz = \int_o^{\text{year}} Q_r dt - \int_o^{\text{year}} Q_a dt + \int_o^{\text{year}}\int_o^{z_o} Q_v dt dz + \int_o^{\text{year}} Q_{z_o} dt.$$

Most of the year-to-year change in stored heat would be recorded by integrating the left-hand term down to the depth of 300 metres, where the seasonal heat impulse from above has decreased to a small fraction of its value at the surface (Patullo, 1957).

In the deep narrow geostrophic currents temperature change from year to year by varying advection may be significant perhaps down to 1,000 metres, but most of

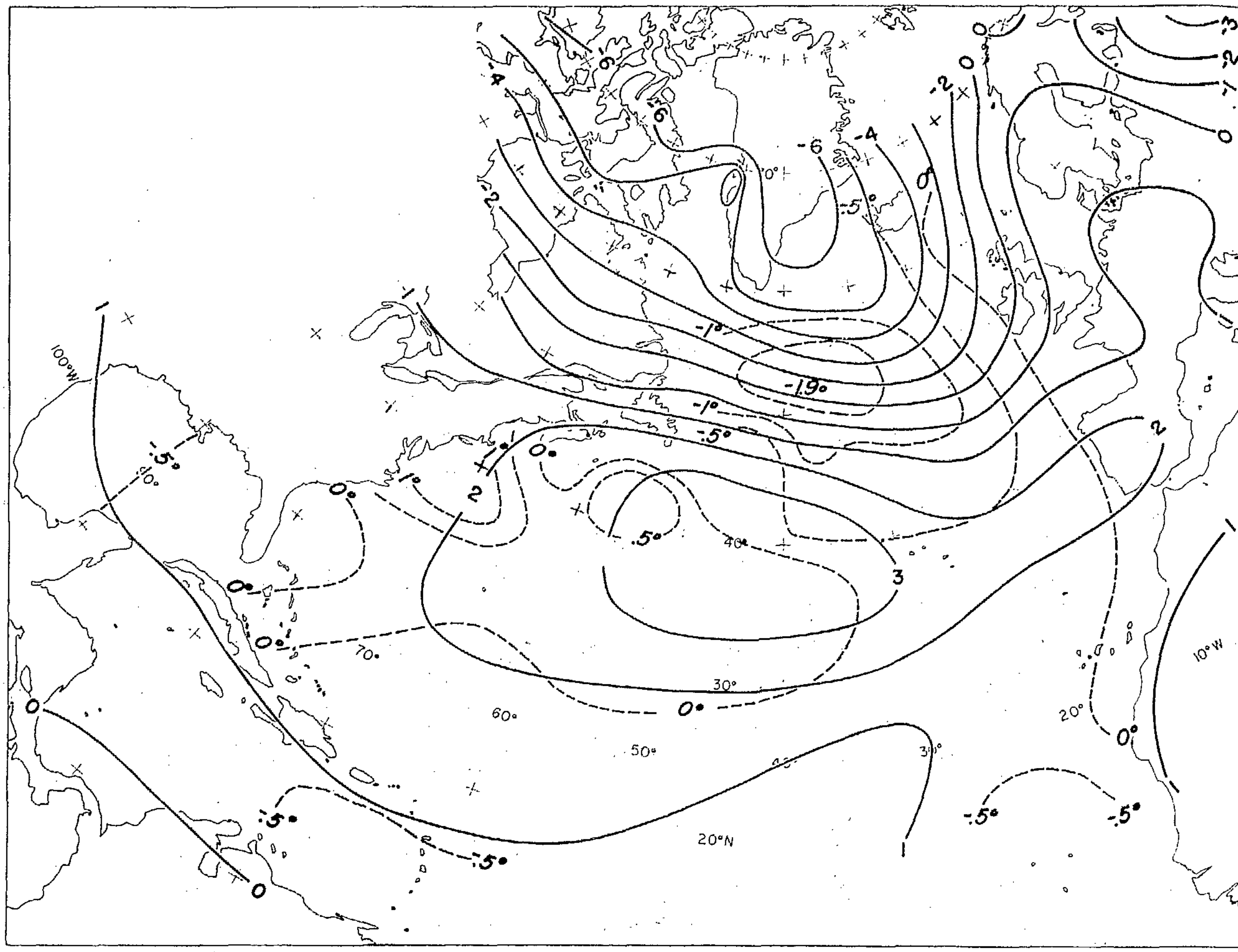

FIG. 8. Change of annual pressure and of sea temperature from 1909 to 1913.

the variability in Q_v must lie near the surface, probably within the realm of the drift current.

Consulting now the Sverdrup-Jacobs maps concerning the normal annual heat balance at fixed location within the region of maximum rate of change of temperature in the two to five year trends, we find, for a point at 50° N., 35° W., within the northernmost branch of the North Atlantic Current, that the heat loss Q_a to the atmosphere is offset by about equal amounts of heat supply from net radiation Q_r and warm water advection Q_v. Our problem is next from the map evidence in Fig. 13 to find the physical reason for the unbalanced condition of the surface-water heat budget.

The mere fact that maximum cooling or warming rates in the two to five year trends coincide geographically with the belt of greatest increase, respectively decrease, of the prevailing westerlies points to

$$Q_a = kW\,[(e_w - e) + 0.64\,(T_w - T_a)]\,\frac{p}{1000}$$

as the unbalancing factor. The loss of heat to the atmosphere is proportional to the average scalar wind W, and to the following bracket quantity which is bigger the colder the air is relative to the underlying water. The stronger the wind blows from the prevailing westerly direction, the colder will be the air it brings along from the cold western part of the ocean and, in winter, also from the cold continent beyond. It also adds to the importance of Q_a that the average wind direction in the region under consideration comes a little more from the north in high index than in low index years, as can be deduced from Fig. 13.

The influence of the wind components transversal to the prevailing wind cannot be checked by Fig. 13. We do know that during the spells of northerlies the ocean would transfer more heat to the atmosphere than it receives during the reign of southerlies (see Petterssen, 1961). But even if that surplus of cooling may be greater during low index than during high index years,

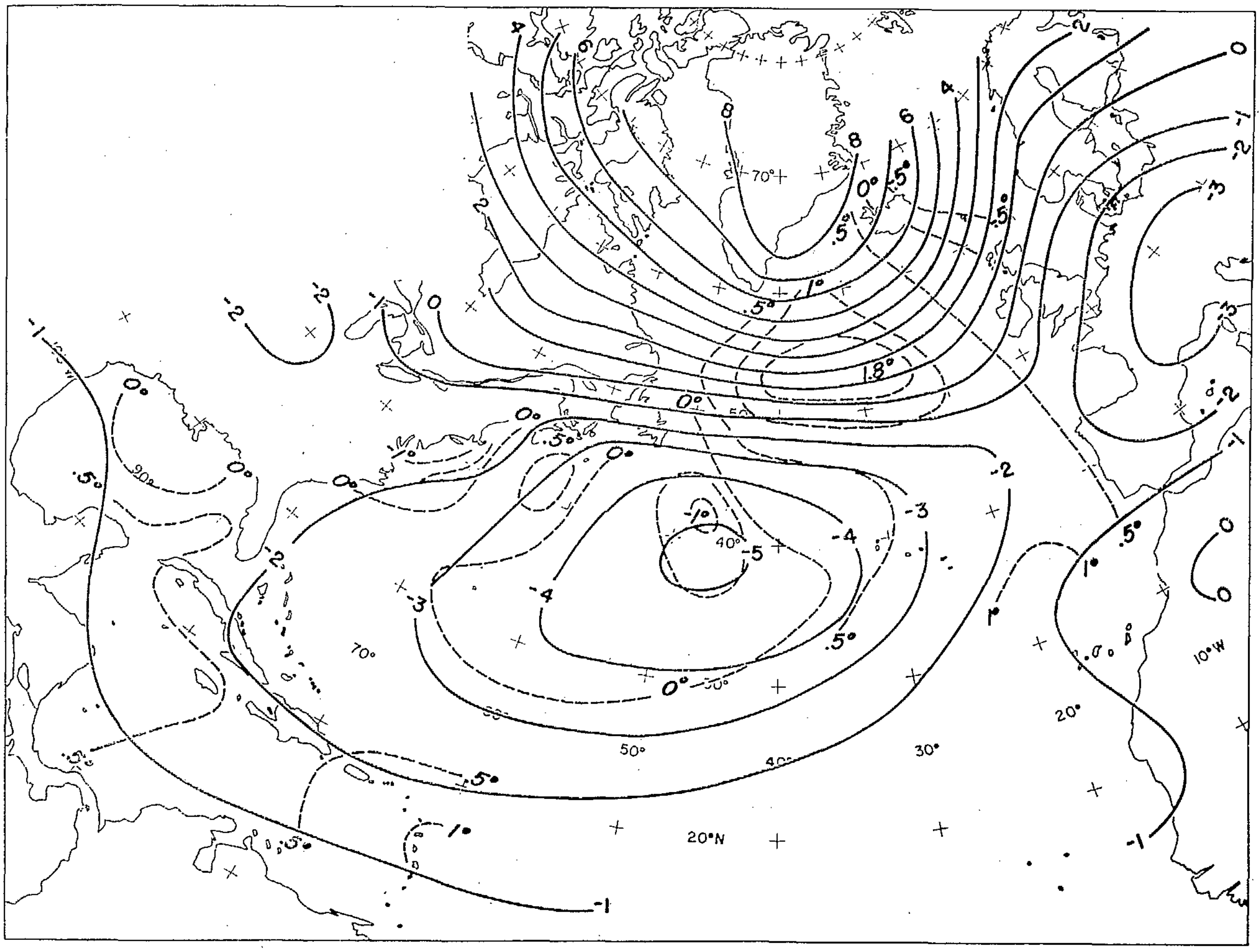

FIG. 9. Change of annual pressure and of sea temperature from 1913 to 1915.

we see from our Figs. 6 to 13 that invariably the high index years are the colder ones, which must be due to the strong westerlies.

None of the other budget items Q_r or Q_v, each of them normally only half as big as Q_a, could have produced the geographical pattern of anomaly of sea temperature in Fig. 13; but it is natural in Q_r and Q_v to seek the compensating action that eventually reverses the trend started by, say, an increase in Q_a. Let us first consider Q_r.

The radiation surplus Q_r of the surface water $Q_r = Q_i - Q_b$ is the difference between the effective incoming short-wave radiation, Q_i, and the effective back radiation in long wave, Q_b. Sverdrup (1942) writes in his discussion of the heat budget of the oceans: "The diurnal and annual variations of the sea-surface temperatures and of the relative humidity of the air over the oceans are small, and the effective back radiation at a clear sky is therefore nearly independent of the time of day and of the season of the year, in contrast to the incoming short-wave radiation from the sun and the sky, which is subjected to very large diurnal and seasonal variations."

We can add for the purpose of our discussion that also from year to year the effective back radiation from the ocean must be unable to compensate for a major unbalance created by Q_a. In fact, although a colder ocean radiates less, the atmosphere, which has also become colder, reduces its radiation to the ocean even more with the result that under a clear sky the effective back radiation of the ocean, Q_b, increases with decreasing surface temperature (Ångström, 1920; Sverdrup, 1942).

Cloudiness influences both the effective incoming radiation to the ocean surface and the effective back radiation from it. For the latter Sverdrup recommends the empirical formula $Q_b = Q_o(1 - 0.083C)$, where Q_o is the back radiation at a clear sky and C is the cloudi-

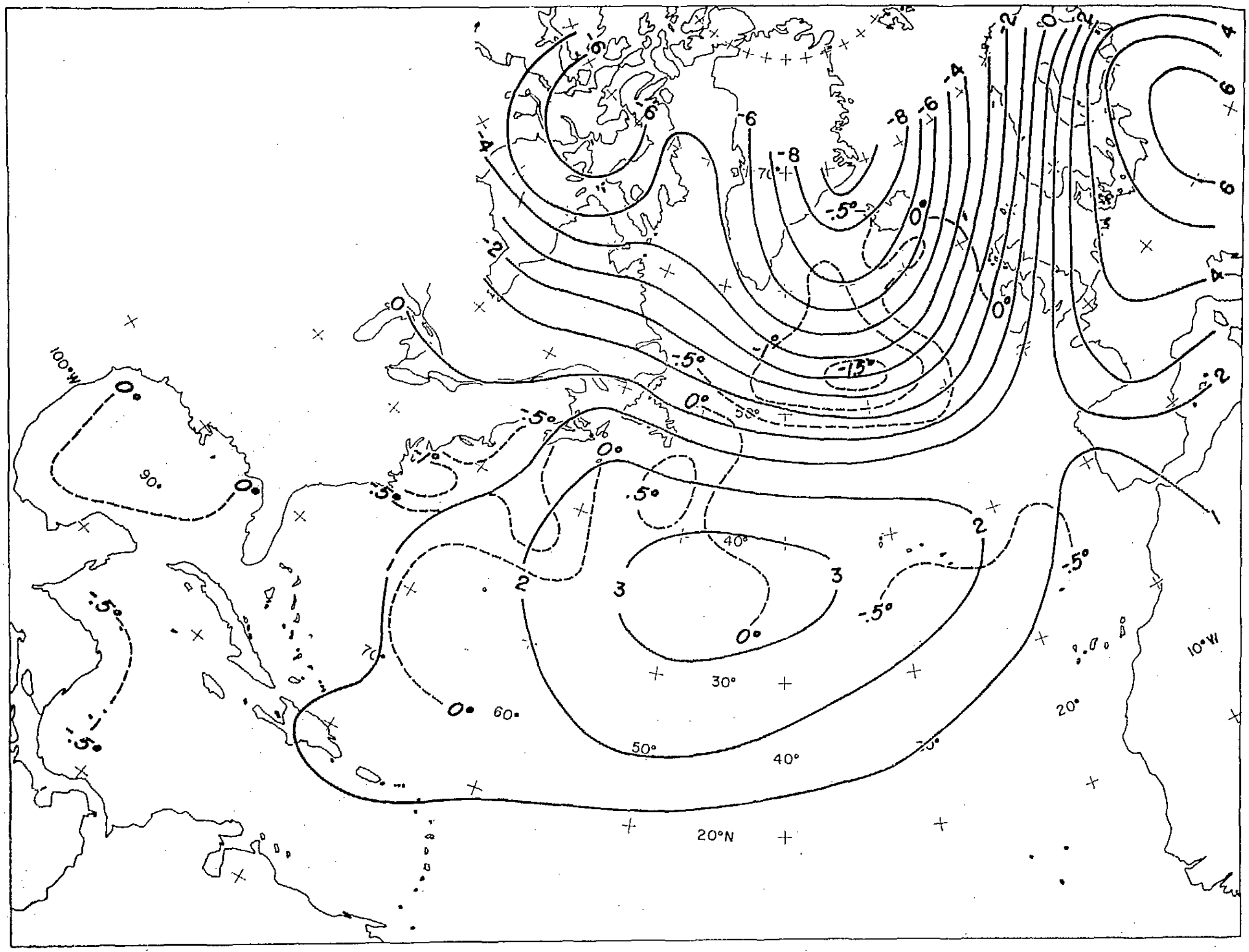

FIG. 10. Change of annual pressure and of sea temperature from 1915 to 1920.

ness on the scale 1 to 10. For the effective incoming short-wave radiation a similar empirical formula by Mosby can be used: $Q_i = k\bar{h}(1 - 0.071C)$. In it $\bar{h}$ is the average altitude of the sun, and the factor k depends upon the transparency of the atmosphere. According to the two empirical formulas above, the influence of cloudiness is percentually a little greater on Q_b than on Q_i, but since Q_i is systematically greater than Q_b (except in the Arctic winter), the influence of increasing cloudiness is to reduce the radiative surplus Q_r of the ocean. If a meteorological trend from low to high index does increase the cloudiness in the North Atlantic cyclone belt, which *a priori* may seem likely because evaporation increases, there is consequently no restoration of heat balance of the ocean water to be expected from the radiation processes. The analogous conclusion would of course be reached for the period of a cooling trend of the ocean.

A more complete discussion of the radiation balance of the ocean based on more modern research references can be found in J. Malkus (1960). The final conclusion remains unchanged.

In the following discussion we will therefore assume that it is the interplay between the time changes of Q_a, the net transfer of heat to the atmosphere, and those of Q_v and Q_{zo}, the advective heat supply and the up- or down-welling, which mainly decides the alternating trends of sea-surface temperature.

Fig. 14, in conjunction with Fig. 2, will permit us to assess the sign of the changes in both Q_a and Q_v during the transition from low to high index circulation. Starting at the American coast, north of Cape Hatteras, we see from Fig. 2 that cold advection prevails in the atmosphere out to the Gulf Stream and a little beyond, and that the corresponding drift current also would tend to move the surface water between the coast and the Gulf Stream in the cold advection sense. Fig. 14 shows that there is relatively little change in that picture from low to high index years, but the slight isallobaric wind from the south-west must be interpreted as a

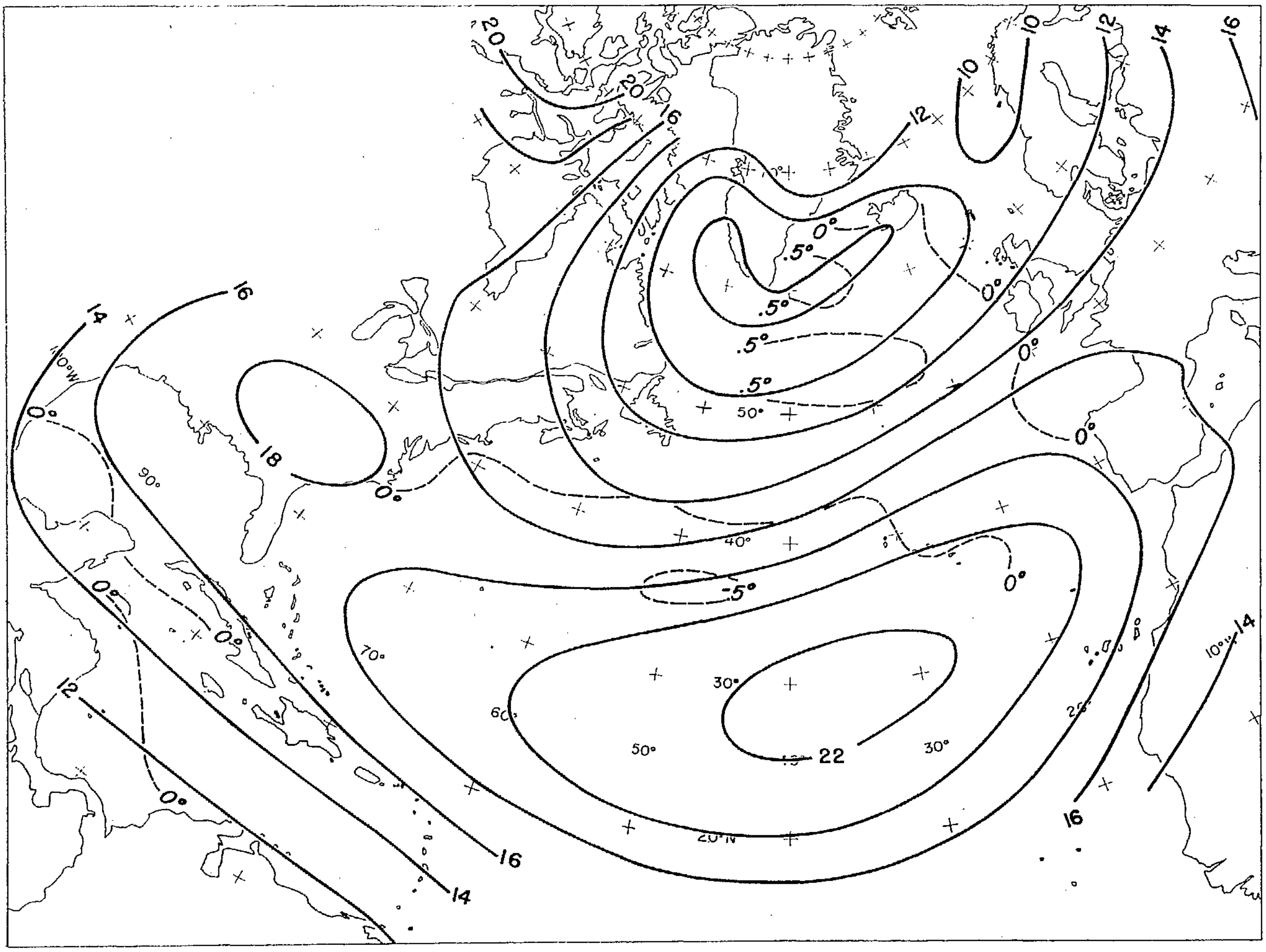

Fig. 11. Average pressure field and average sea temperature anomaly for the "low index" years 1902, 1909, 1915.

somewhat decreasing frequency and severity of the cold waves from the continent. In response, as shown in Fig. 13, the ocean temperatures from the Carolina coast to southern Newfoundland rise a little. It must be admitted, however, that this warming of the ocean from low to high index did not occur in identical fashion on each of the maps in Figs. 6, 8, and 10. Much more analysis, in finer detail, will be needed for obtaining the full understanding of the ocean response to atmospheric anomalies over the western Atlantic. Moreover, the years here selected to illustrate index changes of sea temperature in the central Atlantic are not the best to bring out typical patterns of change in the western part of the ocean.

The cold atmospheric advection, that, according to Fig. 2, is normal for the Labrador Sea and adjacent parts of the North Atlantic Current, becomes much stronger and more extensive from low to high index years. The isallobaric wind in Fig. 14 crosses sea isotherms from cold to warm in an area extending from Labrador-Greenland past the Azores into the trade-wind belt. As we have seen this agrees well with the extent and intensity of ocean cooling in Fig. 13, and with each of the low to high index cases of cooling in Figs. 6, 8, and 10.

In north-west European waters Fig. 14 indicates strongly increasing south-westerly winds from low to high index years, hence also a warm advection drift current adding vectorially to the normal warm water advection shown in Fig. 2. The sea temperature, however, only rises east of the nodal line Iceland-Ireland-north-west Spain shown in Fig. 13. For the area west of that line we may have the following two effects jointly explaining the decreasing ocean temperature:

1. The transfer Q_a of heat to the atmosphere, although not indicated to be important on the base of the average map, Fig. 2, certainly is boosted by an "eddy

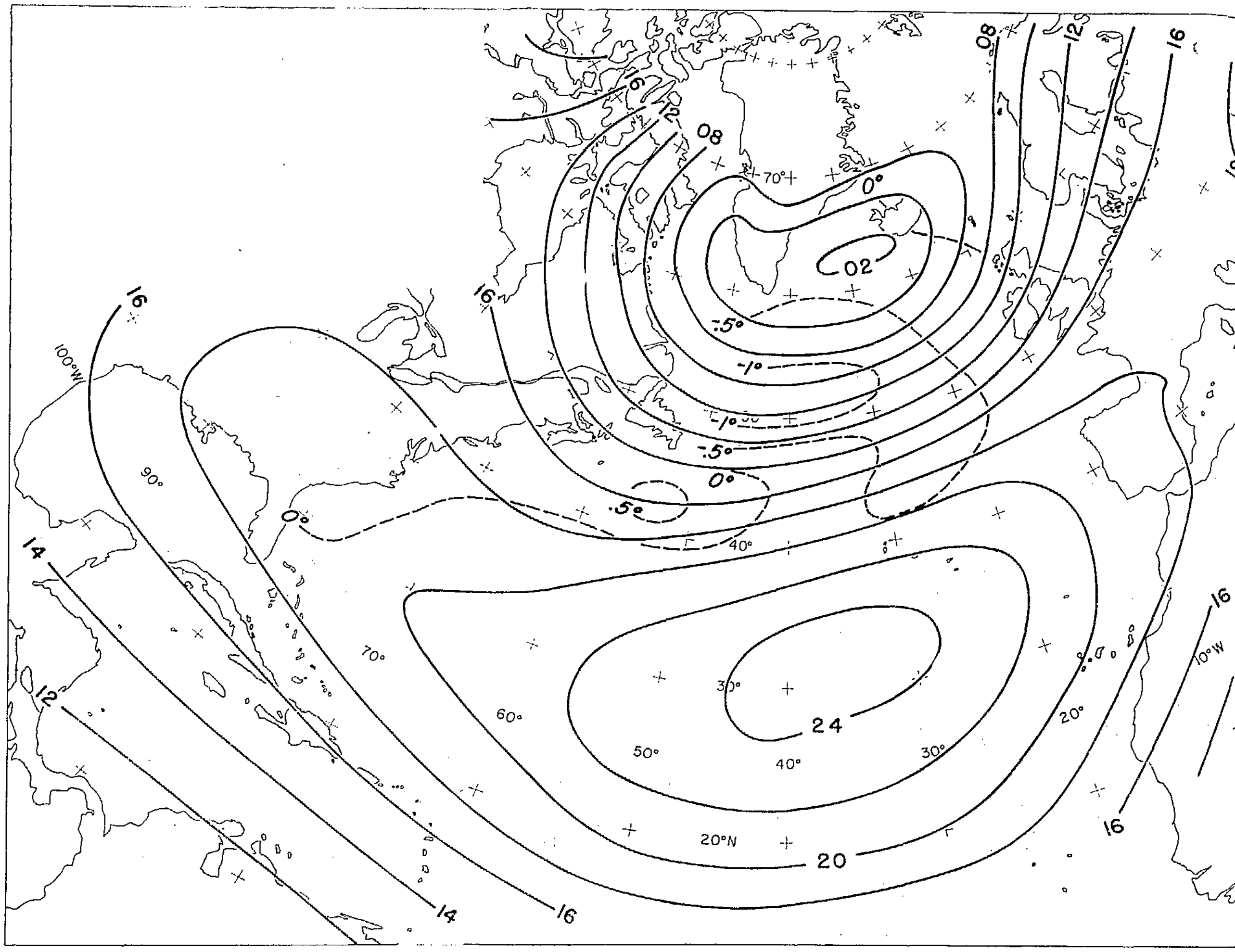

Fig. 12. Average pressure field and average sea temperature anomaly for the "high index" years 1904, 1913, 1920.

term" contribution, the eddies being the individual storm centres. The rear of each cyclone contributes strongly to Q_a, while the front side has close to zero contribution because sea and air temperatures there differ so little (see Petterssen, 1961).

2. The strongly increasing cyclonic vorticity of wind stress from low to high index over the ocean west of the British Isles may exert a noticeable upwelling effect, hence cooling the sea surface.

The centre of greatest index cycle variability of sea-surface temperature, around 53° N., 35° W. in Fig. 13, is located over the southern part of the Labrador-Irminger Sea, but big temperature amplitudes are found also over the adjacent branch of the North Atlantic Current. The nature of the sea temperature fluctuations in the northernmost branch of the North Atlantic Current is tentatively summarized in Fig. 15. The upper half of the diagram represents the observed negative correlation between sea temperature anomalies and the strength of the westerly winds. The time scale is not specified but can be assumed to be such that alternate one-way trends of two to five years are depicted with the seasonal periodicity removed by smoothing. The lower half of Fig. 15 shows, first, the anomaly of oceanic heat loss (sensible and latent) to the atmosphere. That negative quantity has presumably its maximum negative anomaly simultaneously with the maximum of the westerly winds. Secondly, the lower part of the diagram contains the hypothetical curve of the changing advective heat supply by the geographically controlled warm ocean current. This positive quantity in the local oceanic heat budget must be assumed to respond to a quickening atmospheric circulation around the Iceland low and have its maximum with some lag behind the maximum of the westerlies. At about half that lag time the anomalies of heat loss to the atmosphere and heat supply by water advection will be equal and opposite, so that the time derivative of the sea temperature

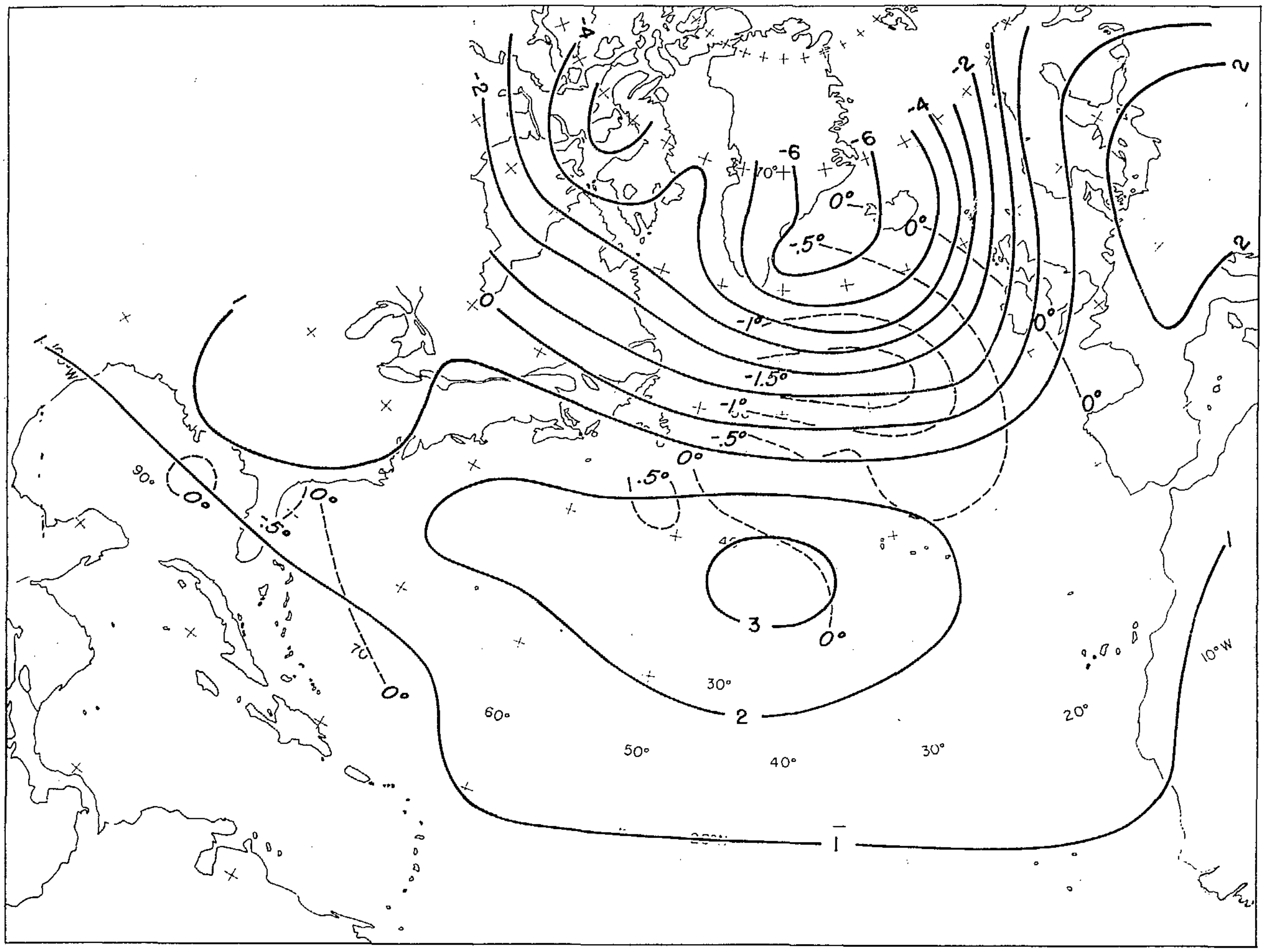

FIG. 13. Difference in pressure and in sea temperature between high index 1904, 1913, 1920 and low index 1902, 1909, 1915.

becomes zero. The maxima and minima of sea temperature should therefore follow the minima and maxima of the westerlies with the very short lag shown in the upper part of Fig. 15, a lag which by and large remains concealed in the time series of annual values in Fig. 5.

The surface waters of the southern parts of the Labrador and Irminger Seas, which share with the adjacent North Atlantic Current the great variability of temperature in two to five year trends, must also have a heat budget dominated by the anomalies of heat loss to the atmosphere and compensating anomalies of heat gain by oceanic advection, with the anomalies of the radiative heat exchange playing a minor part. No quantitative estimates of the annual heat balance in the Labrador and Irminger Seas are available in the Sverdrup-Jacobs maps (because of lack of all-year shipping), but we may assume that the following qualitative differences from the conditions in Fig. 15 would exist.

The annual heat loss to the atmosphere, Q_a, must be less north of than south of the oceanic polar front, in analogy with the conditions found by Sverdrup and Jacobs in the "slope water" and the adjacent part of the Gulf Stream near North America. But, just as in the slope water, so also in the southern Labrador Sea the annual temperature anomalies at the surface become big due to the shallowness of the thermocline which limits the thermal impact of atmospheric anomalies to a thin oceanic surface layer. The annual sea temperature anomalies may also tend to become big because of the slow response of the oceanic heat advective to the southern Labrador and Irminger Seas. The heat supply must come, either by the roundabout Irminger Current continuing into the West Greenland Current and the eastern flank of the Labrador Current, or by lateral mixing across the section of the oceanic polar front extending from the Tail of the Newfoundland Banks to the mid-Atlantic Ridge. Quantitative

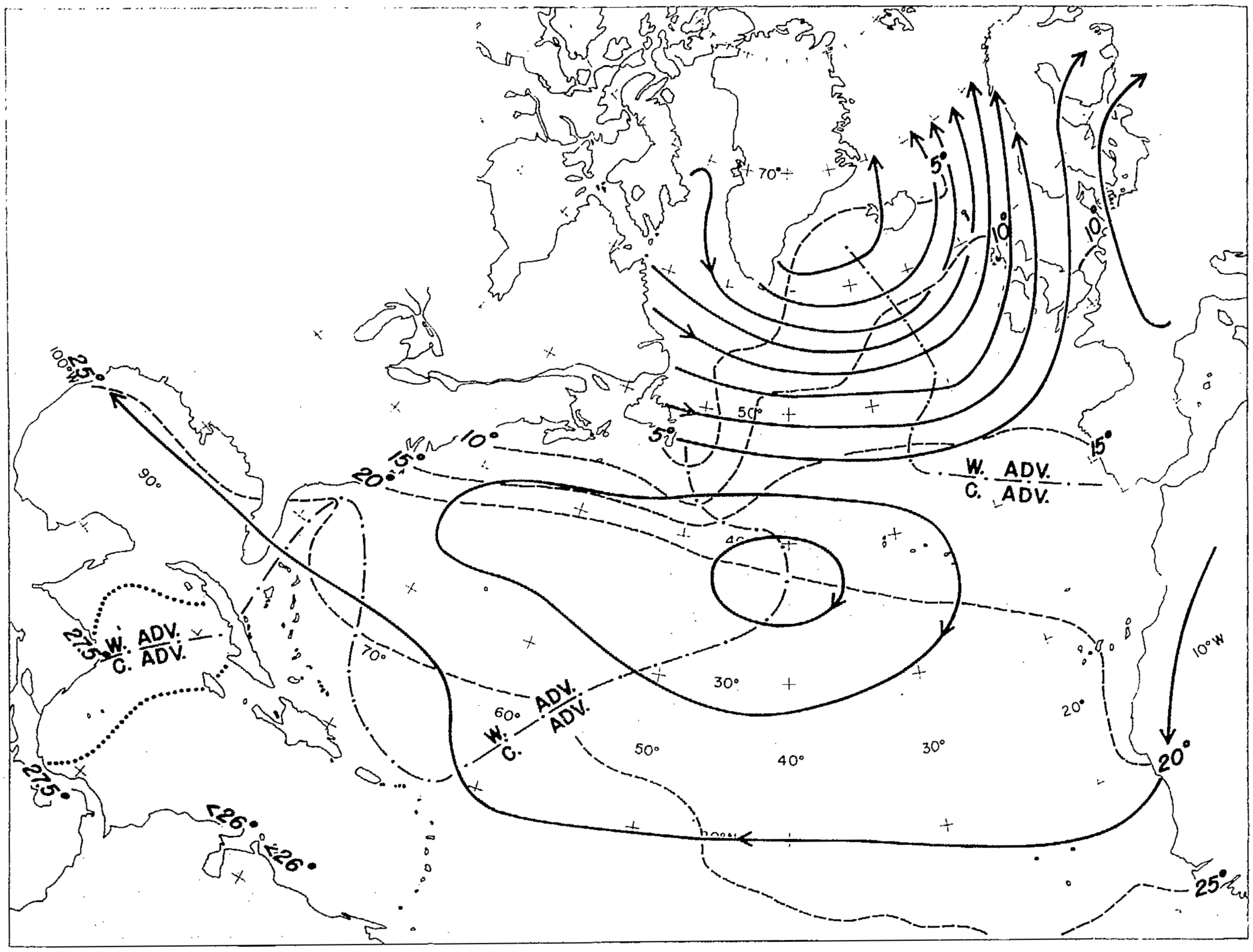

Fig. 14. The geostrophic isallobaric wind of the average trend from low to high index years. Dashed lines are the annual average sea isotherms, while dotted lines indicate borderlines between increasing cold advection and increasing warm advection.

data on these heat budget items are of course not available.

In the Labrador-Irminger Sea north of 55° N., where the heat loss to the atmosphere makes the thermocline vanish over great parts of the ocean by late winter, the sea-surface temperature reaches an absolute minimum of about 3° C. Any further heat loss at the surface would be quickly redistributed over a depth of 2,000 metres and cannot very much depress the surface temperature. In that kind of hydrographic régime the late winter minimum temperature would be almost independent of the degree of atmospheric storminess; but the length of time during which the minimum temperature is established would presumably increase under the influence of high index stormy westerlies, and likewise the size of the area where deep-water and atmosphere are in contact. Summer temperatures of the ocean surface would obviously be lower than normal under high index conditions, since a very thin warm surface layer must bear the full impact of the heat loss to the atmosphere. This is clearly shown in maps (not published) which compare high index summers with low index summers.

The oceanic advection of heat reaches the northern part of the Irminger-Labrador Sea before it reaches the southern part, and the response to the Q_a anomalies may be correspondingly faster.

Summing up, the Irminger-Labrador Sea would have its temperature changes controlled according to the same scheme of processes illustrated in Fig. 15 for the adjacent parts of the North Atlantic Current, but probably with more delayed response of oceanic heat advection to the primary meteorological anomaly of circulation.

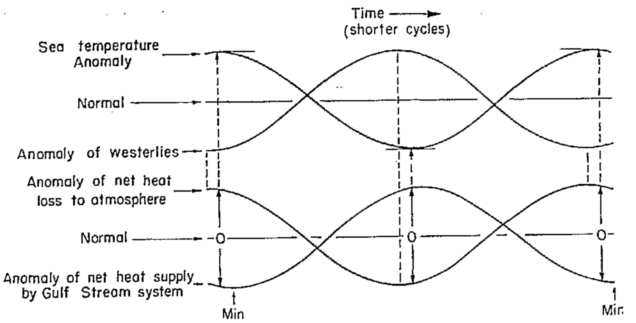

Fig. 15. Oscillations about the normal annual heat balance of the surface water in the northernmost branch of the North Atlantic Current at 35° W.

THE LONG TRENDS

A map representative of the weak Iceland cyclone in the 1890s is shown in Fig. 16. It has been constructed by binomial smoothing of grid-point values of pressure over the five-year period 1894-98. (The particular five-year period was selected as the earliest one for which the sea temperature record south of 45° N. and the pressure record at Ponta Delgada became complete.) In Fig. 17 another map, representative of the strong Iceland cyclone in the early 1920s, has been constructed by identically the same method for the five-year period 1920-24. The difference between the two maps is shown by isallobars in Fig. 18 together with the corresponding trend values of sea-surface temperatures from 1894-98 to 1920-24.

The pressure change map, Fig. 18, shows a zero line crossing the Atlantic from Newfoundland to the Bay of Biscay. North of that nodal line there has been pressure fall, with greatest amounts in the Greenland-Iceland-northern Scandinavian latitudes. South of the nodal line the Atlantic area has everywhere had pressure rise, with greatest amounts over a zone extending from Florida (near 27° N.) to the Strait of Gibraltar (36° N.). Briefly, this indicates a general strengthening of the Atlantic westerlies between 30° N. and 65° N. The

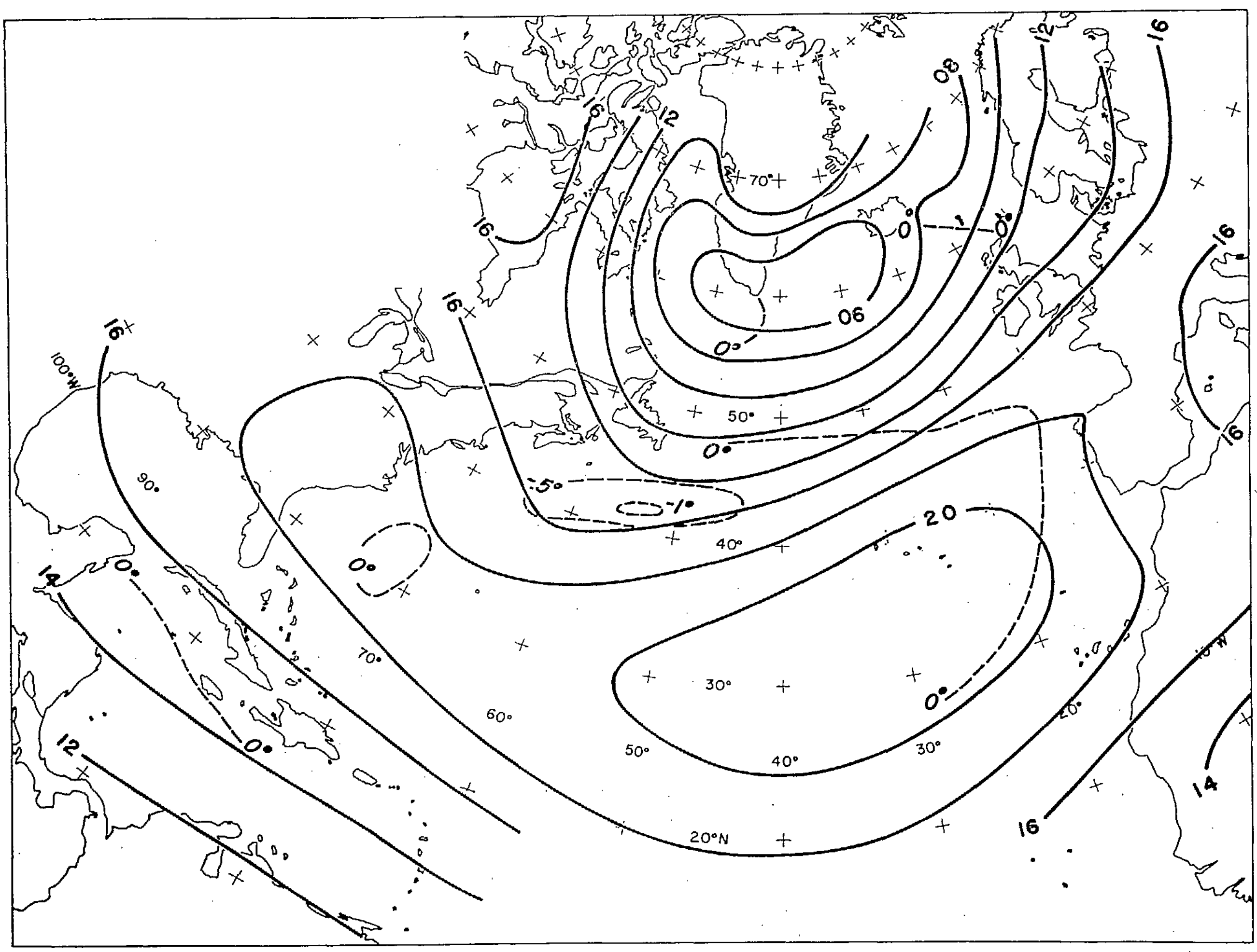

Fig. 16. Binomial average of the fields of pressure and sea temperature anomaly for low-index five-year period 1894-98.

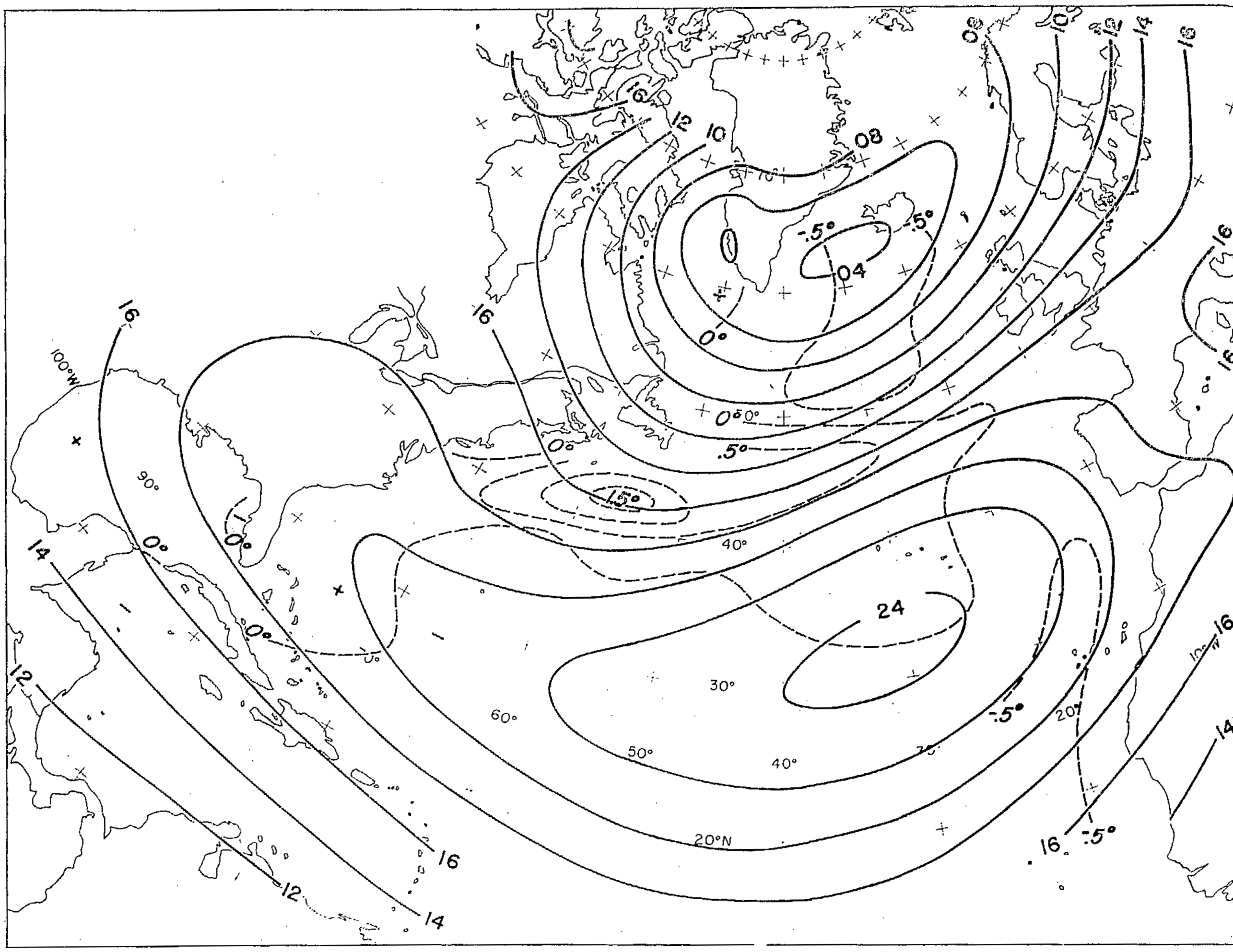

Fig. 17. Binomial average of the fields of pressure and sea temperature anomaly for high-index five-year period 1920-24.

superimposed short-wave pattern in the northern part of that belt must have resulted from the great year-to-year pressure fluctuations which do not get suXciently subdued by the five-year smoothing.

The isallobaric wind, corresponding to the pressure changes from the 1890s to the 1920s, is shown in Fig. 19 together with the annual sea-surface isotherms. An increase of warm advection can be seen to have taken place from the Bahamas along the North American coast and thence across the ocean past the Azores. Correspondingly, increased cold advection is seen to extend from southern Greenland-Iceland to the British Isles and the Bay of Biscay and likewise from southern Portugal along the Canary Current and the North Equatorial Current to the Caribbean. The resulting rise and fall of sea temperature from 1894-98 to 1920-24, recorded on the map in Fig. 18, coincide by and large with the mentioned areas of warm and cold isallobaric advection.

The long-term increase of the winds around the anti-cyclonic gyre shown by Fig. 19 also must increase the component of the drift current normal to the atmospheric isobars, toward the centre of the Azores high. As indicated on page 300 that lateral drift current component in the whole belt of westerlies is apt to submerge in the baroclinic zones. South of the Azores high the water displaced toward higher atmospheric pressure does not encounter lighter water and can stay at the surface where, in principle, it can exert a warm advection influence on the surface isotherms. The evidence of the observed sea temperature changes goes, however, definitely in the opposite sense. The cooling by the isobaric component of the drift current, and by the heat loss to the atmosphere, both of which increase with increasing trade winds, at all times seem to overcompensate the warming by the lateral component of the drift current. We may thus sum up our findings that both north and south of the Azores high the long-term sea temperature

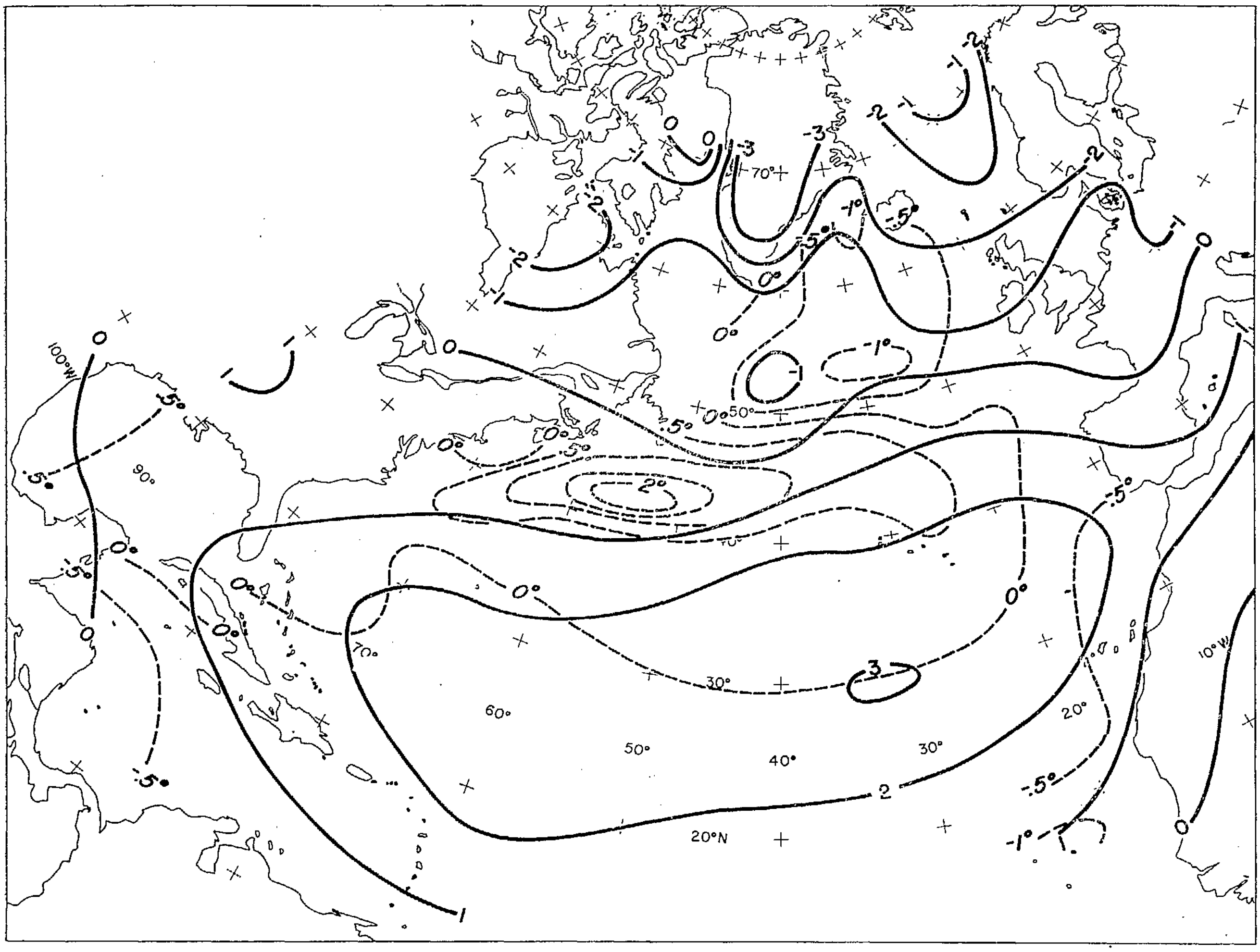

Fig. 18. Change of the fields of pressure and sea temperature from 1894-98 to 1920-24.

change mainly goes in the sense to be expected by the transport of sea isotherms by the isallobaric wind.

The particular question presented by the shift of sign of the correlation coefficient at 50° N. in Table 3 is herewith also answered. According to Fig. 19 there must be more than normal loss of heat to the atmosphere, Q_a, and less than normal warm advection, Q_v, by the isobaric component of the drift current north of 50° N., whereas warm advection in both sea and atmosphere is enhanced south of 50° N.

The long trend of weakening of the Iceland low after 1920-24 (see Fig. 5) led to sea temperatures in Iceland waters equalling those in the warm 1890s, and was associated with a widespread warming of the atmosphere in high northern latitudes. The ocean aspect of that climatic change was described by the present author in 1959 and will not be repeated here. Our remaining topic will be to discuss briefly what may be learnt about ocean-atmosphere feedback processes from the synoptic study of the long and short climatic trends earlier in this paper.

FEED-BACK FROM OCEAN TO ATMOSPHERE

The oceanic response to both short and long atmospheric trends is to set the thermostat, represented by the sea surface temperature, lower in the Labrador-Irminger Sea the deeper is the Iceland cyclone. Simultaneously, the subtropical high intensifies and the ocean sets the thermostat higher along the whole western and northern fringe of the anticyclonic current gyre (1894-98 to 1920-24, Fig. 18), or only slightly higher along its north-western fringe (in short period shifts from low to high index, Fig. 13). Common for both cases is the strengthening of the meridional temperature gradient of the mid-Atlantic between 40° and 50° N. Only in

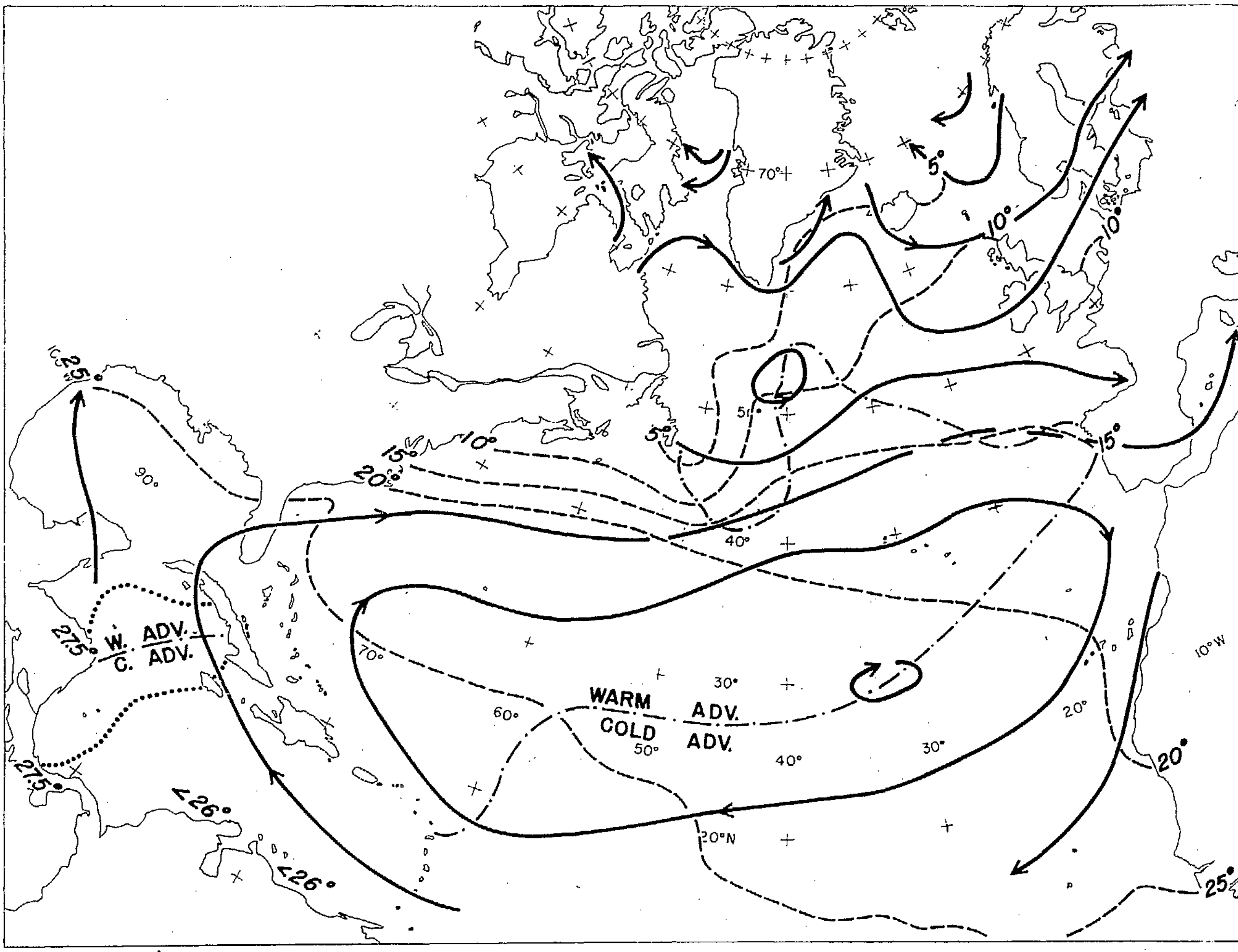

FIG. 19. The geostrophic isallobaric wind of the trend from low-index 1894-98 to high-index 1920-24 and the long term average isotherms of the ocean surface.

the long trend 1894-98 to 1920-24 does this intensification of oceanic baroclinicity extend all the way from 70° to 20° W. longitude, and we will use that case (Figs. 17 and 18) as the best available model of the long term ocean-atmosphere feed-back mechanism in the middle latitudes.

An increasing oceanic baroclinicity automatically introduces an increasing atmospheric baroclinicity at the surface and on up through all the layers in convective exchange with the surface. This is facilitated by the fact that the prevailing west-south-west wind does not deviate much from the orientation of the zone of increasing baroclinicity, and quite often the wind blows right along it.

Increasing baroclinicity in the belt of westerly winds increases the vertical wind shear and the maximum of westerly speed at the tropopause. More upper tropospheric kinetic energy thus becomes available as input into cyclonic storms the further the trend toward increasing baroclinicity proceeds.

The American coast from New England to Newfoundland is known as a place of frequent cyclogenesis on fronts parallel to the coastline, or of intensification of cyclonic disturbances arriving from the west. The reason is again the semi-permanent baroclinicity between the Gulf Stream air and the usually much colder air to its north-west. The trend toward increasing baroclinicity over the stretch from 70° W. to 20° W. will give a statistically noticeable boost to the cyclogenesis, or other intensification of cyclones, along the coastline and on out into the mid-Atlantic.

Young frontal cyclones always set their course north of the pre-arranged zone of maximum baroclinicity. They will thus usually end their careers as fully developed storm centres near Iceland more often than over the British Isles. The deep storm centres tend to become stagnant, and the Iceland low can be said to be maintained in more or less intense condition by the arrival of the once fast moving but later retarding storm centres from the south-west. Statistically we therefore should get a deeper Iceland low the more efficiently the baroclinic mechanism operates from the Grand Banks to the mid-Atlantic, and this therefore appears to be the reason for the progressive lowering of the Iceland pressure from 1894-98 to 1920-24.

With the progressive intensification of the cyclonic vortex between southern Greenland and Iceland the Ekman flux makes the surface water diverge from the centre, so that colder deep-water reaches to or near the surface. This process cannot lower the late winter minimum temperature in the region where each year the thermocline anyway vanishes by winter cooling. But an increased Ekman divergence can widen the area where that happens, and keep the deep-water longer in contact with the atmosphere, or just thin out any remaining warm surface layer and lower its surface temperature. What all these alternatives amount to is setting the oceanic thermostat lower in the Labrador-Irminger Sea and increasing the baroclinicity along its southern fringe, whereby the chain reaction between ocean and atmosphere continues its course.

At this stage we introduce Fig. 20 as a graphical record of the working of the one-way chain reaction and its eventual reversal. The time-scale runs from left to right and covers the period of strengthening of the Iceland low from 1890 to 1920 and its weakening from 1920 to 1940. The sea temperature at the centre goes through a maximum a little after 1890, a minimum a little after 1920, and a maximum after 1940 (see curve for 61.5° N. in Fig. 5). The two lower curves in Fig. 20 represent the schematic behaviour of the heat gain and heat loss of the surface water by the two factors whose fluctuations are believed to be the most important in determining the shifting heat balance. Since we idealize the discussion to be valid at the supposedly stationary cyclonic centre, the heat transfer, Q_a, to the atmosphere, which was essential in the heat budget at a location in the strongest part of the cold westerlies, loses its importance. Instead we are concerned with the upwelling as a cooling factor Q_{z_0}, and the Irminger Current, which flows geostrophically northward under the centre of the Iceland low, as a warming factor, Q_v. If both cooling and warming operated at normal rate no year-to-year temperature change would result. The curves in Fig. 20 show the assumed interplay of the deviations from normal of the two factors.

The upwelling responds to changes in intensity of the Iceland low as fast as does the Ekman drift, which means almost instantaneously. The curve for the cooling rate has therefore been drawn with a positive anomaly (that is, less than normal cooling) when the Iceland low is weak and a negative anomaly (more cooling than normal) at the time of strongest Iceland low.

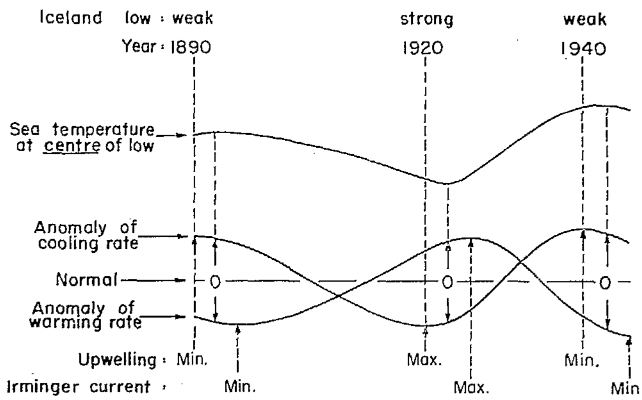

FIG. 20. Suggested model of secular variations in heat balance of the surface water near the centre of the Iceland low.

The Irminger Current, the farthest left branch of the North Atlantic Current, always conveys water of Gulf Stream origin, but it comes presumably from subsurface layers of that current while the topmost, warmest layers have branched off toward points south of the Azores and remain in the anticyclonic gyre. The current finally reaching Iceland waters has also been cooled by lateral mixing at the "cold wall" to its left and, even more importantly, by heat loss to the atmosphere as represented graphically in Fig. 15. Nevertheless, the pulses of heat flux of the Gulf Stream and the North Atlantic Current, in response to a strengthening subtropical high and simultaneously strengthening Iceland low, must be assumed to reach Iceland waters too, although after much attenuation and delay. In Fig. 20 we have therefore arbitrarily placed the maximum heat delivery by the Irminger Current a few years behind the time of maximum atmospheric circulation, and correspondingly the minimum heat delivery a few years after the year of weakest Iceland low.

The equality of cooling rate by upwelling and warming rate by the Irminger Current will then be reached at about half the assumed lag of the extremes of heat delivery behind the extremes in the intensity of the atmospheric circulation. The extremes in sea temperature must coincide with the time of equality of the fluctuating cooling and warming factors, and should occur with a minimum shortly after the year of strongest Iceland low and a maximum shortly after the year of weakest Iceland low.

The presented picture of the heat balance of the ocean at the centre of the Iceland low in Fig. 20 is admittedly over-simplified. Its greatest shortcoming probably lies in the assumption of a completely stationary Iceland low with a calm central area. In reality, winds of all directions, and quite often strong ones, do occur at such a location. A net heat loss to the atmosphere is bound to result if cold advection and warm advection winds have statistically equal strength and frequency. What matters for our problem is whether such net heat loss is greater when the average Iceland low is deeper, or less deep, than normal. The former case would seem to be more likely and, if so, the heat loss to the atmosphere would go in phase with the heat loss by upwelling in Fig. 20. Proceeding southwards to the belt of maximum westerlies the heat loss to the atmosphere increases, and the role of the upwelling decreases, so that a simplified heat budget like that in Fig. 15 can be assumed to apply.

We can probably claim a little bit of support for the above hypothesis from the correlation Tables 1 and 3. The sea temperature at 61.5° N. (representing the centre of the Iceland cyclone) correlates with a factor of —0.66 to the depth of that centre, and thereby indirectly to its cyclonic vorticity, whereas it correlates poorly, —0.34, with the strength of the westerlies between Iceland and the Azores. On the other hand, the sea temperatures of the test fields centred at 57.5° and 52.5° N. correlate well, —0.82, with the strength of the westerlies. As mentioned in the discussion of Fig. 5, there is also a little more indication of the sea temperature lagging behind the extremes of the Iceland pressure record in the 61.5° N. test field, while no systematic lag of sea temperature behind the extremes of the westerlies is discernable in the adjacent fields to the south.

The ocean-atmosphere feed-back in the two to five year trends must also operate by way of the strengthening and weakening of ocean baroclinicity in the belt 40° to 50° N., which makes the atmospheric baroclinicity fluctuate in the same phase. The orientation of the ocean isallotherms involved (Fig. 13) is about west-north-west to east-south-east while those characterizing the long trend were more truly zonal (Fig. 18). It is therefore natural that the storms activated during the short-period maximum baroclinicity hit Europe as far south as Ireland, and leave a statistical imprint on the average pressure map in the shape of a pronounced trough just west of Ireland. The rear of that type of cyclones brings the cold outbreaks to the Azores, and beyond, and account for the minimum of ocean temperature there in high index years.

The oceanic feed-back in the trade-wind belt is perhaps as simple as this: Maximum trade-wind and maximum westerlies (high index) must occur together, so that the skin friction between atmosphere and earth exerts mutually cancelling torques about the axis of the earth in low and middle latitudes. At that high index stage the fuel consumption of the atmospheric thermodynamic engine in the form of low-latitude heat supply from the earth is likely to be at a maximum. The contribution from the low latitude ocean, which must be the decisive item, is given by the integral over the oceanic trade-wind area A of

$$\int^{A} Q_a dA = \int^{A} kW \left[(e_w - e) + 0.64\,(T_w - T_a)\right] \frac{p}{1000}\, dA.$$

The trade-wind velocity W is at its maximum at the high index stage, and there is also some evidence that k (assumed constant by Sverdrup) increases somewhat with wind speed. $(e_w - e)$ and $(T_w - T_a)$ are, according to a set of 59 single measurements from the Wyman-Woodcock (1946) expedition to the Caribbean, negatively correlated with W. The time variations of the Q_a integral (after elimination of the seasonal period) can thus be kept very close to zero. If that were not so, climatic change would take place much faster than actually observed.

J. Malkus (1960) has issued a timely warning about the "precarious position" of the attempts at treating climatic change quantitatively, by the following numerical example: If an initially balanced energy budget of a tropical ocean were disturbed by an increase of 1 per cent in the heat of evaporation, a 200-metre deep ocean layer would in the course of 50 years cool off by 3° C. No measurements of evaporation integrated over a tropical ocean can pretend to be anywhere near the accuracy of 1 per cent. Computing, not to speak of predicting, climatic change from field measurements is therefore rather hopeless.

Our main impression of the workings of the important oceanic feed-back from the trade-wind zone can therefore only be expressed in terms of a working hypothesis, as follows: a trend of increasing kinetic energy of the general atmospheric circulation should be indicative of increasing heat energy input from ocean to atmosphere in the trade-wind zone. If so, the increasing energy input would vary parallel to, and would probably be caused by, the increasing strength of the trades. Analogously, a decreasing energy input, and decreasing intensity of the general circulation, would be caused by the decrease in trade-wind velocity. In that way it can be visualized how the atmospheric circulation, by controlling its own tapping of ocean heat, can lend some degree of persistence to positive or negative changes in its own world-wide energy manifestation.

This purely terrestrial view of climatic change by ocean-atmosphere feed-back should, in due course, be supplemented by sifted and tested ideas on solar control of climate.

CONCLUDING REMARKS

Whereas the fluctuations in time and space of the atmospheric circulation and the resulting changes in sea-surface temperature could be shown to have many clear cut cause-and-effect relationships, quite essential questions still remain unanswered. For instance, although we can probably better understand the persistence of climatic trends, from a couple of years to decades, by studying the interaction of ocean and atmosphere, we have in our data not been able to uncover any clue to the problem of what decides the duration of a trend and its eventual reversal. The shifts of trends do not show the regularity of real periodicities, but yet they do not look like completely random occurrences.

The complexity of the picture must be mainly due to the atmosphere, because atmospheric disturbances travel fast and far and can bring on to the Atlantic scene influences from the whole hemisphere, for instance, represented by the incessantly changing arrangement of the long standing waves in the upper westerlies. A continued study of the ocean-atmosphere interplay (both Pacific and Atlantic) during post-war time, with data from a hemisphere-wide synoptic aerology added (see Namias, 1959), would seem to offer possibilities for explaining part of the phenomena which at this stage are shrouded in uncertainty.

ACKNOWLEDGEMENTS

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Data for my research have been supplied by the Conseil Permanent International pour l'Exploration de la Mer, Copenhagen, and the National Weather Record Center, Asheville, N.C., and the data processing has been in the hands of a team of student helpers at the University of California, Los Angeles. For all the helpful services performed I am herewith expressing my sincere thanks.

RÉSUMÉ

Les fluctuations climatiques, conséquence de l'action réciproque de l'océan et de l'atmosphère (J. Bjerknes)

Les températures superficielles de l'Atlantique-Nord ont été étudiées dans les archives de l'U. S. Weather Bureau, de l'Office météorologique danois et du Conseil permanent international pour l'exploration de la mer (siégeant à Copenhague), en vue de déterminer les causes météorologiques de leurs fluctuations d'une année à l'autre et à de plus longs intervalles.

Le long refroidissement qui, de 1890 jusqu'aux environs de 1920, s'est fait sentir au nord du 50^e degré de latitude N., va de pair avec un renforcement du minimum d'Islande, et le réchauffement qui s'est produit ultérieurement jusqu'aux environs de 1940 est associé à un affaiblissement du minimum d'Islande. Pendant la longue durée du refroidissement septentrional, l'eau s'est réchauffée à l'ouest et au nord du maximum croissant de la zone subtropicale probablement par suite de l'augmentation de l'advection par le vent et par le Gulf Stream. Le refroidissement septentrional et le réchauffement du Gulf Stream ont augmenté la baroclinie le long du 50^e degré de latitude N. Par la rétroaction océanique également, l'atmosphère a dû augmenter sa baroclinie sur cette latitude, intensifiant ainsi la moyenne de l'énergie de cyclogénèse le long du front polaire atmosphérique. Ce fait lui-même a dû entraîner le renforcement progressif du minimum d'Islande.

Le long refroidissement septentrional qui s'est produit de 1890 aux environs de 1920 a été accentué ou contrarié par des fluctuations portant sur des périodes de deux à cinq ans. Leurs amplitudes maximales quant au gradient de pression et aux températures de la mer ont été observées à mi-chemin entre l'Islande et les Açores. Lors de ces fluctuations, l'océan se refroidit toujours quand augmente le vent d'ouest dominant et se réchauffe lorsque le vent d'ouest diminue.

Des observations fragmentaires indiquent que le courant des Canaries, le courant équatorial nord et la mer des Caraïbes se refroidissent quand les vents alizés se renforcent et qu'à ce moment ils absorbent probablement davantage la chaleur (sensible et latente). Il y a lieu de penser que cette rétroaction thermique de l'océan est de nature à accroître la circulation atmosphérique générale et à prolonger la tendance initiale. On peut considérer qu'une tendance contraire ayant pour effet de diminuer la circulation atmosphérique devrait se prolonger dans les mêmes conditions.

Le mécanisme des renversements de tendance est encore assez obscur mais on pourra peut-être s'en rendre mieux compte lorsqu'on aura déterminé si ces phénomènes sont particuliers à l'Atlantique-Nord ou s'ils se produisent, dans la même phase, également dans le Pacifique-Nord.

DISCUSSION

P. A. Sheppard. Since temperature advection and energy exchange over the ocean are markedly dependent upon season, one might expect a different behaviour of secular variation in winter and summer. Has Professor Bjerknes looked at this aspect of the problem?

J. Bjerknes. The geographic patterns of change of sea-surface temperature, derived from summer or winter data separately, do not differ very much from that demonstrated for the annual means. However, during the period of temperature rise north of 50° N. after 1920 the trends of the seasons diverged to some extent. The search for a possible explanation of that phenomenon is under way.

E. Kraus. 1. Professor Bjerknes has said—if I understand correctly—that strong westerlies are correlated positively with a speeded-up Gulf Stream, stronger trade winds and increased subtropical evaporation. If this is correct would these not be two opposing effects: a faster Gulf Stream would tend do transport more heat, but the increased evaporation would tend to decrease the amount of heat available for export by sea currents from the tropical oceans.

2. The available evidence seems to suggest a secular warming of the tropical ocean surface layers up to the middle of this century. This has been brought out by Mr. Lamb's data and by the reduction of tropical rainfall, which must have been associated with decreased evaporation—as there was no corresponding rainfall increase elsewhere. A decrease in evaporation would increase the amount of heat available for export by sea currents—assuming the same radiation balance.

J. Bjerknes. 1. It is correct that my data show a speeding up of the westerlies being associated with a speed-up of the trade winds and a cooling of the ocean in the North Atlantic trade-wind belt. The speeding up of the Gulf Stream and the North Equatorial Current under these circumstances is inferred from dynamic reasoning (no measurements available) and should occur with an as yet unspecified lag behind the primary meteorological change. The drainage of the low latitude oceanic circulation and by the increased delivery of sensible and latent heat (mainly the latter) to the strengthened trade winds accounts for the observed cooling of the low latitude ocean belt.

2. The recent warming of the North Atlantic tropical waters did not get under way until about 1920. The rest of Dr. Kraus's remark deals with rainfall problems which are outside the scope of my lecture.

M. Rodewald. I would like to ask the following question. With respect to the feed-back system. If this mechanism operates in the sense that an increased atmospheric circulation produces an accentuated frontal zone in the ocean, and this sharpened oceanic fronted zone helps to strengthen the atmospheric circulation by producing more cyclonic activity, can we imagine then an "internal" mechanism which is able to cause a turning point in this system, which means a break-down of the circulation intensity?

J. Bjerknes. That question is an essential one but the answer may not yet be within easy reach. My guess is that increase of geostrophic Gulf Stream advection, induced with a lag, by the strengthening Iceland cyclone, will be the factor most likely to put an end to the described one-way trend. But I have no clue to the question as to what decides the exact duration of the various trends.

J. Namias. It is also possible that the termination of the Atlantic feed-back mechanism (between ocean and atmosphere) may be produced by strong alterations in other remote branches of the general circulation—particularly over continental areas where inter-active influences also exist.

J. Bjerknes. I fully agree, but on the other hand I think it is pertinent to recall the fact that Sir Gilbert Walker in his classical work on world-wide climatic tele-connexions found it necessary to accord some degree of autonomy to the "North Atlantic Oscillation", because it correlates poorly with the more world-wide "Southern Oscillation".

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THE INFLUENCE OF THE VARIABILITY OF SOLAR AND TERRESTRIAL RADIATION ON CLIMATIC CONDITIONS

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INTRODUCTION

Since climate in its broader aspects is merely an expression of the general circulation, it follows that one may identify climatic changes with changes in the general circulation. By the latter, we shall include all the macro-scale consequences, with regard to heat and momentum transport, of the large-scale perturbations which, together with the zonal flow, constitute the general circulation. One may therefore examine theoretical studies and laboratory model experiments on fluid circulations in planetary atmospheres in order to isolate the potentially variable parameters.

If we restrict attention to the historical period (or to the Pleistocene) we must rule out topography as a variable parameter. However, the influence of topography will still be important in its interaction with other parameters—such as large-scale heat sources and sinks, and, in particular, their latitudinal and longitudinal distributions. These latter both contribute to and are partially identical with variable heat fluxes—both radiative and convective—which in themselves must be responsible for changes in the general circulation. We shall here concentrate attention on variable radiative fluxes but cannot ignore the accompanying convective heat fluxes.

Smagorinsky (1953) has demonstrated that large-scale longitudinally distributed heat sources produce virtually the same effect on the average zonal flow as the major mountain barriers. Since land-ocean contrasts reverse in summer relative to winter, this implies the possibility of resonant interactions depending critically on the strength of the zonal circulation, which is itself largely determined by the latitudinal gradient of radiation balance. Van Mieghem (1961) has shown, for example, that wave number two has mainly an orographic origin in summer but a thermal origin in winter, relative to the mid-troposphere temperature field. Smagorinsky (1960*a*) has further indicated that purely radiative processes, and their dynamic consequences, are not the significant factors for zonal perturbations so that it is adequate to consider only their zonal averages. Low-level non-adiabatic heating is the vital parameter in low-level perturbations of the zonal flow, and as a result the local climate will be greatly affected by ocean water-temperature distributions, for example, implying the need for a careful consideration of energy feed-back mechanisms. On the other hand, changes in the state of ground surface (its roughness, for example) have little effect on the general circulation, the surface wind speed adjusting itself to fit the angular momentum flux imposed by the circulation requirements. As Smagorinsky (1960*b*) has indicated, this flux is governed chiefly by the heating gradient which is largely responsible for the northward eddy flux of heat (directly) and angular momentum (indirectly). We see, therefore, that some aspects of local climate are tied directly to the primary driving force of the general circulation while others may lag behind any radiative changes, though not appreciably on geological time scales.

Studies of the normal mechanisms of the general circulation over extended periods, and for selected shorter periods, provide us with a general picture of the way in which energy is transformed and re-distributed as the circulation intensifies from summer to winter or changes its state in a shorter period. Large-scale latitudinal differential heating stores zonally-available potential energy by creating baroclinicity. Baroclinic instability permits large-scale perturbations of the zonal flow to occur and grow, leading first to an increase in eddy-available potential energy which is then converted to eddy kinetic energy. The final transition to zonal kinetic energy (i.e., from low to high index conditions) is generally regarded as a barotropic process maintaining the zonal kinetic energy against frictional degradation. As indicated by Lorentz (1960), under equilibrium conditions the rate of energy transfer around this cycle must balance this frictional dissipation, which is of the order of 2 per cent of the incoming solar radiation. Moreover, this appears to represent the maximum intensity of the general circulation, so that the circulation is less sensitive to radiative changes than if it were operating at much less (on the average) than a theoretical maximum efficiency.

Numerical studies by Smagorinsky (1960*b*) have shown that an increase in the gradient of radiation leads to an increase in temperature gradient and an increase in northward heat transfer; as a means of meeting this latter requirement, the ratio of eddy-available to zonal-available potential energy increases and the period of the index cycle becomes shorter. With the increase in meridional temperature gradient, the wave-length of maximum instability is increased, and the character of the general circulation as well as of its mean state (the zonal component plus the ultra-long waves fixed by orography and major heat sources) change, in addition to the reduction in cycling period. The precise consequences for local and general climate are more difficult to establish, however, and would not necessarily be similar for various latitudes and longitudes. Some simple statements could be made, nevertheless: any increase in gain of radiation would be partially balanced by an increase of temperature and hence of infra-red upward flux, and any increased northward transport of sensible heat would be accompanied by an increased northward transport of latent heat—which would be released by precipitation in temperate latitudes.

Model experiments have yielded similar results. Experiments with fluids in cylinders, performed by Fultz (1960), have shown that an increase in temperature gradient leads to an increase in the dominant wave-length, and that a subsequent decrease in gradient often produces hysteresis, with a tendency for an abrupt shift in wave-length after a time lag—i.e., for a period of persistence despite a changing régime in temperature gradient. Another feature observed in such model experiments was a periodic fluctuation in amplitude and pattern of wave trains (vacillation), very similar to an index cycle. A suggestion of a similar phenomenon, depending also in its details upon such parameters as latitudinal temperature gradient, has been provided by numerical experiments of Charney (1959). He found that a steady zonal flow in radiative equilibrium (with appropriate gradients of radiation) was unstable with at least two unstable modes. Qualitatively these corresponded to a single strong jet at middle latitudes and to two distinct jets—at relatively low and high latitudes. The relative importance of these two modes may depend quite critically on the radiative conditions assumed to exist.

We may conclude, therefore, that local radiative heat sources and sinks affect chiefly the ultra-long waves (and hence the areas of greatest development) while gradients in radiation affect the short (frontal) and moderately long waves, and the sequence of transition from one ephemeral period to another. Short-period changes in climate may thus be relatively easy to explain, by dynamic reasoning, but for periods measured in years or tens of years it will be necessary to invoke storage and feed-back mechanisms, involving the oceans, for example. A semi-quantitative analysis would be almost impossible in such cases, and for even longer periods even qualitative deductions must be regarded as dangerous.

GENERAL SURVEY OF POTENTIALLY VARIABLE RADIATIVE PARAMETERS

Since radiation plays a central, if not dominant, position in the operation of the general circulation, it is natural that one should seek a radiative explanation for long-period changes in this circulation. One recognizes that climatic change is essentially a cyclical process, and that therefore any radiative mechanism must also have a cyclical character, either directly or else indirectly. In the latter case one must invoke a complex chain of cause and effect, and the argument is necessarily more difficult to sustain on logical grounds. It is generally accepted that the predictability of the atmospheric state decreases as time increases, but that this is not true for its determinability. This implies that a direct cyclical radiative mechanism will appear more probable than an indirect mechanism, although the true explanation, if indeed there is a single explanation, is more likely to be a rather complex one.

In reviewing radiative parameters on a climatic scale, one may search for variability in three categories: in specific areas, which could influence zonal asymmetries; in specific latitude belts, which could affect meridional temperature gradients and hence fluxes; and over the entire globe, which could have a maximum effect on temperature values rather than on their horizontal gradients. On the purely radiative side, the variability could arise in solar radiation and/or in terrestrial radiation. In the former case, one would have to consider the incident radiation, its absorption in the atmosphere by oxygen and ozone at high levels and by aerosols, water vapour and clouds at lower levels, its reflection from the earth's surface and from clouds and its scattering upwards by aerosols. All these factors are at least potentially variable. Turning to the case of terrestrial radiation, the factors that may be of significance here include the thermal structure of the atmosphere, the amounts and vertical distributions of water vapour, clouds, ozone and carbon dioxide (as absorbers and hence emitters) and the effect of aerosols, either as absorbents or scatterers. It will be recognized that most meteorological theories of climatic change refer to one (or at most two) of the above elements; this paper will endeavour to show that many more processes should probably be considered, even though they may only be involved in an indirect manner in cyclical changes of local or global climate. An attempt will be made to focus special attention on arid zones, to the extent that this is possible. As mentioned earlier, it is not strictly legitimate to analyse single factors without consideration of interactions, especially since most atmospheric constituents and properties play a role in the determination of both solar and terrestrial radiative fluxes. Nevertheless, it will be most convenient, at least initially, to examine various items on an individual basis.

EXTRA-TERRESTRIAL SOLAR RADIATION

It is known that the state of the sun undergoes cyclical changes of both short and long period, well borne out by observations on sun-spots, which extend back over several centuries at least. It has therefore always seemed reasonable to suppose that the solar radiation reaching the earth, and its surface in particular, should also show similar variations. This has long been a controversial question, since the estimation of extra-terrestrial intensity from the radiation received at the ground is by no means a simple task. As these procedures have been refined over the years, the solar constant (the extra-terrestrial intensity at average earth-sun distance) has become more nearly a universal constant, with a diminishing variance ascribable to non-atmospheric causes. This latter variability is now considered to be less than 0.2 per cent. A very simple calculation shows that such a variation in incoming solar radiation could be balanced by an atmospheric temperature variation of about 0.1° C., which is almost certainly too small by more than one order of magnitude in the present context. We may assume that this estimated variability is valid from 0.3 to 3 microns, i.e., from the ultra-long ultra-violet to the near infra-red—the range in which solar radiation penetrates significantly to the earth's surface.

Very little of the long infra-red wave-lengths penetrate the atmosphere, mainly because of absorption by tropospheric water vapour and carbon dioxide. The amount of energy absorbed is almost trivially small, beyond 4 or 5 microns for example, so that a potential variability (which, incidentally, has never been established) could be of no importance, in part since the absorption takes place in a layer of considerable atmospheric mass. In the microwave region, beyond the infra-red, we can again "see" the sun. Here the energy is extremely low but is quite clearly variable, correlating rather well with sun-spots and similar indices of solar activity. This radiation, in the centimetre range, originates in a higher layer of the solar atmosphere than the photosphere which contributes mainly to our visual (and near-visual) radiation. This layer is also much hotter (30,000° K. rather than 6,000° K.) than the photosphere but quite obviously plays an unimportant role in absorption and re-emission in the visible spectrum. Such processes may, however, be significant in the ultra-violet portion of the spectrum, absorbed by the very highest layers of our atmosphere.

It is well known that during solar flares there are very great enhancements in the extremely short wave-lengths, namely the X-rays. At such times, fluxes of highly energetic photons and corpuscules penetrate relatively deeply into the atmosphere, at least to the upper stratosphere, but the total amount of energy involved is extremely small. Similar evidence in the ultra-violet is very scanty, but it is pertinent to note that the short ultra-violet (less than 0.1 micron) does vary over long periods in rhythm with solar activity. Such energy is absorbed at extremely high levels, in the ionospheric F region, and its effect on atmospheric density at such levels is directly measurable by satellite drag. These drag measurements correlate well with solar radiation in the centimetre region (even better than with sun-spots, in fact). The critical region in the spectrum is from 0.1 to 0.3 microns, and there has been no direct proof that it has a variable component. Such radiation penetrates below 100 km. to an appreciable extent and is responsible for the temperature maximum at the stratosphere (50-55 km.) as a result of absorption by ozone. Significant perturbations in this temperature maximum could be caused by a moderate variability in ultra-violet radiation. However, one usually assumes that processes that influence directly layers of very small mass can have extremely little indirect influence on deep layers of great mass, such as the troposphere. This view is certainly true with regard to the radiative and eddy diffusivity of temperature differentials in high layers and is also true for hydrostatic effects of density changes on total pressure at a lower level, and for the vertical propagation of certain classes of wave motion. It is not necessarily true in all contexts, however, or for all classes of vertical interactions. The thermal-wind equation indicates the equivalent importance of temperature gradients at all levels on the wind field. Complex dynamic interactions in the vertical should, therefore, permit a high-level contour-height field to spread its influence downwards, as one sees quite clearly, for example, in the final warming of the Arctic winter middle stratosphere. Although one may reject any "trigger" mechanisms in the present context, one should not discount the possibility of resonance in the vertical. It is known to be important in solar atmospheric tides and could well apply to the much longer periods considered here. In fact, it is pertinent to note that there is a very strong coupling between wave number two in the middle and upper stratosphere, on the one hand, and in the troposphere and lower stratosphere, on the other. This wave mirrors the behaviour of the winter middle stratosphere, which is certainly a distinct and independent entity as far as temperature field is concerned.

Fortunately we have some rather reliable indirect evidence as to solar ultra-violet variability, especially in the 0.2 to 0.3 micron region, since the relative intensity variation across this region of the spectrum is of primary importance in determining the photochemical equilibrium concentrations of ozone in the upper stratosphere (30-50 km.). Recent unpublished studies by this author have shown that ozone concentrations at

Arosa (Switzerland), in the upper stratosphere do correlate, positively and significantly, with the 10 cm. solar flux. Even more reassuring is the fact that these correlations agree, on a relative and absolute basis, with qualitative predictions with respect to height and seasonal variations, taking into account the lag time of photochemistry and the dynamical variance of upper stratosphere circulations. We may conclude, therefore, that during a period of increased solar activity there will be an enhancement of solar radiation near 0.2 microns with little change near 0.3 microns. Not only will this increase high-level ozone concentrations but it will increase the ozone absorption near the stratopause on two counts (incident intensity and absorber amounts both increasing).

Some implications of the above results with regard to climatic changes will be at once apparent. During the winter half-year the increased absorption will be a maximum near the equator and will act to intensify the strong westerlies in the middle and upper stratosphere and in the lower mesosphere. Dynamically, this energy will be fed into the bi-polar wave (wave number two) which dominates circulations at such levels. As we have seen, there will be a corresponding accentuation of wave number two in the troposphere and lower stratosphere, intensifying meridional flow components, as well as the eddy available potential energy and the northward flux of water vapour, in particular, as indicated by Van Mieghem (1961). During the summer half-year, on the other hand, the increased absorption will be greater in magnitude but will have a smaller, if not reversed, north-south gradient. At such times, the chief effect will be to cause a general temperature increase, both throughout the stratosphere and near the ground (since the troposphere will be transparent for the ozone infra-red flux). A general temperature increase at the surface might, therefore, be expected, undiluted by the effects of tropospheric mass. In the winter, the greatest temperature increase will be at higher latitudes, as a result of enhanced northward heat fluxes. Winter precipitation in middle and high latitudes should also be increased, by a similar argument. It is important to realize that, with clear skies, the earth's surface and the upper stratosphere can exchange heat in a rather efficient manner, via the ozone infra-red radiative flux. The carbon dioxide radiative flux, on the other hand, will tend to promote heat exchange over adjacent layers, and will thus dilute the effect of solar absorption near the stratopause as far as climatic considerations are concerned.

EFFECTS OF CARBON DIOXIDE AND AEROSOLS ON RADIATIVE TRANSFER

Reliable temperature records have indicated that there has been a general rising trend in temperature since late in the last century. It is entirely pertinent to ask whether this is part of a long-period climatic trend or is ascribable, wholly or in part, to an increased industrialization over this period. It is certain that "downtown" temperature records show a pronounced increase relative to those at sites unaffected by urban growth. It is quite reasonable to expect some effect of the former areas on the latter, simply because of air motions. Although the amount of energy involved is not great, the real question concerns how much of this energy can be trapped in the lower layers of the atmosphere.

In the first place, it is important to realize that we are not dealing exclusively with the combustion of fossil fuels in homes and factories. The utilization of the hydro power is also rather inefficient and considerable heat energy is released. The growth of urban and suburban areas has led to a decreased mean albedo of the ground surface in such areas and thus to an increased absorption of solar radiation. A similar effect will prevail in regions which have been converted to agriculture, except where large-scale irrigation is practised. The indirect effect of all of these activities must be to increase, at least locally, the near-ground concentrations of water vapour, carbon dioxide and industrial aerosols. All these elements are effective in absorbing infra-red radiation and re-emitting such energy both downwards and upwards. Increases in their concentrations will thus lead to a decrease in the fraction of the radiation emitted by the ground which is lost to space, so that an appreciable amount of the energy being considered is trapped in the lower layers, leading to a general temperature increase, which would be most marked in those areas where the energy is liberated directly but still evident, after dilution by air motions, in other areas to which the warmer air is advected.

One must also consider "side effects" in a discussion of this sort. One fact will be apparent—the increase in carbon dioxide will be a permanent and accumulative effect and will not affect solar radiation fluxes. The increase in water vapour (dut to increased evaporation) will not be accumulative but will chiefly speed up the hydrologic cycle, and should be associated with general precipitation increases, although these could well occur primarily over oceans and thus escape detection. Water vapour absorption of solar radiation is not important in the lowest layers, but increases in cloudiness (especially convective cloudiness) could lead to increased absorption and increased reflection back to space, providing a rather effective damper on the entire mechanism. A quantitative assessment of the reduction in temperature increase would be very difficult to perform. The industrial aerosols will slowly increase in concentration in time, as a result of production but not accumulation, since they will either fall out or be washed out within one to two weeks of emission into the atmosphere. Since these are relatively large particles, scattering of solar radiation will be almost entirely downward so that the major depletion would be by absorption. Such absorption merely enhances the downward infra-red flux so probably balances the slight decrease in solar radiation reaching the ground.

When we examine these processes on a global scale, it is apparent that the greatest temperature increases should be expected in the winter half-year and in the lowest layers of the troposphere, with virtually none of the energy gained being lost to space (except in the most transparent regions of the infra-red spectrum). With the primary energy input occurring in middle latitudes, high-latitude meridional temperature gradients and heat fluxes northward should increase, and their low-latitude counterparts decrease. The corresponding changes in the Southern Hemisphere, by these processes, should be very small. The speed-up of the hydrologic cycle, both in the horizontal and vertical should lead to precipitation increases at middle and high latitudes. The industrial aerosols would not contribute to this event, since there is virtually never any shortage of condensation nuclei and there is no evidence that industrial aerosols are any more effective than natural aerosols as freezing nuclei. With a few rare exceptions, they are probably much less effective, in fact. The net effect of oceans is probably small, the delayed uptake of carbon dioxide balancing the heat reservoir effect.

In this section, we have so far considered only those physical processes which could have contributed to the recent climatic amelioration, in the absence of any really long-period cyclic phenomena. Some of the processes considered have been used, however, as the basis for theories of general climatic change. One such theory is the carbon dioxide theory of climatic change (Plass, 1956), which depends on a complex cyclic exchange of carbon dioxide between the atmosphere and oceans and on the fact that increased atmospheric carbon dioxide will give an increased downward infra-red flux at the ground, permitting a temperature increase at the surface, if no other effects intervened. More recent infra-red calculations, such as those by Kondratiev and Niilisk (1960), using newer data on carbon dioxide transmission and including the effects of water vapour in the same spectral region, indicate that the influence of carbon dioxide concentration is much less than hitherto supposed. When one considers feed-back mechanisms (involving water vapour and clouds, for example), it becomes apparent that the carbon dioxide theory, by itself, is not capable of explaining major climatic changes in the past. There is no doubt, however, that the basic concept, as far as radiation is concerned, would contribute to the relatively recent warming trend, during which there has been a slight increase in carbon dioxide concentration.

A rather different theory of climatic change has often been presented, based on the effects of volcanic aerosols and on the concentration of volcanic eruptions in certain periods. It must be realized that we are dealing here with stratospheric rather than tropospheric aerosols. Typical residence times might be 1-2 years at high latitudes, 2-3 years at middle latitudes and 3-4 years at low latitudes. Any large particles would fall out relatively rapidly, and the small particles that remained would have low concentrations in the troposphere, where their residence time would only be of the order of a month. As a result of their size, these aerosols would be quite effective in scattering solar radiation with an appreciable amount of back-scatter, i.e., of radiation returned to space. The resulting energy loss at the surface would be a maximum at low latitudes, especially in arid regions, and this effect would be enhanced by the greater stratospheric residence time in such areas. The effect would also be greatest near the surface, and this would be intensified by the reduced convection. Once again, the indirect effect of water vapour and clouds would reduce the overall magnitude of the cooling, by reason of reduced evaporation and increased stability. The reduction in cloudiness would thus permit more solar radiation to reach the earth's surface, but would, of course, increase the infra-red flux to space and the net infra-red loss at the surface. In general the solar flux effect will predominate over the infra-red effect, especially where average cloud heights are low. It will be recognized that these damping considerations on climatic change mechanisms will have less influence in arid regions than elsewhere. The volcanic theory would suggest that the maximum effect should be observed in summer, with a general temperature effect but little change in gradient (or of the intensity of the general circulation). In winter, the absolute effect would be less, but the relative effect (in the north-south direction) would be greater, so that the intensity of the general circulation and of its northward transports of heat, water vapour and momentum should be significantly affected.

MISCELLANEOUS RADIATIVE CONSIDERATIONS

It should be apparent that we are not limited to the consideration of purely cyclic phenomena or of those that may change by external causes. On a short-period basis, we know that the general circulation of the atmosphere undergoes significant changes, quite comparable to those that occur on the time scale of climatic variations. We need, therefore, search only for factors that could modify the energy input to the general circulation over a large area and inquire whether these factors could persist for long periods of time. Since the energy balance is determined by radiation and by the circulation itself, maximum changes would be expected if these reinforced one another, but in this case one must find a mechanism capable of eventually reversing the trend. It is not improbable that the solar-ultraviolet and the volcanic mechanisms, for example, might provide these reversal processes, with the major energy differentials being provided internally. On the other hand, it is conceivable that two such internal processes could, when coupled together, provide an adequate explanation for a climatic cycle.

One such internal mechanism involves changes in the earth's albedo, the most significant variation being due to changes in snow cover, since snow alone, of all natural surfaces, has a very high albedo. If the circulation changes produced by an abnormally great area of winter snow were themselves conducive to increased precipitation at moderately high latitudes, the decreased winter temperature produced by the great reflection of solar radiation would maintain a vast snow area. It is not essential that the snow persist through the summer, since the persistence of circulations and of anomalies so produced could well produce early and persistent snow-falls in the succeeding autumn. This would reduce the heat flux from sub-surface layers of the ground and further reduce winter temperatures, which would be enhanced by the smaller ground heat storage in the shortened snow-free season. All these processes would accentuate north-south temperature differences and thus the northward transport of water vapour as well as the cyclonic activity at high latitudes. In other words, a self-sustaining mechanism, capable of producing widespread glaciation, would be possible under these conditions. As the belt of maximum temperature gradient shifted southwards, a critical latitude might be reached such that the northward flux of real and latent heat produced a temperature and humidity stratification for which the infra-red radiative flux downward exceeded the emitted infra-red flux. This would lead to a net removal of snow and ice at the southern edge of the glaciated area and this area would then shrink gradually. At the same time, the increase in convective cloudiness over the low-latitude oceans would increase the upward flux into the troposphere of real and atent heat, as required to maintain the northward transport, but eventually the heat drain, plus the high cloud albedo, would reduce water temperatures and thus diminish the intensity of the general circulation. In this case, therefore, the solar and infra-red radiative properties of water vapour and clouds could well act to reverse the trend established by the effect of high snow albedo over large high-latitude areas. During this reversal phase, relatively high-index conditions would prevail, with the belt of maximum flow and cyclonic activity slowly advancing polewards. At a critical high latitude, the increased cloud albedo would eventually lead to an intensification of the summer circulations, once again reversing the trend and permitting a new expansion of the area of snow and ice.

We have considered in this section, even more than in preceding sections, highly speculative mechanisms involving radiative processes. The separation of truth from fiction will be a very difficult task, but it is clear that a proper understanding of climatic changes will only be possible when we are able to replace qualitative speculations on direct and indirect radiative processes by meaningful calculations for these processes and for their resultant effects on the general circulation.

A SUGGESTED PROGRAMME FOR FUTURE STUDIES OF CLIMATIC CHANGE

The statement is commonly made that, over the world as a whole and over a period of one or more years, the total incoming solar radiation must balance the total outgoing solar and infra-red radiation, since changes in heat storage (i.e., in average temperatures of air, oceans and land masses) are essentially zero. It is very pertinent, and perhaps instructive, to ask why this is so, and to what extent this balance can be perturbed without any net effect on heat storage. It is also of interest to ask whether departures on a daily basis are of possible absolute or relative significance, and to what extent is the mechanism of the general circulation one of rapid adjustment to such departures, as a preferred mode of local balance rather than by changes in the heat storage itself. It should also be helpful to consider the manner in which seasonal changes in heat storage are achieved, since these are much larger than the changes involved in most climatic-change considerations. One is tempted to regard climatic change as a small residual of already small residuals, and therefore beyond the range of quantitative prediction or even qualitative explanation. It is, therefore, reasonable to consider the simpler problems that have been formulated above, as a first step in approaching the much more complex problem of climatic change.

It must be admitted that this problem would be considerably simpler if there were no seasons on our planet, since seasonal changes are large relative to long-period climatic changes and since we have no assurance that annual averages can be employed in these considerations in other than a crude qualitative manner, bearing in mind that the fundamental equations of dynamics, thermodynamics, radiation and turbulence are non-linear, and that in the real atmosphere we do not have symmetry about the Equator, even for annual averages, as a result of quite different distributions of oceans and of topography, with an assist from the elliptical orbit of the earth around the sun. Unfortunately, small effects such as these may or may not be one of importance when we are considering the relatively small magnitude of climatic changes—and the very slow rate at which they become apparent.

The simplest realistic case we might imagine would be that of a planet with no seasons and a uniform land surface over the entire globe. We would exclude hydrogen and its compounds (and, therefore, water substance) but include oxygen and nitrogen. By a suitable increase in the carbon dioxide concentration it should be possible to simulate rather closely the actual temperature structure we observe. The albedo drag coefficient and heat capacity of the surface would be everywhere constant. Despite these seemingly drastic simplifications, we should note that neither numerical nor physical models of the general circulation have as yet significantly advanced beyond such elementary concepts. As a result, we can use these techniques to test any hypotheses we make concerning climatic change. Moreover, since these numerical and physical models do reproduce with amazing skill the very circulations we observe, we may be confident that we have not so over-simplified the problem that meaningful results are automatically excluded. It appears, in fact, that classical numerical studies should be expanded in scope to permit finite heat transfer in the ground, both horizontally and vertically, and to introduce radiation effects explicity rather than implicytly. In this way it would not be necessary to specify, in advance, the mean ground and air temperatures which represented an equilibrium between radiative and dynamic processes.

With a numerical model, amplified as suggested above, we would obtain numerical estimates of the lag between external parameters (solar radiation, for example) and the internal temperature structure, and could study the dynamical changes that accomplished the transition to a new equilibrium, as well as of the net circulation changes between the two régimes. Details concerning the heat transfer in the ground, from ground to air (convective and radiative) and between atmospheric layers (radiative) are probably not important in defining equilibrium dynamic states but are undoubtedly critical factors in defining equilibrium thermodynamic states and the lag between dynamic and thermodynamic changes. To this extent, speculation along these lines would seem premature at present, but should not necessarily be discouraged.

Numerical treatment would be further simplified if one could separate the dynamic transfer processes from the zonal dynamics and thermodynamics, by a formulation of meridional fluxes or of their divergence. This may not be possible, but it would certainly repay further study, particularly in view of its possible byproducts for long-range forecasting. This particular problem should be tackled both on theoretical grounds, by an elaboration of numerical calculations such as those of Phillips, Charney and Eliassen, and also on the basis of actual observations, either for single stations or zonal averages (using observed winds) or from Fourier analyses of contour height (using geostrophic winds). If these fluxes could be formulated in a realistic manner, even if the actual accuracy was inadequate for long-range forecasting, it should be possible to investigate rather simply and rapidly the effects of varying the input of solar radiation (or of changing the albedo, which would more closely correspond to feasible mechanisms of climatic change). The simplification so introduced (which would also greatly shorten the time step for numerical integration) would permit a more rigorous treatment of ground temperature and heat transfer, of convective ground to air heat transfer, and of atmospheric radiative processes (in terms of a number of layers of specified infra-red emissivity).

It seems certain that the oceans must play a fundamental role in regulating the thermodynamic engine, which is the general circulation, both by storing heat and transporting heat. Although these are slow processes on the synoptic scale, this is not true on the climatic scale and proper account should be taken of them. When dealing with these effects, it is not necessary to differentiate explicitly between day and night—in other words, it is adequate to permit a uniform level of solar radiation to reach oceans at all times. This suggests that a useful numerical experiment would be to treat a planet with a fluid surface as a special case, and then generalize by introducing solid surface areas, initially with negligible heat storage in order to allow for flexibility in assigning continental shapes.

As indicated earlier, it appears that one should not ignore seasonal effects in calculations involving the general circulation from which deductions as to climatic change are to be made by a quantitative perturbation of the assumed parameters. This draws our attention once more to the inclusion of ground effects. The existence of the well-known lag between ground and air temperatures (on a seasonal basis) is important because of the net fluxes at the surface which are produced, even after averaging over a period of days. One further difficulty arises immediately, however, and this is the necessity of at least a formal differentiation between day and night when considering a land surface. During the day, net radiation gain at the surface is partitioned between ground and air, while during the night almost all of the radiative energy loss is provided by the ground. It is not possible to evaluate the convective flux contribution solely from parameters of mean daily air and ground temperatures, and a more sophisticated treatment is therefore required. We must remember that the actual general circulation is constantly changing the heat storage terms, primarily on seasonal scales when latitudinal belts are considered, and that the important terms may be those expressing the departure of such storage components from their long-period normals, for the season in question. In any event, it will be necessary to formulate ground and air non-radiative heat fluxes in a realistic manner, for incorporation into numerical experiments, and, initially at least, seasonal considerations should not be ignored.

It is probably not possible to predict whether valid deductions on climatic change can be drawn from experiments in which water substance is absent. The tremendous complexities, which this innocuous molecular species introduces into our atmosphere, are certain to hamper numerical study of the general circulation and of its long-period perturbations. It will undoubtedly be necessary, at least initially, to formulate vertical and horizontal fluxes in a semi-empirical manner, depending primarily on basic parameters rather than on the inner workings of the general circulation. It will also be necessary to take into account vapour storage, liquid storage in the atmosphere and liquid deposition. We know that infra-red and solar radiative fluxes are inextricably linked to cloud amounts and heights and we will need semi-empirical techniques in order to incorporate these effects. Fortunately, these are problems that daily confront the practising forecaster and we may find it helpful to borrow such of his techniques as can conveniently be introduced into numerical experiments.

We may also find that we cannot ignore the stratosphere with its additional feature of significant ozone content, and that topography and land-ocean details are required in order to judge the effects of small perturbations in the energy balance, whether by radiative components directly or by other processes. We should be prepared for the unpleasant realization that a realistic model which mirrors the broad-scale behaviour of the atmosphere may still be inadequate to predict the consequences, over long time periods, of relatively small perturbations of the overall energy balance. However, it seems probable that a model which can produce realistic seasonal variations will enable us to at least discriminate between likely and unlikely mechanisms of climatic change and it is along such lines that I look for great advances in the future.

RÉSUMÉ

L'influence de la variabilité des rayonnements solaire et terrestre sur les conditions climatiques (W. L. Godson)

Si nous acceptons l'identité des changements de climat et des changements de la circulation générale, nous pouvons examiner les travaux théoriques et les expériences de laboratoire sur modèles portant sur la circulation des fluides dans les atmosphères planétaires pour tenter d'isoler les paramètres potentiellement variables. Ce sont la topographie et les flux radiatifs. Le flux de rayonnement solaire pris en moyenne sur une durée caractéristique d'un état climatique donné peut varier en raison de la variabilité solaire (dans les longueurs d'ondes qui sont filtrées à haute altitude), de l'albedo des nuages (nébulosité moyenne et type), de la diffusion particulaire (polluants, y compris les cendres volcaniques), de l'absorption gazeuse (vapeur d'eau et ozone) et de l'albedo de la surface (en particulier l'extension et la durée de la couverture neigeuse). Le flux de radiation infrarouge peut varier en raison de la variabilité de la température de surface, de l'absorption et de la diffusion particulaire, de l'absorption et de l'émission gazeuse (sensibles aux concentrations et à la répartition verticale de la vapeur d'eau, du gaz carbonique et de l'ozone) et de la nébulosité (en particulier quantité et altitude).

Quoique les indices de telles variations à l'échelle climatologique soient faibles, on tentera d'évaluer ces divers facteurs et leur effet sur les changements de climat d'après les modifications de la circulation générale.

DISCUSSION

Dr. GODSON's comments are included in the discussion of the next paper by J. S. Sawyer.

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NOTES ON THE RESPONSE OF THE GENERAL CIRCULATION TO CHANGES IN THE SOLAR CONSTANT

by

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INTRODUCTION

Various causes have been suggested for the changes of climate which have been observed in the past, both for the ice ages and inter-glacial periods and for the smaller, shorter-term changes which are apparent from the historical record. Among the causes to which one first looks is naturally the possibility of variations in the solar radiation received by the earth. This was the basis of Simpson's discussion of the climate of ice ages (Simpson, 1934, 1957, 1959) but interest has also been raised in the reaction of the general circulation to changes in incoming radiation by Wexler (1956) who has revived the idea that the quantity of incoming radiation may be materially influenced by persistent veils of volcanic dust in the stratosphere.

Although it has been suggested that the radiation balance and/or the general circulation might be upset in various other ways [e.g., by changes in ozone content (Kraus, 1960) or carbon dioxide concentration (Callendar, 1961)], it is natural to give first consideration to changes in the primary radiation and to the most direct effects which might arise in the general circulation. This is done in the following paragraphs.

THE ATMOSPHERE AS A HEAT ENGINE

In order to gain some insight into the processes at work and their reaction to a change in solar radiation, it is convenient to think of the atmosphere as receiving heat in one region (region 1) at temperature T_1, broadly identified as the equatorial belt. Part of this is reradiated to space and part is transferred by the general circulation to a sink region (region 2), temperature T_2, broadly identified as high latitudes, where it is lost by radiation to space. The transfer of heat from region 1 to region 2 is partly as sensible heat and partly as latent heat. The former is likely to depend on the temperature difference $(T_1 - T_2)$ between the two regions and the latter upon the difference in humidity mixing ratio $(W_1 - W_2)$. Both will be affected by the intensity of the mixing brought about to the general circulation—itself probably dependent on $(T_1 - T_2)$ and $(W_1 - W_2)$.

This model of the atmosphere is undeniably crude, but it probably contains the main factors involved. The atmosphere does not provide two separate regions at distinct temperatures, heat is received at all latitudes and not merely in the equatorial belt, there is a stratosphere with a different structure, etc. These are all complications which may modify the result but it seems plausible that something may be deduced from the simple model outlined.

It might be thought that the separation of the heat transferred by the general circulation into "sensible" and "latent" heat might be a refinement which could similarly be dropped, but it will be seen below that this is not so. This is because as the temperature rises the saturation vapour pressure rises rapidly, and the general circulation becomes rapidly more efficient in transferring latent heat away from the equatorial regions. It will be seen that this increase in efficiency is such as to reduce the temperature gradient from equator to pole as solar radiation increases, thus out-weighing the tendency for an increase in gradient which would be expected in dry atmosphere.

THE EFFECT OF A CHANGE OF SOLAR RADIATION ON A DRY ATMOSPHERE

We write E = incoming solar radiation in region 1;
A = outgoing radiation from region 1 - temperature T_1;
B = outgoing radiation from region 2 - temperature T_2;
C = sensible heat transferred from region 1 to region 2 by the general circulation.

For our present purpose it is probably adequate to assume that the outgoing radiation A and B are related to T_1 and T_2 by Stophan's law. Although T_1 and T_2 may be identified as the air temperature in the lower atmosphere and outgoing radiation may originate from a higher level, it will be broadly proportional to T_1^4 and T_2^4 and the factor of proportionality can absorb any difference between T_1 and T_2 and the true radiative temperatures. Thus

$$A = K_1T^4 \quad \text{and} \quad B = K_2T^4.$$

We further assume that the transfer of heat from region 1 to region 2 is by quasi-horizontal mixing with an eddy diffusivity K which may be dependent upon the temperature difference, $T_1 - T_2$. Thus $[\log (T_1 - T_2)] = \alpha$. We will assume $d (\log K) / d [\log (T_1 - T_2)] = \alpha$.
Thus

$$C = K_3K (T_1 - T_2).$$

K_1, K_2 and K_3 will be regarded as constants (i.e., independent of changes in the solar constant).

The heat balance of regions 1 and 2 then requires

$$\left.\begin{aligned} E &= A + C \\ C &= B \end{aligned}\right\} \quad . \quad . \quad (1)$$

or

$$\left.\begin{aligned} E &= K_1T_1^4 + K_3K(T_1 - T_2) \\ K_3K(T_1 - T_2) &= K_2T_2^4 \end{aligned}\right\} \quad . \quad . \quad (2)$$

Differentiation of equations (2) then gives the relations between the increments in E, T_1 and T_2

$$\Delta E = \frac{\Delta T_1}{4\,T_1} A + (\alpha + 1) \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} C$$

$$(\alpha + 1) \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} C = 4 \frac{\Delta T_2}{T_2} B$$

Whence

$$\Delta T_1 - \Delta T_2 = \frac{4/T_2}{(\alpha + 1) / (T_1 - T_2) + 4/T_2} \cdot \Delta T_1$$

Since α is almost certainly positive, $(\Delta T_1 - \Delta T_2)$ has the same sign as ΔT_1 and ΔE and an increase in solar radiation increases the equatorial temperature more than the polar one.

Taking $T_1 = 300°$ K. and $T_2 = 270°$ K. as representative values and $\alpha = 1$ we obtain

$$\Delta T_1 - \Delta T_2 = 6.18\ \Delta T_1$$

and if we take $A = \frac{2}{3} E$, i.e., two thirds of the incoming radiation re-radiated in the equatorial belt, then

$$\Delta T_1 = 78 \frac{\Delta E}{E}\ {}^{\circ}C.$$

and a 1 per cent change in the solar radiation would result in $\frac{3}{4}$ °C. change in equatorial temperature.

THE EFFECT OF A CHANGE IN SOLAR RADIATION ON AN ATMOSPHERE CONTAINING WATER VAPOUR

If the preceding analysis is repeated making allowance for the heat transferred by the general circulation as latent heat then quite a different result is obtained. This is because the heat conveyed as latent heat increases with the mixing ratio of the air in the tropical belt, and this can be regarded as proportional to the saturation mixing ratio W_1 at temperature T_1. W_1 increases rapidly with T_1 and the resulting change of latent heat transport will be shown to be important.

An additional term D is now introduced into equations (1) and (2) where D = latent heat transferred from region 1 to region 2 by the general circulation.
Thus

$$\left.\begin{aligned} E &= A + C + D \\ C + D &= B \end{aligned}\right\} \quad . \quad . \quad . \quad (3)$$

It can also be assumed that the transport of latent heat is proportional to the difference in mixing ratio between region 1 and region 2, $W_1 - W_2$, and that the eddy diffusivity K is also dependent on the latent heat of the air in the tropical zone.

Thus we write

$$\delta(\log K) / \delta(\log W_1) = \beta$$

and

$$D = K_4K(W_1 - W_2) \backsimeq K_4KW_1$$

because the mixing ratio in the cold region 2 must be much lower than in the region 1.

In place of (2) we now have

$$\left.\begin{aligned} E &= K_1T_1^4 + K_3K(T_1 - T_2) + K_4KW_1 \\ K_3K(T_1 - T_2) + K_4KW_1 &= K_2T_2^4 \end{aligned}\right\} \quad . \quad . \quad (4)$$

Differentiation of (4) now leads to the following relations between ΔE, ΔT_1 and ΔT_2.

$$\left.\begin{aligned} \Delta E = 4 \frac{\Delta T_1}{T_1} + \left(\alpha \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} + \beta \frac{\Delta W_1}{W_1}\right) (C + D) + \\ + \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} C + \frac{\Delta W_1}{W_1} D \\ \left(\alpha \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} + \beta \frac{\Delta W_1}{W_1}\right) (C + D) + \frac{\Delta T_1 - \Delta T_2}{T_1 - T_2} C + \\ + \frac{\Delta W_1}{W_1} D = 4 \frac{\Delta T_2}{T_2} B \end{aligned}\right\} \quad (5)$$

If W_1 is now identified as the mixing ratio for saturation at the sea temperature of the tropical seas, we can find from hygrometric data that

$$\frac{\Delta W_1}{W_1} = 18 \frac{\Delta T_1}{T_1} \text{ (approx.)}$$

In order to solve the equations (5) we take the preceding estimate that two thirds of the radiation is returned to space in low latitudes and one third transferred poleward by the general circulation. We also use the analysis by Starr and White (1954) as a basis for assuming that one third of the heat conveyed by the general circulation is in latent form.

Then we have

$$A = \frac{2}{3}E, \quad B = \frac{1}{3}E, \quad C = \frac{2}{9}E \ \textit{and} \ D = \frac{E}{9}.$$

We also set $T_1 = 300^\circ$ K. and $T_2 = 270^\circ$ K. This leads to

$$\Delta T_1 - \Delta T_2 = -\frac{9}{5}\,\frac{0.08 + \beta}{\alpha + 1.1}\,\Delta T_1$$

Thus, broadly if β is zero or positive, the latitudinal temperature gradient decreases as the solar heating increases and the equatorial temperature rises. The temperature increase is thus greater at the poles than at the equator.

Substitution into the first equation (5) leads to

$$\frac{\Delta E}{E} = \left(0.015 + 0.02\,\beta - \frac{0.08 + \beta}{50}\,\frac{\alpha + 0.66}{\alpha + 1.1}\right)\Delta T_1$$

whence

$$\Delta T_1 \simeq 67\,\frac{\Delta E}{E}.$$

Thus a 1 per cent increase in solar radiation leads to a rise in equatorial temperature of $\frac{2}{3}$ °C. and to a slightly greater rise in high latitudes if $\beta = 0$. If $\beta = 1$ and $\alpha = 1$ the temperature rise in low latitudes is somewhat smaller, about $\frac{1}{3}$ °C., whereas the rise in temperature in high latitudes is greater—almost 1° C.

THE EFFECT OF LATENT HEAT ON DISTURBANCES IN THE WESTERLIES

The arguments of the previous sections have shown that the effect of the latent heat of the air on the efficiency of meridional mixing in the westerlies is of fundamental importance in regard to the response of the general circulation to changes in solar radiation. This cannot be assessed properly without much further study but some remarks are possible.

The effect arises in two ways: (a) an increase in the water vapour content of the air implies that more latent heat is transported by the same intensity of mixing, and (b) the intensity of the mixing (K) may itself be increased by release of greater amounts of latent heat. We have seen that the former effect alone, $\beta = 0$ materially affects the response of the meridional temperature gradient to solar variation, but there are strong reasons for supposing that the second effect is also important.

The evidence of synoptic charts is that nearly all of the more active cyclonic developments occur where there is a vigorous release of latent heat, and theoretical analysis also demonstrates that the cyclogenesis should be more rapid and on a smaller horizontal scale when condensation occurs. This scale effect may be particularly important in stimulating the instability of the baroclinic westerly current. In the absence of vigorous cyclonic developments the upper westerlies frequently settle down into a system of quasi-stable waves in which meridional transport of heat is relatively low, but a single vigorous cyclonic development can often be seen to disrupt the wave system and establish intense meridional currents.

The effect of latent heat on the meridional transport of heat in the westerlies is likely to be greatest in the lower latitudes of the westerlies, say 30 to 45 degrees from the equator, because here the change in latent heat content of the air will be greatest. The Hadley cell south of the subtropical anticyclones will not be much affected because the latent heat will be reconverted to sensible heat in the ascending branch near the equator. Thus we may expect the greatest changes in meridional temperature gradient to occur in the belt from roughly 30 to 45 degrees latitude. This would imply that a decrease in solar radiation would lead to a marked increase in the upper westerlies in these latitudes and presumably in cyclonic activity. This is the pattern which has been suggested for the circulation in the ice ages (Kraus, 1960) and the increased vigour of cyclonic developments over the oceans in relatively low latitudes could well provide adequate precipitation on the western areas of the continents for the establishment of ice sheets. [Simpson (1934) rejected a decrease of solar radiation as a cause for an ice age because he considered precipitation would be inadequate.]

THE ROLE OF THE TEMPERATURE OF THE TROPICAL OCEANS

The preceding paragraphs emphasize the importance of the humidity of the warm air masses entering the westerlies, essentially the humidity of the tropical air masses. This is probably largely determined by the sea temperature over a somewhat limited area of the oceans over which these air masses are formed—particularly the western areas of the oceans in latitudes 10 to 25 degrees from the equator. It is also important to recall that oceanic temperatures have considerable inertia and that the response of the whole equatorial and tropical ocean to an increase in solar radiation will be neither immediate nor uniform.

Thus although the arguments of the preceding sections may apply broadly to changes taking place over thousands of years, changes of solar radiation over a few years or even decades might evoke more complicated responses because the change in transport of sensible heat and latent heat might not move together.

Lamb (1959) shows an interesting map of the departure of the Atlantic sea temperature during the period 1780-1820 from that of the present day. This shows generally positive departures in the areas where warm air masses form before entering the westerlies amounting to 1° C. or more. His corresponding January mean pressure charts show a generally weaker circulation than during the first half of the twentieth century with a more pronounced trough off the East American coast. This is the type of relation which has been suggested in the preceding section although January temperatures in western Europe were lower than at the present time.

Brown (1961) has also demonstrated relatively low sea temperatures in the subtropical North Atlantic in the period 1910 to 1930, a period of relatively strong westerlies but one of relatively high temperature in the Britain Isles (Lamb, 1959).

Thus there is some support for the relation between sea temperature and circulation suggested above, but none for the relationship with high latitude temperatures. This may be a complication arising from the lag in oceanic temperatures.

CONCLUSION

With our present limited knowledge of the general circulation one cannot hope that theory will give a satisfactory explanation of the facts of climatic change even if they were fully known, and certainly one cannot expect much from such a simplified treatment as the present one. However, it is necessary to start from simple models if one is to select the important factors which are to be considered in more complex treatments or those between which significant relations may be sought in the observational data.

The main result of the present paper is to emphasize the importance of the latent heat transport and its variations as a control on the general circulation, and to point to the important role of sea temperatures in the tropical oceans. These are factors which must be considered in more complex theoretical treatments.

It is also indicated that because of the more efficient transport of latent heat by the general circulation at higher temperatures, a rise in equatorial temperature resulting from increased solar radiation may be accompanied by a weakening of the extratropical circulation and a greater rise of temperature towards the poles.

RÉSUMÉ

Notes sur l'effet des changements de la constante solaire sur la circulation générale (J. S. Sawyer)

L'effet d'un changement du rayonnement solaire sur la circulation générale de l'atmosphère est exposé sur une base théorique simple. Si l'on prend en considération la part de chaleur latente dans le transfert de chaleur par la circulation générale, on voit qu'une augmentation de la constante solaire pourrait provoquer une élévation de température plus grande dans les hautes latitudes qu'à l'équateur. Il apparaît qu'un changement de 1 % dans la radiation solaire provoquerait une augmentation de 0,3 °C de la température à l'équateur et de 1 °C dans les hautes latitudes.

DISCUSSION

J. MURRAY MITCHELL. With reference to Mr. Sawyer's interesting contribution, I have recently used an entirely different empirical procedure to arrive at answers to some of these same problems. There is no time here for me to elaborate, but I did reach one conclusion also reached by Mr. Sawyer, namely that with increasing solar constant the zonal westerlies become strengthened primarily in rather *low* latitudes. I also found a meridional change of air mass in the northern hemisphere associated with a hypothetical 1 per cent increase of solar constant that is entirely consistent with the observed meridional air mass change from minima to maxima of the 11-year sun-spot cycle based on data since 1900.

Having in mind the announcement by the Lowell Observatory some two years ago that from a study of planetary magnitudes they had evidence of a 2 per cent increase of solar constant between 1953 and 1958, this line of study seemed finally to be getting us somewhere. However, I have just a few days ago received a communication from Dr. Giclas of the Lowell Observatory which rather drops the bottom out of such ideas. It appears that a new re-analysis of the planetary magnitude data, in which additional complicating factors in the interpretation of the observations were considered, has failed to reveal evidence of *any* systematic change of solar constant since 1953.

Evidently, we must await direct measurements of the solar constant from satellites, using new instrumentation now being developed, before we can settle once and for all the question as to whether the solar constant varies appreciably from year to year.

H. H. LAMB. The absence of any variation of the solar constant during the very few years for which we have direct measurements of this may mean that there is no variation during the 11-year sunspot cycle; it cannot be taken to mean that there have never been any variations of the solar constant. Mr. Sawyer's paper adds some plausibility to the case which I also made in my paper (by another technique) that the effective solar radiation available around 1800 was somewhat less than it is today. This could be due either to a variation in the sun or to volcanic dust (or both). It would be interesting to see studies of stratosphere (and troposphere) temperature following great volcanic eruptions, similar to those shown by Dr. Godson following great solar flares. Data presumably exist for such studies at least following the Alaska 1952 (or 1953) and Kamchatka 1956 eruptions.

Possibly the dust thrown up from the first hydrogen bomb test (Eniwetok?) in 1954 should be treated as a third case.

W. L. GODSON. It is true that the best modern evidence is that the solar energy from 0.3 to 3 microns can have only a trivial variability correlated with sun-spots. There is no reason whatsoever to suspect that the situation could have been different over the period for which estimates of the sun-spot number have been made. To the extent that evidence for a solar control of weather and climate may be regarded as decisive, it is necessary to search elsewhere for an explanation —i.e., in the ultraviolet or in corpuscular radiation. In the latter case, evidence from the 12 November 1960 solar flare, perhaps the most intense in the last thirty years, gives no grounds for optimism with regard to energy absorption in the middle stratosphere, and examination of all ozone data back to 1925, relative to solar flares, confirms this pessimism. The ultraviolet mechanism seems the only logical alternative and solar variability from 0.1 to 0.3 microns now appears to be reasonably well established. It remains to establish the consequences of such ultraviolet variability. It may well be that formally such consequences are rather similar to those that have been previously suggested for changes in the solar constant itself.

R. FAIRBRIDGE. Regarding variations of the solar constant:

1. There can have been no major change in solar constant during the last 3 billion years, because of the Principle of Biological Continuity. If it had seriously changed (either in secular or spasmodic ways), we, the Earth's present Biota, would not be here.

2. I agree with Dr. Lamb that the A.D. 1800-1820 cold period suggests a radiative control. It coincides with lowest mean sun-spot level in three centuries. The effect was world-wide since sea level was also at its lowest over the same period.

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THEORIES OF CLIMATIC CHANGE FROM THE VIEWPOINT OF THE GLOBAL ENERGY BUDGET

by

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INTRODUCTION

After many marked signs of recent climatic changes had been found, several weather services were faced with the problem of foreshadowing climatic trends in the future, the most difficult question with which a meteorologist can be confronted.

Since we know very little about the real physical causes of climatic fluctuations, hardly more could be done than a simple extrapolation of recent trends. There is only little comfort in the thought that meteorologists involved would hardly survive the success or failure of their forecasts.

Regarding the climatic fluctuations it is necessary to distinguish between different time scales (Manley, 1953). Since only two and a half centuries of instrumental observations are available, and since most urgent questions of this kind deal with the next 50 or 100 years, we may restrict the present discussion mainly to the minor climatic fluctuations in the order of a few decades or, at a maximum, centuries (Table 1).

This restriction enables us to neglect most astronomical, astrophysical and geophysical hypotheses of climatic changes, which can affect climate mainly in a scale of some 10^3 to 10^8 years.

For our purpose only the variations of solar activity must be considered.

Many investigators have expressed the opinion that the cause of the observed climatic fluctuations in a given region can be found in variations of the large-scale patterns of the atmospheric (or oceanic) circulation. However, this idea renounces any physical explanation of those circulation anomalies and therefore must be considered as purely descriptive and unsatisfactory. Anomalies of the atmospheric circulation with a persistency of some months or 1-2 years are frequently observed, and their occurrence and behaviour form the basic problem of long-range forecasting. They may serve us as models for a better understanding of long-period climatic fluctuations. In fact, any shift of the normal circulation patterns can be followed, in a given region, by an advective warming or by decreasing frequency of cyclonic rains, but this is necessarily correlated with advective cooling or an increase of rain frequency at other regions. Excluding some possible local exceptions and all energy conversions, we are entitled to the general statement that *long-period anomalies* of the *large-scale atmospheric circulation* can only produce a *redistribution* of *heat, precipitation, kinetic energy*, etc., provided that the global energy budget remains constant.

TABLE 1. Geophysical and astrophysical hypotheses of climatic changes

I. *Astronomy*
- (*a*) Variations of the earth's orbit
  - (1) Eccentricity
  - (2) Longitude of perihelion
  - (3) Obliquity of the ecliptic
- (*b*) Rotation of the earth: Variation of the length of day

II. *Astrophysics*
- (*a*) Changes of the solar constant
- (*b*) Changes of the sun's activity: ultra-violet radiation, Roentgen and corpuscular rays
- (*c*) Density of interstellar matter

III. *Geophysics*
- (*a*) Shift of the earth's crust relative to the rotation axis or polar shift
- (*b*) Continental drift
- (*c*) Vertical movements and changes of orography

FLUCTUATIONS OF THE ATMOSPHERIC CIRCULATION

The occurrence of long-period fluctuations of the quasistationary cells of the global atmospheric circulations has been carefully studied (Scherhag, 1939; A. Wagner, 1940; Willett, 1949). Different circulation types have been described, and their frequency variations are responsible for the observed long-period fluctuations of the atmospheric circulation. As an example for climatic fluctuations affecting the whole troposphere, the frequency of blocking anticyclones in the European area varies substantially in a 22-23 year cycle. Even the position of the "quasistationary" European upper trough of the meandering westerlies varies with time, as indicated by the resultant wind of two mountain observatories of the Eastern Alps, near the 700 mb.-level (Flohn, 1961).

The large retreat of the Arctic sea-ice during the first 40-50 years of this century—which recently has been stopped—suggests the possibility of an atmospheric circulation with one ice-free pole. In this case —which has been realized in interglacial epochs, perhaps also in the post-glacial warm period—the present asymmetry between northern and southern hemisphere ought to be even stronger. With reasonable assumptions it can be computed (Flohn, 1959), that with an ice-free Arctic the baroclinic summer circulation of the northern hemisphere would be nearly the same as now, but during winter the intensity of the zonal westerlies should be 20-30 per cent smaller, nearly equivalent to May or September today. Such a decrease in baroclinicity is correlated with a sharp drop of cases with dynamic instability, and consequently with rapid and intense cyclogenesis.

Expansion and contraction of the circumpolar tropospheric vortex, the partial breakdown of the westerlies produced by blocking action and the orographically (and thermally) produced meanders are to be considered as peculiarities of the atmospheric circulation fluctuating with time. They are (reciprocally) correlated with the observed climatic variations and constitute an integral part of them. The physical cause of these anomalies can only be completely understood on the basis of the energy budgets of the atmosphere and—since 71 per cent of the surface is water-covered—of the oceans.

Here it ought to be mentioned that one of the few sound physical explanations of persistent circulation anomalies, which has been suggested, is given by a feed-back mechanism between ocean and atmosphere (Namias, 1959; Bjerknes, 1961). An amazing example of this kind has been recently found: rainfall at the Angola Coast of West Africa (Luanda) during January-March is correlated with the rainfall in North-east Brazil (e.g., Fernando de Noronha) during April-August as high as +0.77 (35 years). The strange lag of this correlation can be interpreted as the result of an advective transport of water temperature anomalies with the great equatorial current, which lasts 3-4 months. This effect—together with a strong correlation between rainfall in North-east Brazil and the position of the Intertropical Convergence Zone—may explain largely the occurrence of droughts in North-east Brazil, where a marked and dreaded decrease of precipitation has been observed in recent decades.

CLIMATIC VARIATIONS AND BALANCE EQUATIONS

In many investigations of the global budgets of radiation, heat, water or energy it is tacitly assumed that the over-all budget, at least for years or decades, can be considered as completely balanced. However, recent quantitative studies of the ice budget (Antarctica, Greenland, etc.) have revealed that storage processes, positive or negative, are not negligible. This is true also for other budgets. From such considerations the late C. J. Rossby has suggested the study of the geophysical balance equations including the heat and water storage capacity of atmosphere, continents and oceans. With this suggestion we obtain a rational physical basis for a systematic discussion of theories of climatic change, and we are obliged—disregarding here the nearly complete lack of relevant basic data—to attack the problem from its very roots. In order to avoid some difficulties, we neglect the role of advection, which is only allowed in a global balance, but certainly not at a local level. The complete formulation of the balance equation for radiation, heat and water vapour can be written in the following abbreviated way:

TABLE 2. Balance equations of the earth's surface

1. Radiation balance:		$Q = (S + H)(1 - a) - (E - G)$
2. Heat balance:		$Q = U_B + U_N + U_L + U_V \pm \Delta U$
	2(a):	$\Delta U = \Delta U_B + \Delta U_L + \Delta U_V$
3. Water balance:		$N_E = V_E \pm \Delta W$
	3(a):	$\Delta W_E = \Delta W_M + \Delta W_K (+\Delta W_L)$
	3(b):	$N_K - V_K = A_K \pm \Delta W_K$
	3(c):	$V_M - N_M = A_K \pm \Delta W_M$

Notes

Q = radiation balance at the earth's surface
S = solar radiation } (S + H) (1 — a) = effective global radiation
H = diffuse sky radiation }
a = albedo of the earth's surface
E = terrestrial long-wave radiation } E — G = effective terrestrial radiation
G = atmospheric long-wave counter-radiation }

U = thermal energy transfer
Δ = storage
N = precipitation
V = evapotranspiration
W = water, water-vapour or ice
A = run-off

Indices

B = soil (or sea)
L = air (sensible heat)
V = evaporation (latent heat)
N = warming of fallen precipitation + melting of snow and ice
E = earth
M = oceans
K = continents.

SOLAR RADIATION THEORIES OF CLIMATIC CHANGE

Disregarding the geometrical properties of direct solar radiation, the amount of solar energy available at the earth's surface depends on the solar constant S_0 and the atmospheric transmission, here including the amount of cloudiness. The reality of the observed increase indicated by the Smithsonian measurements of the solar constant (about 0.01 per cent per year between 1925 and 1944) has been doubted by most specialists, since changes in the evaluation and correction of the original data seem to infringe the homogeneity of the observations. This apparent trend has been interpreted as a result of gradually decreasing turbidity, most probably caused by the recent lack of large-scale volcanic eruptions (Wexler, 1953). If S is lowered by increasing turbidity, the diffuse sky radiation H will increase slightly. Since a certain part of S will be diffusely radiated back into space, the decrease of the global radiation $S + H$ will be about 50 per cent less than that of S.

The strong influence of large-scale volcanic activity on the radiation balance has been demonstrated after the enormous ash emissions of Krakatao (1882) and Katmai (1912). These effects produced a global decrease of S by 10-20 per cent lasting 1-2 years; the even bigger eruptions of 1783 (Japan, Iceland) and 1815 (Tambora) obviously led to similar global effects. Extremely cool and wet summers followed in 1816 in Europe and North America, and 1784-86 in Eastern Asia. These effects are better understood now, since we know that radioactive particles with a diameter near 1 micron may remain suspended 5-10 years in the higher levels of the stratosphere, which is the height reached by the ash cloud of Krakatao (32 km.). Such particles scatter the incoming solar radiation substantially with the effect of a (smaller) decrease of $S + H$.

If by any other cause the average cloudiness should be changed, the albedo of the system earth + atmosphere (planetary albedo)—which is in all areas uncovered by snow higher than the surface albedo, due to the high albedo of clouds (40-80 per cent)—can likewise substantially vary with time. This is especially true in regions which are affected by persistent circulation anomalies. There are no convincing reasons for a global change of cloudiness in recent centuries, but certainly this effect cannot be excluded in a geological time scale. The effect of artificial changes in the surface albedo is small and restricted to small continental areas; it seems to be unimportant. However, quantitative estimates are needed.

The contribution of the large observed time variations in some parts of the solar spectrum—in the Roentgen spectrum, for ultra-violet and corpuscular rays—is extremely small, only of the order 10^{-6}. Nevertheless the "solar activity" produces large effects in the upper atmosphere, but cannot penetrate into the troposphere. Here some quasiperiodical circulation anomalies have been demonstrated with the sun-spot period of about 11 years (Willett, 1949, 1951; Wexler, 1953) and also —but less convincing—with periods of 5.5 and 22-23 years; the evidence presented for a cycle of 80-90 years (Scherhag, 1939; Willett, 1951) is hardly sufficient. In spite of all recent efforts we lack a self-consistent physical model correlating the observed responses of the upper atmosphere to solar activity with the simultaneously observed patterns of the troposphere and lower stratosphere. It seems highly unlikely that the tropospheric response to a given solar eruption is always similar, independent of all regional and time fluctuations in the state of the atmosphere. Even if we consider the evidence for solar-tropospheric relationsships as statistically verified, we are by no means permitted to explain the bulk of climatic variations exclusively with this hypothesis. On this basis, Scherhag had in 1939 successfully forecast a reversal of the warming trend, and Willett has issued (1951) an audacious forecast for the climatic trend of the next decades. Having in mind all the inconsistencies of this hypothesis together with all other physical effects (Table 2), the author feels that forecasts of this type are not sufficiently substantiated.

CARBON DIOXIDE AND AIR POLLUTION

According to recent systematic investigations, the CO_2 content of the atmosphere has increased from about 290 ppm ($= 10^{-6}$ volume units) at the end of last century to about 330 ppm in the last decade. From C-14 investigations from living wood H. E. Suess has concluded that the dilution of atmospheric carbon dioxide by C-14-free CO_2 produced by the burning of fossil fuels amounts only to 2-4 per cent, much smaller than the above-mentioned 12 per cent (Revelle and Suess, 1957). It can only partially explain the recent increase. In addition to all combustion processes and to the exchange of CO_2 with the oceans, we have to consider also the CO_2 production of the soil bacteria from the bare soil in cultivated areas, together with the rotting of plants, animals etc., as a consequence of the increasing population. The annual production of fossil CO_2 by industrial combustion has been estimated at 6.10^{15} g., and the additional production of living CO_2 by agricultural operations and bush fires at about 10.10^{15} g. together (Flohn, 1961).

In a recent theory of climatic change (Plass, 1956) —following earlier suggestions by S. Arrhenius and G. Callendar—it has been demonstrated that the increase of CO_2 causes an increase of the atmospheric counter-radiation G and from this a temperature increase nearly equal to the observed rate of 0.01° C. per year. The neglect of other long-wave absorbing constituents of the atmosphere has raised some objections against this challenging and physically well established theory. Parallel to the increase of CO_2 we should expect an increase in the particle content of the lower atmosphere, not only in the relatively small industrial areas of middle latitudes but much more by the bush fires in large areas of the semi-arid and semi-humid continents. The effect on outgoing terrestrial radiation and temperature can be considered as similar, at least above tropical continents.

However there are serious objections against any over-emphasis of the CO_2 theory. First: it deals only with one single term of the global heat balance. The observed constancy of temperature south of 50° S. cannot be explained on this basis, since the CO_2 content of Antarctic air is not significantly lower than in other zones, as has been suggested. The occurrence of apparently world-wide temperature variations before the start of the industrial area and the rapid increase of population—e.g., cooling from the sixteenth century to the Little Ice Age (1680-1740) and warming during the period 1770-1810 (Flohn, 1957)—is followed recently by a small but general tendency to cooling in the last decade, accompanied by the most rapid increase in industrial combustion. Such examples seem to demonstrate that the CO_2 effect—even as supported by a similar effect of artificial air pollution—cannot be considered as the single (nor even as the main) cause of climatic variations, but certainly as an essential contributing factor.

It must be stressed that the observed global rise of air and ocean temperatures in the order of 0.01° C./year involves a heat storage ΔU_L in the air as well as ΔU_B in the oceans; some records from individual stations indicate a similar heat storage in the soil. The geophysical consequences of ΔU_B in the oceans might be far-reaching, as indicated by C. J. Rossby shortly before his untimely death.

MAN-MADE EFFECTS ON THE WATER BALANCE

The boundary between semi-humid and semi-arid climates depends on the relationship between continental precipitation N_K and actual evapotranspiration V_K. The latter term is included also in the heat balance: $U_V = lV$ (l = latent heat of water-vapour). Since V_M yields about 90 per cent of V_E, global variations of V_E or N_E should be controlled to a large extent by the oceanic water budget, so that both quantities are nearly invariant. The present global rise of sea-level in the order of 0.12 cm./year can be explained by the continuous melting of mountain glaciers including the Greenland ice-cap—while the probable recent increase of the Antarctic ice-cap would produce a nearly equal lowering of the sea-level—together with the decrease of the density of surface waters by recent warming.

However, over the continents V_K can be strongly influenced by man's activity, at least at a local level: destruction of the natural vegetation, conversion of forests, savannahs and steppes into agricultural areas, desiccation of swamps, artificial lakes, etc., may lower or raise the amount of evapotranspiration. Such hypotheses have been frequently discussed during the last century. But also recently Schwerdtfeger (1955) suggested that the observed increase of precipitation in the Argentine pampas is due to the increase of evapotranspiration during its conversion to crop land. However, over the western prairie states of the United States of America no similar effect could be found (Flohn, 1957), since the fluctuation of precipitations runs more or less parallel with the adjacent territories, and the severe drought of 1932-35 was followed by a substantial decrease of cultivated areas. In fact, in continental areas of temperate or higher latitudes the water cycle is governed to a large extent by the advection of moist air from the sea, due to the vertical increase of wind, which counterbalances the decrease of water-vapour with height.

Above tropical continents water-vapour transport decreases more rapidly with height, due to the small vertical wind shear, and its vertically integrated velocity is smaller than at higher latitudes. According to recent investigations, the average water vapour transport during summer above 6 stations of the African tropics amounts only to 560 g./cm. sec., while above 8 stations of the Indo-Pacific tropics we obtain 2,013 g./cm. sec. Even the latitudinal average at 45° N. amounts to 930 g./cm. sec., in spite of the much lower H_2O-content of the atmosphere. Therefore the local or regional influence of man's activity in the atmospheric budgets is much greater above tropical continents. In humid or semi-humid countries, conversion of natural vegetation into cultivated areas is mostly accompanied by a decrease of V_K and U_V, and this leads to an increase of U_L—i.e., to rising temperatures—but to a decrease of N_K if no additional sources of water vapour are available. It should be stressed that above tropical Africa the average residence time of a water vapour molecule in the atmosphere is only 8-9 days, compared with the global average of 11 days (Flohn, 1961).

These results demonstrate that the climate of tropical continents is much more sensitive to local or regional alterations of evapotranspiration or other interferences in the natural water budget. Here in cases of decreasing precipitation the role of man's activity cannot be excluded *a priori*. Therefore substantiated investigations on the heat and water budget, as done in East Africa (Pereira, 1959), are strongly needed.

From this point of view of physical (and synoptic) climatology, some words ought to be said in favour of the fascinating idea (Bergeron, 1960) of the possibility of an artificially increased evapotranspiration in the Sudan belt of Africa. According to our present knowledge of weather situations, wind distribution and water-vapour transport, summer rains in the area between the Equator and a line about 200-300 km. south of the Intertropical Convergence Zone (as defined by the equatorial pressure trough near 18° N.) are mainly due to convective activity in an unstable air. The shallow south-west monsoon is overrun, above about 2 km., by an easterly flow, so that the vertically integrated flux of H_2O is relatively small and partly even directed from the east. According to the available data, the main source of water-vapour is not the Atlantic Ocean, but the tropical rain-forest of the Congo Basin. In fact, the actual evapotranspiration of a tropical rain-forest or an irrigated agricultural area is very nearly the same as that of a lake or the ocean at the same latitude (120-150 cm./year, with exception of the Indian Ocean).

Under those conditions, any large-scale increase of evaporation in the Sudan area ought to be followed by a similar increase of rainfall spreading towards the north-east. Here spacious projects of irrigation, supplied by rivers like the Congo, Niger or White Nile could affect the regional water-budget in a positive sense.

CONCLUSIONS

If we consider carefully—at least qualitatively—the complete equations of the radiation, heat and water budgets of the atmosphere near the surface, including the storage capacities of atmosphere, oceans and continents, it seems very unlikely that any theory of climatic change, which is based only on one factor, can give a complete and satisfactory explanation. Obviously climatic variations are a highly complex phenomenon, where several physical factors are interacting. Recent advances in laboratory experiments as well as numerical computations of models of the general atmospheric circulation may enable us, in a foreseeable future, to attack seriously the problem of climatic variations from its very roots. Obviously this is the only way to create a scientific basis for a physically sound prognosis which now is virtually impossible.

If we consider the possible changes of some terms of our balance equations due to the increasing activity of man and the rapid increase of population, we come to the result that at least in tropical areas the occurrence of man-made effects on climatic changes cannot be excluded *a priori.* In humid areas of the continents, conversion of natural vegetation into farm land tends to lower evapotranspiration, in arid or semi-arid areas irrigated agriculture tends to raise it. In semi-humid or semi-arid areas both effects are possible, and consequently other terms of the heat balance do not remain unaffected. Thus we ought to visualize quite seriously the danger that such effects are acting involuntarily against the benefit of mankind, but in an irreversible manner.

RÉSUMÉ

Théories des changements de climat du point de vue du bilan énergétique global (H. Flohn)

L'auteur du document examine les équations des bilans radiatif, thermique et hydrique globaux, ainsi que les capacité d'emmagasinage de l'atmosphère, des océans et du sol. Ces équations servent de base de comparaison entre les théories géophysiques existantes et (partiellement) les théories astrophysiques des changements de climat et elles permettent en outre de procéder à une estimation approximative de certaines des quantités considérées.

Compte tenu de la grande variété des fluctuations climatiques dans le temps et dans l'espace, il est fort peu probable que l'on puisse trouver une explication qui se fonde sur un seul facteur. En ce qui concerne l'équilibre de l'eau, du gaz carbonique et de la pollution de l'air, il ne faut pas sous-estimer le rôle du facteur humain dans les changements climatiques, tout au moins à l'intérieur des continents tropicaux.

DISCUSSION

J. Murray Mitchell. I wish to make just a small comment on this very interesting paper, concerning the apparent discrepancy between secular increases of fossil CO_2 determined from direct measurement ($\approx$10 per cent) and from C-14 measurements (2-4 per cent). Bolin and Erikson, in a contribution to the Rossby Memorial volume, have given evidence to show that this discrepancy is only an apparent one, and that when the processes of CO_2 exchange between ocean and atmosphere are more fully taken into account, the C-14 data are entirely consistent with the observed secular increase of the order of

10 per cent. Therefore, while agricultural practices and bush fires may indeed have contributed to the observed CO_2 increase, it is apparently unnecessary to insist on the importance of such factors to account for this increase.

J. R. PHILIP. Dr. Flohn has mentioned the question of man-made climatic change. I would like to speak briefly on the current status of work on artificially induced local climatic change. For brevity I shall refer only to an arch-typical problem—namely that of the changes in climate induced by irrigating a previously arid area.

The problem can be formulated as one in the turbulent diffusion of heat and water vapour in the lower atmosphere. We need to go somewhat beyond the well-known work of Sutton,[1] and to solve simultaneously the equations for the heat and the water vapour fields, preserving the energy balance at the earth's surface.

Timofeev[2] in the Soviet Union appears to have done the first work on the mathematics of this problem. De Vries,[3] my former colleague, now back in the Netherlands, took the theory somewhat further, and I was able to develop a simpler method of analysis, which has been published in part.[4]

During the last few years our group in Australia has temporarily included Mr. Rider of the United Kingdom Meteorological Office. He has developed an experimental set-up which enables us to study the dry-to-wet problem of local advection micrometeorologically.[5] We now have a large body of data, and there is encouraging agreement with the mathematical-physical theory. What discrepancies there are seem attributable to the change of aerodynamic roughness between the "dry" and "wet" surfaces, and we are giving this matter further consideration.

I believe that we can conclude that this small part (which, though small, is certainly of great economic and social importance, especially for the arid zone) of the overall problem of climatic change is capable of successful and useful mathematical-physical study.

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SURFACE-ATMOSPHERE INTERACTIONS AS FUNDAMENTAL CAUSES OF DROUGHT AND OTHER CLIMATIC FLUCTUATIONS

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INTRODUCTION

For almost a century it has been recognized in meteorology that the general circulation is not uniquely specified by the month or season, and that long-period averages (sometimes called normals) are composed of many different types. In spite of the vast amount of work carried on over the past decade relating to problems of the general circulation, little effort has been given to the urgent matter of explaining irregular variations in large components of the general circulation from one month, season, or year to the next—differences which lie at the root of the problem of climatic variations.

The primary purpose of this report is to present evidence indicating that the persistence and persistent reccurrence responsible for climatic fluctuations, at least of the order of a season to a few years, may be due in large part to abnormal boundary influences on the overlying atmosphere. These influences are in turn varied by the prevailing circulation and weather patterns, so that positive feed-back mechanisms operating over long time intervals are brought into play. Although the number of such variables may be large, three obviously important ones shall be treated: snow cover, moisture or the lack of it over continental areas, and sea-surface temperatures. These factors have been mentioned in the literature many times during the past century, but the innate complexity of large-scale atmospheric behaviour has made it difficult to prove or measure these influences. Although in this report no conclusive proof is given, it is hoped that the empirical evidence presented to support *a priori* hypotheses is reasonably convincing. The report differs from others of this nature in taking advantage of newer synoptic and dynamic concepts, fresh and extensively processed upper-air data, and electronic computational procedures.

INFLUENCE OF SNOW COVER

The first topic treated shall be the positive feed-back mechanisms that operate when a snow cover is laid down in an area where it is uncommon.

A special case in which extensive snow cover played a vital role occurred over Central United States from mid-February to mid-March 1960, when the southern boundary of mow was persistently found well south of its normal position (see shaded area in Fig. 4). The accompanying sea level mean circulation (Fig. 1) for this period shows a tremendous North American continental anticlycone, representing the net effect of repetitious outbreaks of cold polar anticyclones following on the heels of rapidly developing east coast cyclones. The paths of these storms are shown in Fig. 2, where the heavier stiches indicate their 24-hour periods of greatest deepening (up to 35 mb. per day). The resulting thickness pattern, including its departure from normal, is reproduced in Fig. 3. From these figures alone it is not possible to separate the effect of cooling by snow from that which is due simply to the transport of polar air masses southward over the continent, for even in the event that snow were not present, the central portion of the United States would have been colder than normal.

Fortunately there is an objective method which can be used to assist in separating these effects. This involves a procedure developed by Klein, Lewis, and Enger (1959) for specifying temperature as a function of mid-tropospheric height patterns. Briefly it consists of a "screening" procedure whereby the mean temperature departure from normal at a station is related to simultaneous fields of 700 mb. height over a domain covering almost half the hemisphere. An electronic computer programme selects the position of the 700 mb. height which contributes the largest part of the variance of temperature; after this is removed a second point is determined, and so on until the variance is no longer reduced appreciably. Generally, this takes 700 mb. heights at about four

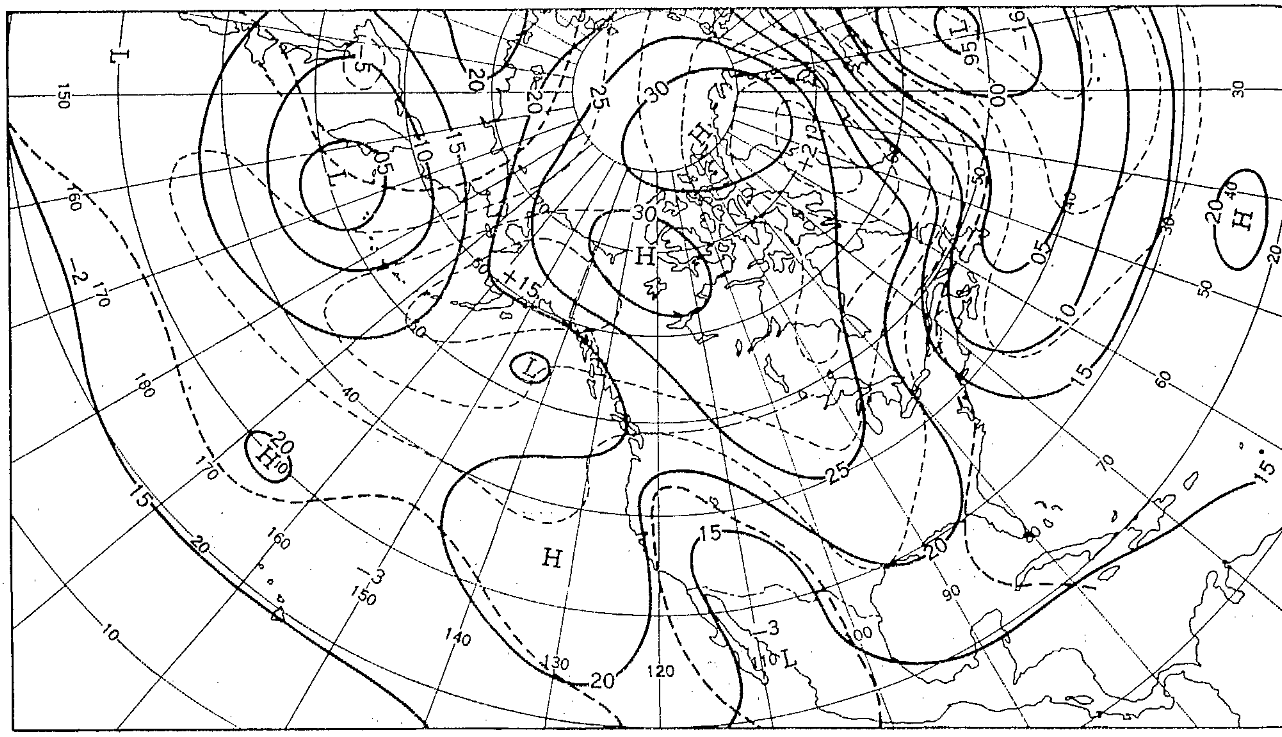


Fig. 1. Mean sea level isobars (solid), and isopleths of departure from normal (broken), for the period mid-February to mid-March 1960.

locations, and from these a suitable regression equation (with correction factors to achieve the proper standard deviations) is established, making possible an estimate of surface temperature from the mean 700 mb. height field. This procedure has been developed for 35 stations within the contiguous United States for each of the four seasons, and accounts for about 64 per cent of the observed variability of monthly mean temperature.

The countrywide estimates can then be analysed into climatological classes of temperature (much above and much below normal, near, above and below normal) and charted on maps. The class estimates for the mid-February to mid-March period, based on computations from the 700 mb. mean chart, showed very good agreement with the observed temperature anomalies, even though the numerical errors of the estimate (Fig. 4) are quite large in some areas. The largest errors (from 8° to 10° F.) are along the prevailing snow boundary. Large errors are also found to the south of the snow boundary and are undoubtedly due to the fact that the prevailing surface air (indicated by the mean sea-level isobars in Fig. 1) was blowing southward off the snow. In areas well to the north (where snow is usual at this time of year) and to the west, errors of the estimates are quite small. Thus, it is probable that the snow cover reduced temperatures in the central areas as much as 8° to 10° F. per day below those which would have been observed had the snow not been present.

A rough computation may also be made to show that the magnitude of this influence is quite reasonable. At the latitude of the snow boundary shown in Fig. 4, about 300 Langleys (calories per cm.^{2}) per day are normally received on horizontal ground from the sun and are potentially available to heat the air. In other words, this is the normal net insolation for this area during the mid-February to mid-March period (Fritz, 1949). If we assume an albedo of 0.8 with snow cover and 0.2 without, then only about $0.2 \times 300 = 60$ Langleys per day become available to heat the air when snow is present, as against $0.8 \times 300 = 240$ Langleys per day without snow. Since little melting would occur during the period because of the observed low temperatures, most of the energy absorbed by the surface was probably used to heat the overlying air.

Now if, with snow, all the absorbed solar energy was used to heat a 100 gramme column of air about 1 km. in depth, and

$$\frac{\Delta T}{\Delta t} = \frac{\Delta Q}{c_p M}$$

where ΔQ is the heat added per day; c_p, the specific heat of air; M, the mass of air; and ΔT, the temperature change, then

$$\frac{\Delta T}{\Delta t} = \frac{60}{0.24 \times 100} = 2.5^\circ \text{ C./day.}$$

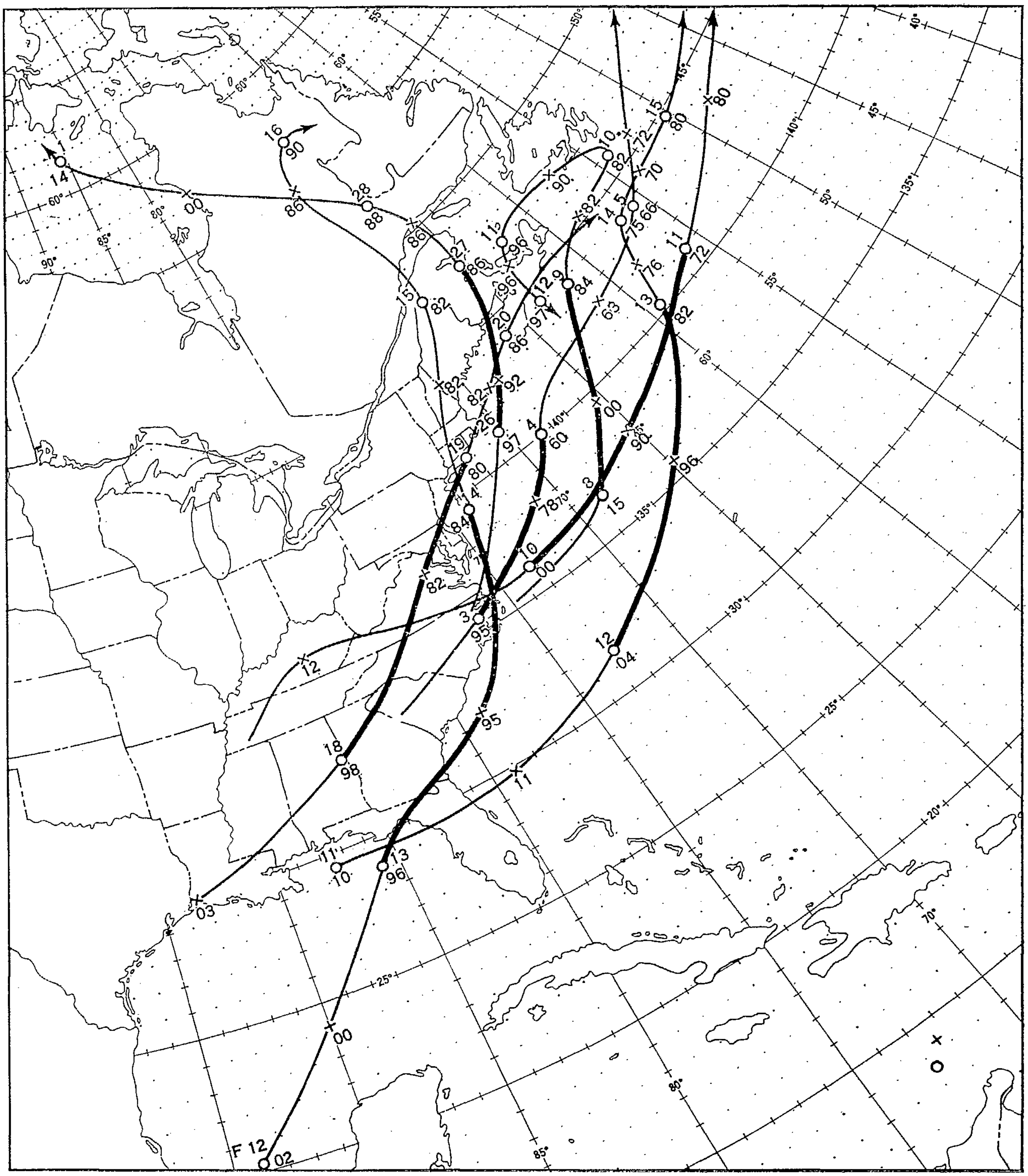


FIG. 2. Paths of major cyclogenetic storms during the period mid-February to mid-March 1960. Figures beside the crosses (0000Z) and circles (1200Z) show the dates (upper) and intensity in millibars (lower), with hundreds omitted. The heavy segments of the paths are those of maximum 24-hour deepening.

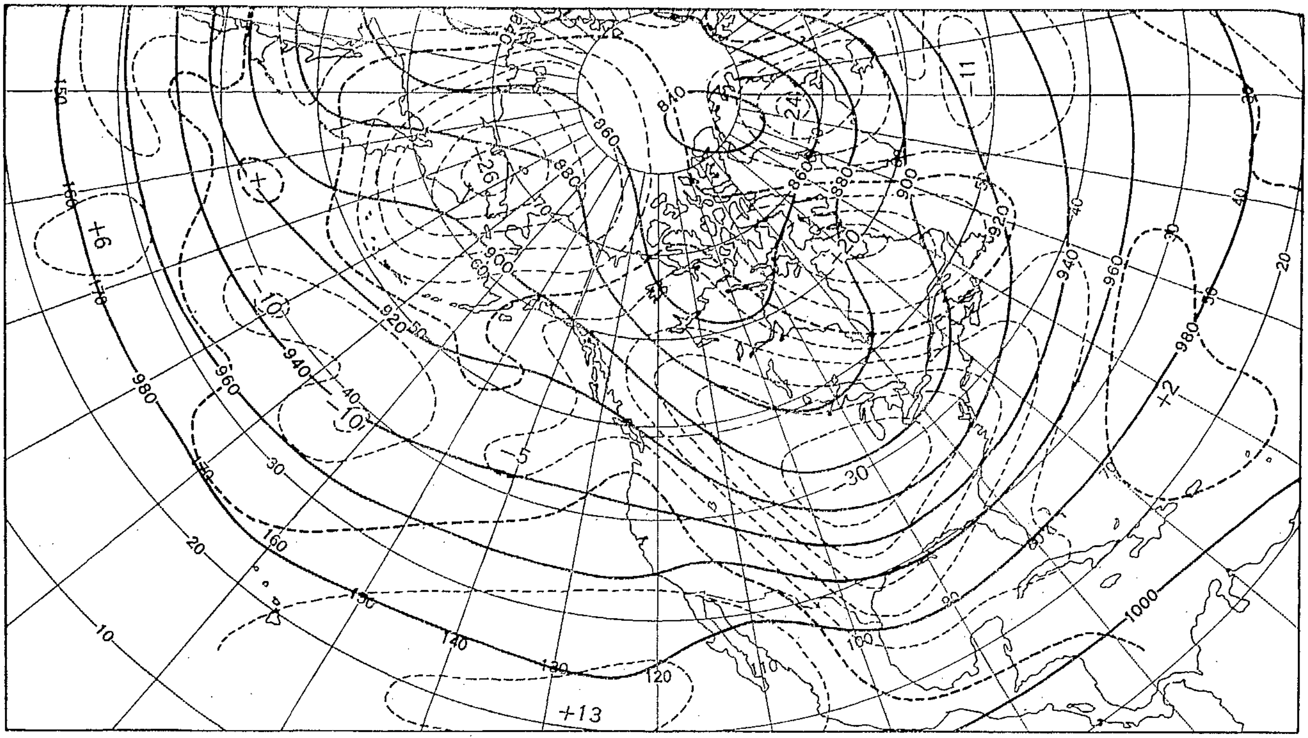


FIG. 3. Mean thickness between 1000-700 mb. (solid), and departures from normal (broken), for the period mid-February to mid-March 1960. Isopleths and anomaly centres are labelled in tens of feet.

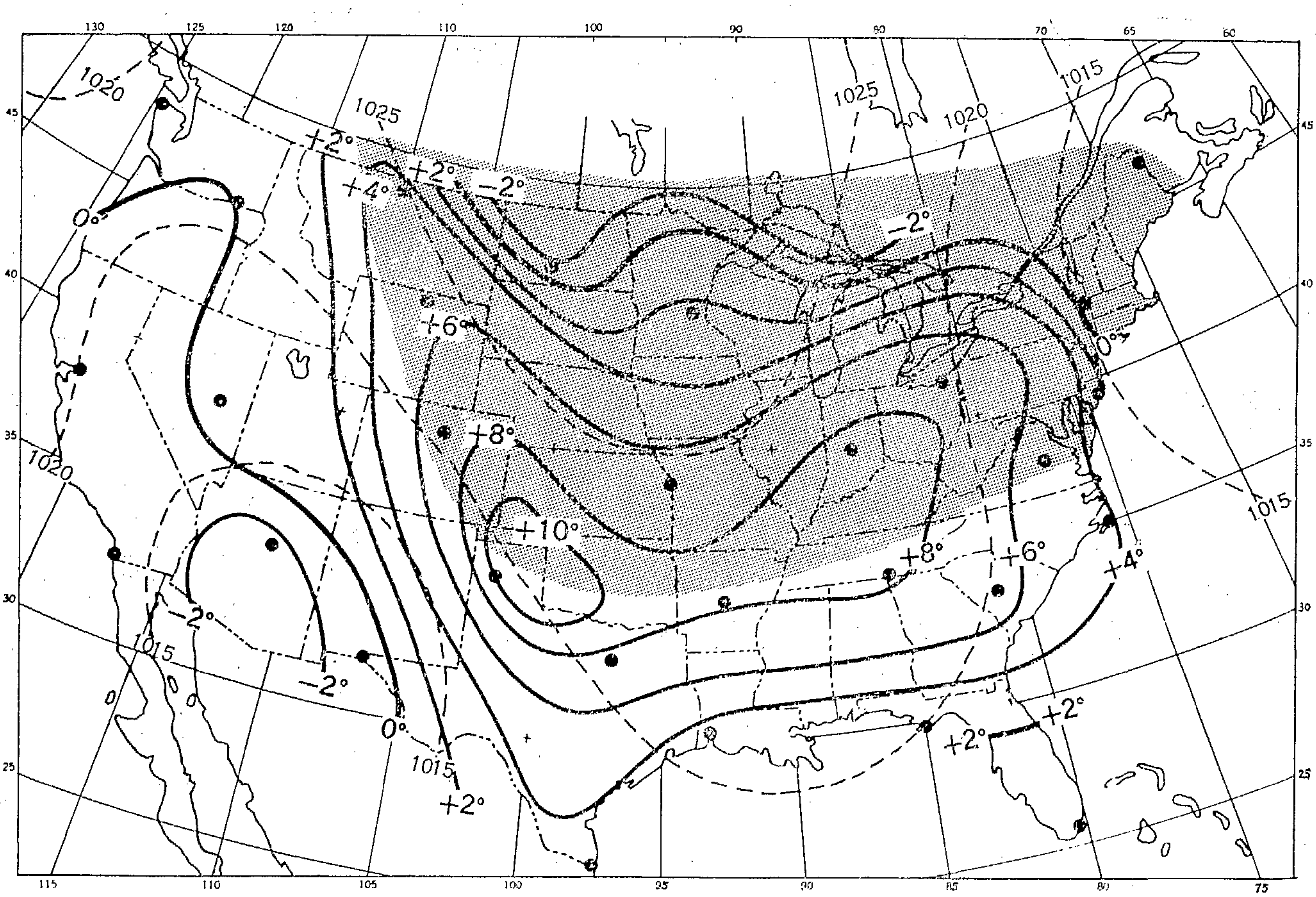


FIG. 4. Isopleths of error in °F. of temperature estimates (solid), and isobars of mean sea level pressure (broken), for the period mid-February to mid-March 1960. Shading roughly indicates prevailing snow cover east of the continental Divide.

Without snow, on the other hand,

$$\frac{\triangle T}{\triangle t} = \frac{240}{0.24 \times 100} = 10^\circ \text{C. per day.}$$

Thus the difference, which may be looked upon as due to the diminished heating of the lower air when snow is present, is about 7.5° C. If we double the air layer to 2 km., the difference is halved to about 3.8° C., or roughly 7° F., a figure comparable to the observed error of the statistical estimates along the snow boundary.

It seems likely that this extensive and abnormal snow blanket, besides refrigerating the air masses in transit, had other more subtle effects. To arrive at an indication of these additional influences we refer again to Fig. 2.

The zones of most intense cyclogeneses (Fig. 2) are found much farther south than normal along the eastern seaboard. Expressed in another way, the occlusion process of these storms was greatly speeded up relative to normal for storms of this type. Now it is well known that the deepening of east-coast cyclones is to a considerable extent baroclinically induced, so that barotropic numerical predictions frequently contain large positive errors in the coastal area.

Extensive statistical studies relating to extended forecasting (Martin, 1953) have demonstrated the interdependence or "teleconnexion" between mid-tropospheric five-day mean height anomalies in various regions of the northern hemisphere. One of these relationships associates negative height anomalies in an area about 500 miles south of Newfoundland with positive anomalies just east of Hudson Bay. Thus strong cyclogenesis of the character described above would in some manner occur along with *anticyclogenesis* over eastern Canada.

In order to demonstrate the impact of the east-coast cyclogenesis during mid-February to mid-March on the North American general circulation, a correlation was made between each day's sea level pressure map and the 30-day mean of which it was a part. This was done for a grid of points extending from 50° W. to 110° W., and from 30° N. to 65° N. The squared correlation coefficients are plotted in Fig. 5, and might be called the "correspondence" between sea-level daily and 30-day mean maps. The fluctuations prevailingly show rises following the major periods of cyclogenesis. A superposed-epoch plot (lower part of Fig. 5) with 0 taken as the whole 24-hour period of greatest cyclogenesis, shows a tendency for the correspondence to be relatively low preceding cyclogenesis and to rise to a plateau subsequently. In other words, it appears that the cyclogenesis is a sort of resuscitating injection for the prevailing quasi-stationary pattern of the 30-day period.

We thus arrive at a "feed-back" mechanism germane to this case:

1. The general circulation for this period, an outgrowth of earlier abnormal forms during the winter, favoured polar anticyclones and their deployment southward following intense east-coast cyclones.
2. The advancing polar air masses were refrigerated in their southward transit by an abnormally extensive snow cover.
3. The low-level temperature contrast between these cold air masses and the warmer air masses overlying the Gulf of Mexico and the Atlantic Coastal waters thus increased over what it would otherwise have been.
4. East coast cyclones, feeding on baroclinicity enhanced by this extra contrast, occluded and developed rapidly.
5. The cyclogenesis helped to re-establish the Canadian anticyclone and consequently assisted in the ejection of fresh polar air masses southward into the United States.

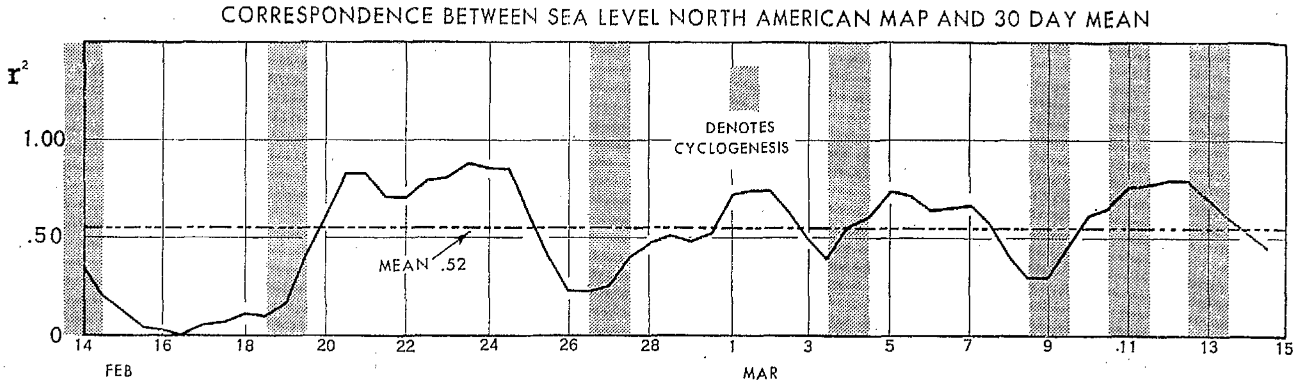
This process, if highly dependent on the snow cover, would be terminated when that cover disappeared, as well as whenever other influences of the general circulation became overwhelming.

POSSIBLE INFLUENCES OF VARIABLE SEA-SURFACE TEMPERATURES ON THE ATMOSPHERIC CENTRES OF ACTION

If one examines carefully monthly or seasonal mean charts of atmospheric pressure or, better, mid-tropospheric height, it soon becomes clear that singular features like troughs and ridges may frequently be followed from one area to another in much the same fashion as cyclones are tracked on daily weather maps. This continuity of long-period systems has been recognized for many years [e.g., by C. E. P. Brooks, (1926)] and, in fact, forms a substantial part of the method used in the preparation of 30-day outlooks in the United States (Namias, 1953). It is naturally more difficult to ascribe plausible continuity to features of seasonal mean charts than to monthly charts, but even here some rather continuous evolutions come to light. For example, Fig. 6 shows mean mid-tropospheric charts for the four seasons from summer 1957 to spring 1958. The regularity of motion here lies in the steady eastward displacement of a trough and its associated anomaly (negative departure from normal) from the west-central Pacific to the west coast of the United States.

A special study of this case (Namias, 1959) suggests that the steady eastward progression may have been associated with an anomalous pattern of water temperatures, which in turn was created and maintained by anomalous prevailing wind systems and by certain adjustments in the mean planetary wave trains. These adjustments were perhaps made necessary by climatologically-associated variations in the position of the Asiatic trough and the change in strength of the zonal westerlies over the Pacific.

In more detail, the essence of the explanation is that the anomalous prevailing winds in the vicinity of the



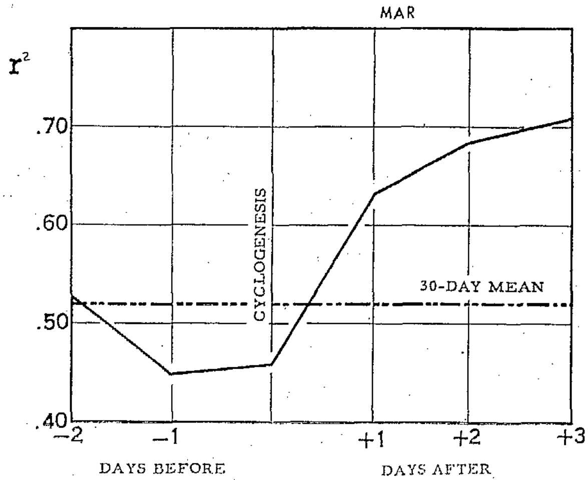


FIG. 5. Square of correlation between daily and 30-day mean during mid-February to mid-March 1960 over North America and adjacent Atlantic (upper). Also (lower) mean of values from upper graph plotted at days preceding and following the most active 24 hours of cyclogenesis (not including these 24 hours).

Pacific trough create an anomalous Ekman drift, which in turn results in warmer than normal water masses east of the trough, and, similarly, colder than normal surface water to its west (inferences supported to some extent by observed water temperatures). This enhanced longitudinal temperature contrast is rapidly and frequently imparted to overlying air masses resulting in greater baroclinic development of cyclones than otherwise in the domain of the mean trough. This enhanced development would then provide longevity to the mean trough. Its geographical location, however, would be determined also by neighbouring parts of the general circulation, especially the upstream trough along eastern Asia. This latter quasi-stationary feature of the general circulation can be found almost in the same location each winter, so that, with only slight variations in position and intensity, it is a climatological fixture. The almost unending series of cyclones along the front of the Asiatic monsoon feed on the contrasting air masses deployed by the Asiatic High and the west Pacific anticyclone, and these occluding cyclones bring about a marked increase in the Pacific westerlies from summer to autumn to winter—another climatological event with high probability of occurrence. From Fig. 6 it is clear that both phenomena, the anchored Asiatic trough and the accelerated westerlies, were observed as the seasons evolved, and consequently, the locus of mean upper level trough development in the Pacific moved eastward in phase with the baroclinic effects induced by the anomalous water temperatures. Thus a continued positive interaction between the two processes was permitted.

A similar series of events was also observed from the autumn of 1959 to the following winter. However, the time scale for the eastward transit of the trough across the Pacific was considerably shorter—of the order of a few months rather than seasons.

Perhaps it should be emphasized that this sequence of events does not proceed every year although it is apparently frequent enough to influence the appearance of normal monthly upper-air patterns. Obviously, the initial state of the general circulation as well as the water temperature anomalies may differ from one year to another. For example, if a mean trough with negative anomaly and the accompanying water temperature deviations has not existed in the west-central Pacific during the summer and early autumn a different series of mean patterns may result.

POSSIBLE INFLUENCES OF SOIL CONDITIONS

It is a well-recognized fact that drought is one of nature's most persistent phenomena, so much so that one of the sayings which has developed among American forecasters is "All signs fail in times of drought". A forecasting rule which has several adherents is not to forecast rain in a persistent dry spell until the day it begins. This experience suggests that some element not conventionally considered might be operating to discourage the formation of rain. At other times the slightest perturbation or weak front seems to set off precipitation. These rainless or exceptionally rainy conditions frequently arise during late spring and summer in the Great Plains, when this continental area normally receives most of its annual rainfall.

The regional pattern of the general circulation associated with drought in the Great Plains is well known. It is the upper-level anticyclone with subsiding dry air flowing into its core from northern westerlies (Wexler and Namias, 1939). Persistent ancicyclones of this type are almost always accompanied by well-developed anticyclones over the adjacent ocean areas, with positive height anomalies like those shown in the composite chart for the three fairly homogeneous drought summers of 1952-54 (Fig. 7). It may be shown from statistics gathered from mean charts of many years that this echelon of well-developed subtropical anticyclones in mid-troposphere is a harmonious arrangement, and that if any two cells exist the other is favoured to develop.

Now between spring and summer there is a tendency for upper-level anticyclones to develop over the Southern Plains, a tendency associated with the northward migration of the westerlies and rapid surface heating in this area. But there are many years when the anticyclone fails to become established. From synoptic studies of aerological data of the past 25 years it appears that if the upper-level anitcyclone is going to emerge strongly and persistently over the plains in summer. the springtime contour pattern will usually reveal a positive anomaly in this area. This hypothesis has been tested by computing fields of seasonal lag correlation between spring and summer mid-tropospheric height anomalies, such as shown in Fig. 8. This chart not only verifies the hypothesis, but also clearly indicates the areas of high persistence associated with the two neighbouring anticyclones in the Atlantic and Pacific.

The central question is: What is responsible for these areas of high correlation? Here intuition and synoptic experience suggest that perhaps the spring circulation régime over the plains determines weather to such an extent that the ground itself is influenced and provides some sort of reservoir which becomes instrumental in favouring certain subsequent circulation and weather patterns. This feed-back mechanism might operate through rainfall, since this element is very responsive to the form of the circulation in late spring and in summer over the Southern Plains and has high variability in monthly or seasonal means. For example, one-third of the Junes in San Antonio, Texas, have less than 0.89 inches of rainfall while one-third have greater than 3.56 inches, the remaining Junes falling between these two limits. The highest June total recorded was 8.41 inches.

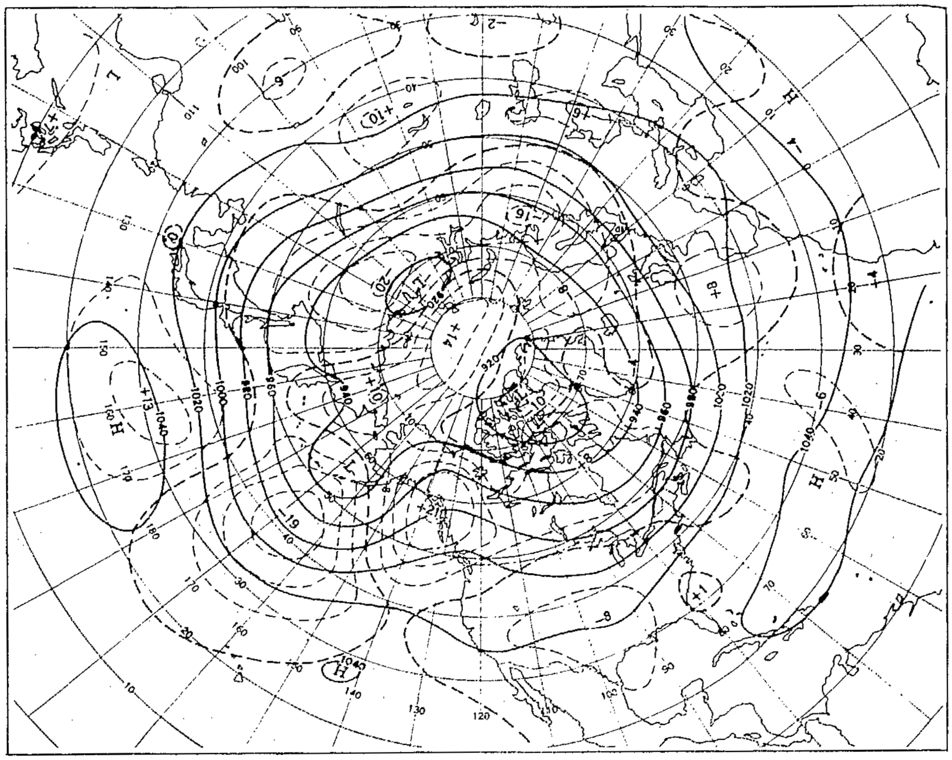
Now when the Southern Plains have been dominated in spring by a very dry régime (which is also customarily warm) and the soil desiccated, it would seem that the opportunity for persistent lodgement of the upper-level anticyclone in early summer would be favoured, for the area may assume characteristics akin to the deserts overlying which upper-level anticyclones are found. On the other hand, following a wet spring some of the heat normally used to raise the temperature of the ground surface might be used to evaporate the excess water in and on the soil, and thus not be available for sensible heating of the air perhaps necessary to sustain the upper-level anticyclone. This speculation was really an *a priori* hypothesis which it was desired to test.

In this test, state-wide average temperatures and total precipitation amounts with lengths of record ranging between 60 and 84 years were assembled for a nine-state area comprising the Western Great Plains (North Dakota, South Dakota, Minnesota, Nebraska, Iowa, Kansas, Missouri, Oklahoma and Arkansas). These values were then categorized into three equally likely classes denoted by Cold, Normal and Warm; and by Light, Moderate and Heavy. From them, contingency tables were prepared showing the frequencies with which the different summer temperature and precipitation classes followed the various combinations of spring conditions (e.g., cold and wet, warm and dry). Table 1 illustrates some of the results. Thus while a cold spring is more apt to be followed by a cold summer than a

TABLE 1. Summer temperature classes over the Western Great Plains following different combinations of spring temperatures and precipitation (totals in italics)

Spring temperature	Spring precipitation	Summer temperature			
		Cold	Normal	Warm	Total
Cold		*101*	*70*	*40*	
	Light	29	21	10	*60*
	Moderate	31	18	19	*67*
	Heavy	41	31	11	*83*
Normal		*53*	*74*	*81*	
	Light	12	18	34	*64*
	Moderate	18	33	27	*78*
	Heavy	23	23	19	*65*
Warm		*57*	*65*	*87*	
	Light	9	27	50	*86*
	Moderate	18	22	22	*62*
	Heavy	30	16	16	*62*

(*a*)



(*b*)

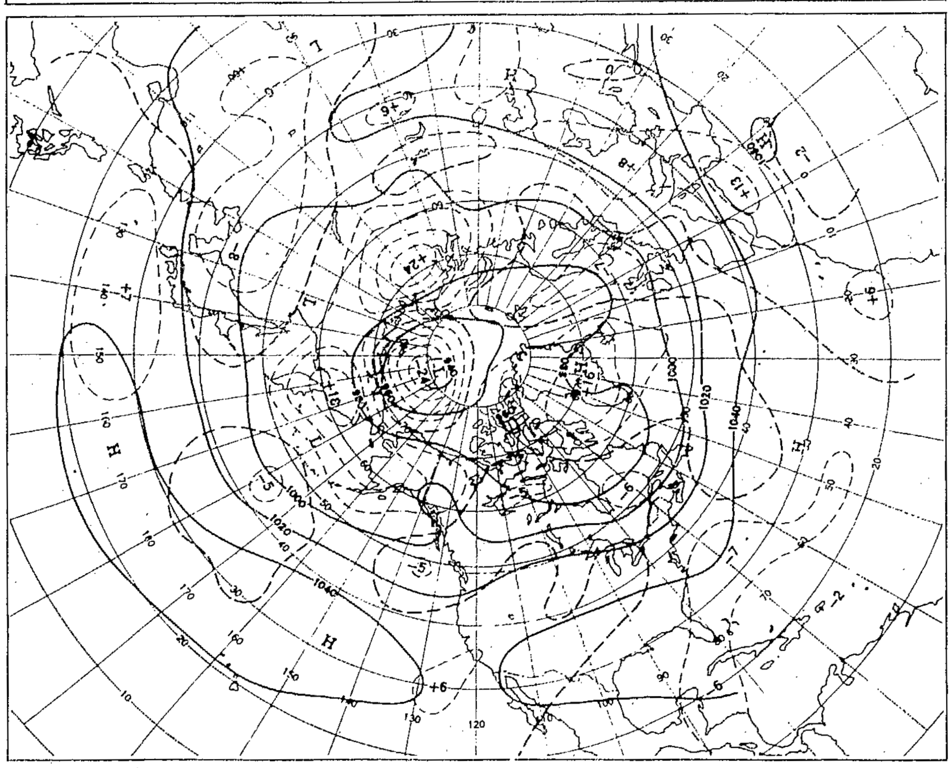
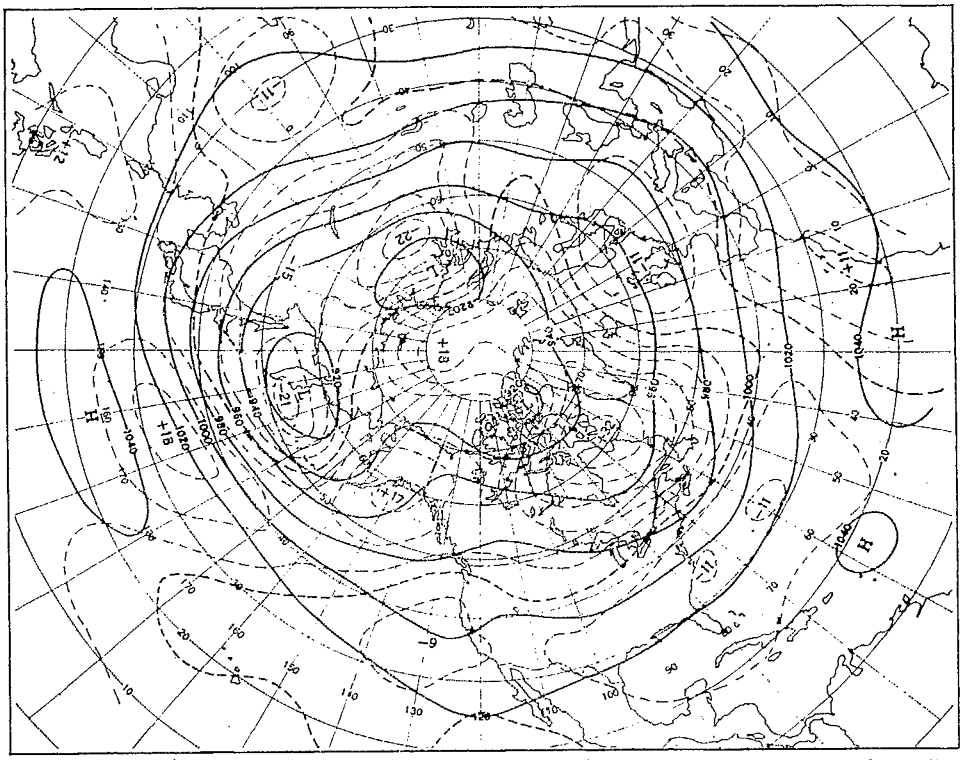
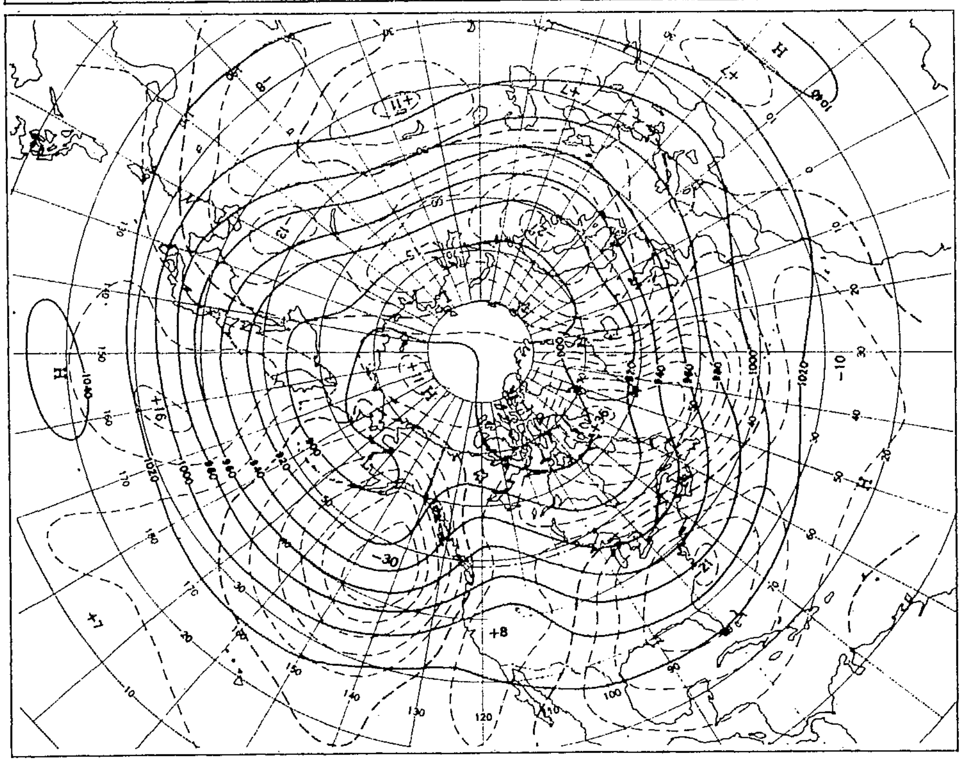


FIG. 6. Seasonal-mean 700-mb. height contours (solid), and isopleths of departure from normal (broken), for (*a*) summer 1957; (*b*) autumn 1957; (*c*) winter 1957; (*d*) spring 1958. Isopleths and anomaly centres are labelled in tens of feet.

(c)



(d)



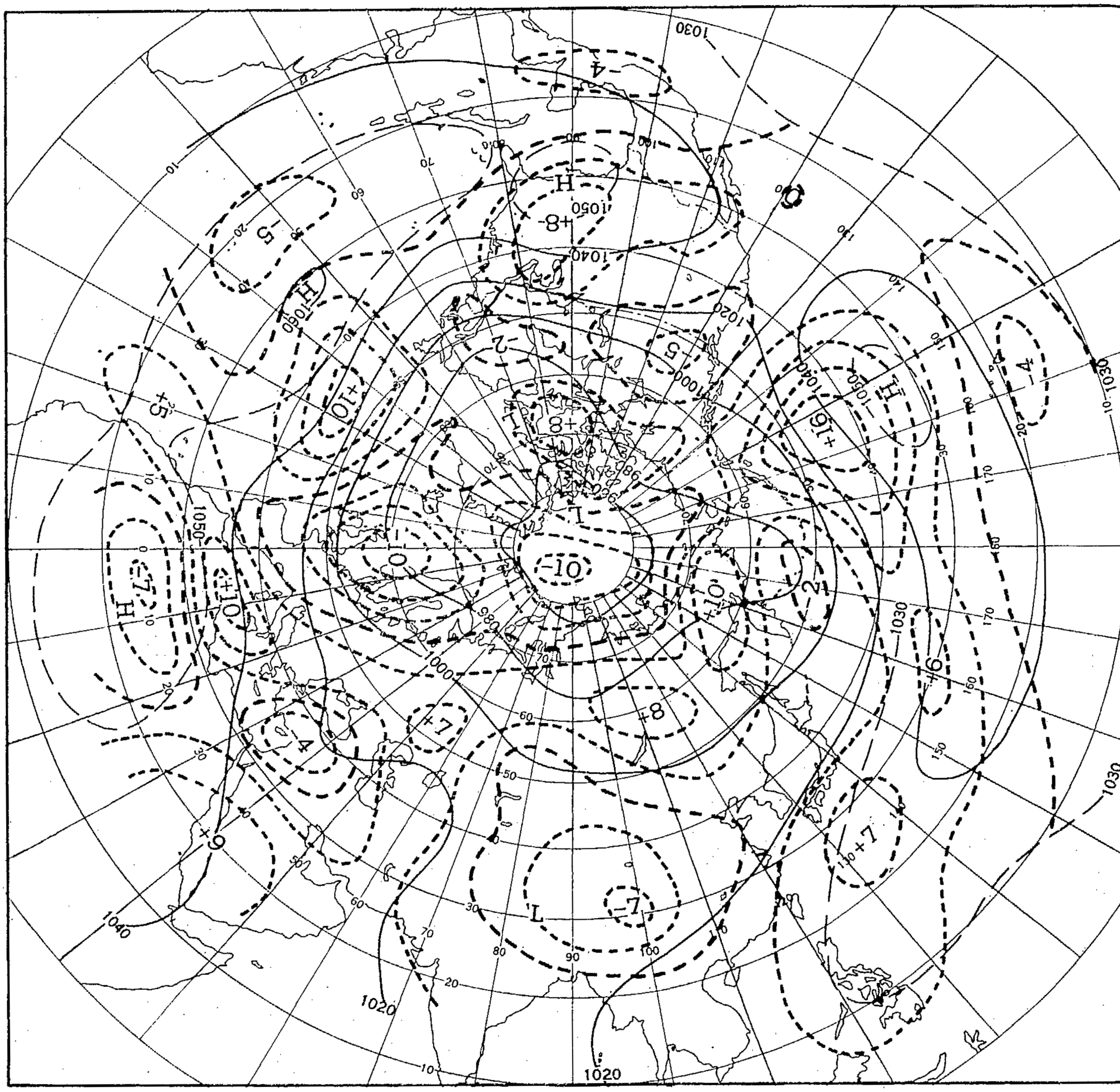


FIG. 7. Mean contours of 700-mb. height (solid), and isopleths of departure from normal (broken), for the three summers of 1952-54.

warm one (in the ratio of 101 to 40), and a warm spring by a warm summer (87 to 57), the odds increase appreciably when temperature and precipitation are combined. Hence, when spring is dry as well as warm, the ratio of occurrences of warm to cool summers goes up from 87/57 to 50/9. Similarly, with cool springs which are also wet, the ratio of cool occurrences in the subsequent summer rises from 101/40 to 41/11.

Apparently, the desiccating springs (warm and dry) favour the droughty summers, for summer warmth in this area goes with dryness. This latter association can be shown by temperature-precipitation correlations (Namias, 1960) or by other contingency tables. Hence, there appears to be some support for the *a priori* hypothesis.

Before leaving this phase of the report, we should note that persistence of the neighbouring oceanic cells during summer drought periods might also be helped by feed-back from the surface characteristics of the ocean waters. With well-developed (and thus usually

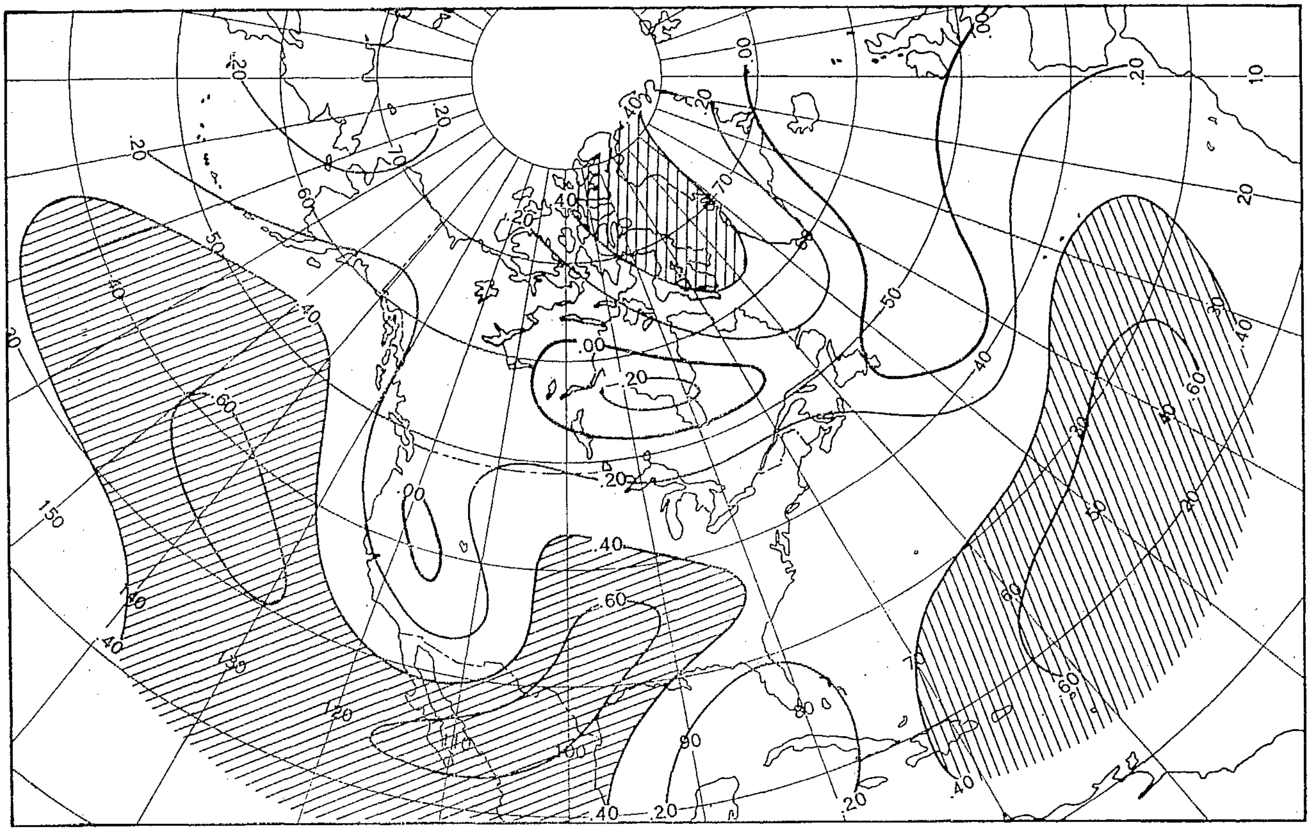


FIG. 8. Isopleths of the spring-summer lag correlation of seasonal mean 700-mb. heights (1933-58). Shaded areas show where the correlations exceed the 5 per cent level of significance.

northward-displaced) sub-tropical high pressure cells the stirring of the surface layers is apt to be less than normal because of the light winds, and the water temperature thus higher than normal. Effectively then, the zone of temperature contrast associated with the westerlies is displaced northward and is probably stronger than normal, thereby leading to stronger westerlies. The increased anticyclonic shear to the south might favour stronger build-up of the oceanic subtropical anticyclones, which as pointed out previously, also favours emergence of the continental upper-level high pressure cell.

EVOLUTION OF FLOW PATTERNS SUGGESTING POSITIVE FEED-BACK OVER SUCCESSIVE YEARS

A very interesting example of the gradual development of a drought-producing circulation pattern has come to light over Northern Europe during the past few years. This abnormality is currently being studied in detail in the hope that the physical factors leading to its inception, growth and decay may be isolated. Some of the charts constructed for this study are so remarkable that even a brief description should be of great concern to students of climatic variation.

The effect of the precipitation-inhibiting circulation on precipitation along the west coast of Norway (e.g., at Bergen and Trondheim) is shown in the middle portion of Fig. 9, where a steady decline from 120 per cent to 70 per cent of normal over four years is indicated. The annual mean 700 mb. flow patterns (Fig. 10) and their departures from normal (broken lines) illustrate the gradual growth of the drought-producing pattern — namely, a stronger than normal ridge over Scandinavia with deeper than normal troughs flanking it on either side. The steady development of the centres of the positive and negative anomaly is especially intriguing.

The deficit in precipitation over Scandinavia is naturally associated with the stronger than normal ridge and positive anomaly, where frequent horizontal divergence and subsidence are favoured. Along the west coast of Norway this effect is augmented by diminished onshore drift of maritime air and more frequent than normal cases in which air descends coastward from the inland mountain ranges. On the other hand, the negative areas are associated with greater than normal cyclonic

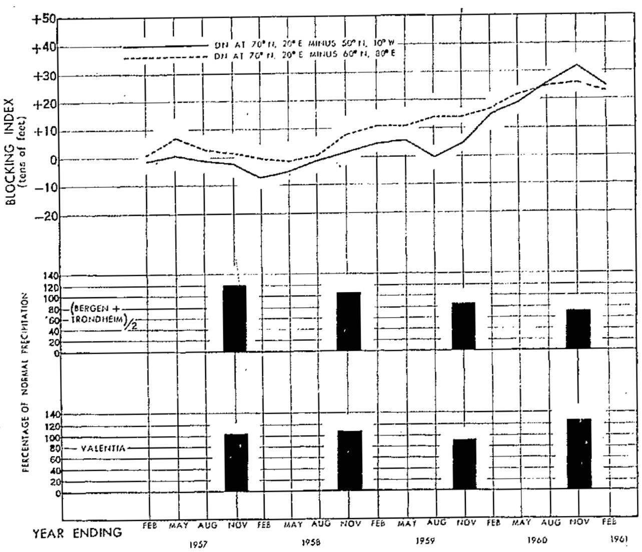


Fig. 9. *Central and lower*: Percentage of normal precipitation for successive years ending in November for western Norway and Ireland. *Upper*: Overlapping 12-month mean blocking index over northern Europe (see text).

activity, upward vertical motion and persistent precipitation, as illustrated by Valentia in Fig. 9 or other recent rainfall records in Great Britain.

Now the three anomaly centres constituting this peculiar amplified wave pattern (called "blocking") over northern Europe and adjacent areas—a positive centre over Scandinavia with negative centres west of Britain and south of Novaya Zemlya—are highly interdependent and, in fact, mutually reinforcing. Part of the reason for this compatibility lies in the principle of conservation of absolute vorticity, whereby the particular long wave pattern is generated each time one or two of the anomalous centres develop. This is frequently observed subsequent to the growth of the negative centre off Great Britain as cyclones intensify along a depressed storm track. The steady growth of this blocking pattern since the winter of 1957-58 is shown in the upper portion of Fig. 9 by two associated indices of blocking: the anomalous gradient between Northern Scandinavia and Ireland (70° N. 20° E. minus 50° N. 10° W.) and between Northern Scandinavia and the area south of Novaya Zemyla (70° N. 20° E. minus 60° N. 80° E.).

The individual seasonal charts composing the annual means (not reproduced here) are also fascinating for

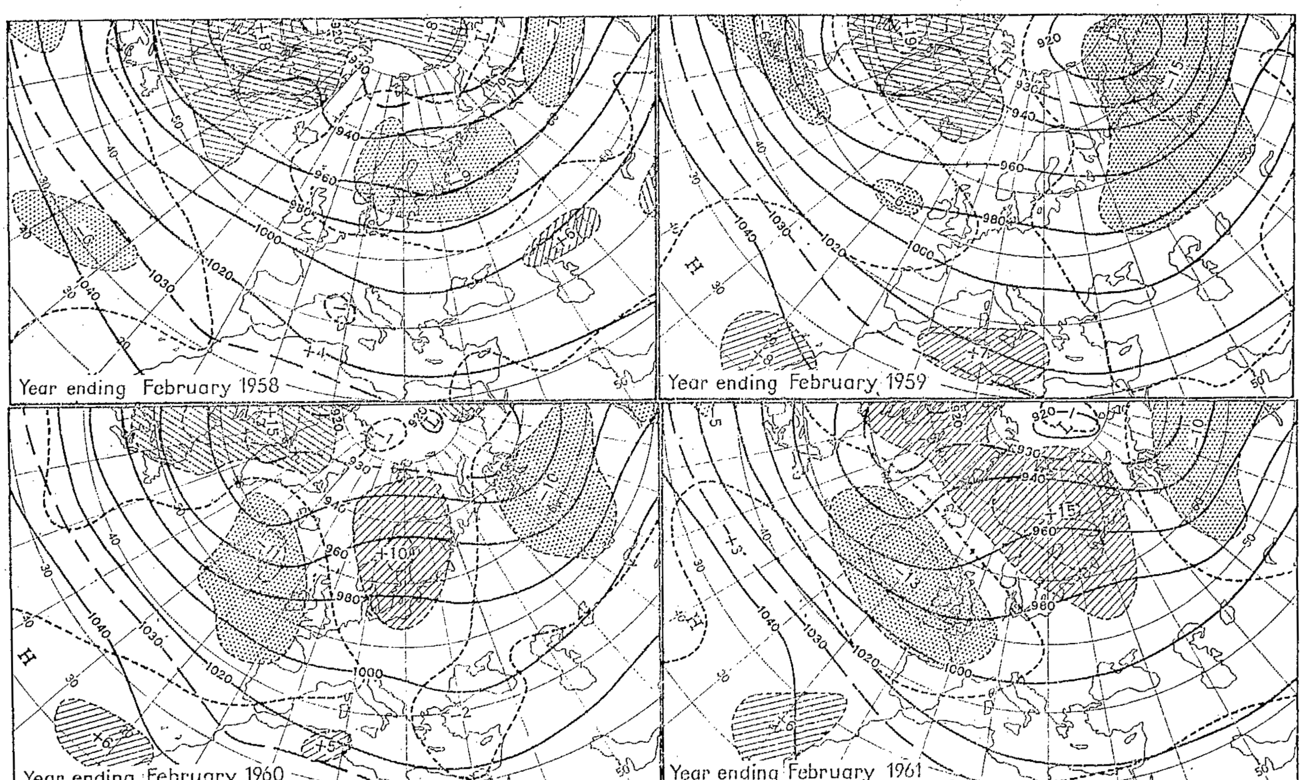


Fig. 10. Annual mean 700-mb. contours (solid) and isopleths of departure from normal (dashed) for years ending as indicated in lower left. Isopleths and anomaly centres are labelled in tens of feet.

their strong tendency to revert to similar anomalous patterns in successive years. For example, seasonal positions of the centres of positive and negative anomaly for the springs, summers, and autumns roughly from 1958-60 are shown in Fig. 11. The northward migration of the positive centre in successive years implies a trend probably indicative of a termination of the northern drought régime.

It is clear from the above synoptic material that some influences external to the atmosphere must be called upon to provide a "memory" in order to cause the persistence and persistent recurrence. These influences might well be provided by abnormalities in the surface both at sea and on land as discussed earlier in this report; abnormalities created in the first place by circulations which remain anomalous in the same sense over intervals at least a season in length. The author hopes to throw further light on this special case by more exhaustive study.

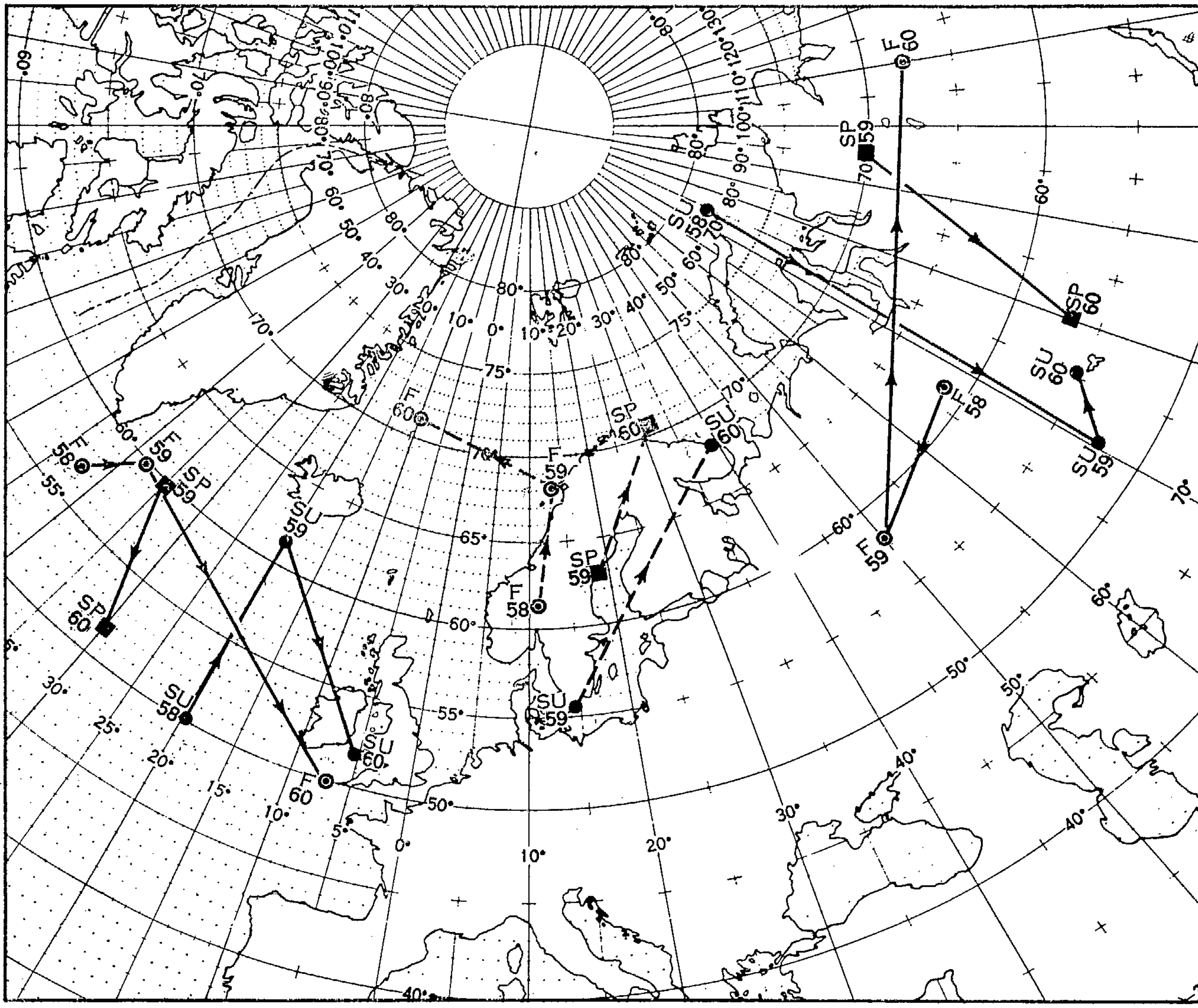


FIG. 11. Centres of positive anomaly (over and near Scandinavia) and flanking negative centres for springs (squares), summers (solid circles) and autumns (open circles) for 1958-60.

RÉSUMÉ

L'interaction de la surface de la terre et de l'atmosphère en tant que cause fondamentale de la sécheresse et des autres fluctuations climatiques (J. Namias)

L'auteur présente des données qui visent à montrer que les fluctuations climatiques, tout au moins celles qui sont de l'ordre d'une saison ou d'une année, sont peut-être dues principalement à une interaction perpétuelle des courants atmosphériques anormaux et des surfaces sous-jacentes anormales. Le caractère anormal de ces surfaces est dû à des facteurs tels que la présence ou l'absence de neige, les précipitations ou la sécheresse et les variations de température des eaux superficielles des océans. Il se crée ainsi des réservoirs durables de chaleur et d'humidité, qui, sous l'impulsion régulière des variations saisonnières de l'insolation. semblent jouer un rôle capital dans le comportement des centres d'action atmosphériques. Tous ces facteurs introduisent quelque régularité dans l'évolution que certaines caractéristiques de la circulation atmosphérique générale subissent au cours de périodes allant d'une saison à plus d'un an et l'on peut donc espérer être en mesure de faire de véritables prévisions à long terme.

DISCUSSION

H. H. Lamb. Dr. Namias's investigations of the persistence tendency associated with a snow cover and of the effects of dry or wet springs on the heating pattern and circulation developments of the succeeding summer elucidate very clearly two of the ideas which have emerged in exploratory seasonal forecast discussions held in the Climatological Research Division of the Meteorological Office. Also our climatic change studies have shown that the most easily demonstrated linkages with observed atmospheric circulation pattern changes are those with anomalies (or more lasting changes) in the extent of ice and cold or warm sea water and implied extent of snow cover on land; but this does not exclude the possibility that other agencies are also of importance—e.g., possible variations in the amount of insolation effectively reaching the surface and lower atmosphere. May I ask:

1. Whether any other regions besides the United States Mid-West have come to light as being particularly liable to persistent effects lasting into the following season?

2. Whether the time distribution of great anomalies in the pressure or temperature fields has been investigated? A Russian source has suggested that great anomalies were exceptionally frequent around the time of the 1957 great sunspot maximum and in the two years of abruptly rising sunspot activity prior to that.

J. Namias. 1. Studies of monthly (i.e., month to month) persistence and also season to season indicate other areas of relatively high long correlation—namely the southern latitudes of the North Atlantic and North Pacific. (See *AMS Bulletin*, articles and *Rossby Memorial Volume* article by present writer.)

2. I do not know of such studies but this appears to be a good idea.

K. W. Butzer. I would simply like to point out how significant Dr. Namias's snow-cover feed-back work is in the case of continental glaciers once formed. It at least provides a tangible idea of the possible range of secondary effects.

R. Fairbridge. Further to Dr. Butzer's point about continental ice, the "memory effect" mentioned by Dr. Sutcliffe might—for an area such as Greenland—play a major role in maintaining a glacial condition at relatively low latitudes during an interglacial age.

Could Dr. Namias refer to any recent meteorological consideration of Greenland as the generator of a self-perpetuating feed-back mechanism of this sort?

J. Namias. I do not know of any recent work of this nature. Of course the late Dr. Hobb's work on the glacial anticyclone of Greenland comes to mind where he ascribed much of the behaviour of the general circulation to this feature. This work was however, very controversial.

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A NUMERICAL STUDY OF THE EFFECT OF VERTICAL STABILITY ON MONSOONAL AND ZONAL CIRCULATIONS

by

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INTRODUCTION

The climatic pattern of the earth was perhaps never steady. Instrumental records can be used to document the most recent fluctuations. Their study has led one of us (Kraus, 1960) to suggest that past surface climatic changes were probably associated with systematic changes of the mean vertical stability of the atmosphere, or—more precisely—of the mean vertical gradient of the cooling rate. A simplified numerical model has now been used in an initial attempt to test the dynamical aspects of this hypothesis. The model provides for an idealized system of warm continents and cool oceans, as well as latitudinal and vertical heating gradients. Variations of the latter have been found to produce in fact changes in the circulation régime which appear to be analogous to those observed in nature.

The analyses, both on the instrumental and on the numerical side, involve generalizations, simplifications and arbitrary selection of the numerical values for various model parameters. However, each step in the chain of reasoning is too complex for possible subconscious bias to have any predeterminable effect. The general agreement and compatibility of the results appears impressive in these circumstances, though they cannot be claimed to be conclusive at this stage.

OBSERVED RECENT FLUCTUATIONS OF THE SURFACE CLIMATE

A striking feature of recent climatic variation was the abrupt decrease, about the turn of the century, of mean annual rainfall volumes on the equatorial and eastern boundaries of the arid regions. The same happened along the subtropical east coasts. As evidence, the diagrams in Fig. 1 are reproduced here from an earlier paper. The change in low-latitude rainfall regimes was associated, in the temperate region of Australia, with an eastward shift of the climatic boundary between the mediterranean-type, winter-rainfall climate of South Australia and the east-coast type of climate which is characterized by more uniform rainfall with a tendency towards summer maxima.

While low latitude regions became drier, the climate tended to become warmer in many middle and high latitude regions of the northern hemisphere. This warming appears to have been more gradual or more irregular than the simultaneous change in the rainfall régime. It may have been associated again with an eastward shift of the climatic boundaries; in this case a tendency for a more maritime climate to spread eastward into the western temperate regions of the continents. There also is evidence for an increase in North Atlantic sea-surface temperatures at this time.

Instrumental and observational changes make the interpretation of surface pressure changes more dubious. Table 1 shows some evidence, though it is not convincing by itself, of an eastward shift in the mean position of the maritime subtropical anticyclone in the northern Atlantic at the beginning of this century. The pressure increase on the eastern stations is more than double the standard error.

Table 1. Mean annual station-level pressures (mb.) in subtropical North Atlantic

	Station	Period 1881-1900	Period 1901-20	Difference
West Atlantic	Bermuda	997.0	997.1	0.1
	Trinidad[1]	996.4	996.6	0.2
East Atlantic	Funchal	1016.3	1017.6	1.3
	Freetown	987.3	988.6	1.3

1. The height of the Trinidad barometer site was changed in 1900 from 133 ft. to 72 ft. This would imply a decrease in sea-level pressure there, unless an unpublished adjustment was made.

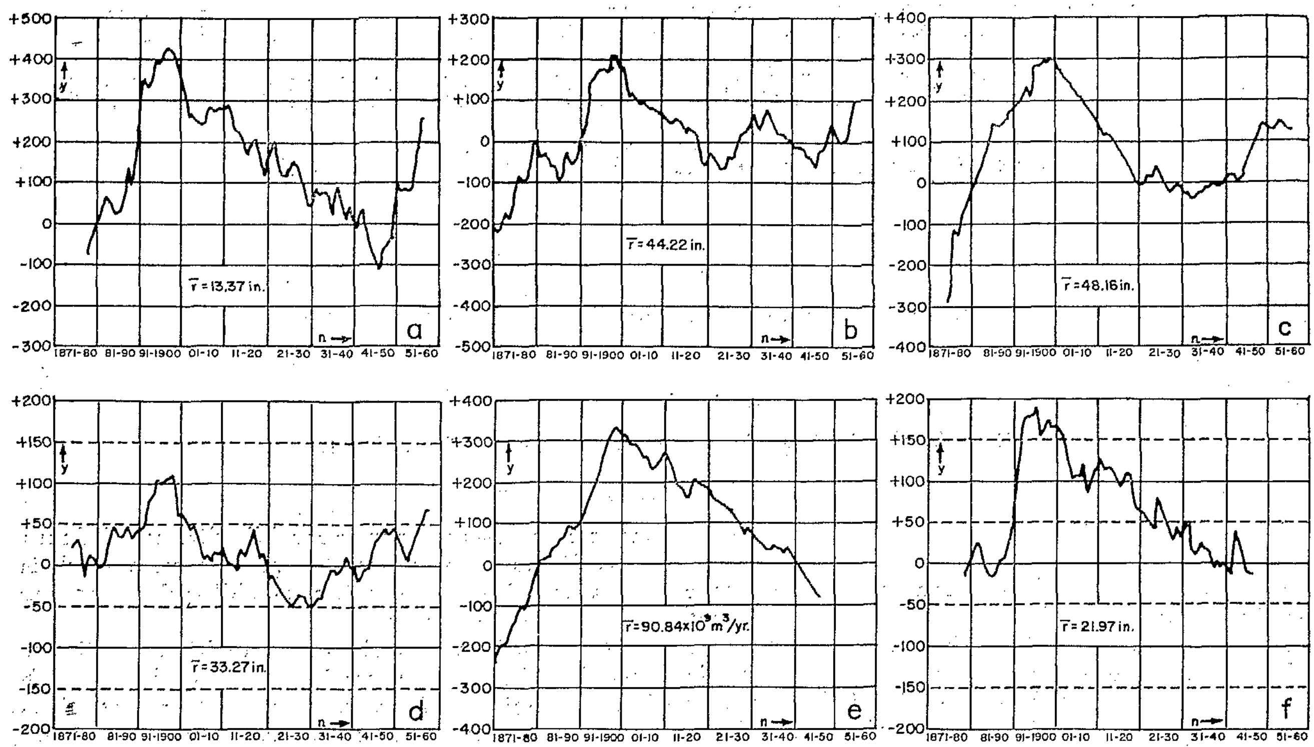

FIG. 1. Cumulative percentual deviations from the 1881-1940 mean. (*a*) North-west New South Wales (Australian rainfall district no. 48); (*b*) Queensland coast (Australian rainfall district no. 40); (*c*) Carolina coast (mean of Charleston and Cape Hatteras); (*d*) India (peninsula); (*e*) Nile discharge at Aswan; (*f*) Central Cape Province (South Africa rainfall district no. 16A).

During the last fourteen or twenty years a change in the opposite direction appears to have operated. There has been more rainfall in many low-latitude and east coast regions and the warming trend seems to have been arrested temporarily. This has been associated with a distinct tendency for tropical hurricanes to reach the Australian or American east coasts, rather than take a more easterly course, as they appear to have done in the preceding forty years.

THE ASSOCIATION BETWEEN UPPER WINDS AND RAINFALL REGIMES

A reasonably dense network of upper-air stations has become available only during the last ten or fifteen years. It is therefore not possible to interpret directly, from records, the climatic fluctuations of the last hundred years in terms of the three-dimensional circulation changes. However, it may be considered that the circulation patterns associated with a relatively cold and wet régime, or with a relatively warm and dry régime, should also predominate in individual years which exhibit these weather characteristics.

Table 2 lists ranking correlation coefficients of mean zonal winds at 300 mb. and seasonal rainfall in various parts of south-east Australia.

Spearman's ranking correlation coefficient is:

$$r_R = 1 - \frac{6\Sigma d^2}{N^3 - N}$$

where Σd^2 is the sum of the squares of the differences between upper wind and rainfall ranks and N is the number of ranked seasons, viz. 14 winters and 12 summers in the present case. The approximate standard error of a rank correlation is

$$\sigma_R = (N - 1)^{-1/2}$$

The coefficients listed in Table 2 suggest a significant correlation between high westerlies and dry summers in the most easterly parts of Australia—a region affected by the general rainfall decrease at the turn of the century. Over the western plains, high upper winds are correlated significantly with increased winter rainfall and decreased summer rainfall. The resultant effect on annual rainfall is negligible, but high westerlies should be associated in this case with a more mediterranean climate with wetter winters and drier summers. This again corresponds to the observed change of the climate in that region at the beginning of the century. It is

TABLE 2. Ranking correlation cœfficient of mean zonal winds at 300 mb. and of rainfall in south-eastern Australia (1945-1959)

Station	Ranking correlation coefficients	
	Winter	Summer
Western plains		
Wentworth	0.81	—0.74
Euston	0.92	—0.94
Balranald	0.83	—0.65
Hay	0.85	—0.41
Deniliquin	0.75	—0.62
Yanko	0.81	—0.58
Eastern slopes and coast		
Adaminaby	0.18	—0.82
Cooma	—0.17	—0.75
Bega	0.14	—0.78
Kurrajong	—0.18	—0.85
Sydney	—0.26	—0.65
Standard error	0.28	0.30

inferred that the high-level upper winds probably increased on the average at about that time.

A table similar to Table 2 was first derived by one of us (Kraus, 1955) on the basis of a shorter data series (1945-53). The ranking correlation coefficients were then found already to be considerable larger than their standard error. The additional independent data further increased the statistical significance of the deduced correlations and that is in itself of some relevance.

A strong negative correlation between upper winds and summer rainfall was shown in the earlier paper to exist also in tropical north-eastern Australia. The similarity in the long-term rainfall time series along the subtropical east coasts of the United States and Australia suggests that a similar association may possibly be found there. No analysis has yet been made to find such a relation.

STIPULATED PHYSICAL CAUSES

Any physical explanation of the recently observed climatic variations must be compatible with the observed pattern. This means that the time scale would have to be of the order of a half-century or less. The process would have to be associated with a negative correlation between high-latitude surface temperatures and rainfall volumes along the subtropical east coasts and on the margin of the arid regions.

Most of the stipulated causes for climatic change appear to be incompatible with such an association. In particular, an increase in the solar constant, or an increase in the carbon dioxide mixing ratio, or a decrease in the turbidity or a primary warming of the ocean surface would all seem to cause higher surface temperatures to be associated with increased atmospheric instability, increased convection and therefore increased rainfall, and vice versa.

On the other hand, persistent variations of the ozone mixing ratio, in the lower stratosphere and in the upper troposphere, would tend to produce changes that have at least the right sign. An increased ozone amount would tend to produce higher surface temperatures in high latitudes and a lower tropopause with an increased overall static stability near the Equator. This could also explain other features of the observed climatic change. In particular, it was thought (Kraus, 1960) that storms of smaller dimensions would be suppressed in low latitudes, and that this could account for the reduction in the number of rainfall days, which had been observed to be a characteristic feature of the general change at the beginning of this century. Disturbances of continental dimensions would be less affected, and this might explain the fact that in the typical monsoon regions the world-wide pattern of low-latitude rainfall change was least in evidence.

To test the validity of these deductions, we shall now try to relate them to a theoretical model. Our deductions will be supported if it is found that an externally imposed increase in the static stability is associated as expected: with decreased convection, suppression of smaller storms, eastward shift of quasi-stationary pressure centres, and an increased zonal wind aloft.

THE EQUATIONS OF THE MODEL

The climate of the world is affected by the internal dynamics of the atmosphere, and also by the influences of the sun and the underlying water and land surfaces. Likewise, the statistical properties (mean values, standard deviations, etc.) of an arbitrary system depend upon the internal dynamics of the system, and also upon the statistical properties of the external influences. In those cases where the internal dynamics are expressible by a set of linear differential equations, an analytic deduction of the statistical properties of the system (output) from the statistical properties of the outside influences (input) is generally possible. When the governing dynamic equations are non-linear, an analytic deduction of the output from the input is often difficult if not impossible, even though a definite relation between input and output exists. In the case of the real atmosphere, the situation is further complicated by an incomplete knowledge of the dynamics.

With the advent of electronic computing machines, it has, however, become feasible to estimate the statistical properties of systems whose governing equations are known, by generating numerical solutions of the equations covering extended periods of time, and then collecting statistics from these solutions. Climatological values so obtained are not exact values, but are subject to sampling errors similar to those encountered in processing real data.

For the present study, we shall use the geostrophic form of the two-layer model derived by one of us (Lorenz, 1960*b*). To the original form we append terms representing the non-adiabatic effects. A somewhat similar form of the equations was used by Bryan (1959).

The equations of the model can now be written in the following form:

$$\frac{\partial}{\partial t}\nabla^2\psi = -J(\psi, \nabla^2\psi) - J(\tau, \nabla^2\tau) - \frac{1}{2}k\nabla^2\psi + \frac{1}{2}k\nabla^2\tau \qquad (1)$$

$$\frac{\partial}{\partial t}\nabla^2\tau = -J(\psi, \nabla^2\tau) - J(\tau, \nabla^2\psi) + f\nabla^2\chi + \frac{1}{2}k\nabla^2\psi - \frac{1}{2}k\nabla^2\tau - K\nabla^2\tau \qquad (2)$$

$$\frac{\partial}{\partial t}\theta = -J(\psi, \theta) - J(\tau, \sigma) + \nabla\cdot(\sigma\nabla\chi) - \left(j + \frac{1}{2}h\right)(\theta - \theta^*) + \frac{1}{2}h(\sigma - \sigma^*) \qquad (3)$$

$$\frac{\partial}{\partial t}\sigma = -J(\psi, \sigma) - J(\tau, \theta) + \nabla\theta\cdot\nabla\chi + \frac{1}{2}h(\theta - \theta^*) - \left(j + \frac{1}{2}h\right)(\sigma - \sigma^*) - H(\sigma - \sigma_c) \qquad (4)$$

$$f\nabla^2\tau = -\frac{1}{2}c_p(p_3^K - p_1^K)p_0^K\nabla^2\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

The operating symbols have their conventional meaning; the other symbols represent the following quantities:

ψ	Stream function for mean wind.
τ	Stream function for mean wind-shear.
χ	Velocity potential for the lower layer in the two-layer model.
θ	Vertical mean of potential temperature.
θ^*	Vertical mean of externally imposed (radiation equilibrium) potential temperature.
σ	Static stability (potential temperature differences between upper and lower layer).
σ^*	Externally imposed (radiation equilibrium) static stability parameter.
f	Coriolis parameter (assumed constant).
p_0, p_1, p_3	Pressures at ground and at centres of lower and upper layer.
c_p, c_v	Specific heats of air.
κ	$(c_p - c_v)/c_p$.
k	Rate of momentum exchange near the ground.
K	Rate of momentum exhcenage in the free atmosphere.
h	Rate of radiational and turbulent heat exchange near the ground.
j	Rate of radiational heat exchange in the free atmosphere.
H	Rate of convective heat exchange in the free atmosphere.
σ_c	Critical stability.

The meaning of most terms is self-evident; in particular the Jacobians present the effect of advection and the linear terms the effect of non-adiabatic processes. Equation (5) is the thermal wind equation. The effect of convection as represented by the last term in equation (4) requires some explanation. Vertical mixing in dry air would tend to produce a uniform potential temperature; that means it would tend to drive the stability parameter σ towards zero. In the actual atmosphere the establishment of such a dry-adiabatic lapse rate is generally prevented by condensation. In the present model it has therefore been assumed that convection drives the vertical stability not towards zero but towards some larger critical value, σ_c.

EXPANSION IN SERIES

One of us (Lorenz, 1960*a*) has described the advantages, in problems of this sort, of simplifying the equations by expanding the field of each variable in a suitable set of orthogonal functions, and then omitting reference to all but a few of these functions. The choice of orthogonal functions must depend upon the region involved.

We shall deal with a region bounded by two parallel infinite walls at the latitudes where $y = 0$ and $y = w$. We shall further require that all functions be periodic in x, with the period $2w$.

Since there can be no flow of mass across the walls, the stream function, and hence, through the thermal wind relation, the temperature can be considered constant on each wall. The set of orthogonal functions

$$\begin{aligned} F_{nm} &= 1 && \text{for } n = 0 && m = 0 \\ &= \sqrt{2}\cos my/a && \text{for } n = 0 && m > 0 \\ &= 2\sin my/a \cos nx/a && \text{for } n > 0 && m > 0 \\ F'_{nm} &= 2\sin my/a \sin nx/a && \text{for } n > 0 && m > 0 \end{aligned} \qquad (6)$$

where $a = w/\pi$, is therefore suitable. The expansions for ψ, τ, ∇^2, χ, and θ in these orthogonal functions are then truncated by retaining only those functions for which $m \leq 2$ and $n \leq 4$. In the expansion for σ, only the function F_{00} is retained, so that static stability is regarded as a function of time alone. Details of the expansions appear in the appendix.

These expansions are then substituted into the governing equations (1) to (5). The products of orthogonal functions, which appear on the right, may themselves be expanded in series of orthogonal functions, which must be similarly truncated. There results a set of 56 ordinary differential equations in which the 56 dependent variables are the coefficients in the expansions for ψ, τ, $\nabla^2\chi$, θ and σ.

These equations have been further simplified by omitting the interactions between different wave numbers (products of two orthogonal functions with two different non-zero values of n), while the interaction of each wave with the zonal current is retained. The complete set of equations appears in the appendix.

SCALES AND NUMERICAL VALUES OF COEFFICIENTS

The area between the two latitudinal boundary walls is supposed to be bisected by the thirtieth parallel. The length of this parallel around the globe is about 34,800 km. We assume a cyclical repetition of the motion pattern every 120° of longitude ; that means the largest waves could occur three times around the globe and their lengths along the thirtieth parallel would therefore be equal to 11,600 km. This length was stipulated above to be twice the distance between the latitudinal walls ; therefore $w = 5{,}800$ km. A scale length is now defined conveniently by

$$a = w/\pi = 1{,}846 \text{ km.} \qquad (7)$$

For our time scale we set the reciprocal value of the Coriolis parameter at 30° latitude as unity.

$$f(30^\circ) = 7.29 \times 10^{-5} \text{ sec.}^{-1} = (3.81 \text{ hours})^{-1} \qquad (8)$$

One unit of time was also chosen for the time increment in the numerical integrations.

The choice of a non-dimensional unit of temperature is based on consideration of equation (5). Assuming

$$p_0/p_1/p_3 = 1000/750/250$$

we set :

$$B = \frac{2a^2 f^2 p_0^{\varkappa}}{c_p\,(p_1^{\varkappa} - p_3^{\varkappa})} = 146^\circ \text{ C}. \qquad (9)$$

The various rates of turbulent mixing and radiational heating have all the dimensions of inverse time and can therefore be expressed readily as multiples of f.

On the basis of the earlier computation by Bryan and by Lorenz we set arbitrarily :

Constant	*Dimensionless value*
f	1
k	4/32
K	1/32
j	4/32
h	4/32
H	1/32

The critical stability $\sigma_c = 10^\circ$ C. or 0.0685 in non-dimensional units.

THE EXTERNAL HEATING FUNCTION

We stipulate a variation of θ^* with $\cos y/a$. The difference between the extreme polar and equatorial values of θ^* is assumed to be 75° C.

In addition to the resulting meridional heating gradient, we stipulate latitudinal heating differences caused by an idealized system of oceans and continents. The continents are supposed to be half as wide as the oceans between them at all latitudes. This gives them a uniform zonal extent or 40° or 3,930 km.—about the width of Australia or North America along the thirtieth parallel.

The radiation equilibrium temperature θ^* over the continents is assumed 25° higher than that over water along the thirtieth parallel ; that means we deal with summer only in the present study. The heating difference is supposed to be zero at the polar and equatorial walls.

The variations of θ^* have been expanded on this basis with the aid of the orthogonal functions (6) into a series, which was truncated in the same way as the series for the dependent variables :

$$\theta^* = B\,(F_{nm} \cdot \theta^*_{nm}) \qquad (10)$$

The usual convention requiring summation over all products that contain the same values of m and n in both factors has been used in writing the expression (10). In the present case m is allowed to assume only the values 0 and 1, while n varies again from 0 to 4. The individual terms of the expansion have the numerical values :

$$\theta^*_{01} = 0.1815$$
$$\theta^*_{11} = 0.0460$$
$$\theta^*_{21} = 0.0230$$
$$\theta^*_{31} = 0$$
$$\theta^*_{41} = -0.0115$$

The term θ^*_{00} is an arbitrary constant and the coefficient B has been defined by the relation (9).

The vertical heating rate as determined by σ^* is a constant parameter of the computation. It is the basic aim of this paper to study the various circulation patterns which are associated with different values of this parameter σ^*.

DISCUSSION OF COMPUTATION RESULTS

The numerical computations were performed on a Royal-McBee LGP-30 electronic computer. Starting from arbitrary initial conditions, we permitted the computer to operate until a statistically stationary state had apparently been reached. Means and variances of the coefficients in the expansions of ψ, θ and σ were then formed from the subsequent computations. In most cases these were based on a sample, made up by every fourth time step in a computational run covering 800 steps, or approximately four and a half months.

Radiational cooling in the free atmosphere should tend to increase baroclinic and convective instability. The effect is measured by σ^*. In the present series of computations we used the values $\sigma^* = -5^\circ$, 0° and $+5^\circ$ for this parameter.

From the statistical means of the dependent variables, it was possible to construct mean "climatological" maps of the model. These maps, as reproduced in Figs. 2, 3 and 4 show several features which the observational analysis had led us to expect. The most stable case, that is the case of least cooling at high levels, $\sigma^* = 5^\circ$ C., is associated with the fastest thermal wind, a more zonal pattern, an eastward shift of quasi-stationary features and a much weaker "climatological" high-pressure cell over the oceans. The differences between the cases $\sigma^* = 0^\circ$ and $\sigma^* = -5^\circ$ are less pronounced.

The mean maps tell only part of the story. Plotting of a series of instantaneous model maps shows individual pressure centres of about equal intensity in all three cases. However, in the case $\sigma^* = 5^\circ$, these large cyclones and anticyclones move with an average speed of about 7 or 8 degrees of longitude per day. With the higher rates of upper cooling characterized by $\sigma^* = 0^\circ$ or $\sigma^* = 5^\circ$ the speed of translation is much more irregular and averages only about 5 degrees longitude per day.

An even greater difference is associated with the longevity of the travelling pressure centres. In the case $\sigma^* = 5^\circ$ their intensity changes little over long periods of time. In the more stable cases, there is a strong tendency for anticyclogenesis over the western tropical oceans and for cyclogenesis over the western parts of the continents at higher latitudes. The appearance of the climatological highs and lows in the maps for the cases $\sigma^* = 0^\circ$ and $\sigma^* = -5^\circ$ are due to these developments. The climatological pressure centres are most pronounced for $\sigma^* = 0^\circ$. In the case $\sigma^* = -5^\circ$, the picture becomes somewhat blurred by the emergence of smaller disturbances with higher wave numbers.

The deduction is confirmed by a study of Table 3, which lists the mean integrated kinetic energies associated with the different wave numbers n for different values of σ^*. Disturbances characterized by $n = 2$ or $n = 3$ are mainly responsible for the appearance of pressure centres in the "climatological" maps. It can be seen from the table that the energy associated with these waves is as large in the case $\sigma^* = 5^\circ$ as in the two other ones, but because of their small intensity variation and rapid translation this does not appear in the mean climatological picture.

TABLE 3. Mean kinetic energies per unit mass (m.^{2} sec.$^{-2}$) associated with different wave numbers n for different values of σ^*

n	-5° C.	0°	$+5^\circ$
0	9.1	20.3	47.4
1	13.4	15.2	15.9
2	22.2	54.2	81.6
3	151.3	105.1	93.9
4	51.1	1.5	1.0
Total	247.1	195.3	238.8

There is surprisingly little variation between the values of the total kinetic energy in the three cases. The energy of the zonal motion ($n = 0$) and the very long waves ($n = 1, 2$) increases with increasing stability; that of the shorter waves ($n = 3, 4$) decreases. In fact, wave number 4 probably would not appear at all in the more stable cases without a forcing function. The minimum of the total kinetic energy which characterizes the case $\sigma^* = 0^\circ$ may be explicable by the contrary variation of the longer and shorter waves with vertical stability.

The rate of convective heat transport through the free atmosphere, in our model, is proportional to $(\sigma_c - \sigma_0)$. The concept of convection includes in this case not only phenomena on the cumulus scale, but also the effect of all waves with numbers larger than four. Table 4 lists values of the time mean of σ_0 associated with different values of σ^*.

TABLE 4. Time mean and standard deviation of σ_0 associated with different vertical cooling gradients

σ^*(°C.)	-5	0	$+5$
Time mean of σ_0	7.1	8.9	12.6
Standard deviation of σ_0	0.8	1.3	1.1

The comparatively large difference between $\sigma^* = 0^\circ$ and $\sigma^* = 5^\circ$ as compared to that between $\sigma^* = 0^\circ$ and $\sigma^* = -5^\circ$ is again evident. With $\sigma_c = 10^\circ$, the sign of $(\sigma_c - \sigma_0)$ is positive for the two cases $\sigma^* = -5^\circ$ and $\sigma^* = 0$. Convective mixing transports heat upward in these two cases. It transports heat downwards in the other case.

COMPARISON OF THE NUMERICAL MODEL WITH ACTUAL CLIMATIC REGIMES

In establishing any relationship the great simplification involved in our model has to be considered. We neglected the convergence of the meridians and the variation of the Coriolis parameter f with latitude. We also used only two parameters, $m = 1$ and $m = 2$, to characterize the mean meridional distribution of wind and temperature. In the actual atmosphere the mean meridional motion probably involves three cells at least in winter —a tropical and a polar direct meridional circulation, and an indirect circulation in temperate latitudes. This three-cell system cannot be simulated with two values of m. The omission is permissible for the present case of summer conditions with the polar boundary of our strip at about 60° latitude. It would become important if a larger part of the hemisphere were to be modelled during winter.

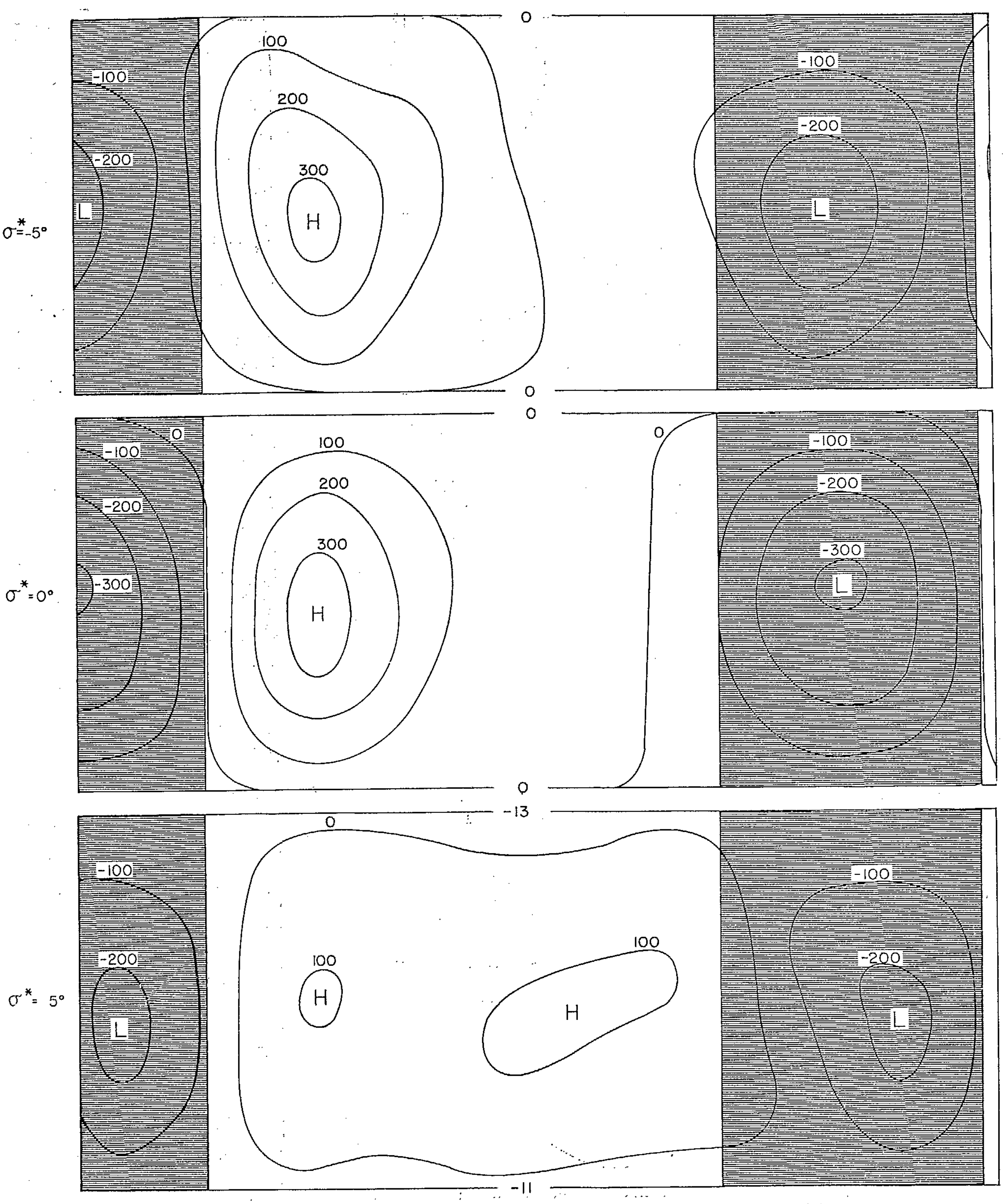

FIG. 2. Contour lines ($\psi - \tau$) for lower layer.

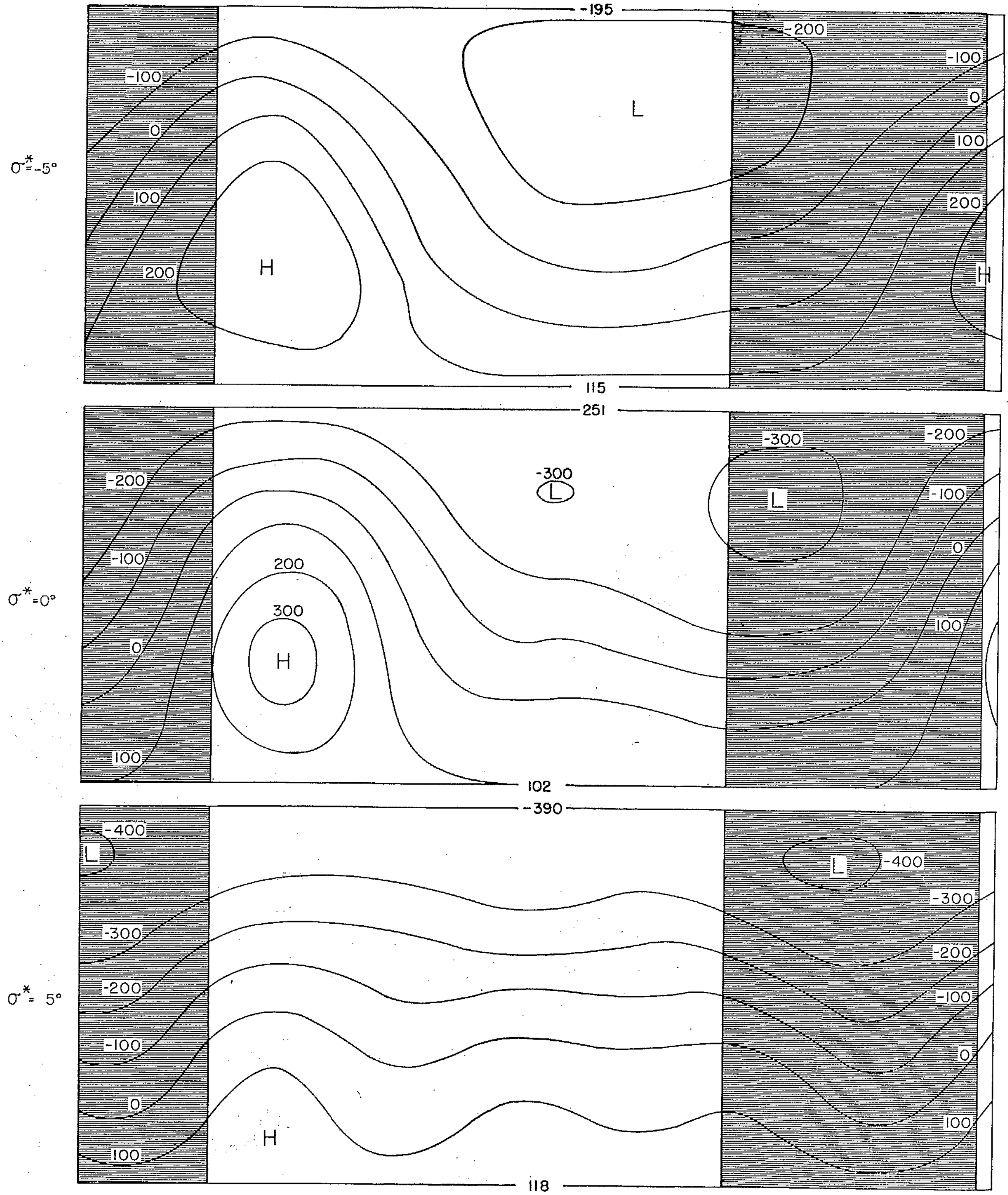

FIG. 3. Contour lines (ψ) for mean flow.

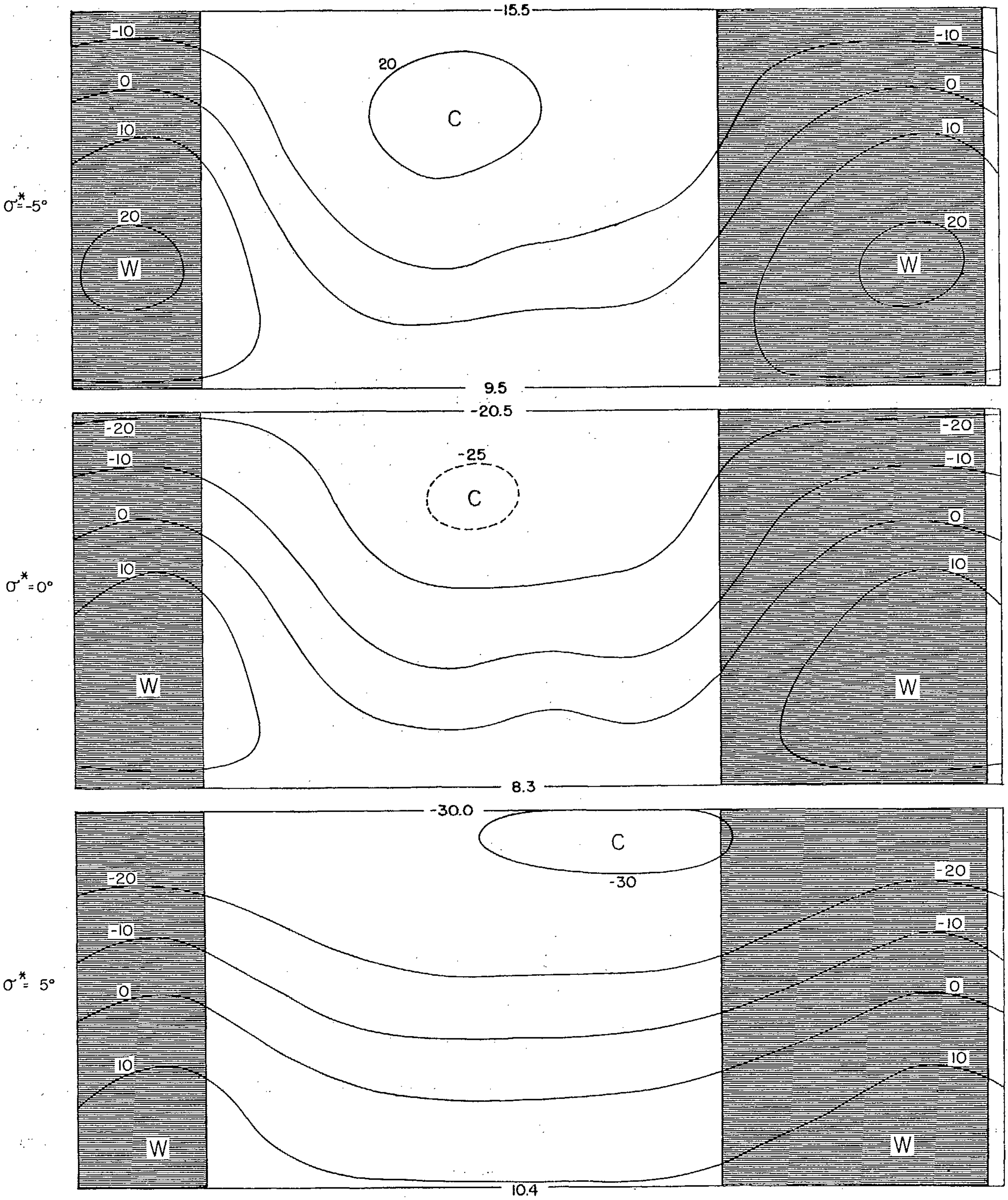

FIG. 4. Lines of equal mean potential temperature θ.

The model agrees with the deductions from natural observations in showing positive correlations between vertical stability, zonal winds at high levels, and eastward displacement of the mean position of pressure centres. It also suggests a qualitative explanation for the changes in rainfall régimes and hurricane incidence. The mean upward heat flux and convection $(\sigma_c - \sigma_0) > 0$ associated with the more unstable cases $\sigma^* = -5^{\circ}$ and $\sigma^* = 0$ might be alone sufficient to account for a wetter régime in low latitudes. The frequent anticyclogenesis off the subtropical east coasts in the model and the resulting surges from the east could explain the extension of this higher rainfall régime to temperate latitudes along the east coasts. The climatic mean maps associated with the more unstable values of σ are also obviously conducive to a relatively frequent northward steering of hurricanes along the east coasts. It is of interest to note that a somewhat similar mean synoptic situation was associated by Flohn (1952) with the establishment of the North American ice age.

The shorter wave-lengths associated with lower stability might also be favourable to more frequent northerly winds over the oceans and therefore to a higher evaporation rate.

A decrease in the vertical gradient of the cooling rate—that is, a higher value of σ^* in our model—would be compatible with the climatic changes which occurred about the turn of the century and which were described at the beginning of this paper.

Our model fails to account for the warming at high latitudes which appears to accompany the dry periods at low latitudes, or for the colder régime which exists there during wetter periods. In fact, as can be seen from Fig. 4, the mean meridional temperature gradient increases with increased stability in the model.

The discrepancy may be the result of specific simplifications in the model; in particular, the lack of horizontal variability of stability, the absence of a third cell in high latitudes, and the omission of evaporation and condensation. One might argue, for example, that an increase in ozone mixing ratio would increase the stability at low latitudes while decreasing it at high latitudes because of surface heating (Plass, 1956). One could also argue that reduced evaporation in low latitudes would be conducive to a greater poleward transport of heat by ocean currents.

Further investigations along the present lines can now be readily defined. It would be of interest to introduce a seasonal variation of σ^* and to use at least three meridional wave numbers instead of two. We also might gain a better insight by a modification of the present model which would permit introduction of a horizontally variable stability σ and Coriolis parameter f. At a later stage, an attempt might be made to extend the number of layers in the model and to include in this way the circulation of the stratosphere and perhaps of the oceans separately.

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APPENDIX

The right-hand sides of the partial differential equations (1) to (4) contain quadratic functions of the dependent variables ψ, τ, χ, θ and σ. When these variables are expressed as truncated series of the orthogonal functions F_{oo}, F_{om}, F_{nm} and F'_{nm}, and the series are substituted into equations (1) to (4), the right-hand sides of the resulting equations will contain Jacobians of the orthogonal functions. These Jacobians must be expressed as new truncated series of orthogonal functions.

The expansions which will concern us are as follows:

$$a^2 J(F_{0k}, F_{nm}) = -\sum_{l=1}^{\infty} n\gamma_{klm} F'_{nl} \qquad (11)$$

$$a^2 J(F_{0k}, F'_{nm}) = \sum_{l=1}^{\infty} n\gamma_{klm} F_{nl} \qquad (12)$$

$$a^2 J(F_{nl}, F'_{nm}) = -\sum_{k=1}^{\infty} n\gamma_{klm} F_{0k} - \frac{1}{2} n(l-m) F_{l+m,\, 2n} + \frac{1}{2} n(l+m) F_{l-m,\, 2n} \qquad (13)$$

$$a^2 J(F_{nl}, F_{nm}) = -a^2 J(F'_{nl}, F'_{nm}) = \frac{1}{2} n(l-m) F'_{l+m,\, 2n} - \frac{1}{2} n(l+m) F'_{l-m,\, 2n} \qquad (14)$$

where

$$\gamma_{klm} = \frac{2\sqrt{2}}{\pi}\int_0^{\pi} k \sin k\gamma \sin l\gamma \sin m\gamma \, d\gamma \qquad (15)$$

$$= 0 \text{ if } k + l + m \text{ is even}$$

$$= \frac{\sqrt{2}}{\pi} k \left(\frac{1}{k + l - m} + \frac{1}{k - l + m} + \frac{1}{-k + l + m} - \frac{1}{k + l + m} \right)$$

$$\text{if } k + l + m \text{ is odd.}$$

We now introduce the index s, and, for values of s from 1 to 6, define the orthogonal functions $G_S(n)$ according to Table 5. The corresponding eigenvalues $C_S(n)$, which satisfy the relation $a^2\nabla^2 G_S = -C_S G_S$, also appear in Table 5.

TABLE 5. Values of $G_S(n)$ and $C_S(n)$

s	1	2	3	4	5	6
$G_S(n)$	F_{01}	F_{n1}	F'_{n1}	F_{02}	F_{n2}	F'_{n2}
$C_S(n)$	1	$n^2 + 1$	$n^2 + 1$	4	$n^2 + 4$	$n^2 + 4$

For simplicity we first consider the case where the series of orthogonal functions are further truncated so that only one non-zero value of n occurs, i.e., the total circulation consists of a zonal circulation plus disturbances of a single wave-length. We may then write the truncated expansions for the dependent variables as:

$$\psi = a^2 f \sum_s \psi_S G_S \qquad (16)$$

$$\tau = a^2 f \sum_s \tau_S G_S \qquad (17)$$

$$\nabla^2 \chi = \sum_s \omega_S G_S \qquad (18)$$

$$\theta = B\left(\theta_0 + \sum_s \theta_S G_S\right) \qquad (19)$$

$$\sigma = B\sigma_0 \qquad (20)$$

The constants in (16) to (20) make the new variables dimensionless. The thermal wind equation (5) tells us that $\tau_S = \theta_S$. To express the new differential equations in a concise from, we introduce a second index $r(s)$, related to s according to Table 6. We also introduce coefficients α_S.

TABLE 6. Values of $r(s)$ and α_S

s	1	2	3	4	5	6	7	8	9	10	11	12	13
$r(s)$	2	3	1	2	6	1	5	6	4	5	3	4	2
α_S	111	111	111	212	122	122	122	212	212	212	212	212	212

We shall adopt the convention that $\bar{G}_S = G_{r(s)}$, $\bar{C}_S = C_{r(s)}$, etc. With this convention we may write the truncated form of equations (11) to (13) as

$$a^2 J(\bar{G}_S, \bar{G}_{S+1}) = \begin{array}{ll} -n\alpha_S G_S & , s = 1, \ldots, 6 \\ -n\alpha_S G_{S-6} & , s = 7, \ldots, 12 \end{array} \qquad (21)$$

When the truncated series (16) to (20) are substituted into the governing equations (1) to (4), the resulting equations may now be written in the form

$$\dot{\psi}_S = n C_S^{-1} (\bar{C}_{S+1} - \bar{C}_S)\, \alpha_S (\bar{\psi}_S \bar{\psi}_{S+1} + \bar{\theta}_S \bar{\theta}_{S+1}) + n C_S^{-1} (\bar{C}_{S+7} - \bar{C}_{S+6})\, \alpha_{S+6} (\bar{\psi}_{S+6} \bar{\psi}_{S+7} + \theta_{S+6} \theta_{S+7}) - \frac{1}{2} k (\psi_S - \theta_S) \qquad (22)$$

$$\dot{\theta}_S = n C_S^{-1} (\bar{C}_{S+1} - \bar{C}_S)\, \alpha_S (\bar{\psi}_S \bar{\theta}_{S+1} + \bar{\theta}_S \bar{\psi}_{S+1}) + n C_S^{-1} (\bar{C}_{S+7} - \bar{C}_{S+6})\, \alpha_{S+6} (\psi_{S+6} \theta_{S+7} + \theta_{S+6} \psi_{S+7}) - C_S^{-1} \omega_S + \frac{1}{2} k \psi_S - \left(\frac{1}{2} k + K\right) \theta_S \qquad (23)$$

$$\dot{\theta}_0 = -\left(j + \frac{1}{2} h\right) (\theta_0 - \theta_0^*) + \frac{1}{2} h (\sigma_0 - \sigma^*) \qquad (24)$$

$$\dot{\theta}_S = n\alpha_S (\bar{\psi}_S \bar{\theta}_{S+1} - \bar{\theta}_S \bar{\psi}_{S+1}) + n\alpha_{S+6} (\bar{\psi}_{S+6} \bar{\theta}_{S+7} - \bar{\theta}_{S+6} \bar{\psi}_{S+7}) + \sigma_0 \omega_S - \left(j + \frac{1}{2} h\right) (\theta_S - \theta_S^*) \qquad (25)$$

$$\dot{\sigma}_0 = -\sum_s \theta_S \omega_S + \frac{1}{2} h (\theta_0 - \theta_0^*) - \left(j + \frac{1}{2} h\right) (\sigma_0 - \sigma^*) - H (\sigma_0 - \sigma_C) \qquad (26)$$

Here a dot denotes a derivative with respect to "dimensionless time" ft. It is possible to eliminate ω_S from the alternative expressions (23) and (25) for $\dot{\theta}_S$ and also from equation (26).

We now consider the more general case where several non-zero values of n are permitted. In the present study these values are $n = 1, 2, 3, 4$. The truncated series for ψ now takes the form

$$\psi = \sum_s \sum_n \psi_S(n)\, G_S(n)$$

with analogous expansions for τ, $\Delta^2\chi$, and θ, where it is understood that the summation over n runs from 1 to 4 if $s = 2, 3, 5$ or 6, but that only the value $n = 0$ occurs if $s = 1$ or 4.

If interactions between different wave numbers are suppressed, while the interaction of each wave number with the zonal current is retained, the governing differential equations will be unaltered, except that in certain terms summations over n will appear. Specifically, in equations (22), (23), and (25), when the index s on the left-hand side has the value 1 or 4, the quadratic terms on the right-hand side are summed over n, but otherwise there is no summation over n, and each equation stands for four equations, one for each value of n. Equation (24) is unaltered, while the quadratic term in equation (26) is to be summed over n and s.

RÉSUMÉ

Étude numérique de l'influence de la stabilité verticale sur les circulations de mousson et zonales (E. B. Kraus et E. N. Lorenz)

Vers le début du siècle, la pluviosité a diminué rapidement sur les lisières équatoriales et orientales des régions arides, ainsi que sur les côtes orientales subtropicales, et il semble qu'en même temps la position moyenne des centres subtropicaux de hautes pressions se soit déplacée vers l'est. Des données fournies par l'observation indirecte montrent que les changements en question étaient associés à une augmentation des vents d'ouest de haute altitude aux latitudes moyennes inférieures ; et des considérations théoriques qualitatives ont conduit à supposer qu'il existait un lien entre ces phénomènes et des modifications de la stabilité verticale.

La validité de cette hypothèse est vérifiée numériquement. Un modèle d'atmosphère à deux couches est mis en mouvement par un champ thermique à trois dimensions, caractérisé par un gradient thermique méridional, des différences d'échauffement entre les diverses parties d'un système figurant les océans et les continents, et un gradient thermique vertical. On constate que l'influence des variations du gradient thermique vertical sur la circulation confirme les déductions tirées de l'observation.

DISCUSSION

J. S. Sawyer. 1. Could Dr. Kraus indicate whether the variations in his parameter σ^* correspond to realistic variations possible in the atmosphere from variation in ozone? 2. Has the variation of humidity been considered as a possible factor leading to variations in the effective value of σ^* which would correspond to the atmospheric problem?

E. B. Kraus. 1. The variations in σ^* cannot be considered realistic in terms of ozone. The three values chosen were meant to illustrate simply the circulation differences that can be created by different vertical heating gradients.

2. The variations in humidity can be considered a powerful amplifying factor. If instability is increased by any factor more vapour is transported upward and that increases upper cooling and instability further. The opposite holds when any factor decreases instability.

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ESSAI D'EXPLICATION HÉLIOGÉOPHYSIQUE DES CHANGEMENTS PALÉOCLIMATIQUES

par

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I

Le climat de notre Terre, au cours de son long développement géologique et jusqu'à la fin du tertiaire, était non glaciaire. Sur toute la Terre prédominait un climat doux, très uniforme, avec de légères différences entre les zones distinctes, et sans couverture glaciale dans les régions polaires. Le problème des pôles chauds pendant la durée du type de climat non glaciaire est, comme l'a fait ressortir Brooks (1949, 1951), la question centrale dans l'étude des causes des changements paléoclimatiques.

L'explication la plus satisfaisante des changements paléoclimatiques sera évidemment celle qui aura réussi à expliquer le plus complètement les causes des différences essentielles survenues dans la disposition des zones climatiques et dans le changement du type de circulation atmosphérique dans la brusque transition du type paléoclimatique non glaciaire en type paléoclimatique glaciaire. On peut supposer que l'explication satisfaisante de cette rupture paléoclimatique servira aussi de base pour la compréhension des mécanismes qui avaient conditionné aussi bien le type non glaciaire que le glaciaire.

En supposant la constance des facteurs des conditions orographiques, Willett (1949, 1953) a donné une explication très documentée des oscillations de la circulation atmosphérique par rapport aux cycles d'activité solaire.

Au cours du quaternaire, Willett distingue le type de climat glaciaire et le type interglaciaire. Le type glaciaire est attribué à l'élargissement des tourbillons dans chaque hémisphère, avec déplacement des zones climatiques vers l'équateur, et le type interglaciaire à la contraction des tourbillons avec déplacement des zones climatiques vers les pôles. Dans ses conclusions, Willett attribue la contraction des tourbillons dans chaque hémisphère à l'état calme du Soleil, lorsque les émissions corpusculaires et à ondes courtes sont les plus faibles, en reliant les états des tourbillons élargis aux périodes d'activité modérée du Soleil, lorsque la radiation ultraviolette est forte, mais avec intensité modérée d'émissions corpusculaires. Les états de perturbation extrême de la circulation atmosphérique, tels que nous les vivons ces dernières années, sont attribués aux périodes des grandes oscillations de l'activité solaire, alors que prédominent les émissions corpusculaires intenses et les radiations de la partie ultraviolette du spectre, avec des éruptions fréquentes. De tels états apparaissent à la branche ascendante des cycles d'activité solaire aux temps de grands maxima de taches solaires.

La conclusion de Mather (1954) sur l'importance des dérèglements climatiques actuels est fort intéressante pour la possibilité d'interprétation des oscillations climatiques au quaternaire. Mather, probablement le premier, affirme clairement que les périodes glaciaires et interglaciaires au cours du quaternaire doivent être considérées comme périodes d'oscillations climatiques d'intensité et d'envergure un peu plus fortes, mais avec des caractéristiques semblables aux oscillations climatiques actuelles.

Cependant, ce qu'il faut tout spécialement faire ressortir ici, c'est que les périodes interglaciaires ne concernent que le quaternaire et qu'elles ne doivent pas être confondues avec le type de paléoclimat non glaciaire qui prédominait sur la Terre au cours des neuf dixièmes de son histoire géologique (Brooks, 1949, 1951).

Le problème des changements géologiques de climat ne doit pas pour cela être étudié comme une question de fluctuations glaciaires et interglaciaires au quaternaire, comme c'est le cas dans l'ouvrage de Craig et Willett (1951). Par là, consciemment ou non, on évite le fait de la brusque rupture des conditions climatiques, et le fait que le type paléoclimatique non glaciaire et le type glaciaire, quoique essentiellement différents par la durée aussi, étaient des processus atmosphériques très stables.

Il est hors de doute que l'explication du brusque changement paléoclimatique à la transition du tertiaire au quaternaire doit être recherchée dans le changement des conditions d'échauffement différentiel de la Terre par le Soleil. Mais en même temps, il faut tout de suite supposer que le Soleil, étoile d'un type déterminé, est resté sans changements au point de vue de la qualité et de la quantité de sa radiation, aussi bien qu'au point de vue de la cadence du cycle de son activité dans une longue période géologique avant et après la rupture climatique à la transition du tertiaire au quaternaire.

La cause de cette brusque transition du type paléoclimatique non glaciaire en type glaciaire ne doit donc pas être recherchée dans les changements survenus au Soleil même, mais dans les changements de la répartition des radiations solaires sur la Terre. La répartition inégale de l'énergie de radiation sur la surface de la Terre et la différence de température entre les régions équatoriales et polaires annoncent et développent la circulation de l'atmosphère ; et les changements dans la répartition de l'énergie solaire sur la surface du globe terrestre provoque des oscillations de l'intensité et de la forme de circulation atmosphérique.

Du point de vue des météorologues, nous poserons la question suivante : Qu'est-ce qui a pu provoquer le brusque changement dans la grandeur du gradient méridional de température qui s'est exprimé en changement radical de la circulation atmosphérique, ce qui a conditionné la nouvelle différenciation zonale du climat à la brusque transition du type climatique non glaciaire en type glaciaire ?

Examinons maintenant la représentation schématique de la répartition de température pour les types paléoclimatiques non glaciaire et glaciaire donnée par Brooks (1949). Nous trouvons la différence essentielle, on pourrait même dire unique, dans la température des régions polaires. Dans le type paléoclimatique glaciaire, la température des régions polaires est de 30 degrés environ plus basse que la température des régions polaires dans le type paléoclimatique non glaciaire. Les différences de température des latitudes moyennes chez les deux types paléoclimatiques sont notablement moindres, et elles disparaissent dans les contrées équatoriales.

Comparons ces différences de température du gradient méridional pour les types paléoclimatiques glaciaire et non glaciaire avec la répartition actuelle d'intensité de radiation solaire pour un ciel clair d'été et d'hiver (fig. 1). Nous pouvons constater tout de suite une grande ressemblance de répartition. Dans la répartition de la radiation potentielle solaire aussi, nous ne trouvons de différences essentielles entre l'été et l'hiver que dans les régions polaires, tandis que ces différences sont très peu marquées dans les latitudes géographiques restreintes. La disposition hivernale de la radiation solaire correspond donc aux changements du gradient méridional de température du type paléoclimatique glaciaire, et la disposition estivale de la radiation aux changements du gradient du type paléoclimatique non glaciaire.

Il faut ajouter encore que la ressemblance des deux courbes n'est pas seulement qualitative, que les changements de température dans les régions polaires au cours d'une révolution sont du même ordre de grandeur — comme l'a jugé Brooks — que le changement de température dans les mêmes régions à la brusque transition à la fin du tertiaire et au commencement du quaternaire.

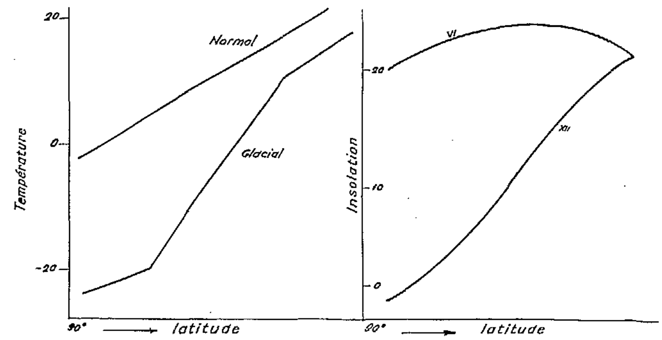

FIG. 1. Courbe de température du gradient méridional pour les types paléoclimatiques glaciaire et non glaciaire.

Les différences saisonnières dans la disposition de la radiation solaire résultent du changement d'inclinaison de l'axe de rotation de la Terre par rapport au Soleil au cours d'une révolution. C'est par là qu'arrivent les changements cycliques des saisons, les oscillations de la circulation atmosphérique et les déplacements des zones climatiques, ainsi que les oscillations séculaires liées aux cycles d'activité solaire.

Ce sont les recherches de la paléoécologie des vertébrés et du monde végétal qui nous permettent de juger de la grandeur des brusques changements dans la circulation atmosphérique et dans la disposition des zones climatiques.

D'après Colbert (1953) : « With the advent of Pleistocene times the patterns of climatic succession and climatic variations as we know them became set. The climate of the earth became sharply zoned . . . Definite alternation of season were established—wet and dry seasons in equatorial regions, hot and cold seasons in the higher latitudes. »

Nous y ajouterons encore la constatation de Barghoom (1953) : « One impresive indicator of uniform climate over the great areas of the Carbonifereous continents is the general absence of annual growthring in coal-swamp trees. »

Donc, l'une des différences essentielles entre les types paléoclimatiques non glaciaire et glaciaire que nous pouvons constater dans les recherches de la paléoécologie est l'alternance des saisons qui apparaît dans le type paléoclimatique glaciaire.

Cette constatation nous amène à la pensée que c'est le changement de position de l'axe de rotation de la Terre qui nous offre la seule possibilité d'explication entière du brusque changement du type de climat non glaciaire en type glaciaire. *Pendant le type paléoclimatique* *non glaciaire, l'axe de rotation de la Terre était perpendiculaire au plan de l'écliptique et, à la transition du tertiaire au quaternaire, elle avait obtenu une position oblique, et c'est ce qui a conditionné l'apparition de l'alternance régulière des saisons, avec la différenciation correspondante des zones climatiques.*

II

Les récents examens paléoclimatiques et paléomagnétiques ont révélé des faits extrêmement importants. Nous en noterons un des plus intéressants pour nos recherches (Irving, 1956). L'axe de rotation, l'axe de zones de climat et l'axe de géomagnétisme, depuis l'ère paléozoïque jusqu'à nos jours, étaient toujours étroitement liés entre eux en un ensemble géophysique et se sont ensemble déplacés sur la Terre. Ils sont donc restés aussi entreliés après la rupture paléoclimatique à la fin du tertiaire.

Le ferme lien de cet ensemble d'axes géophysiques indique certainement l'existence d'un mécanisme unique qui le conditionne. La rotation des planètes, par rapport à leur atmosphère, indique une caractéristique importante de notre système planétaire. Les planètes et les grands satellites qui n'ont pas d'atmosphère ne tournent pas, c'est-à-dire que le temps de leurs rotations égale la durée de leurs révolutions. Ce fait indique certainement l'existence d'un lien physique fort et déterminé entre la circulation de l'atmosphère et la rotation des planètes, ce qui nous amène à la question du rôle de l'atmosphère quant à la provocation et au maintien de la rotation des planètes (Obuljen, 1954).

Le point de vue de Newton d'après lequel la rotation des planètes est prédestinée par un choc accidentel et ne peut pas changer sans action des forces « extérieures » ne peut plus être maintenu aujourd'hui. Il est probable que c'est précisément en raison de l'autorité de Newton qu'on parle peu aujourd'hui encore des causes de la rotation des planètes, et qu'aucune théorie sur la formation des systèmes planétaires ne s'est saisie de cet important problème géophysique.

Certes, il faut approfondir davantage la cause d'une concordance aussi parfaite des parallèles géographiques et des lignes des courants dans l'atmosphère. Cette concordance parfaite est-elle seulement fortuite, est-elle prédestinée ou conditionnée par des facteurs physiques ? Il faut constater que la même concordance est restée la caractéristique inchangée de toute l'histoire géologique de notre planète et qu'une concordance semblable existe sur d'autres planètes aussi (Mars, Jupiter, Saturne).

L'explication du mécanisme de l'ensemble d'axes géophysiques doit être recherchée dans l'importante caractéristique des systèmes planétaires qu'est la coïncidence des plans orbitaux des planètes.

En effet, c'est la coïncidence des plans orbitaux et équatoriaux qui conditionne la situation de l'équateur des planètes. La situation de l'équateur, de la partie la plus chaude de la surface d'une planète, est géométriquement déterminée par la direction verticale de la chute des rayons solaires sur la surface de la planète. La situation de l'équateur détermine par elle-même la situation de l'axe, qui est perpendiculaire sur le plan équatorial et traverse les deux régions les plus froides de la surface de la planète, où les rayons solaires ont la situation de tangente.

Donc, la coïncidence des plans orbitaux et équatoriaux conditionne aussi la répartition différentielle de la radiation sur la surface de la planète et, par cela même, la forme de la circulation atmosphérique, c'est-à-dire la répartition déterminée des zones de climat.

Les considérations théoriques ont démontré (Lorenz, 1960) que l'intensité de circulation de l'atmosphère sur la Terre oscille autour de la valeur maximale déterminée par l'énergie potentielle disponible. La grande constance de rotation de la Terre montre que l'équilibre entre le moment d'inertie de la Terre et le moment de rotation est atteint et, d'autre part, que les petites oscillations de la vitesse de rotation, déterminées avec exactitude ces temps derniers, indiquent l'action des oscillations d'intensité de rotation consécutives aux changements cycliques de l'activité solaire. Il est cependant évident que l'atmosphère — qui, dans sa partie la plus active, celle des tourbillons d'hémisphères, a une vitesse angulaire supérieure à celle de la Terre — donne l'impulsion nécessaire au mécanisme qui provoque et maintient la rotation de la Terre. C'est pourquoi les conceptions d'une circulation atmosphérique conditionnée par la rotation de la Terre doivent être revisées à fond.

La question qui s'impose maintenant est la suivante : Comment est déterminée la situation même du corps, du globe de la planète, dans ce système de coordonnées héliogéométrique données de l'équateur et de l'axe de rotation ? Il est inutile d'accentuer particulièrement que l'axe de la planète n'est pas un axe matériel, mais l'un des axes libres possibles de la planète toupie, axe avec le moment d'inertie optimum par rapport à l'impulsion agissante.

En cas de forme de sphère parfaite et d'homogénéité absolue de répartition de la matière par rapport au centre de la planète, la situation de l'axe libre serait indéterminée. Tout axe passant par le centre d'un globe sphérique et homogène serait un axe libre, et ce serait le cas d'instabilité la plus grande. Les planètes sont de forme sphéroïdale et ont deux possibilités au moins d'axes libres, qui diffèrent par la grandeur du moment d'inertion, passent par le centre de gravité et sont perpendiculaires entre elles.

Des changements de situation de l'équateur de la Terre, qui ont pu être constatés dans les recherches paléoclimatiques et paléomagnétiques précisément quant à ces propriétés des axes libres des corps en rotation, on peut relever un fait extrêmement important. La plus ancienne situation déterminée de l'équateur, celle de l'ère cambrienne, et la situation actuelle de l'équateur (Ruhin, 1955 ; Krotov, 1959), sont perpendiculaires entre elles (fig. 2).

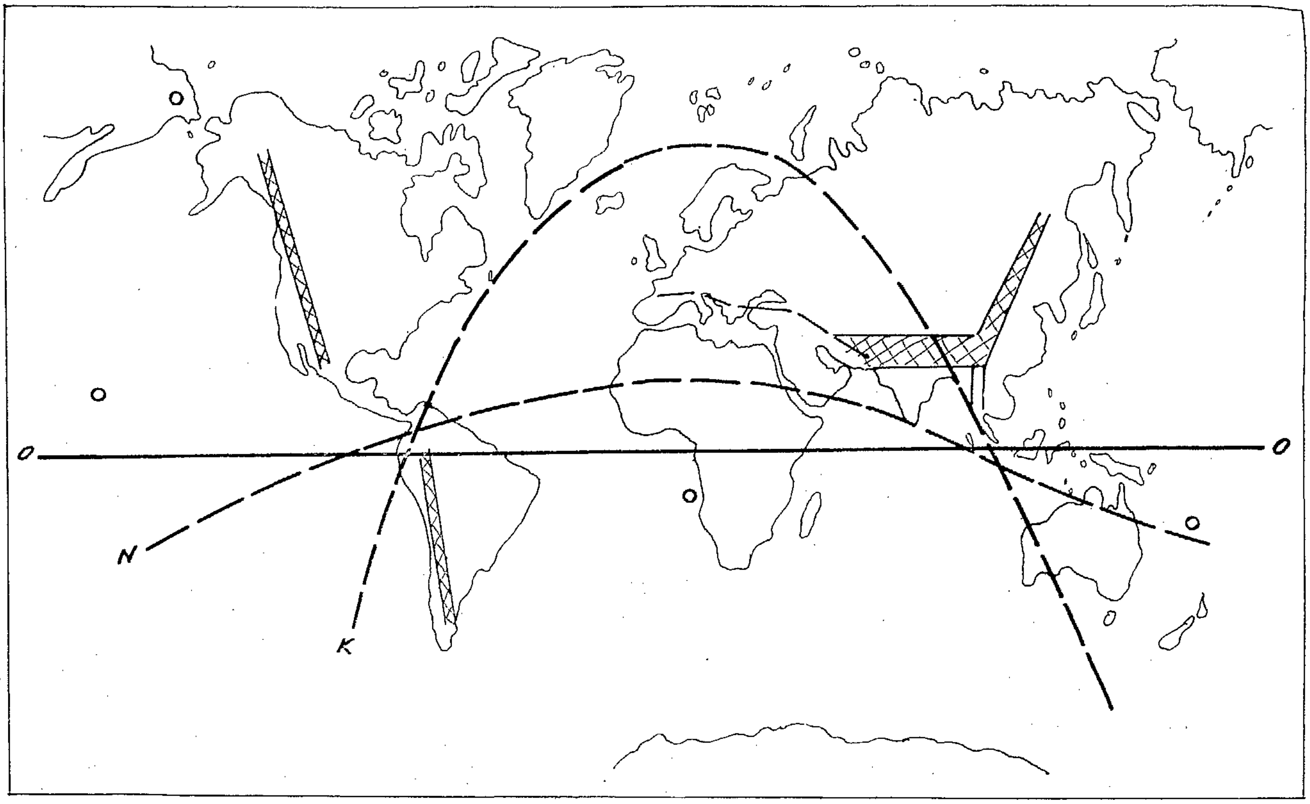

FIG. 2. Changements de situation de l'équateur.

La situation perpendiculaire satisfait donc la condition des axes perpendiculaires des principaux moments d'inertie du corps en rotation. Tout de suite, il faut relever ici encore un fait géologique important : les systèmes des deux principales ruptures continentales montrent également la perpendicularité mutuelle de direction (Wilson, 1957), et nous y ajouterons encore que les directions de ces ruptures sont en accord correspondant avec les situations extrêmes de l'équateur.

Revenons maintenant à l'image des parallèles géographiques et des lignes des courants de circulation atmosphérique. Ajoutons-y l'image de macro-orographie de notre Terre et consacrons l'attention nécessaire à la disposition et à la situation des grandes barrières de montagnes. Pour ceux qui s'occupent de l'hydrodynamique, l'image est fort intéressante. Les courants, par rapport aux macrobarrières, ont la situation hydrodynamique optimum, qui conditionne le maximum de stabilité de l'ensemble des courants et des obstacles. Les montagnes Rocheuses et la Cordillère des Andes sont perpendiculaires à la direction des tourbillons d'hémisphères de la circulation atmosphérique, et les Pyrénées, les Alpes et l'Himalaya lui sont parallèles.

Cette situation hydrodynamiquement déterminée ne peut pas être fortuite ! Le globe terrestre, à la suite de l'action des chaînes de montagnes, créées au cours des grands procès orogéniques, sur les courants existants d'atmosphère, devait s'adapter au changement et prendre une situation nouvelle et déterminée, qui va satisfaire aux conditions nouvelles des courants et des obstacles.

Le changement de situation du globe terrestre a conditionné la rupture paléoclimatique. L'axe de rotation de la Terre, jusque-là perpendiculaire au plan de l'écliptique, avait pris une direction oblique. Par là avait cessé la possibilité de disposition uniforme de climat doux, sans alternance de saisons et avait com-

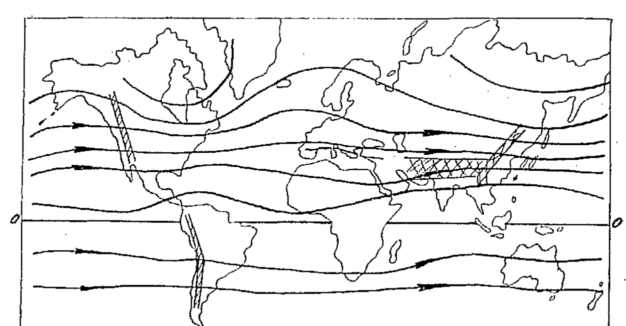

FIG. 3. Lignes de courants de la circulation atmosphérique et grandes barrières de montagnes.

mencé la période du type paléoclimatique glaciaire avec les grandes oscillations de la circulation atmosphérique et l'alternance de saisons très marquées, surtout dans les latitudes polaires et tempérées. Il faut avoir présent à l'esprit qu'au cours du type paléoclimatique non glaciaire, à cause de la situation perpendiculaire de l'axe de rotation, la durée du jour et de la nuit était de douze heures pendant toute l'année et sur toute la Terre. Après la rupture paléoclimatique, la durée du jour et celle de la nuit sont dans les régions polaires de six mois, tandis que la succession du jour et de la nuit dans les régions équatoriales reste sans changement.

Cela avait provoqué le changement correspondant dans la répartition de la radiation, des changements notables dans la répartition de la température, des changements du gradient méridional de température et les changements dans la disposition et dans la grandeur des zones de climat à la suite des grands changements dans la circulation de l'atmosphère.

Par des expériences simples, pour le moment préliminaires, on a essayé de démontrer le bien-fondé de ces considérations. L'expérience des balles tournantes, avec des « barrières de montagnes », avait montré que ces balles se posaient toujours de façon que les « barrières » étaient perpendiculaires à la direction du courant et prenaient la situation hydrodynamiquement la plus stable, précisément comme le bout de papier lâché qui ne tombe pas sur son bord, mais sur tout son côté large.

Dans mon rapport de 1954 sur la circulation de l'atmosphère de la Terre comme problème géophysique, j'ai posé la question de la situation des continents par rapport aux grands courants de la circulation générale : « Est-ce que la situation globale des montagnes Rocheuses et de la Cordillère des Andes, qui se tiennent perpendiculairement sur les grands courants, ainsi que des Pyrénées, des Alpes et de l'Himalaya, qui se tiennent parallèlement à ces courants, n'est que fortuite ? La situation du globe terrestre n'a-t-elle changé par rapport aux courants atmosphériques qu'après la formation des grandes chaînes de montagnes et l'élargissement des continents ? »

Et je ne savais pas alors qu'une question identique avait été posée quatre-vingt-cinq ans auparavant !

C'est pourquoi je termine mon exposé par la question posée en 1876 par lord Kelvin, citée d'après Munk (1956) :

« Considering the great facts of the Himalayas and the Andes, and Africa and the depths of the Atlantic, and America, and the depths of the Pacific, and considering further the ellipticity of the equatorial section of the sealevel (about 1/10 of the mean of meridional sections at sealevel) we need no brush from the comet's tail (ignorance of elementary dynamical principles) to account for a change in the earth's axis.

» . . . it is highly probable that the axis of maximum moment of inertia and the instantaneous axis of rotation, always very near one another may have been in ancient time very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40 or more degrees without at any time any perceptible sudden disturbance of either land or water. »

SUMMARY

A tentative heliogeophysical explanation of palaeoclimatic changes (A. Obuljen).

The question of palaeoclimatic changes revolves around two basic considerations—that a mild climate prevailed almost uniformly over the globe for the greater part of geological history and that an abrupt and radical change in climatic conditions occurred during the transition from the Tertiary to the Quaternary epochs.

It can be confidently stated that this alteration was not due to any changes in the astrophysical properties of the sun or in the elements of the earth's orbit.

On the other hand, palaeogeological, palaeoclimatic and palaeomagnetic research all indicate a marked displacement of the axis of the earth's rotation and likewise that the axis of the atmospheric circulation (hence the axis of the climatic zones) is closely linked to the rotational axis in a single geophysical complex.

For the explanation of this coincidence of the geophysical axes, we must look to an extremely important characteristic of planetary systems, the coincidence of the equatorial and orbital planes. Obviously the orientation of the equator, the hottest part of the planetary surface owing to the vertical incidence of solar radiation, is determined by the orientation of the orbital plane.

By taking into account the important part played by the circulation of the atmosphere in starting and maintaining planetary rotation, it is possible to evolve a satisfactory explanation of palaeoclimatic change. The long period of uniformly very mild climate was due to the earth's rotational axis being almost at right angles to the plane of the ecliptic. The abrupt and radical change of climate followed the great orogenic movements. The orientation of the globe, which then acquired its present highly irregular surface, had to become adjusted to the atmospheric circulation; probably there were a few rather greater oscillations and then the optimum orientation was reached in relation to air

movement with the Andes-Rockies barrier at right angles, and the Eurasian massif parallel to, the westerly zonal current.

The correspondence of the axis subsists in accordance with the complex laws of gyrostatics and the orientation of the equator continues to coincide with the plane of the ecliptic with the corresponding nutation between the geometric axis and the fixed impulse vector in space.

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SECTION IV

THE SIGNIFICANCE OF CHANGES OF CLIMATE

PORTÉE DES CHANGEMENTS DE CLIMAT

Chairman / Président: Dr. R. O. Whyte

THE SIGNIFICANCE OF CLIMATIC CHANGE FOR NATURAL VEGETATION AND AGRICULTURE

by

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The main objective of Section IV insofar as it relates to vegetation and agriculture would seem to be twofold:

1. To consider those major or minor changes in the vegetative cover or in patterns of agriculture that can be directly correlated with periods of climatic change or fluctuation.
2. To review the biological and economic significance of these changes in terms of regression or progression in plant associations or in the nature of systems of crop and animal husbandry.

THE MASKING EFFECT OF MAN'S ACTIONS

It must be admitted with respect to natural vegetation that it is extremely difficult to distinguish between those changes in plant communities that may be due directly to climatic change, those that are due primarily to the action of anthropogenic and biotic factors, and those that are due to the cumulative effects of changes in the mosaic of micro-climates over vast areas of land caused by man-induced regression of the vegetative cover towards a more arid type of community.

We may take as an example the southward extension, not of the Sahara, but of man-made desertic conditions in Western Africa into country that was formerly wooded steppe and savannah (Stebbing, 1935), at an estimated rate of 200 to 300 kilometres during the last three centuries. The destruction by man of the original climax vegetation throughout the arid zones has been of such long duration and so widespread that plant ecologists have come to look first for man-induced causes and to require much convincing with regard to the reliability of some of the plant ecological evidence brought forward in support of climatic change as the sole or primary cause for deterioration of the total environment.

Historians agree that desiccation in Northern Africa, for example, began before historical times, but authors disagree as to the epoch during which the disequilibrium between precipitation and the evaporation from rivers and lakes began to make itself felt. There is evidence that man was in the Sahara in the Quaternary Age and has been present during the long period of increasing desiccation which has changed the Quaternary Sahara to the Sahara of the present day. But superimposed upon long-term climatic trends has been the concurrent and progressively increasing role that man has played (through the practices of burning of woodland, shifting cultivation and overgrazing) in creating the present-day boundaries of the desert.

It must, however, be remembered that it is not only the primitive agriculturist who has destroyed the vegetative cover by clearing land for his crops, nor the animal grazier who has permitted his flocks and herds to reduce the plant cover to an ecologically lower, more arid level, and who practises uncontrolled burning of natural grasslands or shrub associations with the intention of providing more palatable or more accessible grazing. Even before their arrival on the scene, the hunters used fire, probably on a very large scale, to concentrate their game and to make their territories more open and suitable for future operations. The history of devegetation is, therefore, closely associated also with the history of fire, the history of natural burning, and of man's use of fire since he developed it as a major part of his culture. This further emphasizes the need for care when attempting to relate major and ancient changes in vegetation solely or primarily with changes in climate.

TYPES OF CLIMATIC CHANGE

From the plant ecological and agricultural points of view, we are probably correct in considering four broad types of alterations in climate which vary in their biological and economic significance:

1. Major changes, into or out of ice ages or pluvials.

2. Minor changes which persist for 100 to 300 years.
3. Variations or trends which are experienced for 10 to 50 years.
4. Changes induced by the action of man, which, as has been stated, may be distinct from or may be interwoven into types 2 and 3.

The first type is the field of the palaeochorologist, palynologist and palaeobotanist, as far as the distribution of plant species is concerned, of the archaeologists dealing with very early sites, of the geologists who can determine the geological age of prehistoric archaeological deposits by the use of palaeoclimatic indicators, and of the students of the history of the distribution and geographical movement of vegetation. The workers of the Oriental Institute of the University of Chicago (Wright, 1960) state that with depression of the pleistocene snow line in the interior mountains of the Zagros, life zones including woodland descended into the lower foothills and piedmont above northern Mesopotamia, and perhaps into the lowland itself. If ice recession and the climatic sequence occurred at the same time in the Zagros Mountains and the Alps, states Wright (loc. cit.), the cultural transition from food-gathering to food-producing in the Kurdish foothills (10,000 to 7,000 B.C.) would fall at about the time of rapid climatic change. But we are warned not to infer a cause and effect relationship between climatic change and the origin of agriculture, because a wide range of ecological habitats suitable for domestication of animals and grains had probably long been available at lower elevations in the Mesopotamian lowland and piedmont through much of the preceding glacio-pluvial period.

The second type of climatic change (the relatively minor changes that persist for 100 to 300 years) calls for the attention first of the archaeologist, and later of the agricultural historian. The archaeologist would use his own specialized criteria and methods of deduction and correlation to decide, for example, whether the fall and regeneration of primitive communities or a change in type of farming or of the crops that were grown could be connected with climatic change. The agricultural historian would produce evidence of the effect of these minor changes on land use, agriculture and the availability of commodities, evidence from the more recent recorded history and literature.

But again it must be very difficult to decide whether the long-term effects of these relatively minor changes are really due to significant modifications in macroclimate over major altitudinal or latitudinal zones, or to the man-induced deterioration of many contiguous microclimatic environments over very large parts of a bioclimatic region. Climatologists cannot tell us how many microclimates make a macroclimate, whether the myriad changes in microclimates throughout the Near East have been sufficient in their extent and their degree of continuity one with the other to be equivalent to a macroclimatic change, or to be sufficiently strong to mask any effect of the meteorological macroclimate of the region.

That feature of land use which Sir Mortimer Wheeler (1959) has graphically described in the statement: "Mohenjo-daro was wearing out its landscape", has been widespread for millenia in the critical environments in and around the arid zone. It may well be that the abandonment of some ancient sites was due largely or primarily to some such cause, and that the return of peoples to the same site after an interval of 200 or 300 years occurred after revival of the landscape—of the water supplies for domestic use and the growing of crops, of the trees for timber and fuel, and the grazing lands for the free-ranging domestic livestock.

Nevertheless, there is no doubt that climatic changes or fluctuations over periods of 100 to 300 years, if of sufficient magnitude, must have a profound effect on the economic life and products of the people. Many of the crops of the desert fringes are grown perilously near the lower threshold of their moisture requirements. If the rainfall and/or the available water resources should fall below that threshold value and remain below it for a long period, large-scale abandonment of land and movements of peoples would inevitably follow and start a chain-reaction of migration and conflict along the humidity gradient. Perhaps this is even more true of the grazing communities who venture further into the arid environments and whose flocks and herds are the first to suffer from a long or short-term change towards aridity. Their movement to the favourable side of a climatic threshold gives rise to the age-old and constantly recurring enmity between the graziers and the cultivators.

CLIMATIC CHANGE AND MODERN AGRICULTURE

Our main interest at the present time should be in the third type of alteration of climate, the variations or trends which are experienced for periods between 10 and 50 years, and in their significance in land use planning. These variations are generally smaller in scale than the preceding type, both with respect to duration and meteorological parameters. Although they are more transitory in their effects than the long-term fluctuations, they nevertheless do have a marked influence on agricultural systems or crops if a threshold is crossed. In fact, in terms of modern agriculture, these fluctuations are by far the most important and must be taken into account in all planning operations.

For example, the nature and the possibility of improving the agricultural systems of the Mediterranean and Near Eastern regions, on dry, not on irrigated land, are governed by three important thresholds :

1. The point at which the rainfall becomes sufficient in amount and reliability to make cereal farming possible on the cereal/fallow rotation, with grazing still on the semi-arid ranges (approx. 250 mm.).

2. The point at which it becomes possible to grow grain legumes or pulses for human consumption in rotation with the cereals, but with no change in livestock husbandry (approx. 350 mm.).
3. The point at which the rainfall is sufficient to justify the cultivation of legumes for fodder or even the sowing of pastures in rotation with cereals or other food or cash crops, with integration of crop and animal husbandry (over 450 mm.).

The figures given for these thresholds vary considerably between one part of the region and another. Any short-term variation at one place, if of sufficient magnitude to entail the crossing of one of these thresholds, must have a profound effect on crop and animal husbandry, the degree of its integration, the source and nature of protein for the human diet, and in fact the entire way of life of the rural people. Another winter-rainfall environment provides an instance of great local economic significance—when the winter rainfall over the grazing areas of Southern Australia increased slightly at the same time as rabbits decreased and the world wool market improved, a bonanza year was had by all.

Agriculturists concerned with the problem of crop cultivation along the marginal regions of the semi-arid zones do not refer to climatic change so much as to reliability of the environment. Their main interest is naturally in reliability of rainfall, since it is the seasonal and geographical variations in availability of moisture that can have such marked effects on the economic and social characteristics of a region. The cultivators and the graziers of the semi-arid zones have long adapted their ways to these variations, the cultivator by the selection of the most suitable sites and agronomic practices, the grazier by keeping an excessive number of livestock so that a 50 per cent loss in a bad year will not ruin him. Modern land planning demands a less empirical approach to the problem. The FAO-Unesco-WMO project on the agroclimatology of the arid zones should do much to bring more precision into the subject.

The rainfall threshold for successful growing of grain (the lowest rainfall-demanding crop) in East Africa (Kenya, Uganda, Tanganyika) is regarded as 30 inches per annum with a specified degree of reliability. Adopting this criterion, half the land area of East Africa should be classified for pastoral use only (two-thirds of Kenya, one-third of Tanganyika, and limited areas in Uganda). In more than half the remainder, ecological conditions are of an unreliable and marginal nature, highly susceptible to relatively minor climatic fluctuations. Three-quarters of the population of Kenya live in one quarter of the country, which is surrounded and interlaced by pastoral areas which suffer not only from bad grazing management, but also from climatic fluctuations. Two years of drought have set back all the development in these nomadic areas.

It so happens that adequate data are available for the classification of land in Kenya, Uganda and Tanganyika on the basis of the primary criterion of rainfall reliability. It would be desirable to adopt a similar standard for the vast Sahelian and Sudanian belt lying to the south of the Sahara, 4,000 km. long from Dakar to Khartoum, but data are probably inadequate for the purpose. There is, however, no doubt that the success of marginal cropping in great tracts of country in Africa alone is likely to be affected by relatively slight climatic change, expressed in total amount of rainfall for a sequence of seasons above and below the critical threshold values. And what applies to the cultivators of pearl millet and sorghum along the Saharan fringe applies even more to the nomadic and migratory peoples of these zones and those further to the north. Their particular advantage or adaptation is that their enterprises are mobile and can to some extent be moved to the other side of the threshold in critical years.

It must, however, be realized that one of the major objectives in modern technological progress in zones affected by periodic drought is to eliminate or reduce as far as possible the agronomic and economic effects of climatic change. For example, the risks involved in semi-desert nomadism may be overcome by the establishment of fodder reserves at strategic sites, where fodder can be grown under irrigation or imported from agricultural regions in less susceptible areas. The losses incurred in sheep flocks in the lean years may thus be reduced from 80 to 15 per cent, as has been demonstrated in southern Algeria. New methods of land management and crop husbandry can also do much to reduce the risks involved in cultivation around the threshold values.

Although Moss (1952) has produced evidence to show that the western Prairie Provinces of Canada were much more arid than they are today, there is on the other hand some evidence that there is a warming trend in Canada, but with no clear-cut effect on agriculture (Leahey, 1961). The range of economic plants has certainly been expanded, but Leahey believes that most if not all the credit for the absence of serious consequences from current climatic fluctuations should be attributed to plant breeding and selection and to better management practices. In 1961 the Prairie Provinces experienced one of the worst droughts since settlement took place, yet nearly all the stricken areas had some crop. Farmers in southern Alberta were of the opinion that, if they had been farming according to methods in vogue 20 or 30 years ago, the crop would have been a complete failure. A good discussion of the history of recurrent drought in the Prairie Provinces, including incidental reference to the so-called Palliser triangle, is presented in Volume I of the series *Canadian Frontiers of Settlement* (Mackintosh and Joerg, 1934).

CLIMATIC CHANGE AND NATURAL VEGETATION

The effects of major changes in climate, e.g., those related to the last Pluvial period, are fairly well known or at least relatively easy to study in terms of geographical movements of the major types of vegetation and to some extent of their component species. It is less easy to find reliable data regarding the disappearance and subsequent return of plant communities and individual plant species during the periods of minor change which persist for 100 to 300 years. This is partly due again to the confusing interference of man-induced devegetation or lowering of the status of plant associations in the ecological succession, and partly to the absence of qualified observers.

What we do have, however, with reference to the short-term variations, are the results of detailed studies made before, during and after a series of drought years in the Great Plains of the United States of America. These studies were made by Professor (now Emeritus) J. E. Weaver and his associates in the University of Nebraska, and have been thoroughly documented in *The Grasslands of the Great Plains* (Weaver and Albertson, 1956) and elsewhere (Albertson, *et al.*, 1957; Albertson and Weaver, 1945; Weaver, 1961*a*).

The great drought of 1934-40 was so severe and so prolonged that only fragments of the major consociations of which the true prairie is composed remained at its conclusion. Moreover, invading xeric grassland dominants had taken over most of the area and with other species had almost overwhelmed any climax survivors. In 1941-42 a changed environment prevailed. The major area was at that time occupied by thriving invaders, dominants of the much more xeric mixed prairie to the west. If climax prairie was to return, these invaders had to be largely replaced. Two decades were required for this process to be completed (Weaver, 1961*a*). The deterioration during the drought years themselves was accentuated by overgrazing of the drought-suffering vegetation and by smothering of the plants by dust from the cultivated land. Thus we have modern consequences of the misuse of the natural vegetative cover and the extension of cultivation beyond the climatic threshold superimposed upon the normal reactions of the grass species to recurrent drought. These grasslands had certainly suffered from droughts as part of normal climatic fluctuations for centuries, but probably before overgrazing and the ploughing up of the Great Plains they suffered less and recovered more rapidly. The 1953-55 drought has also been recorded in terms of regression and recovery of the plant cover of the Great Plains.

In Professor Weaver's own words (1961*b*): "Droughts come and go; native vegetation is not entirely destroyed; some grasses lie dormant for 5-7 years and then revive. The grassland-prairie border is fairly stable, despite drought, as regards man's lifetime. It is true that over a belt 50-150 miles wide, Great Plains vegetation moved eastward into normal true prairie in 1933-40, as we have amply recorded, but it is also true that the reverse of this occurred following the cessation of drought in 1941-50. Not much change has occurred along grassland-*forest* borders of which I am aware. Death of shrubs in brushland and savanna in the south-west has occurred to some extent."

PLANT TOLERANCES AND REQUIREMENTS

It is the plant physiologist and crop ecologist who can provide information of the probable response of plant species to the extreme conditions produced by excessive climatic fluctuations. They can supplement the data on rainfall reliability in semi-arid zones by information on just how much a plant can tolerate and still give an economic return, or still persist in a natural plant cover ready to regenerate when favourable conditions return. Plants vary widely in their degree of tolerance or range of adaptability.

Some periods in a plant's life are more vulnerable then others. Seeds will not germinate without their required quota of soil moisture, but tender seedlings will die under conditions of transient drought. The tender parts of flowers may be caught by an early drought or cold period before their seeds are safely formed and covered by a protective seed coat. The longevity of seeds in the ground is an important characteristic governing the capacity of a natural plant association to regenerate.

Perennials are in general superior to annuals in their tolerance of periods of excessive drought, and their ability to survive. Deep-rooted trees and shrubs can hold out longer (even if they cannot produce seeds) than annuals which depend on the seasonal availability of soil moisture for their germination and growth. The effects of climatic fluctuations may not, therefore, become very noticeable for some years in protected vegetation with a high percentage of perennials. It is a case again without reproduction until favourable conditions return.

THE INCIDENCE OF PESTS AND DISEASES

The plants in natural communities and the crops in their dry or irrigated fields live in a state of uneasy symbiosis with a malevolent assembly of insect pests and fungous diseases. Short-range fluctuations in the macro- and microclimates may have a profound effect on the balance that exists between these inhabitants of a semi-arid biome. A change in climate may increase the virulence of attack by local pests and diseases just at a time when the normal degree of resistance of the host plants is reduced by that same climatic change. A temporary fluctuation may also lead to a disastrous invasion of ravenous pests from other more severely affected localities. This is an aspect of great economic significance to land use and agricultural production that merits a full review by a competent authority.

Suffice it to refer here briefly to the interference or the accentuation caused by anthropogenic factors. For example, the heaviest losses of crops from locust invasions so far recorded in many countries have been those of the last decade, largely as a result not of climatic change but of the progressive extension of agriculture into the semi-arid regions which are the home of the desert locust (Uvarov, 1957; Aspliden and Rainey, 1961). It is probably true to say that agricultural development, and particularly the introduction of irrigation, creates changes in the above-ground microclimate and so in the crop-pest relationship which are greater than the changes caused by the normal climatic fluctuations characteristic of the present decades. The building of the Rajasthan Canal in Western India and the creation of a long tongue of irrigated land in a semi-arid area will have a much greater and more dangerous effect on this relationship than the short-term variations in rainfall characteristic of the zone lying along the border with West Pakistan. It will provide an excellent breeding ground and new sources of palatable food for all the insects that are at present held in check by the rigorous conditions of aridity of the region. Again, therefore, we must be aware of the masking effects of man's activities and agronomic practices when assessing the significance of climatic change in terms of crop-pest relationships. We look forward with interest to the results that will be forthcoming in this connexion from the FAO-Unesco Ecological Survey of the breeding areas of the desert locust.

On a broader canvas in respect of the time span involved, an interesting study has been made of the relation between the past and present ecology of the Acridid population of the Sahara and the climatic history of the region (Uvarov, 1953). These locusts and grasshoppers represent an important actual or potential economic hazard to the natural vegetation and crops; they can be grouped into four different ecofaunae: deserticolous (species of open desert, mostly living on the ground), saxicolous (species connected with stony slopes of eroded mountains, also mostly living on the ground), arbusticolous (living on shrubs and trees) and graminicolous (living on grasses). The last group is particularly interesting in relation to the past climatic history of the Sahara.

The grassy habitats in the desert are discontinuous —even xerophytic grasses normally occur in isolated depressions or near mountains. The distribution of the grass-eating Acrididae is accordingly also insular. The sources of graminicolous Acrididae are found on both sides of the Sahara: tropical savannahs on the south and temperate steppes on the north, but it is a striking fact that the northern steppe elements are completely absent from the graminicolous fauna of the Sahara, which is wholly Ethiopian. The same picture is obtained when the fauna of oases is analyzed.

Uvarov concludes: "Since the present ecological conditions in the Sahara appear to preclude active distribution of graminicolous Acrididae, particularly those connected with mesophytic grasses of oases, there can be no doubt that isolated grassy habitats in the desert have been populated when the climate of the desert was essentially different from the present. This should have been possible during the Pleistocene pluvial periods when more abundant precipitation over northern Africa allowed a more or less continuous extension of grasslands over the Sahara. The composition of the Acridid fauna of the present grassy "ecological islands" in the desert indicates clearly that the Sahara during the pluvial periods was invaded by graminicolous fauna only from the south, and it provides no evidence of a southward dispersion of northern steppe elements, such as has been often postulated in the past."

From the present truly insular distribution of the Acridid fauna of East African mountains, Uvarov again finds that the widely accepted theory of a southward migration of Palaearctic elements into tropical Africa during the Pleistocene pluvial period is at least not applicable to Acrididae.

CONCLUSION

The main conclusion to be drawn from these introductory remarks and from the papers that follow is that ecologists and agriculturists are fully aware of the great influence of climatic change on the past and present distribution of plant associations and of types of agriculture and animal husbandry. The trends towards more desiccated conditions in the semi-arid zones are certainly discernible, as are also the human responses to the challenge of that desiccation, as referred to by Toynbee. Yet in analysing these trends ever since man came on the scene, it has become increasingly difficult to distinguish between the changes in vegetation and agriculture that have been due entirely to climatic change and/or fluctuation, and those that are a direct or secondary consequence of man's activities. This might well be the subject of another inter-agency symposium, between Unesco, WMO and FAO.

The ecologist and agriculturist express climatic change in terms of reliability of climate for economic land utilization. The early work at the Waite Agricultural Research Institute (Trumble, 1948) with regard to climatic reliability in the semi-arid zones of Australia, and the studies in East Africa referred to here need to be extended wherever long-term meteorological data are available. This type of analysis should be a fundamental part of any project of land development.

The plant physiologist concerned with the response of wild or cultivated species to a fluctuating environment can provide biological data of great value in considering how particular species, growth forms or ecotypes respond in a particular way. These data can be used by the plant breeder or the agronomist to reduce the economic consequences of short-term climatic fluctuations by the introduction of more resistant cultivars or of improved cultivation practices.

Wild and cultivated plants are always accompanied by insect pests and fungous diseases in their own particular ecological niches. These plant-animal communities are highly susceptible to microclimatic fluctuations, natural or man-induced. The insect ecologist has therefore also an important part to play in forecasting dangers that may follow the introduction of a new crop, or of a new cropping practice such as alternate husbandry or irrigation.

CONSÉQUENCES DES MODIFICATIONS DU CLIMAT POUR LA VÉGÉTATION SPONTANÉE ET L'AGRICULTURE

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La section IV, dans la mesure où elle concerne la végétation et l'agriculture, semble avoir principalement pour objet:

1. L'étude des changements, profonds ou superficiels, de la couverture végétale ou des formes d'agriculture qui peuvent être rapportés directement à des modifications ou des fluctuations du climat.
2. La recherche de l'importance biologique et économique de ces changements (régression ou progression des associations végétales; nature différente des méthodes de culture et d'élevage).

L'EFFET DE MASQUE DE L'ACTIVITÉ HUMAINE

Pour ce qui est de la végétation spontanée, il faut convenir qu'il est extrêmement difficile de distinguer, parmi les changements qui surviennent dans les groupements végétaux, ceux qui sont directement imputables à des modifications du climat, ceux qui sont dus essentiellement à des facteurs humains ou biologiques et ceux qui sont la résultante, à l'échelle de toute une région, de modifications provoquées dans la mosaïque des microclimats par une régression de la couverture végétale vers un type de groupement plus xérophytique, consécutivement à l'action de l'homme.

Prenons par exemple l'Afrique occidentale où le désert, non le Sahara mais une sorte de désert qui est l'œuvre de l'homme, a gagné de 200 à 300 kilomètres vers le sud en trois cents ans, sur un territoire qu'occupaient autrefois la steppe herborée et la savane (Stebbing, 1935).

La destruction par l'homme de la végétation climacique primitive des régions arides est un phénomène si ancien et si général que les spécialistes de l'écologie végétale cherchent d'abord dans l'activité de l'homme les raisons de la dégradation d'un milieu et ne se laissent pas aisément convaincre que des modifications du climat attestées par des faits d'écologie végétale puissent en être la cause unique ou principale.

Les historiens s'accordent à penser que l'assèchement de l'Afrique du Nord, par exemple, a débuté avant les temps historiques, mais les avis diffèrent quant à l'époque où le déséquilibre entre les précipitations et l'évaporation de l'eau des rivières et des lacs a commencé de faire sentir ses effets. On a la preuve que l'homme habitait le Sahara non seulement au quaternaire mais aussi pendant la longue période d'assèchement qui a fait peu à peu de cette région le désert que nous connaissons. Mais aux effets d'une lente transformation du climat est venue s'ajouter l'action de plus en plus sensible de cette population qui, par l'incendie de parties boisées, la culture itinérante et le surpâturage, a contribué à donner au désert ses dimensions actuelles.

Il ne faut cependant pas perdre de vue que la destruction de la couverture végétale n'est pas imputable uniquement aux agriculteurs primitifs qui défrichaient le sol pour le cultiver ou aux pasteurs qui laissaient leurs troupeaux dégrader la végétation, la ramenant à des formes xérophytiques écologiquement inférieures, et qui brûlaient inconsidérément la prairie ou la brousse pour procurer à leurs bêtes des pâturages plus palatables ou plus accessibles. Avant eux, en effet, les chasseurs se servaient déjà du feu, et même très largement sans doute, pour rabattre le gibier et faciliter leurs chasses futures en éclaircissant la couverture végétale de leur territoire. L'incendie, tant d'origine naturelle que provoqué par l'homme, lorsque le feu fut devenu un élément essentiel de la civilisation, a donc joué un grand rôle dans la destruction de la végétation au cours des temps. Là encore, on voit combien il faut être prudent avant d'attribuer uniquement ou principalement à des modifications du climat des changements anciens et profonds de la végétation.

LES DIFFÉRENTS TYPES DE MODIFICATIONS DU CLIMAT

Du double point de vue écologique et agricole, il est sans doute légitime de ranger les modifications du climat en quatre types principaux ayant des effets différents d'ordre biologique et d'ordre économique :

1. Les modifications profondes (début et fin des époques glaciaires ou pluviales).
2. Les modifications mineures dont des effets se font sentir pendant une période de cent à trois cents ans.
3. Les variations ou évolutions dont les effets se font sentir pendant une période de dix à cinquante ans.
4. Les changements provoqués par l'activité de l'homme qui, comme on l'a vu, peuvent être distincts des types (2) et (3) ou au contraire se confondre avec eux.

Les modifications du premier type ressortissent à plusieurs domaines : celui des spécialistes de la paléochoroologie, de la palynologie et de la paléobotanique pour ce qui est de la distribution des espèces végétales ; celui des archéologues spécialisés dans l'étude des sites très anciens ; celui des géologues qui déterminent l'âge géologique des dépôts archéologiques préhistoriques grâce aux indicateurs paléoclimatiques, et enfin celui des spécialistes de l'histoire de la répartition et des déplacements géographiques de la végétation. Les recherches menées à l'Institut d'études orientales de l'Université de Chicago (Wright, 1960) indiquent que, lors de l'abaissement de la limite des neiges au pléistocène dans les chaînes intérieures du Zagros, les zones biologiques, notamment la zone boisée, sont descendues jusqu'aux hauteurs et plaines de piedmont qui dominent la Mésopotamie septentrionale et peut-être même dans la plaine elle-même. Wright (*loc. cit.*) estime que si le recul des glaciers et le changement de climat consécutif se sont produits dans les Alpes à peu près à la même époque que dans le Zagros, le passage de l'économie de cueillette à l'économie agricole sur les hauteurs du Kurdistan (de 10000 à 7000 av. J. C.) coïnciderait approximativement avec le changement rapide du climat. On nous avertit cependant de ne pas en déduire l'existence d'une relation de cause à effet entre le changement de climat et l'apparition de l'agriculture car, pendant une bonne partie de la période glacio-pluviale précédente, l'homme pouvait sans doute trouver à moindre altitude, dans la plaine de Mésopotamie et sur les plaines de piedmont, de nombreux habitats écologiques propices à la domestication des animaux et des céréales.

Les modifications de climat du second type, qui sont relativement légères et se font sentir pendant cent à trois cents ans, requièrent d'abord l'attention de l'archéologue puis celle de l'historien de l'agriculture. Le premier, appliquant les critères et les méthodes de déduction et de corrélation propres à sa discipline, dira par exemple si le déclin et la renaissance de telle collectivité primitive et tel changement dans le mode d'exploitation des terres ou dans la nature des cultures pratiques peuvent être rapportés à une modification du climat. L'historien de l'agriculture attestera l'effet de ces changements mineurs du climat sur le mode d'utilisation des terres, l'agriculture, et l'abondance des denrées, à l'aide de faits plus récents tirés de documents littéraires et historiques.

Mais là encore il sera très difficile de dire si les effets lointains de ces changements relativement mineurs sont réellement dus à des modifications profondes du macroclimat sur de grandes zones d'altitude ou de latitude ou bien à la dégradation, provoquée par l'homme, de nombreux milieux microclimatiques contigus sur de très grandes étendues d'une région bioclimatique. Les climatologues ne peuvent préciser combien de microclimats font un macroclimat, et si les innombrables modifications des microclimats intervenues dans l'ensemble du Proche-Orient ont eu une ampleur et un degré de continuité suffisants pour produire les mêmes effets qu'une modification du macroclimat, ou au contraire ont été suffisamment fortes pour masquer tout effet du macroclimat météorologique de la région.

Depuis des millénaires, dans les milieux critiques de la zone aride ou de ses abords, l'exploitation du sol a pour effet d'« user le paysage » comme a si bien dit sir Mortimer Wheeler (1959) au sujet de Mohenjo-daro. Il est fort possible que l'abandon de certains sites habités dans l'antiquité ait été dû en grande partie ou essentiellement à un phénomène de ce genre, et que le retour de la population au même endroit, deux ou trois siècle après, s'explique par la reconstitution du paysage, c'est-à-dire, en fait, par celle des réserves d'eau nécessaires aux usages domestiques et agricoles, des réserves de bois d'œuvre et de bois de chauffage, et des terrains de parcours nécessaires au bétail.

Il n'est cependant pas douteux que des modifications ou fluctuations du climat qui se font sentir sur une période de cent à trois cents ans, si elles sont d'une ampleur suffisante, ont des répercussions profondes sur la production et la vie économiques de la population. Nombre de plantes cultivées en bordure des déserts ne disposent que de doses d'humidité dangereusement proches du strict minimum. Si, par suite de l'insuffisance des précipitations notamment, ces quantités tombent au-dessous du minimum et s'y tiennent longtemps, il est inévitable que les populations quittent en masse cette zone marginale et que leur mouvement entraîne une suite de migrations et de conflits qui gagnera de proche en proche selon la direction du gradient d'humidité. Et sans doute en sera-t-il ainsi plus encore dans le cas des collectivités pastorales, qui s'aventurent plus profondément dans le milieu aride et dont les troupeaux sont les premiers à souffrir lorsque le climat devient provisoirement ou durablement, plus aride. Leurs déplacements vers des régions dont le climat reste au-dessus du seuil d'aridité est à l'origine de l'hostilité qui existe depuis toujours entre pasteurs et agriculteurs et qui se manifeste en toutes occasions.

LES MODIFICATIONS DU CLIMAT ET L'AGRICULTURE ACTUELLE

A notre époque, c'est surtout le troisième type d'altération du climat qui doit nous occuper, à savoir les variations ou tendances qui se font sentir pendant un temps allant de dix à cinquante ans, considérées du point de vue de leur importance pour la planification de l'exploitation des terres. Ces variations ont généralement moins d'ampleur que celles du type précédent, tant en ce qui concerne leur durée qu'en ce qui concerne leurs paramètres météorologiques. Bien qu'elles aient des effets moins durables que les fluctuations à long terme, elles ont néanmoins une influence marquée sur les méthodes agricoles ou la nature des cultures si un seuil est franchi. En fait, même, ces fluctuations sont de loin les plus importantes pour l'agriculture actuelle et doivent entrer en ligne de compte dans tout travail de planification.

C'est ainsi que dans le bassin méditerranéen et le Proche-Orient, la nature et les possibilités d'amélioration des procédés de culture en terrain sec non irrigué dépendent de trois éléments principaux:

1. Le point auquel les pluies deviennent suffisamment abondantes et régulières pour permettre la culture des céréales en alternance culture-jachère, les prairies semi-arides étant utilisées comme pâturages (seuil de 250 mm de pluie environ).
2. Le point auquel il devient possible d'alterner les légumineuses à grains comestibles et les céréales mais sans changement dans les méthodes d'élevage (seuil de 350 mm environ).
3. Le point auquel la pluviosité est suffisante pour permettre la culture de légumineuses fourragères ou même l'alternance de prairies artificielles et de céréales ou autres cultures vivrières ou de rapport, avec intégration de la culture et de l'élevage (seuil de 450 mm).

Les hauteurs de pluie auxquelles sont chiffrés ces seuils varient considérablement à l'intérieur d'une même région. Et toute variation de courte durée en un point, si elle est d'une valeur suffisante pour que l'un des trois seuils soit franchi, a nécessairement des effets profonds sur l'agriculture et l'élevage, sur leur degré d'intégration, sur l'origine et la nature de la ration protéinique des humains, en fait sur tout le mode de vie de la population rurale. On trouve un exemple de l'importance des effets exercés sur l'économie locale dans une autre région à pluies d'hiver: l'Australie-Méridionale, où il a suffi que les pâturages reçoivent une quantité de pluie légèrement accrue à une époque où les lapins se raréfiaient et où le marché mondial de la laine devenait plus favorable, pour que l'année soit fructueuse au total.

Les agronomes qui étudient les problèmes d'agriculture se posant dans des régions situées en bordure d'étendues semi-arides parlent moins de modifications du climat que de stabilité du milieu. Bien entendu, ils s'intéressent surtout à la régularité des pluies car ce sont les variations — dans le temps et l'espace — des quantités d'eau disponibles qui ont des effets profonds sur les caractères économiques et sociaux d'une région. Les cultivateurs et les pasteurs des régions semi-arides se sont depuis longtemps adaptés à ces variations, les premiers en choisissant des emplacements favorables et des procédés de culture appropriés, les seconds en entretenant plus de bétail qu'il ne serait nécessaire, de manière à ne pas être ruinés si une mauvaise année leur en fait perdre la moitié. Aujourd'hui, l'exploitation rationnelle des terres exige que ce problème soit abordé de façon moins empirique; le projet mixte FAO-Unesco-OMS sur l'agroclimatologie des régions arides devrait permettre d'en préciser les données.

On estime qu'en Afrique orientale (Kenya, Ouganda, Tanganyika), la culture des céréales, qui sont parmi les plantes cultivées celles qui demandent le moins de pluie, exige une pluviosité d'au moins 75 cm par an et présentent en outre une certaine régularité. D'après ce critère, il faudrait considérer que la moitié des terres de l'Afrique orientale ne peuvent porter que des pâturages (deux tiers au Kenya, un tiers au Tanganyika et de petites étendues en Ouganda). Dans plus de la moitié du reste, les conditions écologiques sont irrégulières et de caractère marginal, très sensibles à des fluctuations relativement faibles du climat. Les trois quarts de la population du Kenya se concentrent sur un quart seulement du territoire et cette région est entourée et parsemée d'étendue de pâturages qui ont à souffrir non seulement de mauvaises méthodes d'exploitation mais aussi de fluctuations du climat; deux années de sécheresse ont arrêté tout développement sur ces aires de nomadisme.

Il se trouve que l'on dispose d'un ensemble de données permettant de classer les terres du Kenya, de l'Ouganda et du Tanganyika d'après le critère principal, celui de la régularité des pluies. Il serait souhaitable d'adopter une norme de ce genre pour la vaste zone sahélienne et soudanaise qui, au sud du Sahara, s'étend sur 4 000 kilomètres de Dakar à Khartoum, mais il est probable que l'on manque de données suffisantes pour le faire. Cependant, il n'est pas douteux que le succès des cultures marginales, sur de grandes étendues de la seule Afrique, sera vraisemblablement influencé par des modifications relativement légères du climat, se traduisant par un écart en plus ou en moins, pendant plusieurs saisons consécutives, des quantités de pluie effectivement reçues, par rapport aux seuils critiques. Et ce qui est vrai pour les cultivateurs de la frange saharienne qui produisent du petit mil et du sorgho l'est plus encore pour les éléments nomades et migrateurs de ces régions et de celles qui sont situées plus au nord; ils ont cet avantage, que leurs exploitations, par nature ou par adaptation, sont mobiles et peuvent dans une certaine mesure, les années critiques, être transportées du côté favorable de la limite.

Il faut bien se rendre compte, néanmoins, que dans les régions qui ont périodiquement à souffrir de la sécheresse, la technique moderne doit viser principalement à éliminer, ou à réduire autant que possible, les effets d'ordre agronomique et économique des modifications du climat. Par exemple, on peut écarter les risques que comporte le nomadisme dans les régions semi-désertiques en constituant des réserves de fourrage en des points judicieusement choisis, lorsqu'il est possible de cultiver des plantes fourragères sur des terres irriguées ou d'en importer de régions agricoles situées dans une zone moins menacée. Ce moyen permet de ramener de 80 à 15 % les pertes que subissent les troupeaux d'ovins pendant les mauvaises années, comme l'expérience l'a prouvé dans le Sud algérien. Des méthodes nouvelles d'exploitation rationnelle des terres et de culture permettent aussi de réduire les risques que court l'agriculture au voisinage des seuils.

Bien que Moss (1952) ait conclu d'un certain nombre de faits que la partie occidentale des provinces canadiennes de la Prairie était beaucoup plus aride autrefois qu'aujourd'hui, d'autres constatations témoignent au contraire d'une tendance au réchauffement en ce pays, mais sans effet bien net sur l'agriculture (Leahey, 1961). Le nombre des plantes cultivées s'est certainement accru, mais, selon Leahey, le fait que les fluctuations actuelles du climat n'aient pas eu d'effet sensible s'explique surtout, sinon uniquement, par la sélection des espèces et le perfectionnement des méthodes d'exploitation. En 1961, les provinces de la Prairie ont subi une des plus fortes sécheresses que l'on ait connues depuis la colonisation et pourtant la presque totalité des régions touchées ont eu des récoltes. Les agriculteurs du sud de l'Alberta ont estimé que s'ils avaient employé les méthodes en usage vingt ou trente ans auparavant, les récoltes auraient été complètement perdues. On trouvera une bonne étude historique sur les sécheresses périodiques des provinces de la Prairie, étude dont l'auteur se réfère d'ailleurs incidemment au « triangle de Palliser », dans le premier volume de la collection *Canadian frontiers of settlement* (Mackintosh et Joerg, 1934).

LES MODIFICATIONS DU CLIMAT ET LA VÉGÉTATION SPONTANÉE

Les effets des grandes modifications du climat, par exemple de celles qui sont en corrélation avec la dernière période pluviale, sont assez bien connus, ou du moins assez faciles à étudier en fonction des déplacements géographiques et, dans une certaine mesure, de la composition floristique des principales formations végétales. Mais il est plus malaisé de trouver des données sûres concernant la disparition et la réapparition ultérieure de certains groupements végétaux et de certaines espèces dans le cas des modifications climatiques mineures d'une durée de cent à trois cents ans. Dans ce cas également, les effets des modifications du climat sont masqués par ceux de l'activité humaine (destruction de la végétation ou évolution régressive dans la succession écologique), ce à quoi s'ajoute l'absence d'observateurs qualifiés.

En revanche, dans le cas des modifications climatiques de courte durée, nous possédons les résultats d'études détaillées faites pendant et après une série d'années sèches dans les Grandes Plaines des États-Unis d'Amérique. Ces travaux, solidement étayés de faits, sont l'œuvre du professeur — aujourd'hui professeur honoraire — J. E. Weaver et de ses collaborateurs de l'Université du Nebraska ; ils ont paru dans *The grasslands of the Great Plains* (Weaver et Albertson, 1956) et dans d'autres publications (Albertson *et al.*, 1957 ; Albertson et Weaver, 1945 ; Weaver, 1961*a*).

La grande sécheresse de 1934-1940 a été si dure et si prolongée qu'elle n'a laissé finalement subsister que des fragments des grandes consociations qui composent la prairie véritable. De plus, la majorité de la région a été envahie par des espèces dominantes de prairies xériques qui, avec d'autres espèces, ont presque fait disparaître ce qui restait de la formation climacique. En 1941-1942, le milieu s'était transformé. La plus grande partie de la région était alors occupée par les espèces dominantes de la prairie mixte plus sèche de l'ouest, qui l'avaient envahie et y prospéraient. Pour que la prairie climacique pût se reconstituer, il fallait que la plupart de ces espèces disparaissent, ce qui a pris une vingtaine d'années (Weaver, 1961*a*). La dégradation de la végétation pendant les années de sécheresse proprement dite a été aggravée par la surcharge des pâturages, qui, déjà privés d'eau, étaient étouffés par la poussière venue des terres cultivées. On trouve là un exemple actuel des conséquences que peuvent avoir le mauvais usage de la couverture végétale spontanée et l'extension des cultures au-delà du seuil climatique, lorsque leurs effets s'ajoutent aux réactions normales des espèces herbacées soumises à une sécheresse périodique. Ces prairies souffraient sans doute depuis des siècles déjà de sécheresses représentant des fluctuations normales du climat, mais il est probable qu'elles se détérioraient moins et se reconstituaient plus rapidement lorsqu'elles n'étaient pas encore surpâturées et que les Grandes Plaines n'avaient pas encore été labourées. Les effets de la sécheresse de 1953-1955 concernant la régression et la reconstitution de la couverture végétale des Grandes Plaines ont également été enregistrés.

Selon les termes mêmes du professeur Weaver (1961*b*) : « La sécheresse vient puis disparaît ; la végétation spontanée n'est pas entièrement détruite car certaines espèces restent cinq à sept ans en sommeil puis revivent. Les modifications de la bordure de la prairie ne sont guère perceptibles, malgré la sécheresse, dans l'espace d'une vie d'homme. Il est vrai que, sur une zone de 80 à 240 kilomètres de large, la végétation des grandes plaines s'est déplacée vers l'est entre 1933 et 1940, se transformant en prairie pure de type normal, comme on l'a maintes fois observé, mais il est également vrai que l'inverse s'est produit à la fin de la sécheresse de 1941-

1950. En bordure de la *forêt pure*, la végétation n'a pas subi de transformations profondes, à ma connaissance. Une certaine proportion des arbustes de la brousse et de la savane du sud-ouest a péri. »

TOLÉRANCES ET EXIGENCES DE LA VÉGÉTATION

Ce sont les spécialistes de la physiologie végétale et de l'écologie des plantes cultivées qui peuvent dire quelle sera la réaction probable des espèces végétales à des conditions extrêmes résultant de fluctuations climatiques excessives. Ils peuvent compléter les données sur la régularité des pluies dans les régions semi-arides en indiquant exactement ce qu'une plante peut tolérer sans que sa culture cesse d'être rentable ou sans perdre la faculté de reprendre sa place dans la couverture végétale naturelle lorsque les conditions redeviendront favorables. Le degré de tolérance et le pouvoir d'adaptation des plantes sont très variables.

Les plantes sont plus vulnérables à certaines périodes de leur existence qu'à d'autres. Les graines ne peuvent germer si elles ne trouvent pas dans le sol la dose d'humidité dont elles ont besoin et une sécheresse passagère peut tuer les jeunes pousses. De même, les parties les plus fragiles des fleurs peuvent être détruites par la sécheresse ou le froid précoces, survenant avant que les graines soient suffisamment formées et recouvertes de leur enveloppe protectrice. Le pouvoir de régénération d'une association végétale spontanée dépend dans une large mesure de la longévité des graines dans le sol.

En général, les plantes vivaces tolèrent mieux la forte sécheresse et s'en remettent mieux que les plantes annuelles. Les arbres et arbustes profondément enracinés résistent plus longtemps, même s'ils ne peuvent plus produire de graines, que les plantes annuelles, qui ont besoin de l'humidité saisonnière du sol pour germer et croître. Par suite, les effets des fluctuations climatiques peuvent n'apparaître très nettement qu'au bout de plusieurs années dans le cas d'une végétation protégée contenant un fort pourcentage d'espèces vivaces, car elle vieillira sans se reproduire jusqu'à ce que les conditions redeviennent favorables.

INSECTES NUISIBLES ET MALADIES

Les espèces des groupements spontanés et les plantes cultivées, irriguées ou non, vivent malgré elles en une difficile symbiose avec toutes sortes d'insectes nuisibles et de champignons pathogènes. En milieu semi-aride, de légères fluctuations du macroclimat et des microclimats peuvent avoir des répercussions profondes sur l'équilibre de ce biome. Un changement de climat peut accroître la virulence des insectes et agents pathogènes locaux tout en réduisant la résistance des végétaux qui les portent ; il arrive aussi qu'une fluctuation passagère provoque une invasion désastreuse d'insectes affamés venant de localités plus gravement touchées. Il y a là un problème d'une grande importance économique du point de vue de l'utilisation des terres et de la production agricole ; ce problème mérite d'être étudié à fond par des spécialistes.

Nous nous contenterons de dire ici quelques mots des facteurs humains dont l'intervention peut être utile ou nuisible à cet égard. Par exemple, dans bien des pays, c'est au cours des dix dernières années que les dommages causés aux récoltes par les invasions d'acridiens ont été les plus lourds, ce qui s'explique non pas tant par des modifications du climat que par l'extension progressive de l'agriculture dans les régions semi-arides qui constituent l'habitat du criquet pèlerin (Uvarov, 1957 ; Aspliden et Rainey, 1961). Il est probable que le développement de l'agriculture, notamment l'emploi de l'irrigation, entraîne, dans le microclimat au voisinage du sol et par suite dans les rapports entre les plantes cultivées et les insectes nuisibles, des changements plus importants que ceux qui résultent des fluctuations climatiques normales, caractéristiques de la présente décennie. La construction du canal du Radjasthan, dans l'Inde occidentale, et l'irrigation d'une longue bande de terrains dans un secteur semi-aride auront des effets beaucoup plus sensibles et beaucoup plus dangereux sur ces rapports que les variations à court terme de la pluviosité dans la région qui borde la frontière du Pakistan-Occidental ; en effet, tous les insectes dont la prolifération est actuellement gênée par la grande aridité de cette région vont trouver là des aires de reproduction excellentes et de nouvelles sources d'aliments de choix. Ici encore, il nous faut tenir compte de l' « effet de masque » de l'activité humaine et des pratiques culturales pour évaluer l'importance des changements climatiques sur les rapports entre les plantes cultivées et les insectes. Nous attendons avec intérêt les résultats de l'étude écologique FAO-Unesco sur les aires de reproduction du criquet pèlerin.

A une échelle chronologique toute différente, Uvarov (1953) a fait une intéressante étude sur l'écologie passée et présente de la population acridienne du Sahara, en fonction de l'histoire climatique de la région. Ces criquets et sauterelles présentent un grand danger, réel ou potentiel, pour la végétation spontanée et les plantes cultivées ; on peut les grouper en quatre écofaunes : les déserticoles (espèces vivant en plein désert et la plupart du temps sur le sol) ; les saxicoles (espèces vivant sur les pentes rocheuses de montagnes érodées et la plupart du temps sur le sol elles aussi) ; les arbusticoles (qui vivent sur les arbustes et les arbres) ; et les graminicoles (qui vivent sur les herbes) ; ce dernier groupe est particulièrement intéressant du point de vue de l'histoire climatique du Sahara dans le passé.

Les habitats herbacés du désert sont discontinus ; les herbes xérophytiques elles-mêmes se trouvent normalement dans des dépressions isolées ou au voisinage des montagnes. Par voie de conséquence, les acridiens qui se nourrissent de graminées sont également dispersés. On a constaté que leurs régions d'origine se situent de part et d'autre du Sahara : les savanes tropicales du sud et les steppes tempérées du nord. Il est cependant frappant que ceux des steppes méridionales soient complètement absents de la faune graminicole du Sahara, qui est uniquement d'origine éthiopienne. L'analyse de la faune des oasis conduit aux mêmes constatations.

Uvarov conclut en ces termes : « Comme les conditions écologiques actuelles du Sahara semblent interdire une répartition active des acridiens graminicoles, notamment de ceux qui sont associés aux herbacées mésophytiques des oasis, il n'est pas douteux que les habitats herbacés dispersés dans le désert ont été peuplés à une époque où le climat du désert était tout différent de ce qu'il est aujourd'hui ; cela devrait avoir été possible aux périodes pluviales du pléistocène, alors que les précipitations, plus abondantes en Afrique du Nord, permettaient une extension plus ou moins continue de la prairie au Sahara. La composition de la faune acridienne des « îlots écologiques » herbacés qui se trouvent actuellement dans le désert montre clairement que pendant les périodes pluviales le Sahara a été envahi par une faune graminicole venue exclusivement du sud, mais elle ne fournit aucun indice d'une dispersion vers le sud d'éléments venus des steppes septentrionales, ainsi qu'on l'a souvent supposé dans le passé. »

De la répartition actuelle, purement insulaire, de la faune acridienne des montagnes d'Afrique orientale, Uvarov conclut de nouveau que la théorie généralement admise d'une migration d'éléments paléo-arctiques vers le sud, jusqu'en Afrique tropicale, pendant la période pluviale du pléistocène, ne s'applique nullement aux acridiens.

CONCLUSION

De ces premières remarques, et des articles que l'on lira par la suite, il ressort essentiellement que les écologistes et les agronomes ont pleinement conscience de l'importante influence qu'exercent les modifications du climat sur la répartition passée et présente des associations végétales et des types d'agriculture et d'élevage. On distingue nettement dans les régions semi-arides les tendances à la sécheresse, de même que les réactions de l'homme menacé par cette sécheresse, selon le schéma de Toynbee. Cependant, lorsqu'on analyse cette évolution depuis l'apparition de l'homme, il devient de plus en plus difficile de distinguer, parmi les changements intervenus dans la végétation et l'agriculture, ceux qui sont entièrement dus aux modifications et fluctuations du climat et ceux qui sont une conséquence directe ou indirecte de l'activité humaine. Ce problème pourrait fort bien faire l'objet d'un autre colloque organisé conjointement par l'Unesco, l'OMM et la FAO.

Les écologistes et les agronomes caractérisent les modifications d'un climat en fonction de la régularité de ses composantes, qui conditionne l'exploitation du sol à des fins économiques. Les travaux entrepris jadis par l'Institut de recherches agricoles Waite sur la régularité du climat dans les régions semi-arides de l'Australie et les études faites en Afrique orientale dont il a déjà été question ici, devraient être étendus à toutes les régions pour lesquelles on dispose de données météorologiques portant sur de longues périodes. Ce genre d'analyse devrait être un élément essentiel de tout projet de mise en valeur agricole.

Les spécialistes de la physiologie végétale qui s'occupent des réactions des espèces sauvages ou cultivées aux fluctuations du milieu peuvent fournir des données biologiques d'un grand intérêt en recherchant quelles sont les réactions particulières de chaque espèce, forme de croissance ou écotype. Ces données pourraient servir aux sélectionneurs de semences ou aux agronomes pour réduire les conséquences économiques des fluctuations climatiques à court terme en introduisant l'usage de variétés plus résistantes ou de méthodes de culture perfectionnées.

Dans les conditions écologiques qu'elles affectionnent, les plantes sauvages ou cultivées sont toujours accompagnées d'insectes nuisibles et de champignons pathogènes. Ces communautés végéto-animales sont très sensibles aux fluctuations naturelles ou provoquées par l'homme du microclimat. Le spécialiste de l'écologie des insectes a donc lui aussi un grand rôle à jouer en prévoyant les dangers que pourrait entraîner l'introduction d'une culture nouvelle ou un changement des méthodes culturales tel que l'adoption de l'alternance agriculture-élevage ou l'irrigation des terres.

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THE QUATERNARY CLIMATE AS A MORPHOLOGICAL AGENT IN IRAQ[1]

by

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INTRODUCTION

Iraq offers an excellent opportunity for studying the influence of past and present climates upon the morphology of the country. It is interesting to note that, although the various regions are very different from each other and although so far hardly any accurate chronology could be established, features have been found in several regions which can only be explained as effects of changes in the climatic pattern.

A good deal of the data on which this report is based has been condensed from the results of consultants' activities during several years in Iraq in connexion with various development projects. These required the study of well-defined separate problems, consequently this exposition does not pretend to be the outcome of a survey of a more general nature.

The authors wish to express their appreciation and gratitude for the generous attitude of the Iraqi authorities, who not only invited Netherlands experts to participate in the technical development of their country, but also show full comprehension for the importance of publication and discussion of data of scientific interest.

GEOMORPHOLOGICAL UNITS

The geological structure is clearly reflected in the present morphology of Iraq. Three main units can be distinguished, each of which is subdivided into sub-units (Fig. 1):

I. Tauros-Zagros mountain chain

Bordering the country in the north and east, its central part chiefly lies in Turkey and Iran. Its main structural features are sub-parallel anticlinal ridges, separated by long, comparatively narrow valleys. During periods of intense tectonism (chiefly during Pliocene), major faults and over-thrusts were formed parallel to the fold axes. The valleys were subsequently partly filled with erosional products from the high ridges, during Pliocene with coarse molasse (Bakhtiari Formation) and during Quaternary with sediments, the character of which depended on climatological and morphological conditions. Minor tectonic movements continued until recent times. Rivers in the valleys collected drainage water from the mountain streams and eventually broke through a ridge, thus forming a gorge and continued in a lower-lying subsequent valley. This drainage pattern has resulted in a trellis valley system, composed of relatively large, longitudinal valleys interconnected by short, gorge-like transverse valleys. Two sub-units can be distinguished:

(a) *The high, central range.*

(b) *The foothills*, representing the south-west border-zone of the Tauros-Zagros Fold System. The valleys are wider than in the central range and are separated by narrow anticlinal ridges.

II. Mesopotamian Syncline

This is a deep synclinal trough, filled with sediments supplied by the mountains. Sedimentation was at its maximum shortly after the Pliocene diastrophism in the Tauros-Zagros mountains, when huge quantities of Bakhtiari molasse were supplied. The basin is tilting to the south-east. Sub-zones are:

(a) *Upper Mesopotamia*, the island (Arabic: Jezirah) between the middle courses of the rivers Euphrates and Tigris, representing the uptilting part of the syncline. It is characterised by erosion by wind and water. Desert and steppe cover its surface, locally interrupted by depressions with internal drainage.

(b) *Lower Mesopotamian-Persian Gulf area*, the subsiding part of the trough. Its south-east part is

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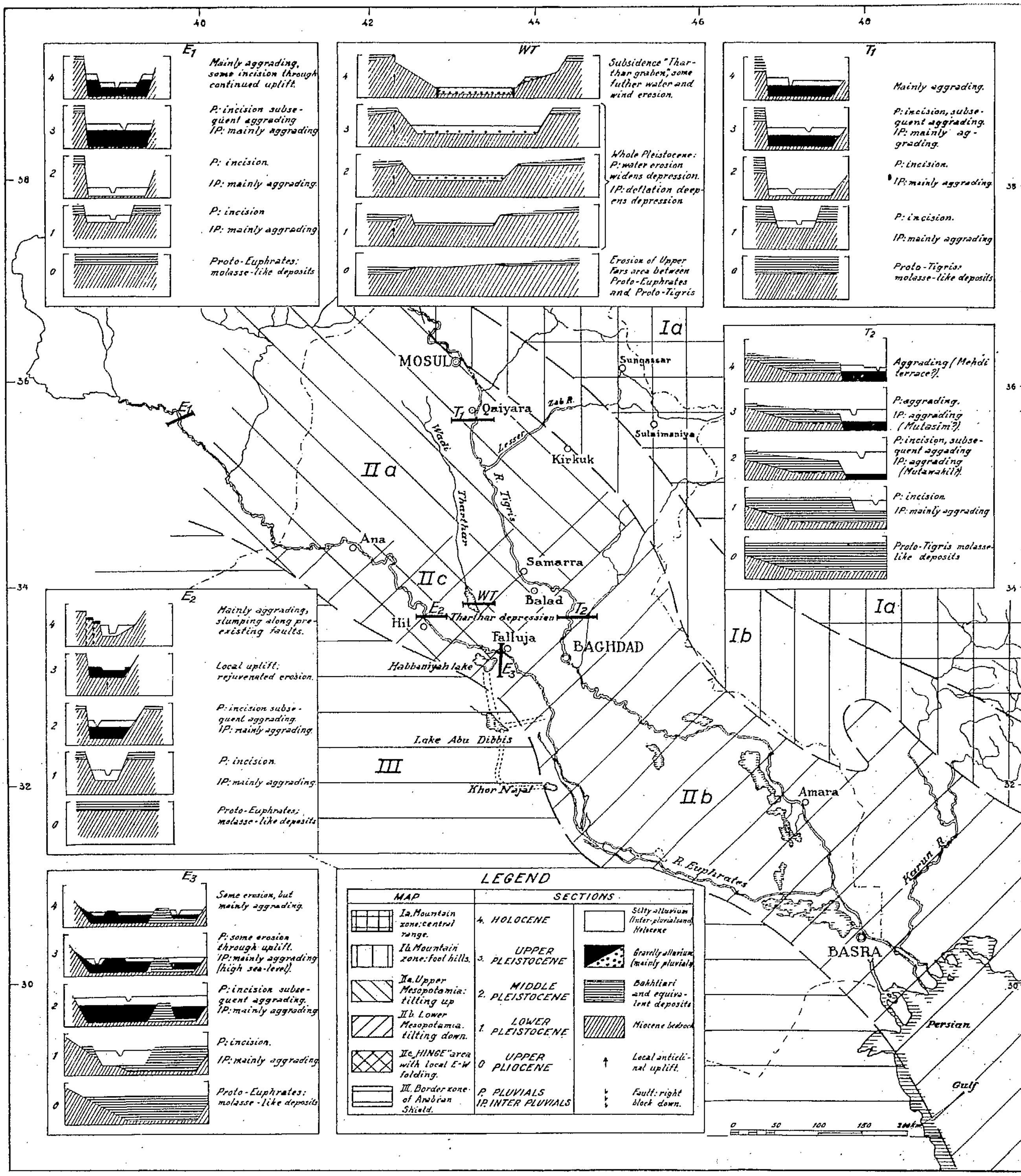

FIG. 1. Tentative reconstruction of the Quaternary history of Lower Mesopotamia.

at present covered by the waters of the Persian Gulf, which is slowly encroaching upon the land. Minor tectonic movements have greatly influenced the quaternary history of the area. Even during historic times differential earth movements interfered with the work of man, modifying the régime of the rivers and irrigation canals and changing the position of the shoreline of the Persian Gulf (Lees and Falcon, 1952).

(c) *The "hinge area"*, turning point of the tilting syncline. In this zone east-west directed tectonic structures occur, which have influenced the morphology of the area. It is largely covered by steppe and desert and the large Tharthar Depression lies within the boundaries of this region.

III. The Western Desert

The Western Desert covers the eastern part of the Arabo-Syrian Shield, for tens of millions of years a comparatively stable area, where deflation and wadi-erosion are prevailing. Along the valley of the lower course of the river Euphrates a string of depressions occurs now incorporated in the desert landscape. But during the Pleistocene it was flooded by the waters of the Mesopotamian Rivers, therefore it permits a chronological correlation between morphological and sedimentary features of Mesopotamia proper and its borderland.

The examples discussed are based on personal studies, namely the Sulaimaniyah valley (high central range), the Mesopotamian Rivers (Mesopotamian Syncline), the Tharthar Depression (hinge area of the Mesopotamian Syncline) and Lake Abu Dibbis (Western Desert). Comparisons are made with studies by others, viz the Sungassar valley in the high central range (Buringh, 1960) and the Chemchemal Plain in the foothills (Wright, 1952, 1960).

CLIMATE AND MORPHOGENY

The oscillations of the sea level during Pleistocene influenced the relative elevation of the terraces along the beaches and in the lower river courses, the climate-controlled discharge and the character of the sediment load of the rivers mainly determined the morphology of the upper and middle courses of the river valleys. However, tectonic movements and other events may have seriously interfered with the effects of the climatic variations. For example, the obstruction of mountain valleys caused by tectonic uplift and "climate-triggered" landslides was fairly common in the Zagros Mountains. This resulted in the diversion of a river or creation of a lake, causing a temporarily elevated base level, which naturally changed the sequence of sedimentation radically. The morphological effect of such "outside events" for example may have been that during a Pluvial a thick layer of clayey material was deposited in a lake created by a landslide, whereas in the adjoining, non-obstructed valley a gravel terrace was deposited or a new stream bed was eroded. Consequently the correlation of climate and sedimentation is very complicated and in many cases an absolute dating by means of archeological finds or C-14 dating is the only way of solving the problem.

The Pleistocene climatic variations have left vestiges equally on the plateau of the Arabo-Syrian Shield. Deflation and water-erosion formed and deepened depressions. Some of these were temporarily incorporated in the regime of the Mesopotamian Rivers, as the Abu Dibbis Depression; others, as the Tharthar Depression, were entirely endoreic.

SULAIMANIYA VALLEY

The morphological features of the Sulaimaniya valley has been described in an earlier paper (Voûte, 1960). It is one of the larger longitudinal valleys, which shows very pronounced results of the influences of climatic agents; it stretches from Halabja over more than 150 km. north-westward, as far as to the Dokan area (Fig. 2). The north-west part of the valley is drained by the Tabin and Cham-i-Charnaga Rivers towards the Lesser Zab River, the south-east part drains in the opposite direction to the Sirwan River. In traversing the Baranand Dagh mountain ridge, which borders the Sulaimaniya valley to the south-west, both the Lesser Zab and the Sirwan Rivers have formed gorges, the Dokan Gorge and the Darband-i-Khan Gorge respectively; in each a barrage dam is under construction.

The Baranand Dagh range consists for the greater part of black marls showing a strong tendency to creep and slumping. Here many landslides can be observed (Fig. 2), most of them stabilised and fossilized.

On the slopes of the Sulaimaniya valley two gravel terraces occur; the higher representing the top of the original Bakhtiari valley fill, the lower of Pleistocene age, partly eroded again by the Av-i-Tanjero (Fig. 2). It is a remarkable fact that landslides, which are by no means exceptional in the Zagros Mountains (Knetsch, 1957; Harrison, 1946), were found to have occurred here almost exclusively just above the level of the lower gravel terrace, whereas the slope below the terrace level is strongly affected by gully erosion. The top of this terrace is often encrusted with lime and is locally covered with a thin layer of red clay, mixed with gravel, suggesting solifluction to have been active. Under the present-day arid climatic conditions gully erosion and formation of badlands are prevailing; nowadays slides of minor importance occur only under the influence of human interference, such as deforestation.

The morphology of the Sulaimaniya valley has been interpreted as follows: the Bakhtiari molasse, deposited

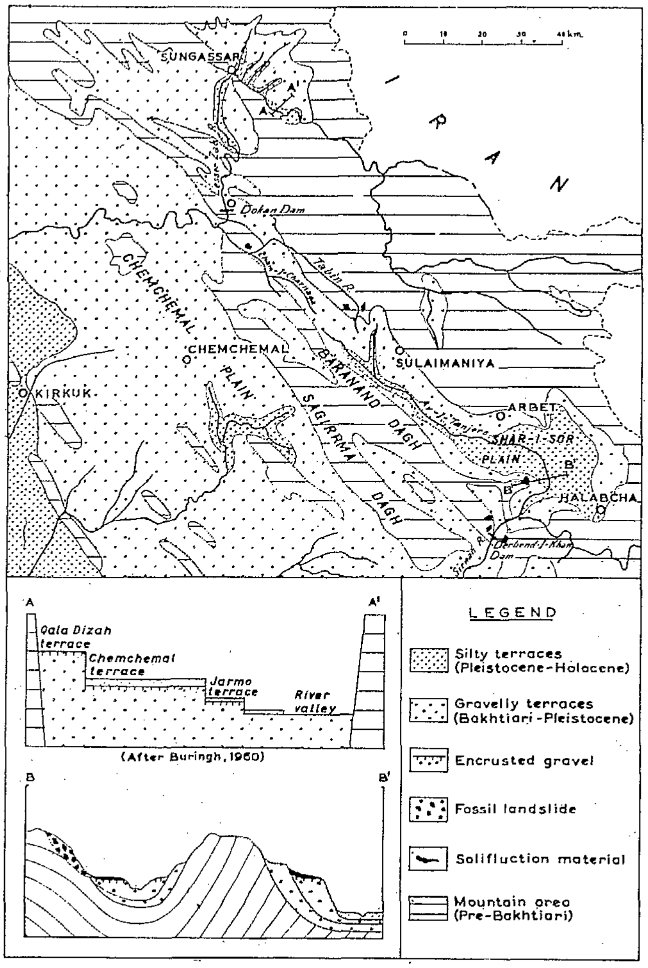

FIG. 2. Zagros Mountains.

in the valley during Pliocene shows signs of folding, indicating a continued tectonic activity during post-Pliocene times. During Pleistocene a new valley was eroded in the Bakhtiari gravels, which was subsequently partly filled up with gravel. Later a new period of erosion set in. During this period the Tabin River cut its gorge to the north-west and part of the valley drained to the Lesser Zab River. At the same time in the south-east part of the valley the Av-i-Tanjero River started incising, thus creating the lower gravel terrace. In its turn this deeper valley was filled with sediments in which fine-grained deposits prevailed, suggesting sedimentation in a lake. It is assumed that lakes were formed through obstruction of the river-valleys by landslides, where they cross the Baranand Dagh Mountains. The Cham-i-Charnaga and the Shar-i-Sor plains are such lake bottoms (Fig. 2). After this depositional period erosion became active again, the obstructed Darband-i-Khan Gorge was reopened and the lakes drained. The rivers incised into the lake-bottom deposits, thus creating a third terrace.

A very important indication for a correlation of the morphological phenomena and the various climatic changes during Pleistocene is provided by the position of the fossil landslides just above the lower gravel terrace (Fig. 2). A wet climate is highly favourable for the "triggering" of sliding and slumping and thus the landslides are most probably of pluvial origin. The same holds true for the various phenomena of masses of layered rocks deformed by gravity and described as "collapse structures" (Harrison and Falcon, 1934) or "gravitative denudation" (Knetsch, 1957). It is suggested (Voûte, 1960) that the lower gravel terrace coincides with the Chemchemal A surface of Wright (Wright, 1952), the period of solifluction and the high-level landslides corresponding with the deposition of the Chemchemal silts (Riss Pluvial). The formation of the Shar-i-Sor and Cham-i-Charnaga lakes may have taken place during the last Pluvial (Würm), caused by obstruction of the Darband-i-Khan Gorge. The erosion of the lower gravel terrace would then correspond with the Riss/Würm Inter-pluvial, while the deep re-eroding of the Darband-i-Khan Gorge, the subsequent draining of the lakes and formation of the third terrace took place in post-Pleistocene times.

SUNGASSAR VALLEY

The presence of two terrace levels between the Bakhtiari terrace and the present valley bottom as found in the Sulaimaniya valley can also be recognized in the valley of the Lesser Zab near Dokan. The morphology of this valley further upstream near Sungassar has been described by Buringh (1960). Above the valley bottom he recognizes three terraces, the highest coinciding with the late Pliocene Bakhtiari valley bottom, the middle and lowest terrace consisting of gravel, covered with a silty layer (Fig. 2). He interprets their features as a result of changes in the processes of erosion and sedimentation, induced by variations in rainfall and in the density of the vegetational cover protecting the slopes. He thus makes a distinction between various sub-stages of the interpluvials and pluvials, each typified by some special process of erosion and sedimentation. The higher of the two Pleistocene gravel terraces mentioned by him is encrusted with secondary lime, on account of which we correlate it with the lime-encrusted terrace found in the Sulaimaniya valley. Buringh tentatively correlates the pluvial periods in the Zagros Mountains with pluvial stages in Africa, as named by Cole (1954). The higher and lower Pleistocene terraces are correlated by Buringh with the Chemchemal and Jarmo terraces of Wright.

It is impossible as yet to date the various morphological features of the Zagros Mountains on the basis of typical archeological finds or C-14 datings. Also agreement is far from being reached as to the relation between climate and sedimentation-erosion. However, correlation of landslides and solifluction with a pluvial period in the Zagros Mountains seems indicated, whereas gully erosion and badlands are highly suggestive for an arid climate.

MESOPOTAMIAN RIVERS

Figure 1 shows a tentative reconstruction of the Quaternary history of the middle and lower courses of the Mesopotamian Rivers. Data are based on the mapping of river terraces (Van Liere, 1954; Buringh, 1956) and on borings executed for various engineering projects. Exact chronological information, however, is still missing for the time being. After having deposited coarse molasse sediments from the young high Tauros-Zagros Mountains during Pliocene mainly, the rivers began incising themselves. These early Pleistocene valleys with a depth of more than 50 metres were subsequently filled with coarse gravelly sediments, covered again later with silty deposits. The present rivers are flowing in this fine-grained top layer. Various terrace levels occur on the slopes of the river valleys between the top of the Pliocene Bakhtiari and equivalent deposits and the present valley bottom.

Several authors have stated already that the Quaternary history of Mesopotamia has been influenced by both climatic and tectonic phenomena (Lees and Falcon, 1952; Voûte, 1960; Wedman, unpublished paper). It is highly probable for example that the erosion and partly filling up with coarse gravel of the deep valleys of the Tigris and Euphrates is caused by the considerable discharge of the rivers during pluvial periods and not by the small, underfit rivers, meandering at present in their too wide valleys. But there are also several indications for a tectonic uplifting of the middle course area of the Mesopotamian Rivers to have taken place, which compensated the subsidence of Lower Mesopotamia. This uplifting may have intensified the incision of the rivers. Local tectonics have also played their part, as is illustrated by the valley of the River Euphrates near Hit. In this part the gravel, still present upstream and downstream from there, has been eroded (Fig. 1). Moreover sea-level variations must also have played a part in the evolution of the main rivers.

As to Lower Mesopotamia proper, post-Pleistocene sedimentation in the Mesopotamian delta conceals all older deposits and present-day morphology is only reflecting the mean geological trend: a synclinal trough, subsiding slowly, in which a huge quantity of clayey deposits is almost completely compensating for this subsidence. Local tectonic movements, superimposed on this general sinking, account for small oscillations of the shoreline, which as a whole, slowly invades Mesopotamia. Moreover, ever since the dawn of history man has profoundly modified in many places the natural processes of sedimentation and shifting river-beds by building embankments and irrigation channels, the pattern of which has been altered several times.

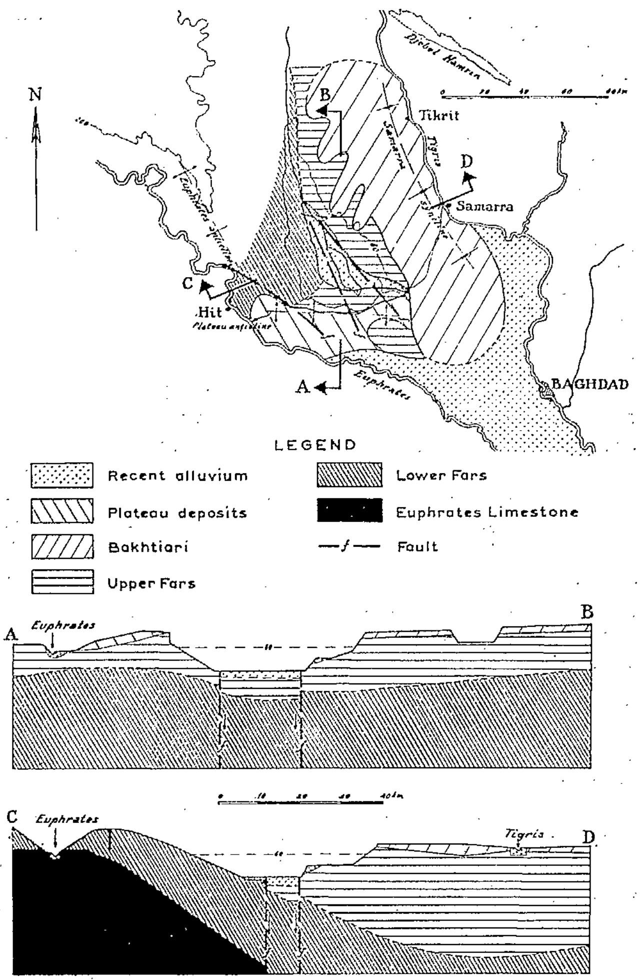

FIG. 3. Tharthar Depression.

THARTHAR DEPRESSION

Al Jezirah, the island between the middle courses of the Euphrates and Tigris, can be described as a gently south-eastward sloping flat desert or steppe area. In the north it is bounded by the hills of Jebel Sinjar. Its smooth, gravel-covered surface is occasionally interrupted by some flat-topped mesa or cuesta hillocks, wadi-valleys and shallow depressions which are fairly common. The walls of these playas are sometimes steepened by headward water erosion during the rainy season, the eroded material being deposited as fine-grained sediments on the flat bottom. During the dry season deflation is active, the net result being in many cases a slow deepening of the depression. The largest by far of the depressions in the Jezirah desert is the Tharthar Depression (Fig. 3). Its bottom is situated more than 50 metres below the present level of the Mesopotamian Rivers and 4 metres below mean sea-level.

The depression is situated on the gently dipping western flank of the Mesopotamian Syncline. To the west and south it is bordered by minor anticlinal structures.

The southern and eastern walls of the depression consist of escarpments, eroded in sub-horizontally layered claystones, sandstones and some marly limestones of the Upper Fars Formation (Upper Miocene), topped by the gravelly deposits of the Pliocene Euphrates and Tigris Rivers, the Bakhtiari Formation and Plateau Deposits. The central part of the southern escarpment is a steep wall, towering more than 30 metres above a gently northward sloping pediment. It is dissected by deeply excavated wadis. The eastern part of the escarpment is less steep and covered with gravelly outwash from the desert plateau to the south and sand dunes. To the west the steep southern depression-wall gradually flattens out to merge into the gentle dip slope of gypsum and marly limestone beds of Lower Fars age (Middle Miocene). The eastern escarpment shows a step-like profile. On the middle terrace level several *playas* occur, the largest of which is Lake Rufai.

The eastern and western walls converge towards the north and at their meeting point the Wadi Tharthar debouches into the depression. The central part of the depression is filled with at least 7 metres of unconsolidated silty sediments. Wind-erosion, block faulting, folding and caving as a result of underground solution have been suggested as the chief agents in forming the depression. The hypothesis exposed in this paper is a result of the blending of former theories with new ideas, acquired in detailed field-work (Fig. 1).

During the first Pleistocene Interpluvial the climate was dry and hot and wind erosion was active. The soft clayey and sandy deposits of the Upper Fars Formation were easily attacked by deflation, but the gravelly deposits of the pliocene Tigris and Euphrates Rivers and the hard gypsum and limestone layers of the Lower Fars were more resistant. Thus a shallow geologically predetermined "windhole" originated between the converging valleys of the "proto-Tigris" and "proto-Euphrates". During the next Pluvial headward wadi-erosion attacked the walls of the depression and widened it. Thus the Tharthar Depression was mainly deepened during Interpluvials and widened during Pluvials. In late Pleistocene-early Holocene, the central part of the depression subsided graben-like, the eastern border fault cutting through the gravelly downwash of the depression bottom, deposited there during the last Pluvial. After the downwarping headward erosion continued, creating the step-like profile of the eastern wall. In the south uplift of the east-west running Plateau Anticline intensified erosion of the southern wall to such an extent that all traces of the middle terrace were erased.

The Euphrates, flowing on the southern flank of the "Plateau Anticline", was gradually pushed towards its present valley, whereas subsidence of the Mesopotamian syncline forced the Tigris to shift its bed more to the east.

During dry periods of the Holocene deflation will have further deepened the depression, although the cyclic erosional pattern of the Pleistocene was never completed again. The erosional processes mentioned may be compared to those forming *playas* under present-day arid or semi-arid climatic conditions, though with the difference that the seasonal alternation of the latter is completed within a year, whereas a cyclic phase of evolution of the Tharthar Depression during Pleistocene lasted for thousands of years.

ABU DIBBIS DEPRESSION

South of the Tharthar Depression, on the fringe of the desert plateau, a string of depressions is found parallel to the Mesopotamian Plain. They once formed part of a large valley, connecting Habbaniya Lake, the Abu Dibbis Depression and Khor Najaf (Fig. 1). Tectonic movements segmented the valley and each part developed into a separate basin. The largest is the Abu Dibbis Depression (Voûte, 1957). Ancient shorelines and buried valleys point to variations in the drainage pattern of the area. The depression, now used as a flood storage basin, has been twice a lake during Quaternary. The last and largest of these lakes has been dated by a Mousterian-type palaeolithic flint tool, found buried in undisturbed soil in a boring. This lake was brackish, the supply of Euphrates water being just enough to keep it filled. Gradually the climate became more arid and, evaporation exceeding the supply, the lake dried out. Prior to its use as a storage basin, equilibrium had established itself between evaporation from the restricted surface of two small lakes in the depression and its supply by wadis and springs.

In contrast to the Tharthar Depression, Lake Abu Dibbis has been included during Quaternary in the régime of the Mesopotamian rivers. The find of an artefact forms a first step towards a chronology of the palaeomorphology and palaeoclimatology of this part of Lower Mesopotamia.

CONCLUDING REMARKS

Landslides and solifluction in the mountains, deep, gravel-filled buried valleys in Mesopotamia and elevated shorelines on the slopes of desert depressions are strongly suggesting the occurrence of pluvial periods during Quaternary in Iraq. Intercalated dry periods are indicated by the position of badland levels in the mountains, by the morphology of the Tharthar Depression in Upper Mesopotamia and by the drying out of lakes. Chronological criteria, permitting a regional correlation of the climate-morphological features, are still extremely scarce.

In developing the natural resources of a country, man is often forced to disturb the equilibrium of nature. It is therefore imperative when planning engineering and conservation projects, to know the environmental conditions of the local morphology. Some climato-morphological features are fossil and more or less stabilized, others, such as deflation, gully erosion and salt encrustation, are still being formed in Iraq. The study of past and present climates as morphogenetic agents should be included in any major development programme, in order to achieve a better adaptation to the local conditions. In this respect it is important to note that the examples mentioned from widely different landscapes show a distinct but typical evolutionary history, resulting from the interaction between climate, morphology and often also tectonic movements. The postulate of climatic variations, although of fundamental significance in scientific studies and eminently applicable to the investigations of practical problems, has therefore to be used with care and taking into consideration all other factors involved.

The distributing effects of the activities of man have not been mentioned as such in the foregoing discussion on natural processes, although allusion to them has been made a few times. Moreover the periods dealt with considerably exceed the history of human civilization. However, the results of human interference may be far from negligible, even when seen from the geologist's or morphologist's viewpoint. Apart from the far-reaching effects of modern technology, which need not be emphasized, other human activities which have been going on for centuries or even for millennia, have altered the landscape in the long run. One example may be given here: in the Zagros Mountains it is very apparent that deforestation and overgrazing have strongly promoted and accelerated erosion. They are one of the main reasons for the present instability of many mountain slopes, thus causing difficulties in the construction and maintenance of roads amongst other things. But they did not fundamentally modify the processes of erosion and denudation.

Therefore the expert dealing with the problems discussed in this paper should also critically study the results of man-induced disturbances before giving his opinion in scientific or practical matters. It should be borne in mind however that, with the exception of modern achievements such as the creation of huge reservoir lakes or other major works, the influence of human activity in many cases only stimulates tendencies already existent in nature and increases or decreases the intensity of natural processes.

RÉSUMÉ

Le climat quaternaire en tant qu'agent morphologique en Irak (C. Voûte et E. J. Wedman)

Au cours de plusieurs années de travail en Irak, un certain nombre d'études séparées ont été effectuées dans le cadre des activités d'un groupement d'ingénieurs-conseils. Bien que l'occasion de faire une étude scientifique d'ensemble ne se soit pas présentée, il a été néanmoins possible de dégager de ces recherches des observations géologiques intéressantes. Mention est faite ici de conclusions sur l'effet qu'ont eu les variations climatiques sur l'évolution géologique et morphologique des zones désertiques, des régions montagneuses et des principaux cours d'eau de ce pays. Dans chacun des cas présentés, des processus divers ont joué un rôle pendant le quaternaire; leur corrélation chronologique pose de nombreux problèmes. Les problèmes à étudier sont compliqués du fait qu'on voit non seulement agir des agents atmosphériques mais également de véritables processus géologiques, comme par exemple les mouvements tectoniques du sous-sol, qui ont eu lieu jusqu'à des époques très récentes, en quelques endroits même pendant la période historique. Il est donc nécessaire de faire des études approfondies pour établir une distinction entre ces deux catégories de phénomènes. L'interprétation correcte de nombreux détails géologiques, en termes de l'influence du climat passé et du climat présent, s'est souvent révélée d'une importance capitale pour la préparation de projets agricoles et de travaux publics.

DISCUSSION

This paper was discussed together with the paper submitted by Dr. H. Bobek.

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NATURE AND IMPLICATIONS OF QUATERNARY CLIMATIC CHANGES IN IRAN

by

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INTRODUCTION

The aim of my paper is to deal with the nature and implications of quaternary climatic changes in Iran, by summarizing the results of pertinent investigations carried out in the course of five major field campaigns distributed over a quarter of a century. It must be noted, however, that these field trips were not exclusively devoted to the topic in question.

Methods of investigation and study were mainly of the geomorphologic or related geographic type. It is fully recognized that these, while yielding important information on the types and development of specific land forms and other features of the country, generally do not provide us with exact dates which can be obtained from radiocarbon, palynological (pollen-) or archaeological findings. However, such investigations may build up the indispensable frame into which the more exact dates can be satisfactorily fitted in, and thereby brought to bear within a specific range. At the stage of exploration reached in Iran, investigations of this type are still of primary importance and a prerequisite for the successful application of any more detailed research of the second type. My paper will indicate clearly that in Iran we are still far from a satisfactory knowledge of the most fundamental facts. This implies that the establishment of any ambitious detailed sequence of quaternary events in Iran is still far ahead of sound research.

Mention must be made of the invaluable support experienced by the extensive use made of aerial photographs which were made available to me in a most liberal way by the courtesy of the Director of the Iranian Oil Company Research Section, Dr. B. Mostofi, to whom my sincere gratitude is expressed.

An important finding in my studies is that Iran occupies a very distinct position in the Near East in that its vast interior plateau (at least) did not experience pluvial periods in any way comparable with those of other Near Eastern countries (or subtropical countries in general). Evidence will be brought forward to show that the conventional theory of a general and more or less uniform pluviation taking place all over the subtropical belt (or its margins) during the period of glaciation of the higher latitudes requires modification. Facts demand a more subtle view and more concern for regional peculiarities as well as for the actual complexity of the factors involved in producing what are conventionally accepted as pluvial features.

As for Iran, the influence of continentality is pronounced and seems to have been strengthened rather than weakened during the cold spells of the Pleistocene. Facts disavow any argumentation disregarding it.

I also wish to stress the vital need for a careful analysis of the real nature of the much-referred-to "desiccation" or "desertification" of many regions in the arid zones, so as better to distinguish the part due to the agency of man (and his subordinates) from that caused actually by changes of the physiographic environment, especially the climate. Only in this way shall we reach an adequate understanding of the natural endowments of these regions or countries as they really are, and the extent to which damage caused by the carelessness of man might be repaired.

PHYSIOGRAPHIC DIVISIONS

Iran displays a great variety of physiographic conditions. Thus it falls into a number of differing physiographic regions which would have been affected by climatic changes in quite different ways.

A basic fact is the opposition of mountain ranges, of various width and elevation it is true (the latter ranging from more than 4,000 to less than 2,000 metres), bordering a central plateau which actually consists of a great number of separate closed basins with bottom elevations ranging from 2,000 metres down to less than 300 metres. The topographic opposition is weakened by the existence of many interior ranges, but accentuated by the fact that the border ranges take most of the moisture out of the passing air currents, whereas the interior depressions, with mostly descending air, are left to depend mainly on frontal clashes. Annual precipitation rates, therefore, range from 300 to 500 mm. upwards to 1,000 mm. and more in the border ranges and outer façades, but from 300 downwards to less than 50 mm. in the interior basins.

Thus, a belt of aridity hovers over the central plateau while a peripheral zone of humidity follows the outward slopes. This zonation is well brought out by the distribution of the natural forests of Iran, Afghanistan and Baluchistan, as shown by my own attempt to re-establish the original forest types and areas of distribution.

Moister types. Caspian (Hyrcanian) forest; Himalaya forest; 800 mm.

Intermediate. Zagros forest, mainly oak and similar mixed oak forests from 500 mm. upwards.

Dry. Juniper forest; Pistachio-Almond-(Maple) from 300 mm. upwards.

Three hundred millimetres is also the approximate border-line for rainfed cultivation. Here the different forest types are again represented, but the humidity zones thus shown are crossed by the altitudinal zones of decreasing temperature, shown by tints. I have tried to indicate the altitudinal position of these zones, which is by no means horizontal, by analysing the pattern of (irrigated) cultivation in terms of perennial (mainly arboreal) crops, taking account of the popular division into:

1. *Garmsir*, or hot and frostless region (coinciding with date cultivation).
2. A fringe of precarious date cultivation (up to 300 mm.) with citrus cultivation.
3. (white). The subtropical medium zone which includes most of the big oases, with cultivation of various delicate fruits.
4. *Sardsir* or cool zone with very cold winters, with cultivation of grains and temperate fruit trees.
5. *Sarhadd* or cold zone above potential grain cultivation and mostly above upper limit of forests.

Of course the upper limits of these zones rise towards the south, but characteristically show a dome-like deformation above the interior high-land, as brought out by the upper limit of the regular date cultivation.

It is most interesting to compare the areal differentiation of other physiographic features with this spatial arrangement of the zones of decreasing humidity and temperature. With the help of the air photographs I was able to obtain the necessary view over the distribution of the *main types of land formations* (as climatically conditioned), and of the *closed basins of the interior* of Iran, together with the respective terminal lakes or *kavirs* (playas).

One of the most characteristic topographic features of the interior plateau are the wide, fan-like gravel-plains sloping down from the edge of the (interior) mountain ranges to the edge of the respective bottomlands, or *kavirs*—their popular name is *dasht.* On closer inspection they invariably reveal themselves as pediments (that is, sloping erosional rock-plains), covered in many cases with a thin veneer, at some places with thicker beds of mostly angular gravels, washed and sorted, or bedded into fine-grained material (fanglomerates). The process of pediment formation, or pedimentation, is still active. As B. A. Tator recently summarized, it requires the upkeep of a delicate balance between the rate of weathering, that is supply of debris, and the transportational capacity of the unconcentrated run-off (sheetfloods or scattered, braided streams) which nevertheless remains incapable of persistent valley deepening mainly because of its ephemeral character.[1] This process and the respective landforms—including the much-dissected hill areas—are therefore *bound to arid climates.*

From the sketch map I have just shown, the spatial extension of pediments (and active pedimentation) in Iran may be seen. The quasi-coincidence of its limits (within the uplands) with the aridity limits of the potential cultivation on rainfall is striking—it follows approximately the 300 mm. isohyet. It overlaps this limit, however, in the "Garmsir" of Khuzistan.[2]

While in this region of pediment-forming the main agents are weathering and running water, both in specific forms—the agency of the wind being restricted to a secondary role—there exists a distinct type of landforming in the lower eastern depressions, namely the Southern Lut, Seistan and Jaz Muriyan and other smaller ones. It is characterized by the predominance of wind forming, excavation as well as deposition, and by a certain "arrested" appearance of pedimentation due to the rareness of active floods, precipitation being decidedly lower than 500 mm., and highly irregular. The numerous small shallow, braided channels, which come out so well on the air photographs because of their lighter tint (as the gravels, frequently moved, do not take on the desert varnish to the same extent as those on the beds in between), are not a feature of these regions—partly because they are lacking, and partly because their gravels, rarely moved, have taken on the same dark varnish as the others, and therefore do not stand out.

Towards the west and north of the region of pedimentation, the pediments dwindle and finally disappear (e.g., in the surroundings of Shiraz and immediately west of the Lake of Niriz, or west of Arak, etc.). The forms of normal valley-erosion set in: river-commanded valley bottoms border on steep or gentle valley sides (slopes). Slope-erosion is less pronounced. The soil cover is largely maintained on its original place, etc. We must,

1. B A. Tator, The Climatic Factor and Pedimentation, *Nineteenth International Geological Congress*, Algiers 1952. Algiers, 1953, Fasc. VII, p. 121-130.
2. In the southern Garmsir uplands, another peculiar type of landforming prevails, which is not interesting in our context, and is not shown.

however, distinguish between the interior high plateaux and uplands of the Gardsir with largely rounded forms and also fossil remains of solifluidal coverings, and the much more intensively eroded lower outward slopes of the border-ranges which enjoy a more truly Mediterranean climate, and therefore resemble Mediterranean hillsides.

The higher crests of the border-ranges finally, upward of about 3,000 metres, get their character from active solifluction, while a few of the highest peaks like Demavend (5,654 metres), Alam Kuh (4,830 metres, in the Takht-e Sulaiman group, Central Elburz), Savelan Kuh (4,500 metres) and Zardeh Kuh (4,575 metres) even bear small glaciers and display features of active nivation and glaciation. The snowline remains around 4,000 metres.

Not one of the highest peaks in the south and southeast of the country reaches the actual snowline although a number of them surpass the elevation of 4,000 metres by several hundred metres. This is easily understandable if we extrapolate the actual snowline (with the help of the height-values of the above-mentioned altitudinal zones) for the rest of the country—it repeats the domelike deformation just explained.

Summing up: Iran displays, from the highest peaks downwards into the lowest interior depressions, five main zones of climatically controlled types of landformation, that is the zones of:

1. Glaciation and nivation.
2. Solifluction and other forms of cryoturbation.
3. "Normal" upland erosion (but influenced by former solifluction.
4. Pedimentation.
5. Predominant wind erosion.

It is necessary to deal with them separately concerning potential climatic changes and their implications, as no generalizations concerning geomorphic agents can be valid over zones which are so different in character.

The second physiographic feature which will be compared is the hydrographic conditions in terms of terminal lakes or related phenomena, with their respective catchment basins.

This, to my knowledge, is the first complete and fairly exact survey of this element:

In black are shown permanent (or quasi-permanent) lakes.

In blue: bottom fills of silty character, with various salt contents, and high groundwater levels (near surface).

In blue with horizontal hatching: the same, with seasonal water tables. In the dry season displaying dry mud with salt efflorescence, or salt crusts of various appearance, according to the salt contents given (*kavirs*). (Blue stripes in the Great Kavir are eroded surfaces on Upper Red Formation, as will be explained later.)

Yellow with stipples: large sand accumulations (with an indication of the main directions of the sand ridges, indicating the ultimate direction of the sand shift).

Red: important areas of excavations caused by wind.

Continuous black lines: divides, bordering the different catchment basins, running through mountainous or hilly land.

Intermittent black lines: the same, but running through *dasht* or other open country.

A distinct zonation is recognizable:

1. In the humid areas in the west and north we find permanent lakes through which streams flow (though only small ones, as these areas are hilly).
2. Close to the humid area are a few permanent or quasi-permanent lakes without outlet, like Lake Rezaiyeh, the Lake of Qom (first formed in the early eighties), the Lake of Niriz, Lake Maharlu. The Hamun lakes also belong to this category, though far from any humid area, but fed by the strong permanent River Hilmand, among others.
3. Within the region of pedimentation, with an annual precipitation below 300 mm. there are extensive bottom lands with corresponding ground-water tables, through which rivers usually flow, and also extensive seasonal lakes which become transformed into *kavirs* when dry. Salt crust form is most pronounced in the northern parts where the so-called Upper Red, or Salt and Gypsum formation (or Upper Miocene age), is an inexhaustible source of salt. On the contrary, the *kavirs* of the south, or *kaffehs*, have much less salt.
4. In the lowest and driest region, like the basin of the Southern Lut, this phenomenon of wet bottom lands or *kavirs* becomes insignificant, besides being completely scattered, while the features of wind action, excavation as well as deposition, become predominant. The Seistan depression, though belonging climatically to the same type, appears to be overwhelmed by the mighty Hilmand River, so that features of the second and last type are closely interwoven (as will be shown later). The Jaz Muriyan depression also appears to receive enough water from the surrounding subhumid to humid heights to mask its real condition.

Having thus given some idea of the far-reaching diversity of the different physiographic units of Iran, I shall now discuss the main topic; the climatic changes which have taken place in these different zones or regions during the quaternary period (primarily and more especially, during the last important cold or "pluvial" period).

QUATERNARY CONDITIONS IN THE ZONES OF GLACIATION AND SOLIFLUCTION

More than twenty-five years ago, I started to investigate the former glaciation within the mountain ranges of north-western Iran and the adjacent parts of Turkey (Bobek, 1937, 1940, 1953, 1957). A. Desio studies the same problem within the Zardeh Kuh range (Desio, 1934*b*). Since then, little progress was made until I had the opportunity in 1956 to see parts of the Ushturinan Kuh and to search on air photographs of all other ranges except Savelan Kuh (which is not covered) for traces of former glaciation. A fair number of traces not previously known were discovered (besides definite traces of a pre-Würm glaciation in the Ushturinan Kuh).

Apart from some stray corries, there are six major centres of former, obviously Würm, glaciation. They are the Central Alburz; Savelan Kuh; the Irano-Turkish and adjoining Irano-Iraqian border ranges; Ushturinan Kuh (near Dorud, Ab-e Diz); Zardeh Kuh; Kuh-e Dina(r). The most important single group is the Takht-e Sulaiman group in the Central Alburz.

Present glaciation: Sarchal glacier north of Alam Kuh, 4,830 metres, 4 km. long.

Würm glaciation: Sarchal-Sardabrud glacier, 20-22 km.
Dalir glacier, 13 km.
Barur glacier, 11 km.

Outside the Central Alburz and possibly the Savelan Kuh, there was no glaciation of this extent.

The climatic snowline was about 600-800 metres below the present level and, most characteristically, also closely imitated the dome-like deformation displayed by the former.

This along with other peculiarities seems to prove that in that period there existed the same fundamental thermic structure as today, with the only difference that the mean temperature was about 4-5° C. lower.

In all the groups mentioned and in a great number of other more elevated groups, there are remains of gravel terraces of considerable thickness in the upper reaches, but losing thickness with increasing distance from the centres of the groups concerned. Some may be classified as fluvioglacial, but the majority were caused by increased supplies of material deriving from solifluction. The lower limit of solifluction, according to the findings, was lowered by some 700 metres, so that it reached 2,300 instead of 3,000 metres. Therefore there was much material available to overload the rivers and force them to aggradate even—and more especially—in the upper reaches.

In what way pluviation would have helped to build up such gravel terraces in the mountain valleys (as many scholars conventionally assume) I do not know, as I can see no combination of agents which should induce a markedly increased run-off to aggradate in the upper reaches. I believe in increased sedimentation—under pluvial conditions—in the downward stretches of the rivers where it is normal.

There are, however, stronger arguments available which militate against the adoption of the pluvial theory in this and other cases in similar circumstances.

First, there is a difference in the position above sea level of the present climatic snowline within the Tell Atlas (Djurdjura, near Algiers) and within the Alburz and Zagros mountains (in about the same latitude), amounting to about 700 metres. This difference is generally taken as an expression of the opposition between more maritime conditions on the one side and more continental ones on the other. But the difference was nearly double this amount (1,300 metres) during the Würm period. This clearly suggests an accentuation of the contrast, probably affected by the pluvial spell having drenched the Tell Atlas (which was always open to maritime influences) but not having really reached the Iranian uplands.

Second, in 1956 I found a former outlet of Lake Niriz, proving that formerly the whole basin of this lake, together with the Kur and Pulvar rivers, were part of the exorheic Kara Aghach-Mand River system. On closer inspection I found that the blocking of the former outlet was due to an aggradation of the Valley of Istahbanat, effectuated by the drainage of Kuh-e Istahbanat (3,000 metres).

There is practically no doubt that this aggradation at the foot of Kuh-e Istahbanat, as with the building-up of many other, similar cones of detritus all over Iran, took place during the Würm period. The reaction of the dammed-up river was to form a shallow lake at the place of the present Lake Bahtegan, or Lake of Niriz (which is only 1 metre deep). There exists a shore bank of 2-3 metres (the only one) which probably belongs to this phase. The conclusion is obvious: Had the joint rivers Kur and Publvar then carried a much heavier water load, it would not only have forced its way by eroding the gradually rising gravel bar in question (at present 70 metres above lake level), but even more convincing, it would have been impossible for this quantity of water to evaporate from an area only slightly larger than the present lake surface, and this at a reduced evaporation rate.

There are other such cases of the formation of closed basins by the obstruction of originally exorheic rivers by aggrading side streams, e.g. the basin of Meidan-e Gil, east of Niriz.

Third, as I showed many years ago (Bobek, 1937), the water balance of the late-Pleistocene Lake Rezaiyeh in Azerbaijan, when calculated for a mean air temperature 5° C. below that of today, and correspondingly reduced evaporation, requires a régime of precipitation not higher than the present.

As to post-glacial variations of climate in the zones considered, both A. Desio and myself have observed a series of stadial moraines. They indicate, e.g. in the Takht-e Sulaiman group, snowline depressions of 700, 450-500, 300, 250, 170, 100 and 50 metres (as compared with a Würm depression of 800 metres), and must be taken for halts or more or less important relapses of cooler conditions in the post-glacial climatic development.

I shall omit any discussion of potential indications of climatic changes within the two humid zones (interior uplands, and lower outward slopes of the border ranges) as so far little pertinent investigation has been carried out within them. I mentioned the rounded character of the higher parts of the upland hills, probably due to the lowering of the zone of solifluction in the Würm period. In the lower reaches of the Zagros ranges, landslides with the damming up of lakes and sedimentation are frequent, and are taken by some scholars as specific features of the postulated pluvial periods which, of course, is not necessarily convincing. H. E. Wright's analysis of the Chemchemal plain (*Bulletin of the American School of Oriental Research*, 128, 1952) deals with the pedimental zone rather that the humid slope. We shall have to await the results of further investigations (pollen analysis during the 1960 field campaign of the Oriental Institute, Chicago). There is no doubt that the fill of the longitudinal valley bottoms (as well as some karstic plains) may provide useful information.

QUATERNARY CHANGES OF CLIMATE WITHIN THE REGIONS OF PEDIMENTATION

Within this zone there are two main elements which may provide information in the desired direction: the first are the pediments themselves (including their coverings), and the second the more or less *kavir*-like bottom fills of the closed basins.

As to the first, it is well known that, in the western Mediterranean regions, pediments (*glacis d'érosion*, etc.) are considered by many scholars to be the result of pluvial land-forming conditions. I find it difficult to share this opinion as they are being formed before our eyes in Iran under highly arid conditions.

Furthermore, whereas in the western regions a step-like arrangement of a number of pediments frequently occurs and is considered to represent as many pluvial phases or periods, such arrangements are exceptional within the interior of Iran. They always occur in localities or areas where recent tectonic uplifts are evident, or at least made very probable by many other facts. There is good reason to assume that the process of pediment-forming has been going on since time immemorial, that is at least since the upper Pliocene. This seems to be confirmed by the fact that (partly) thick beds of conglomerates or well-rounded gravels, which fringe the basin of the Great Kavir and are considered by geologists as equivalents of the (Pliocene) Bakhtiari conglomerates of the south-west, are cut by the pediments, as well as all older formations. By being largely rounded, they seem to require another more humid type of climate.

Pediment formation is not generally to be separated from the formation of its cover. For this and other reasons, I cannot agree with H. E. Wright's analysis of the Chemchemal plain.

As for the second element: the *kavirs*, especially the Great Kavir, have long been considered to be the last, dried-up and more or less obliterated remains of former (Tertiary or pluvial) lakes. Also K. W. Butzer, in his very useful compilation on "Quaternary Stratigraphy and Climate in the Near East" (1958) reckons the Kavir among the "clear evidences of a Pluvial" epoch.

Recent investigations in and around the Great and Masileh Kavir have, however, revealed the following facts: A large part, probably up to 60 per cent, of the Kavir surface consists of eroded plains, pediplains or peneplains, which cap anticlinal structures of the Upper Red formation, but also older rocks in places. These erosional surfaces merge into the surrounding *dasht* which is distinguished by its gravel or grit cover. Where this comes to an end, the decomposed, mostly silty material of the Upper Red formation, with its heavy salt content, produces a ground which closely resembles the silty and salty fill of other depressions, bearing the popular name of *kavir*.

Another quarter of the total surface is taken up by drained *kavir* grounds in marginal position. Altogether, therefore, only about a quarter or less of the total surface is occupied by true *kavir* basins. As was proved by excavations, the fill of these is clearly transgressing both on the *dasht* pediments and on the erosional surfaces within the *kavir*. These are in large areas "becoming drowned" within the *kavir* fill. There is no evidence that the parts of the eroded surfaces not yet drowned were ever covered by *kavir* mud or water. On the contrary, there is evidence that they were not (in the form of karstification of parts of the erosional surfaces, on the basis of salt leaching). As shore terraces could not be discovered (in spite of older statements, which mistook erosion-features within uplifted (tilted) saddles or blocks of Upper Red formation), we are forced to draw the following conclusions:

1. A big *kavir* lake, covering the whole area of the Great Kavir, has never existed since pediment-formation set in. Speculations that pluvial conditions were necessary to supply and maintain such a large volume of water are therefore meaningless.
2. The fill of the five or six separate small *kavir* basins has never before reached a higher level than at present. The formation of the eroded surfaces, especially the drowned ones, requires a long period of much lower fill.

We can add:

3. The climate during this long period, which coincides with the period of pediment-forming outside the Kavir, must have been—in view of these low fills and the "arid mechanism" required for an undisturbed pediment-formation (with mainly angular gravels)—essentially arid throughout. There is not one important fact known which would contradict this conclusion.

The heavy salt crusts are all associated with these true Kavir basins. I cannot here describe their surface form which displays a distinct zonation: a marginal zone of accrescent silt (called *zardeh*), a silt zone which is wet throughout the year, and the central parts taken by different forms of salt-crusts including polygons. They are covered by shallow water bodies in late winter and spring.

What interests us most in this connexion is the structure of the fill. Shallow excavations by hand have so far not pierced the salt crusts which reveal a structure of fairly regular beds separated by clay-filled joints. This suggests a build-up in the rhythm of seasons or groups of seasons. Fortunately, in winter 1959-60 a series of profiles were recovered by the Iranian National Oil Company from the southern part of the Masileh Kavir with the help of seismic soundings and drilling. By the courtesy of the Iranian National Oil Company, a short exposé by H. Huber with the respective profiles were put at my disposal. Thus it is possible to inspect the structure of the fill of the Masileh Kavir.

The bottom of the unconsolidated fill was found to be 400 metres lower than the surface (788-390 metres). The sediments fall into two sections: the lower one, some 350 metres thick, consists on top of some basal layers of grit, including dune material, of a uniform sequence of red-brown clay and silt which only in its lowest parts contains appreciable quantities of salt crystals.

The upper section is 46 metres thick near the centre of the whole basin. It consists of an alternating sequence of five salt-beds, intercalated layers of brown or green clay and silt, and one or two sand horizons. Towards the margin of the basin the thickness of this section decreases, and some members fall out.

Unfortunately no microfossils or pollen suitable for direct dating were secured. We are left to speculate. However, as the upper section appears to be too thick for Holocene origin, and on the other hand seems to represent a sequence of climatic changes comparable with those of the Pleistocene, I tend to take it for Pleistocene. After examining the potential explanations for the abrupt change in the sedimentation, H. Huber also concludes that a change in the climatic conditions seems to be the best explanation.

Under this assumption, the lower section (which was most probably sedimented under a permanent water cover) should correspond to the main period of pedimentation, whether it is to be placed within the early Pleistocene or in the upper Pliocene or in both. There are indications that the Masileh basin (and probably others) was gradually and continually subsiding while being filled, actually during the process of pedimentation. The climate of this prolonged period must have provided at the same time for the permanent, though probably shallow water cover of the basin, and for the equilibrium of agents indispensable for the pedimentation. This means that it cannot have deviated much in its essential traits from the present one, as pedimentation is still maintained without any marked break.

Of the upper section the salt-banks (white!) must belong to the warm "inter-glacial" periods as the uppermost salt crust seems to imply. The clay middles, whether brown or green, should represent the cold periods, and they also seem to suggest a permanent water cover, while the salt banks of course require a seasonal drying up of the lakes.

The basins in question are small enough for a relatively slight change in the amount of affluent water (which is by no means only through the perennial rivers) to be sufficient to produce the change from seasonal to permanent lakes. If you remember the map of the terminal lakes and *kavirs*, you will agree that such a change is indeed possible within the range of active pedimentation. The only prerequisite is that humid uplands be sufficiently near to provide the necessary supply of water. The required increase of supply can easily be effected by the marked decrease of the evaporation rate during the cold periods (as my calculation for Lake Rezaiyeh has shown). For the earlier period, slightly increased precipitations may have been responsible.

There is also evidence for markedly drier periods within the region of the Great Kavir. One such series of facts is connected with the sands. There are groups of sand dunes which have "wet feet". And the drowned parts of the eroded surfaces seem to infer a rising groundwater table after much lower stands. Nevertheless, this phenomenon keeps within the type of "seasonal lakes" and we must not forget that the gradual filling up of the basins may also contribute to a secular rise of the groundwater table. More convincing evidence for former drier periods is provided by the areas of wind-excavated ridges (resembling those of the southern Lut), which are to be found east of the Siyah Kuh, in the southern part of Kuh-e Gugird, on an inner-kavirian anticline south-west of Torud in 35°10′ N. and 54°40′ E., finally on another Upper Red anticline south of Tabbas. It is interesting thet these features affect old, uplifted surfaces, and are out of function themselves—remains which escaped destruction by the present dominant agencies of rain and running water.

Probably evidence of slightly more humid conditions in the present phase is provided by the shallow gullying (1-2 metres deep) with affects some covered pediments in their higher reaches. Also the fact that many streams are slightly cut (up to 4-6 metres) within their fans and in the drained Kavir, may point in the same direction. But this explanation is surely a matter of contention.

QUATERNARY CHANGES OF CLIMATE WITHIN THE ZONE OF PREDOMINANT WIND EROSION

The main example is the Southern Lut, of which we have able descriptions by A. Gabriel and one attempt at an explanation by G. Stratil-Sauer who travelled there years ago. I myself have seen only marginal parts, but have studied the air photographs closely and designed a tentative geomorphological map. The essential facts are as follows.

The Southern Lut is an enormous topographic and geological basin where large-scale block faulting, tilting and folding have played a decisive role and are still going on. The central part of the basin had been filled at least 200 metres deep with horizontally-bedded, silty material which grows progressively coarser towards the margins. Very extended pediments with inselbergs appear at the sloping-up surface, especially in the north (north-east) and south. This phase of filling obviously took place under conditions of normal pedimentation which do not exist any longer below 800 metres. The climate has become too dry and the remaining surfaces are therefore out of function, abandoned to the forces of wind and weathering, partly excavated, partly clad in a cuirass of blackened angular pebbles, decomposed underneath into a powder rich in salt and gypsum.

The central part of this basin fill, where the material is of the finest grain, has been excavated by the prevailing strong north to north-west winds into an area of corridors and ridges, up to 150 km. north-south and 70 km. east-west, and with a maximal depth of about 200 metres. There is evidence that the material of these ridges and furrows belongs to the same general fill and not to a second, younger series of sediments (as Stratil-Sauer postulated). There is not the slightest evidence or indication that wind erosion was ever interrupted in the central part of this area. This is why the ridges (in the central parts) have been moulded into streamlined whale-backs with a perfection equalled nowhere in the world to my knowledge. In the marginal parts of this area, forms of more rudimentary or even incipient excavation prevail. The unique arrangement into straight parallel corridors and ridges requires a wind system which should not have changed its main direction for a very long time.

For us, the margins of this area of excavation attract the main interest as there an interplay of two sets of agencies or agents—wind and water—has taken place through time with changing results according to changing conditions.

The water is not at all groundwater but water brought in by permanent or intermittent streams. (The only permanent stream at present is the Kal-e Shur, which comes down from the Kuhestan uplands through Birjand.) The Kal-e Shur, with the rare help of other ephemeral streams from the north-east, has filled the bottom of the northern marginal excavation with a poor *kavir*. This excavation, stretching west to east for more than 75 km., is especially deep (200 metres?) at the foot of the *cuesta*-like edge of the excavation. This is all done by wind, water erosion playing a secondary role only on the steep walls. This is the lowest of all interior closed basins of Iran (260 metres?). It is not possible for water and mud to penetrate further, unless it raises its surface to penetrate into the corridors. But for this the amount of water available is too low, and there is no sign or indication of any (essentially) bigger extent of this *kavir*. Three or four erosional terraces do exist to indicate a step-like progressive excavation with intervening (coeval) *kavir* formations. This interplay, especially the renewal of the wind excavation, is of course only workable if the local water table of the *kavir* ceases to exist, i.e., if the Kal-e Shur, because of poor water supply, cannot penetrate into this area but ends somewhere upstream (30-70 km. upstream there is an extensive *kavir*, now drained). It appears that the Kal-e Shur is at present at its best, that is to say, it is penetrating deepest.

The streams coming down from the Kerman mountains have partly overwhelmed incipient wind excavation, and built up some small *kavir* patches against the first larger ridges.

In the south-east is the Shurgaz-Hamun Lake, a *kavir* fed by an intermittent stream draining the Zang-e Ahmad desert in the south. It also fills a wind-excavated basin, less deep than the first (about 400 metres). The river, though intermittent, is strong enough to keep its bed (which crosses 50 km. of shifting sands) free of obstruction. There is also a second *kavir* some 60 km. upstream and drained which again fills a shallow depression excavated mainly by the wind. Probably the same interplay of forces was working here as just described.

It is most impressive to see the sand ridges emerge from the wind-eroded area in turning eastwards. They evoke the idea of a standing cyclone, with the main deposition area in the east. Between the big longitudinal ridges there are transverse chains of small, single, moving dunes (*barkhans*). There are signs that the air movement in a former period was stronger than today, for, between the turning sand ridges, the corridors and wind ridges continue their direction until they disappear under the sand—the cyclone thus should have had a larger radius.

CONCLUSION

On the grounds of comparison of investigated former forms and processes with presently going on processes and conditions a tentative time-scale of events has been composed (see Table below).

It should be understood that the "Plio-Pleistocene" main period of pedimentation and filling of the *kavir* basins must have been slightly more humid because of the quasi-permanent lakes then existing, though within the range of precipitation allotted to present-day function of pediments (100-300 mm.) At the same time pedimentation and corresponding basin-fill was also going on within the south-eastern basins which in the Pleistocene period got too dry for such processes. Advances and retreat of intruding rivers should have been caused by increased water load of the rivers. The connected deposition of *kavir* mud within the Lut basin, marginal to the central area of continuous wind erosion, corresponds to the quasi-permanent lakes within the zone of pedimentation (Great Kavir, etc.) which also require increased afflux of water. Both facts appear to have been effectuated rather by a lowering of the rate of evaporation (in the cold phases of the Pleistocene) than by a more humid condition of the local climate.

For the recent "slightly more humid phase", however, a true increase of rains, though very slight, must be inferred.

Tentative time-scale of events within three zones of Iran

			Zones of glaciation and solifluction	Zone of pedimentation with Great Kavir, Masileh, etc.	South-eastern basins with dominant wind erosion
POSTGLACIAL	Recent (since 3000-4000 B.C.) / Early	HOLOCENE	Recent glaciation (snowline 4000 metres) solifluction upward of 3,000 metres	Slightly more humid phase. Transgression of Kavir fill on *basht* and "eroded surfaces". "Wet feet" of sand dunes within Kavir.	Slightly more humid phase. Advance of rivers against Central Area of wind. Excavation deposition of poor Kavir fill in depressions.
	Late Glacial		Series of stadial retreats and re-advances of glaciers.	Predominantly dry phases. Wind erosion, sand accumulation.	Predominantly dry.
PLEISTOCENE	Würm		Würm-glaciation : snowline depression 700 metres; depression of solifluction 700-800 metres; deposition of gravel terraces.	Upper section of Kavir fill (Masileh). Alternating sequence of 4-5 salt banks (= Warm and dry periods) and brown and green clay and silt, partly sand (= cold periods).	(*a*) Continuous wind erosion within Central part. (*b*) Three (or more?) advances and retreats of intruding rivers against central area according to cold and warm (dry) periods
	Older		1-2 (-3?) Older Pleistocene gravel terraces indicating cold phases with increased solifluction.		
Plio-Pleistocene			Uplift erosional terraces (partly gravel covered).	Lower section of Kavir fill (Masileh). Brown silt and clay quasi-permanent lakes. Forming of *dasht* = pediments and "eroded surfaces" within Kavir.	Filling of Lut Basin together with pedimentation on margins.
Bakhtiari (Pliocene).				Conglomerates at margins.	

RÉSUMÉ

Nature et conséquences des changements de climat à l'époque quaternaire en Iran (H. Bobek)

Le bassin du Lout méridional a été formé et rempli par un processus normal de pédimentation, à une époque où le climat devait évidemment être un peu moins sec qu'à l'heure actuelle mais non pluvieux. Peut-être existait-il alors un lac terminal peu profond ou *kavir*, analogue au Djas-Morian qui se trouve aujourd'hui dans le grand bassin du climat plus humide situé immédiatement au sud du Lout.

Le climat est ensuite devenu plus sec, comme il l'est à l'époque actuelle. L'érosion éolienne tourbillonnaire a commencé à s'exercer dans la partie centrale, et elle n'a pas cessé depuis lors. On peut discerner, en étudiant les effets combinés du vent et de cours d'eau à action marginale, une série de trois ou quatre fluctuations climatiques.

La similitude de ce cycle avec celui dont on discerne les traces dans les terrains de remplissage de Masileh est frappante. Dans les deux cas, les fluctuations n'ont pas réellement modifié le caractère aride du climat au cours de la seconde période (pléistocène).

Dans le Seistan, la situation est compliquée par le fait qu'une importante rivière venant de l'extérieur (Hilmend) forme un lac terminal quasi permanent, tandis que l'influence de l'érosion éolienne est localement plus forte que celle des agents « normaux » de pédimentation. En outre, des mouvements tectoniques récents ont exercé une action importante.

Compte tenu des dislocations tectoniques, il est impossible de se fier à l'altitude actuelle des terrasses, sauf peut-être en ce qui concerne la plus basse (5 m). Toutes les terrasses sont inclinées vers le sud sur la rive occidentale. Des mouvements de ce genre ont également modifié le delta terminal de la rivière. Le lac a dû changer de forme et de position à plusieurs reprises au cours du remplissage de l'ensemble de la dépression. Telle est la véritable cause de la multiplicité des couches successives d'argile et de sable ou même de grès fin —phénomène observé par E. Huntington qui l'a expliqué à tort par une série de changements climatiques.

Cette évolution, ainsi que les fluctuations d'origine réellement climatique du lac, expliquent aussi le fait que les structures dues à l'érosion éolienne se mêlent à de véritables formations aquatiques, à des alluvions déposés sur des fonds recouverts d'eau à certaines saisons et à des formations constituées autrefois sur ce qui était à l'époque les rives ou le fond du lac. Il est également intéressant de constater que si l'érosion éolienne tourbillonnaire est plus forte sur les anciennes surfaces du delta, elle agit aussi — quoique avec une intensité moins grande — sur les surfaces plus récentes aussitôt qu'elles se dessèchent, et y crée des formes analogues, comme dans les parties marginales du bassin du Lout. L'érosion éolienne a un caractère hautement *sélectif*: elle épargne les anciens lits (ou bras) de rivière, où la texture du terrain est relativement grossière, et entraîne les particules plus fines situées dans les zones intermédiaires.

DISCUSSION

H. Flohn. Professor Bobek has stated that in northern and central Iran there is no evidence for increasing precipitation during the Pleistocene. Is this also true for southern Iran, especially for the coastal ranges of the Persian Gulf and Makran?

H. Bobek. I have not investigated these coastal ranges on the ground, only by air photographs. They show a type of landforming which requires considerable amounts of rain (250-400 mm. or more) which, however, mostly fall in a few violent rainstorms. I cannot say whether the precipitation was increased. The peculiar type of complete dissection does not show any sign of an important change in controlling conditions.

C. C. Wallén. I was interested to note the slightly different approach to the study of changes in climate by geomorphological methods other than those we heard the other day. The weakness in these cases seems to be especially in the difficulties of dating. There is one special question in this connexion: the tectonics has been referred to both by Dr. Voûte and Professor Bobek as important in concluding from geomorphological conditions on climatic changes; is it possible to say anything about how recent are the tectonic movements referred to by the speakers?

C. Voûte. There is evidence available as to the relative age of the tectonic movements in Iraq. In a few cases even exact dating has been possible. From my own studies of the Abu Dibbis depression on the edge of the Arabian shield it has become apparent that tilting by tectonic causes of lake terraces took place after the deposition of sediments which contain Mousterian type tools, that is generally speaking sometimes during or after the Palaeolithic. Other observations with respect to even more recent movements—the southern part of Mesopotamia and at the foot of the southern Zagros mountains—have been recorded by geologists of the J.P.I. (See: Lees and Falcon, "The Geographical History of the Mesopotamian Plains", *Geographical Journal*, 1952, vol. 118, p. 24-39). They mention for instance the case of a channel constructed during Early Persian (Sassanian) times, which has become upwarped considerably at the crossing point of a growing anticline. Dating of the tectonic movements in and around the Tharthar depression is less accurate, as we can only say with certainty that they postdate the deposition of the (Upper Pliocene) Bakhtiari deposits and the cutting of the oldest of the Tigris and Euphrates valleys after the Bakhtiari period.

H. Bobek. In Iran orogenetic tectonics go on right into the present. There are numerous evidences for this in the way of recent anticlinal uplifts (with *dasht*-regeneration on them) and young-fold lines at tilted blocks. Dating, however, is up to now only by morphological and stratigraphical criteria, that is "post-Bakhtiari" (Middle, perhaps Upper, Pliocene) and interesting forms or sediments actually in function, like the *dasht*—i.e., the pediment plus gravel cover—which, however, began to function immediately after, or even during, the Bakhtiari. That leaves for dating the whole Pleistocene including the Holocene.

D. Amiran. Are landslides in the Zagros Mountains caused by tectonic or by climatic forces?

Would it be possible to produce more precise evidence on the Quaternary climate in Iran, especially on the thickness of glaciers and the desert varnish of the large fans? Might not mountain glaciation, fan formation and absence of pluvial lakes refer to various climatic phases of the Quaternary?

H. Bobek. Taking the question of the desert varnish first: Differences in its development have indeed been one basis for separating the lower south-eastern basins from the rest of the upland pediment zone. The active pediment fans, as shown in one aerial view, display various shades of varnish: the darkest are the oldest gravel beds, the lightest the shallow sills of the unconcentrated run-off. On the contrary, the surface of the pediment cover and corresponding fill in the Lut basin are entirely dark, the few still existing rills and stream beds having been blackened to the same extent as the gravel beds, because they are very seldom in function any longer.

As regards the Pleistocene glaciers, their thickness is not easily established. Most probably the thickness of the longest of the glaciers did not exceed 150-200 metres. To produce the glaciers of, for example, the Central Alburz additional precipitations do not seem required as they are nowadays probably of the order of 1000 mm., and evaporation certainly was reduced.

Fan (pediment) formation starts in the Upper Pliocene as the (probably Middle-Pliocene) "Bakhtiari" conglomerates are cut by the pediments at narrow or wide angles as tectonics may rule. It is still active at present without any break being apparent (polygenetic pediments). Pedimentation therefore went on during the different Pleistocene phases. Permanent or semi-permanent lakes were not absent during the cold spells of the Pleistocene if the "upper series" of the big profile shown is to be taken for Pleistocene, as is very probable since 46 metres sedimentation seems to be too much for Holocene sedimentation. They were, however, shallow and of much smaller extent than was believed up to now. As they were filled by streams coming from the humid to semi-humid border ranges which certainly had more water because of the reduced evaporation no Pluvial for the plateau is needed nor even possible. As the intermittent dry phases (salt crusts of the profile) are linked by the uppermost salt crust (postglacial) to the warm periods, the contemporaneity of lakes and glaciation seems to be established.

C. Voûte. The morphology of the Zagros Mountains in the area which I have visited is characterized by very steep mountain sides which as such are subject to major landslides. This is especially the case as the rocks forming the mountains are often rather weak (marls for instance). I do not believe, however, that tectonic forces, for instance earthquakes, have triggered the landslides which occurred. Two arguments can be put forward to stress the opinion that they have been triggered by a more humid, and probably also a colder climate than the present one. In the first place the landslides have not been taking place continuously, but they are concentrated in a single or maybe a few well-defined periods and they seem to be related also to the occurrence of soils of a solifluction type *sensu lato*. Secondly there are all transition forms to be found between major landslides of a chaotic structure and deformations of a more souple nature caused by gravity, for instance the "collapse structures" as described many years ago from the Iranian part of the Zagros by Harrison and Falcon or the phenomena of "gravitative denudation" recently mentioned by Knetsch from almost the same area as was visited by us. These souple deformations of rock on steep mountain sides certainly are not caused by earthquakes but must have been evolved gradually. Under the present climate I have seen no indications of such structures being formed and it appears that they also need a higher humidity and/or lower temperature, that is to say longer winters with snowfall and alternating freezing and snowing.

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OSCILLATIONS ET MODIFICATIONS DE CARACTÈRE DE LA ZONE ARIDE EN AFRIQUE ET EN AMÉRIQUE LATINE LORS DES PÉRIODES GLACIAIRES DES HAUTES LATITUDES[1]

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En schématisant, on peut dire que les systèmes de reconstitutions paléoclimatiques concernant l'Afrique, continent qui a fait l'objet des travaux les plus nombreux, se résument à deux :

1. La position la plus traditionnelle, soutenue notamment par J. Büdel, H. Flohn et K. Butzer, admet une atténuation considérable, sinon une disparition de la ceinture aride tropicale de l'hémisphère nord lors des périodes glaciaires des hautes latitudes. Les pluviaux auraient alors envahi tout le Sahara.
2. La position la plus récente de L. Balout (voir Tricart, 1956), que nous avons adoptée dès 1956, aboutit au contraire à admettre un véritable balancement des zones climatiques. Le nord du Sahara aurait connu, lors des périodes glaciaires européennes, des pluviaux atténuant son aridité. Au contraire, le bord sud du désert serait devenu alors plus aride et le climat sec aurait envahi les régions actuelles de savane du Soudan.

La discussion de ces deux systèmes paléoclimatiques ne présente pas seulement un intérêt académique. En effet, ces deux positions aboutissent à des explications complètement différentes de la mise en place des formations superficielles et des nappes alluviales, souvent minéralisées, de l'Afrique occidentale, ainsi qu'à des datations discordantes des formations d'altération et des paléosols. Enfin, dans le domaine biogéographique, l'explication de la diffusion des espèces végétales et animales change du tout au tout suivant que l'on adopte l'une ou l'autre des théories. Suivant la position 1, la barrière saharienne entre les mondes intertropical et méditerranéen aurait presque disparu à une date fort récente, au Würm, il y a entre 20 000 et 100 000 ans environ. Plantes et animaux tropicaux auraient dû envahir alors l'Afrique du Nord. Si l'on adopte la position 2, au contraire, la persistance de la barrière saharienne a opposé un obstacle à la mixion des espèces tropicales et méditerranéennes.

La position 1 est soutenue par des chercheurs qui n'ont travaillé que très épisodiquement en Afrique de l'Ouest et qui ont transposé dans cette région des résultats obtenus en Afrique orientale où les préhistoriens admettent, depuis plus de 20 ans, une équivalence entre les pluviaux locaux et les glaciaires européens. Nous ne la discuterons pas du point de vue archéologique, qui échappe à notre compétence, mais nous ferons seulement remarquer que les corrélations à longue distance fondées sur cette méthode sont discutables. De plus, les arguments géomorphologiques avancés par nos confrères travaillant en Afrique orientale ne nous semblent pas convaincants. Ils reposent sur le postulat implicite que les nappes alluviales grossières, caillouteuses, impliquent des climats plus humides que les nappes fines, sablo-argileuses. Tout ce que nous connaissons de l'Afrique occidentale et de l'Amérique du Sud nous montre le contraire. Les nappes grossières, liées à une érosion à dominante mécanique, se mettent en place sous des climats plus secs que les nappes fines. Elles correspondent aux crues violentes des régions semi-arides et sont nourries par le ravinement des sols antérieurs, qui fait apparaître la roche saine et nettoie les débris de filons de quartz noyés dans les altérites. Tous les forestiers savent que la couverture végétale dense réduit la torrentialité. Ces notions se sont récemment imposées à la suite des progrès de la géomorphologie climatique (Tricart et Cailleux, 1955 ; Tricart, 1957 ; Ehrart, 1956). Elles amènent à jeter le doute sur certaines interprétations.

En Afrique occidentale, lors des régressions glacio-eustatiques et, tout particulièrement, lors de la dernière d'entre elles, nous avons des preuves multiples et diverses de climats plus secs que l'actuel. Au Sénégal, des dunes se sont formées au détriment de nappes alluviales,

1 Les données utilisées dans cette communication ont été rassemblées depuis huit ans par les équipes du laboratoire de géographie physique du Centre de géographie appliquée que nous avons dirigées en Afrique occidentale et ont été complétées par diverses observations de J. Vogt et P. Michel du BRGM et de nous-même à l'occasion de missions au Brésil, au Pérou, au Chili, en Amérique centrale. Que tous ceux qui nous ont aidé par leurs discussions, leur connaissance du pays, leur hospitalité ou leur dévouement dans l'exécution de tâches matérielles soient ici remerciés.

comme celles du delta du Sénégal. Elles ont été ensuite noyées par les dépôts contemporains de la transgression flandrienne. Lors de la régression pré-ouljienne (avant-dernière glaciation), le même phénomène s'est produit, avec une bien plus grande intensité, ce qui lui a permis de ne pas être effacé depuis. Lors des périodes de haut niveau marin, à l'ouljien (interglaciaire Riss-Würm), et depuis la fin de la transgression flandrienne (post-glaciaire), des sols se sont développés sur les dunes fixées. Ceux de l'ouljien, rubéfiés sur 1 à 2 m, impliquent un climat nettement plus humide que l'actuel (au moins 800 mm de pluies contre 350 mm de nos jours). Sur la côte du golfe de Guinée, la forêt a reculé vers le sud et des terrasses climatiques importantes se sont mises en place dans les vallées, qui, au quaternaire, ont connu, à plusieurs reprises (3 ou 4), des régimes à chenaux divagants qui impliquent une disparition des forêts-galeries, des crues brusques et irrégulières, un intense ravinement des interfluves, dont la partie basse a été recoupée en glacis semi-arides, parfois cuirassés. Deux systèmes de glacis étagés, attribués au quaternaire ancien, ont une existence très générale, du Nord-Dahomey au pied du Fouta-Djalon. Les formations d'altération ont été en grande partie décapées, ce qui explique leur relative minceur. En Côte-d'Ivoire, au nord d'Abidjan, elles oscillent entre 4 et 10 m alors que dans la Zona da Mata du Brésil oriental, vers Recife, où le climat est resté continuellement humide au quaternaire, elles en ont de 20 à 60. On conçoit les conséquences multiples de telles différences sur le plan pédologique, biogéographique, agronomique.

Les régions de savanes sèches à intense décapage des sols antérieurs se sont avancées jusqu'au golfe de Guinée depuis le Bénin jusqu'à l'ouest de la Côte-d'Ivoire. La région sèche actuelle du V Baoulé et du Bas-Togo s'était donc considérablement élargie, exactement comme au cours de l'année 1959, caractérisée par une sécheresse exceptionnelle. L'étude des conditions météorologiques de cette dernière fournirait certainement d'intéressantes données pour la reconstitution de ce qui s'est passé lors des périodes glaciaires quaternaires. Seul le Libéria et, semble-t-il, le sud-ouest du Cameroun sont restés alors dans le domaine forestier. Ailleurs, la forêt a effectué une reconquête aux dépens des savanes sous l'effet de l'oscillation climatique récente. C'est ce qui explique la persistance de savanes reliques, isolées au milieu de la forêt sur les sols les moins favorables à cette reconquête (savanes des sables de la basse Côte-d'Ivoire).

Mais cette oscillation générale des zones climatiques en Afrique de l'Ouest n'est qu'un schéma d'ensemble, nécessairement simplifié. En effet, du fait même de leur déplacement leur faisant occuper des terres de configuration géographique différente, ces zones modifiaient leurs caractères. En Afrique du Nord, par exemple, les beaux travaux de R. Raynal amènent à admettre que les pluviaux, ici contemporains des glaciations, étaient plus froids que le climat actuel, ce qui entraînait une moindre évaporation. Ils étaient caractérisés aussi par une plus grande brusquerie des écoulements, attestée par la nature des accumulations alluviales. Ces caractères se comprennent aisément : l'inlandsis rejettait vers le sud la zone de circulation cyclonale qui s'établissait approximativement sur la Méditerranée et les dépressions devaient passer droit au travers de l'Afrique du Nord, avec des phénomènes frontaux exacerbés par la différence de température entre les eaux de l'Atlantique, refroidies par les icebergs, et celle de la Méditerranée, plus chaudes. Le climat n'était donc pas celui de l'actuelle région méditerranéenne sur le bord nord du Sahara. Il présentait des caractères originaux. Néanmoins, certaines plantes méditerranéennes pouvaient s'en accommoder tant bien que mal et se réfugier ainsi sur les massifs élevés du nord du Sahara, tels les cyprès décelés par l'analyse pollinique dans le Hoggar. Mais, néanmoins, une sélection d'espèces, probablement assez sévère, a dû se produire. On peut penser qu'elle a hâté la disparition des mammifères tropicaux endémiques d'Afrique du Nord : rhinocéros, éléphants nains.

La même brusquerie du climat se retrouve lors des phases sèches des régions actuelles de savanes de l'Afrique occidentale. Certaines alluvions ont des caractères torrentiels très accusés. Un appauvrissement des flores et des faunes en est certainement résulté. Lors de la reconquête, les espèces les plus migratrices se sont avancées le plus vite et une modification de la composition des associations végétales s'est produite. Lors de certaines périodes plus humides que nos jours — ouljien, néolithique — les espèces tropicales ont partiellement colonisé le sud du Sahara : crocodiles des gueltas, acacias de Mauritanie centrale. Certains acacias, profitant de la moindre aridité du Sahara occidental, se sont même avancés jusque dans la région de la Saoura.

Notre reconstitution paléoclimatique aboutit ainsi, malgré son caractère très rudimentaire, à esquisser quelques hypothèses intéressant l'évolution biogéographique du Sahara et de l'Afrique intertropicale de l'Ouest. Le balancement d'ensemble des zones climatiques a laissé subsister, au quaternaire moyen et supérieur, la barrière saharienne. On comprend dès lors que les espèces tropicales de mammifères de l'Afrique du Nord, malgré leur mobilité, y soient restées enfermées et aient évolué en vase clos, se différenciant progressivement, par endémisme, des autres branches issues du même tronc. La persistance de la barrière explique aussi la profonde différence entre les flores de part et d'autre du Sahara, phénomène qui oppose cette partie du Vieux Monde à l'Extrême-Orient ou à l'Amérique du Sud. Ce balancement a provoqué également des migrations importantes, qui ont joué un rôle sélectif. Enfin, il s'est accompagné de modifications fort appréciables dans les caractères écologiques des climats. Les paléoclimats des périodes froides et, notamment, du Würm ne sont pas les stricts homologues des climats actuels. D'une manière générale, ils semblent avoir été plus rudes, caractérisés par des variations plus amples et plus brusques donc moins favorables, ce qui a dû jouer dans le sens de l'appauvrissement des faunes et des flores.

En Amérique latine, les conditions sont bien différentes de celles de l'Afrique. Cela se conçoit fort bien : en Afrique, le Sahara est le type même du désert zonal, tandis que les régions sèches de l'Amérique du Sud sont des déserts de position, régionaux, dûs aux anomalies de la circulation atmosphérique résultant de la configuration des continents. Celle-ci ne s'étant pas modifiée, la répartition des grandes régions climatiques a beaucoup moins changé qu'en Afrique.

Dans le nord-est du Brésil, par exemple, le rapide passage de la Zona da Mata, occupée le long de la côte par la forêt, à la caatinga des régions arides de l'intérieur, qui se fait de nos jours en 150 km au droit de Recife, a persisté au quaternaire. Le glissement des limites climatiques n'a pas dépassé 20 à 30 km. L'émersion partielle de la plate-forme continentale sous l'effet des régressions glacio-eustatiques semble avoir seulement déplacé légèrement vers l'est la bande forestière littorale, faisant avancer d'autant la zone de transition et celle de la caatinga. Il y a donc eu permanence approximative des mêmes climats pendant des centaines de millénaires du quaternaire moyen et supérieur. En milieu stable les altérations climatiques se sont développées profondément, ce qui explique que la puissance des altérites de la Zona da Mata soit tellement supérieure à celle qu'on observe en basse Côte-d'Ivoire. De même, cette permanence a permis l'élaboration de formations végétales fort originales, comme la caatinga ou la brousse de cactées du nord du Venezuala (Güajira), qui semble avoir bénéficié d'une permanence analogue.

Par contre, dans le sud du Brésil, à partir de l'axe Rio de Janeiro-São Paulo et, dans l'intérieur, dans le sud de Minas Gerais, des oscillations climatiques importantes semblent avoir eu lieu (Tricart, 1958). Leur datation reste conjecturale. Cependant, leurs effets sur les formations végétales semblent considérables. Ces périodes sèches, dont la dernière paraît dater de la fin de la transgression flandrienne (quelques milliers d'années seulement), expliqueraient la tendance, reconnue par certains botanistes, à un remplacement d'espèces xérophytiques par des espèces plus exigeantes en eau.

Le littoral du nord du Chili et du Pérou doit son aridité au courant de Humbold, dont l'intensité a été nécessairement modifiée par les variations d'extension glaciaires. En effet, les périodes d'englaciation ont diminué la masse des eaux froides des cuvettes océaniques par stockage dans les inlandsis. Inversement, la déglaciation a libéré de grandes masses de telles eaux, dont la remontée alimente justement le courant de Humbold. Or nous avons relevé dans ces régions différentes traces de périodes plus humides. Près de Lima, avec O. Dollfus (1960), nous avons observé des formations non fonctionnelles constituées par des fragments détachés sous l'effet de la cristallisation du sel, ce qui implique un paléoclimat plus ensoleillé, facilitant l'évaporation des embruns. Dans le désert du Grand Nord chilien, l'escarpement littoral est zébré de bassins de réception torrentiels aboutissant à des cônes de déjection plongeant parfois sous la mer, qui décèlent une période pendant laquelle les averses permettaient l'élaboration d'un réseau hydrographique aujourd'hui mort. Il y a donc eu, sur la face occidentale de l'Amérique du Sud, des oscillations paléoclimatiques plus amples que dans le nord-est du Brésil, sous l'influence des modifications du courant de Humbold, particulièrement sensible aux phénomènes glaciaires. Cependant, dans le nord du Chili et le sud du Pérou, il a régné, en permanence depuis le début du quaternaire, des climats arides, ce qui a permis des adaptations biologiques particulières, endémiques, comme les tillandsia, qui captent uniquement l'humidité atmosphérique des brouillards caractéristiques de ce type de littoral. Les oscillations climatiques relevées, qui sont à l'origine, notamment, de nappes alluviales volumineuses, semblent s'être limitées à des alternances de périodes pendant lesquelles le courant de Humbold était plus constant, comme de nos jours, ce qui entraînait un écoulement torrentiel tout à fait exceptionnel et une fragmentation mécanique réduite, et de périodes pendant lesquelles ce même courant était, au contraire, plus instable, ce qui permettait le déclenchement plus fréquent d'averses épisodiques et diminuait, au moins de temps à autre, la nébulosité. Ces périodes, qu'on hésite à appeler « pluviales », semblent coïncider avec les bas niveaux marins glacio-eustatiques, donc avec des périodes glaciaires. Mais il n'y eut jamais, dans le désert d'Atacama, d'écoulements comparables à ceux des pluviaux sahariens, ce qui entraîne un très faible développement des nappes d'eau fossiles, à la différence du Sahara, et ce qui fait que ce désert est resté, tout au long du quaternaire, une barrière biogéographique infranchissable.

Dans les Andes vénézuéliennes, nous avons pu établir l'existence de périodes d'intense accumulation alluviale, pendant lesquelles, vers 1 000 à 1 800 m d'altitude, se sont mises en place des nappes détritiques de plus de 100 m d'épaisseur. Ces accumulations sont contemporaines des glaciations, car elles se raccordent aux moraines à l'amont. A l'aval, la plus récente plonge sous le lac de Maracaïbo, sans être déformée, ce qui la date de la régression préflandrienne. Mais ces nappes détritiques ne sont pas fluvio-glaciaires : elles sont aussi épaisses dans les vallées qui n'ont pas été englacées. Elles résultent donc uniquement d'oscillations climatiques et se sont formées lors des crues très violentes, de caractère catastrophique, périodiquement renouvelées. Elles indiquent une couverture végétale moins continue et moins dense que de nos jours, et un climat beaucoup plus instable, plus apte aux averses diluviennes, peut-être déclenchée par le passage de cyclones circulant maintenant plus au nord (Antilles, Mexique).

En Amérique centrale, au Salvador, nous avons relevé des traces de périodes plus sèches que de nos jours. Le problème est ici compliqué par le volcanisme, car les grandes éruptions explosives avec saupoudrage de cinérites ont tué la végétation à de multiples reprises et déclenché des déséquilibres pseudo-climatiques. Mais les tracés de ces périodes sèches se retrouvent dans des régions épargnées par les chutes de cendres quaternaires. Il semble donc qu'ici comme en Afrique occidentale, il y ait eu un balancement des zones climatiques avec avancée vers le sud de la zone aride tropicale du Mexique jusque sur le Salvador. La côte du Pacifique semble avoir été beaucoup plus affectée que la côte des Caraïbes, ce qui, joint au volcanisme, expliquerait la pauvreté beaucoup plus grande des flores.

Exactement comme de nos jours, les paléoclimats se sont donc répartis de manière bien différente en Afrique et en Amérique latine. En Afrique, le fait primordial a été un balancement d'ensemble des grandes zones sur l'ouest du continent, accompagné de modifications fort appréciables des conditions écologiques dans chacune d'entre elles. Des changements d'aires de répartition des espèces importants et un appauvrissement général des biotopes en sont résultés hors des refuges de la forêt pluviale. En Amérique latine, au contraire, les conditions régionales ont joué le plus grand rôle, diversifiées par le facteur géographique. On peut souligner le contraste entre la permanence de la zonation dans le nord-est du Brésil et les variations assez amples de la façade pacifique ou du sud du Brésil.

Comme celle des climats actuels, la répartition des paléoclimats est donc nuancée et complexe, d'autant plus que nous avons à tenir compte de modifications dans les conditions de circulation atmosphérique déclenchées par le facteur géographique, et qui ont abouti, au moins en certains cas, à l'apparition momentanée de climats qui ne sont pas exactement homologues des climats actuels. Il faut donc se défier de l'esprit de système et accumuler les observations pour aboutir à de patientes reconstructions. De telles recherches ne peuvent se placer sur le plan individuel, car elles doivent s'appuyer sur les résultats de disciplines fort variées. Nous sommes, quant à nous, partis des méthodes géomorphologiques et nous nous sommes efforcés d'ouvrir des horizons du côté de la biogéographie. Nous souhaitons que nos collègues de cette spécialité nous apportent leur aide et leur critique, et nous remercions les organisateurs du colloque d'avoir permis cette confrontation indispensable entre les spécialistes de disciplines différentes.

SUMMARY

Oscillations and characteristic modifications of the arid zone in Africa and Latin America during the periods of high latitude glaciation (J. Tricart)

Geomorphological studies based on detritic sediments analysis have led us to believe, along with L. Balout, that in western Africa the last cold period resulted in a general shifting of climatic zones towards the south. In northern Africa the cold periods were also Pluvials while the dry tropical climate extended over the Sudan and dry savannahs even extended as far as the coast of the Gulf of Guinea. Only in Liberia and eastern Nigeria could rain forests persist. A large part of the present forest zone was only recently re-covered by forest vegetation, thus making it easier to understand some of its phytosociological characteristics: the permanency of savannah islands on poor sandy soils and the generally thin weathering products. These palaeoclimatic oscillations resulted in the aggradation of the climatic terraces consisting of coarse materials (gravel, sands)—sometimes mineralized—which are found along nearly every river in western Africa.

In South America these oscillations are of minor importance because, unlike western Africa, the source of aridity is not zonal but linked with the geographical configuration. In north-eastern Brazil, for example, the very sharp delimitation between the different climatic zones along the coast suffered only a slight change. Thus, in a humid climate weathering products are very much thicker than in Africa. In the dry interior of Brazil the *caatinga* attained a remarkable form of xerophytic adaptation depending basically on great climatic permanency. Only south of 20° S. can we find climatic terraces, i.e. remnants which suggest alternating dry and humid periods (south of Minas Gerais, region of Rio de Janeiro and of São Paulo). On the other hand, along the Pacific coast the Humboldt current seems to have varied as a result of changes in the amount of melt-water originating principally from the continental ice masses of the Antarctic.

In northern Chile and Peru there is evidence of past periods which were not as dry as the present one and which, in northern Chile, were accompanied by torrential dissection. Therefore, certain plant migrations must have occurred along the coast during these periods. Climatic oscillations whose traces were obscured by recent volcanic activity were also observed in Central America (Salvador). These appear to have some similarity with those which were observed in Africa.

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SIMPLE MEASUREMENTS OF MORPHOLOGICAL CHANGES IN RIVER CHANNELS AND HILL SLOPES

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One of the principal types of observational evidence on climatic changes in the recent geologic past is in river position and elevation. It is well known that river channels, particularly those flowing through alluvium or on relatively soft bedrock, tend to develop flood plains by lateral migration of the channel. Abandoned flood plains at elevations distinctly above the present river channel are the origin of river terraces, widespread through the world but particularly noticeable in arid regions. Climatic change is one of the causes of the abandonment of flood plains and the consequent formation of river terraces. Therefore, the identification and stratigraphy of river terraces is one of the methods by which climatic changes in the recent geologic past can be studied.

There are, of course, morphologic changes in river channels of a more subtle nature. Even when a channel is progressively degrading—a trend which will eventually result in the formation of a river terrace—there are no obvious criteria by which the current changes in a river channel can be positively identified. For this reason simple techniques, which will aid in the direct observation of current changes in a channel's position, can be helpful in identifying the nature of changes in progress.

It is the purpose of this paper to describe some relatively simple techniques which have been found to be useful in observing morphological changes on slopes and in channels. The methods have been tested primarily in arid climates but to some extent they can also be useful even where vegetation is prominent.

MONUMENTED CROSS-SECTIONS

A technique often used is the survey of a cross-section across a river channel, monumented at each end in such a manner that it can be found and resurveyed at some later date. The technique is simple enough but experience has shown that many cross-sections have been lost because of failure in the initial survey to monument and locate the end of the cross-section in a sufficiently definitive manner. The easiest and probably the best method of monumenting the end of a cross-section is to drive into the ground a steel stake which should be 3 to 4 feet in length and should be driven close to flush with the ground. The iron stakes must be relocated at some time in the future and this is where a mistake is ordinarily made. At least two additional tie points should be located and described in detail in the field notebook. The tie points may be a permanent rock, easily recognized, a nail in a tree, or some other landmark which is not likely to be destroyed in a reasonable time period. If the tie point is to be of maximum usefulness it should be in a location where a transit or plane table can be set up over it. The tie points should be so located that lines of sight from them will intersect over the iron stake at an angle not too far from 90 degrees. It has been our experience that no monument at the end of the cross-section can be relocated unless it is described by reference to independently described separate tie points where distances or angles are carefully measured. Distances are usually best. If by chance the iron stake is covered by soil creep or with sod, the intersection of the two or more lines from tie points will give an accurate location of the stake, and digging with a shovel can then be used to recover the stake.

Another important problem to be remembered in locating both the tie points and monumented ends of cross-sections is the fact that survey notes are subject to loss. The original survey notes, therefore, which describe the location of tie points and cross-sections should be photographed, or copied, when the field books are brought into the office. More than one copy should be made, and the copies must be filed and referenced in a way that if the field notebooks and one of the copies should be lost there is still another copy which could be located at some time in the future. Monumented cross-sections have been lost due to failure to observe any one or all of these simple rules—the careful description of tie points in the field, copying, and separate filing of copies of the field notes. If the tie points are well enough described, if the original monument at the end of a cross-section could not be found in the field, it could be relocated with sufficient accuracy from the descriptions, angles, or distances from tie points.

The other and probably equally important factor governing the usefulness of monumented cross-sections concerns the original location of the section itself. No one section will document sufficiently well more than one kind of change with time. If, for example, the thing to be measured is the rate of bank recession and point-bar building as the stream swings across the flood plain in time, the maximum erosion on one bank and deposition on the other can be expected in a channel bend. One cross-section in a channel bend, however, cannot be considered sufficient to give a definitive picture of the average lateral movement of a stream channel. Therefore, in attempting to measure lateral movement, cross-sections should be located in several bends and in several straight reaches in the general area.

The cross-section, of course, serves its primary usefulness in measuring aggradation or degradation with time of the channel bed itself. Consideration must therefore be given to whether the cross-section is located in a pool or on a bar in the channel. Again, several cross-sections should be established in order to represent both conditions at bars or riffles and conditions in deeps or pools in the channel.

For all these purposes the surveying should be done in such a manner that the individual points chosen for elevation determinations should represent breaks in slope so that, when connected by straight lines on the plotted profile, they would fairly represent the true conditions at the time of the survey. For such purposes the survey should ordinarily be carried out to tenths of a foot; no additional accuracy or information is provided by surveying to hundredths of a foot. It is our practice to refer all distances and elevations to the iron pin on the left bank of the channel.

PINS FOR MEASURING RATES OF BANK RECESSION

Resurvey of monumented cross-sections may not give sufficient information on the actual rates of recession of individual stream banks. In the bank for which details of bank recession rate are needed an iron pin 1 to 2 feet long is driven into the bank horizontally, usually above the level of low water but generally about half-way up the original bank. The pin is driven in so far that only one tenth of a foot remains protruding. At the time of resurvey the protrusion of the iron pin is recorded. This measurement less one-tenth of a foot is the amount of bank recession since the last observation. After the measurement is made the pin is driven with a hammer back into the bank so that again only one-tenth of a foot protrudes. The protruding end of the pin is often painted in order to make it easier to find. The location of these horizontal pins in stream banks must be recorded for later resurvey.

In banks where details of bank recession were desired we have driven such pins on 5- or 10-foot centres through a reach of 100 or 200 feet. The whole reach is then monumented and surveyed with respect to tie-points described in the case of monumented cross-sections.

An alternative is to drive such an iron pin in the stream bank on a monumented cross-section line because, once the cross-section is found, the pin can easily be located if it is still in place at the time of the next resurvey.

CHAINS AS INDICATORS OF BED SCOUR

It has long been known that the beds of channels tend to scour during high flows and to refill to a greater or lesser extent as the flood recedes. Measured cross-sections, therefore, only tell the changes which occur over relatively long periods of time and they do not indicate the amount of scour or fill that takes place in individual floods. In an attempt to get information on this factor, the following procedure has been devised which has worked well both in ephemeral streams in arid regions and in gravel streams in humid regions.

On a monumented cross-section line holes are dug in the stream channel either with a soil auger or with a shovel depending on the condition of the material in the bed and its angle of repose. The holes should be dug at least twice as deep as the estimated maximum scour which is to be expected. This is often very difficult to estimate. In ephemeral channels we usually dig the hole about 4 feet deep; in gravel streams in humid eastern United States, 1 to 3 feet has been used.

When the hole is open a piece of chain is held vertically in the hole. The lower end of the chain is usually wrapped around a flat rock, wired securely, so that the rock will act as an anchor at the lower end of the chain. The chain is held vertically in the hole until the hole is carefully refilled. When completed the chain is standing in a vertical position with the stream bed material packed carefully around it.

The purpose of this vertical chain in the stream bed is to indicate the maximum depth of scour at that point between times of observation. If the scream bed scours, a portion of the chain is exposed and the current lays the exposed portion of the chain horizontally on the stream bed. In that position it is then covered when fill occurs after the initial scour. On the resurvey, then, the location of the chain is determined by tape distances, a hole is dug carefully until the chain is reached, and the position on the chain where it changes from a vertical to a horizontal position is measured.

It will be seen that in cases of deep scour when a considerable length of chain is exposed to the flow, the anchor becomes less firm and the stress exerted on the long exposed portion of the chain becomes great. There is a tendency for the stress of the water or of debris which hangs to the chain to pull it bodily out of its position in the stream bed. More important, probably, than the rock anchored at its base is the choice of the size of the chain link. The key to the use of chains is to select a chain having a sufficiently large link that the stream bed material packs closely in the links of the chain itself. For sandy stream beds chain links having an opening of at least a half an inch are found necessary. In fine gravel the chain links should be even larger, up to perhaps one inch in diameter. A chain with a galvanized coating of zinc probably adds to the life of the installation.

With regard to placement of a series of chains on the monumented cross-section, it is our usual practice to space the chains evenly at 5- or 10-foot intervals so that, once the monuments are found, the location of the individual chains can be determined easily because of their equal spacing.

One of the techniques which involve the use of these vertical chains is the location of individual chains at equal spacing of 500 to 1,000 feet along the length of a channel. In this case a single chain is put on the centre-line of the channel at each location along the reach where measurements are desired. By plotting the data of scour and fill it can be determined whether along one portion of the reach net scour is taking place and perhaps in another reach net fill is taking place.

It should be remembered, however, that whether the chains are located individually at the centre-line of the section or several chains on a cross-section, the chains record only the maximum depth of scour at each individual point. It may be that during an individual flood one portion of the stream channel will be scoured while another portion of the same cross-section will simultaneously be filling. Then, during another part of the same flood the situation will change and the part which had previously filled will then scour. The cross-section of scour plotted from the several chains on the cross-section will indicate the maximum amount of scour but not necessarily implying simultaneity in the occurrence of that scour.

DEPTH OF FLOW

A technique has been developed by the United States Geological Survey for recording in a very simple fashion the maximum depth of water attained between individual measurements. The simple instrument is called a "crest-stage gauge". Standing vertically at the stream bank is a piece of iron pipe, perforated near the bottom and the top and capped at each end. At the base of the pipe, and resting in the bottom cap, is sprinkled some burnt cork. Standing vertically inside the pipe is a wooden stick, ordinarily marked with graduations.

When rising flood water enters the crest-stage gauge, the water in the pipe will be approximately level with the water in the channel. The burnt cork rises inside the pipe, and when the water begins to fall the cork tends to stick to the wooden rod enclosed in the pipe. This accumulation of cork indicates the highest water level attained. When the observer comes to look at the crest-stage gauge he removes the cap at the top of the vertical pipe, draws out the wooden rod, and notes the elevation of the water-mark indicated by the burnt cork.

MOVEMENT OF INDIVIDUAL ROCKS

The ability of specific flows to move rocks of various sizes can be determined by painting individual rocks and placing them on the stream bed. After an individual flow the channel is searched and all the painted rocks recovered, their positions plotted on a map and the necessary data recorded regarding their distance of travel and place of origin. In order to do this it is necessary to have each rock specifically identifiable. This has been accomplished by weighing each individual rock before it is placed on the stream bed.

It has been found that a cement-base paint lasts best under conditions of intense sunshine and of tumbling by floods in the stream channel. Bright colours are ordinarily desirable. After the rock has been painted a number is painted, in a different colour—the number being the weight of the rock in grammes. Weight expressed in three to five digits gives such a large number of combinations that no individual set of numbers is likely to be repeated.

In the experiment we are conducting in an ephemeral stream in New Mexico, the rocks painted vary in size from about 3 to 15 inches in diameter. They have been sorted by size classes. The experiment has as one objective the determination of the importance of spacing, or distance apart, of individual cobbles relative to their resistance to movement by flows of varying sizes.

One of the results of the experiment, for which four years of data are available, is that the travel distance of individual rocks during a given flow is amazingly independent of the size of the rocks. One might suppose that there would be a tendency for the small rocks to be carried farther downstream in a given flow than the large ones. This finding applies to cobbles and gravel occurring as a minor element in an ephemeral stream bed composed principally of sand.

One of the other particularly interesting and unexpected results of these observations is that the cobbles lying in a stream bed consisting primarily of sand and, containing only an admixture of gravel, are not uniformly distributed through the sandy alluvium. Rather there is a tendency for all the cobbles and gravel to lie at or very close to the surface. Not only is this a characteristic of the cobbles which occur naturally in the stream channel but also of those placed in the stream for the experiment.

Corroborative evidence was obtained in drilling holes for the placement of chains. Nearly all of the cobbles and boulders encountered in drilling the holes were immediately at the surface. Below that, through a section of three or four feet of sand, practically no cobbles were encountered.

The explanation of the tendency for the large rocks to appear on the surface of a sandy stream bed appears to lie in the effect of the dispersive grain stress of Bagnold.[1] The dispersive stress increases as the square of the grain diameter, and is greater on large than on small rocks. There is a tendency, therefore, for the rocks sustaining the largest amount of dispersive stress to be pushed toward the zone of zero dispersive stress, which is the surface of the stream bed.

After this was first observed in the experiment on the ephemeral streams, a check was made in gravelly streams in eastern United States, and the same tendency was found there. The largest rocks seemed to be concentrated near the stream bed surface.

ROCK MOVEMENT IN HEADWATER EPHEMERAL RILLS

In large channels the marking of individual rocks for observation of their movement requires the weighing of each individual cobble. In small, upstream rills the distance any individual rock is likely to move is considerably smaller and a more simple technique may be employed.

Starting at the mouth of an ephemeral rill, the drainage area of which may be several acres, individual rocks are picked out of the channel for painting. In a channel where the grain size varies from sand to 4-inch gravel, the rocks chosen are of a relatively uniform size between 2 to 4 inches in diameter. Once the size has been chosen in an individual rill, all rocks painted should be close to that same size.

The rocks are located at 10-foot intervals along the stream channel beginning at the chosen downstream point. After being completely coated with paint, the individual rocks are placed at uniform intervals up the thalweg of the rill.

When the initial coat of paint has dried, the rocks are numbered in a new colour, the numbering system beginning at the most downstream point, and each number represents the distance in feet upstream from the base point. Thus, the rock placed 250 feet upstream from the base line will carry the number 250. At the time of resurvey, the movements of individual rocks can be easily distinguished owing to the fact that the painted rocks will no longer be equally spaced, nor will they be in consecutive order.

The purpose of this type of observation is to determine how far individual rocks will move in storms of a given size. Further, it would be desirable to know whether rocks of a given size located in the steeper headward positions of a rill move farther or less far than those downstream in the same channel.

The technique described is so simple that it may be employed with little effort in a number of rills in a given area. In the New Mexico experiments, adjacent rills have been chosen for such study representing different amounts of topographic relief. To date, however, the painted rocks have all been of a uniform size, 3 to 4 inches in diameter. Such observations should be extended to determine the relative distance of movement of rocks of different sizes in similar rills.

PINS TO MEASURE RATES OF EROSION

The following technique is being used in the New Mexico experiment to measure the rates of erosion on hill slopes. Iron pins or nails, 6 to 8 inches long, are slipped through a large washer and driven into the ground in a vertical position until the head of the nail and the washer are flush with the ground surface. Erosion undermines the washer, which then falls down the length of the pin. The pin protrudes above the washer at a distance equal to the erosion during the intervening period.

A series of such pins are laid out in a grid system on a hillslope so that the amount of hillslope erosion between observations can actually be mapped in the form of a topographic map of erosion quantity.

Techniques to measure erosion on slopes, quite apart from the scour and fill of rills and channels, is a matter of considerable geomorphic interest. Much has been written about amounts of sheet erosion as judged by individual plants existing on pedestals or stools above the present land surface. However, there is always considerable doubt in attempting to explain why vegetation stands on pedestals. Accumulation of windblown sand and silt around and in the crown of a shrub will gradually tend to build a similar mount or pedestal. Therefore, unequivocal measurement of erosion during specific periods of time will yield data now lacking in the geomorphic literature.

It is particularly important that these kinds of measurements be obtained under various conditions of soil and topography and in various parts of the world in order to improve our general knowledge of relative rates of erosion under different conditions. Furthermore, because most experimental areas contain precipitation gauges, it may be possible by the accumulation of such data to improve our knowledge of the relation of erosion rates to rainfall characteristics.

1. R. A. Bagnold, "The flow of cohesionless grains in fluids", *Phil. Trans. Roy. Soc. Lond.*, vol. 249 (1956), p. 235-297.

FORM AND GRADIENT OF DEPOSITION BEHIND BARRIERS

It was once supposed that when a barrier was put in a stream channel, lifting the local base level, there would be a tendency for a wedge of deposition to accumulate behing this barrier and, in time, gradually to work headward. The end result might be to lift the streambed elevation at all points upstream by an amount of the same order of magnitude as the height of the barrier. Actual experience has shown that this is definitely not the case; rather, the deposition above a barrier generally consists of a wedge thinning upstream. The deposition as a result of the barrier extends upstream a shorter distance than one might have supposed.

Surveys of the grade of deposition behind barriers in ephemeral stream channels have indicated that the deposition appears more to be related to the initial slope of the channel than to any other factor. The distance upstream that the wedge extends depends principally on the percentage of the original gradient represented by the gradient of the deposited wedge. These percentages of original gradient vary from 30 to 60 per cent under the few conditions where such measurements have been made. Here, again, much can be learned by extending these observations to other combinations of lithology, climate, and topography.

For such observations, only the simplest kind of barrier need be constructed. We have constructed small check dams out of rock or cement blocks so that the barrier stands only 2 to 3 feet above the original stream bed elevation. Even with such small check dams, much can be learned about the grade of deposition upstream and further studies should provide improved knowledge of the effect of the size of bed material, slope, and other factors.

STAKES FOR THE MEASUREMENT OF SOIL CREEP OR MASS MOVEMENT

It has been our observation that, even in arid regions, a surprising amount of downslope soil movement occurs through soil creep. In an attempt to measure the magnitude of such mass movement, the following techniques are now in use.

A line is chosen essentially parallel to a contour on a slope where the rate of soil creep is to be measured. At 5- to 10-foot spacings along the length of this line, small iron rods or pipes are driven into the ground. The stakes should be of the order of 7 to 12 inches long and will protrude one-half to one inch. They are generally driven as nearly vertical as possible. The alignment of the stakes on the chosen measurement line should be as accurate as possible. The two ends of the line are monumented and are located in such a place that the monuments themselves are subject to no downhill motion. The ends of the lines thus may be an iron stake driven 4 to 5 feet deep and located at the crest of a spur, or might be a nail driven into the trunk of a large tree located on a spur. At least one of the monuments at the end of the cross-section line should be of such a nature that a transit can be set up directly over the monument. The transit is then oriented to the centre line of the monument at the far end of the line and the individual stakes along the line are so aligned. After each stake is driven an indelible notch is made with a file across the top of the iron stake, the file mark being as close to the line of sight of the instrument as possible.

In the resurvey the transit is again set up over the monument at one end of the line, oriented, and the downhill movement of each individual iron stake is measured from the line of sight.

It has been our practice to make such a line not more than 100 feet long because of the requirements for accuracy in the placement of the individual stakes.

Results to date have shown downhill movement averaging about 0.75 inch per year in alluvium of sandy silt standing at about 30° slope.

SUMMARY

The techniques just described have been found both practical and profitable. The types of measurements described are considered to be both useful and simple. Their utility, however, will depend to a great extent on whether a sufficient variety of observational sites will gradually become available. It is hoped that other scientists will try these methods and data will be collected under the widest possible variety of conditions of climate, topography, and vegetation.

RÉSUMÉ

Expériences sur le terrain en vue de l'étude géomorphique des effets des variations climatiques (J. P. Miller et L. B. Leopold)

Les mécanismes et les vitesses des phénomènes de surface présentent un intérêt vital pour les géomorphologistes parce que la connaissance du présent facilite l'interprétation de l'histoire géomorphique. Les régions arides se prêtent particulièrement aux études sur le terrain des phénomènes d'érosion et d'alluvionnement, du fait que les modifications y sont assez rapides pour être mesurées facilement. Dans les régions de relief appréciable et de constitution rocheuse uniforme, en particulier, il est possible de délimiter les influences de conditions climatiques différentes. Pendant plusieurs années, les auteurs ont effectué des recherches sur l'érosion et le mouvement des sédiments dans des stations situées près de Santa Fé, au Nouveau-Mexique. Les vallées de cours d'eau éphémères dans cette région ont été soumises au cours des derniers millénaires à plusieurs cycles successifs d'érosion et de dépôt et l'archéologie et le carbone radio-actif permettent de connaître avec précision la chronologie de ces phénomènes.

Parmi les phénomènes qui font l'objet de cette enquête, on mentionnera notamment : *a*) l'érosion sur les pentes ; *b*) l'effet d'un relèvement du niveau de base sur de petits cours d'eau ; *c*) le transport de sédiments grossiers dans les cours d'eau, étudié en utilisant des pierres peintes ; *d*) l'érosion et l'alluvionnement dans le lit des cours d'eau. L'étude rassemble également des données climatiques et hydrologiques sur la question. Les résultats préliminaires montrent que des stations sur le terrain organisées pour recueillir des données spécifiques pendant plusieurs années permettent d'étudier, de façon très efficace et à peu de frais, de nombreux problèmes posés par la dynamique et la morphologie des cours d'eau.

DISCUSSION

F. A. Van Baren. Did Dr. Leopold in his earth-movement experiments take into account differences in types of soil, their physical properties and, specifically clay, mineralogical character? Differences in soil might explain the unexpected behaviour of the soils in the sites chosen for the experiment.

L. B. Leopold. Indeed, the importance of soil types and local development of soil structure cannot be overlooked. Recalling that the present one is merely a progress report, it will perhaps be understood that no attempt has been made to explain how the soil factor enters. If other scientists would make similar measurements, we may accumulate enough data to be analysed for the effects of such factors.

C. Voûte. I would like to emphasize the importance of experiments of the type undertaken by Dr. Leopold. A few years ago a general survey was made of the Niger and Benue rivers in Nigeria in order to find ways of improving the efficiency of shipping on these rivers. One of the problems put before us was to determine how the rivers are behaving. This raises problems which cannot be answered by geologists or geographers on account of their studies only.

J. Namias. Can you give us some indications of plans to correlate the very interesting data you are assembling with meteorological parameters (e.g. rainfall intensity, duration, etc.)?

L. B. Leopold. In the New Mexico experiment, a network of about 10 simple rain gauges are maintained. Streamflow is measured at two recording stations in the 4-square-mile area. Flow measurement in ephemeral streams is not possible by standard methods, however, because of channel scour. The method of chains, explained in this paper, provides a measure of channel scour. Together with slopes of the water surface from high water marks, the peak discharge may be computed.

The present report is only a progress report. No quantitative correlations have yet been carried out but in some work already published we have shown how the combination of winter freezing frequency and stream-flow appears to govern the rate of river-bank erosion near Washington, D.C., on a single study reach of Watts Branch (see: M. G. Wolman, "Measurements of streambank erosion", *Trans. Amer. Geophys. Union, circa* 1958).

C. S. Christian. I would like to support the experimental approach referred to by Dr. Leopold. Apart from wanting to know what has happened geomorphologically in the past, and why it has happened, we are also interested, in the practical sense, to know something about the present balance between the landscape and climate. There is frequently a very delicate balance between climate, landscape and land use. If climate and landscape are already balanced it is important to know this in order to understand the potentials and problems of the land surface.

With reference to the comment about studying the movement of sediments in large streams I might mention the use of radioactive isotopes as is being done for instance in the Hunter River of New South Wales in Australia.

O. M. Ashford. Experiments of the kind described could also be done in the laboratory where conditions could be controlled. What are the essential advantages of the field observations?

L. B. Leopold. A large laboratory programme in hydraulic flumes is being carried out by the United States Geological Survey. The problem is that more attention has been paid in the past to laboratory methods owing to the complications of field conditions. The present work, preliminary as it is, is intended to bring to field conditions quantitative measurements of factors not represented in the laboratory. Also, the laboratory misses one of the most important factors in geomorphologic work—that of time. The measurement methods described here have their value in time effects, and it is our duty to scientists of the future to provide data that can be compared with conditions found by them at their time. The long-range importance of documentation has been realized by many, but few are willing to invest time and work now for the use of future scientists. I emphasize the point made in the present paper that copies of the records taken currently must be stored in several places lest one set of the data is lost. Also field ties to recognizable and ineradicable points on the ground are essential to obtain the full future value of current observations.

E. Kraus. Dr. Leopold, have you measured the downstream dispersion of your groups of stones? Is it small compared to mean displacement?

L. B. Leopold. The downstream lateral dispersion of rock groups is limited by channel width whereas the longitudinal dispersion is nearly unlimited. We have shown positions of individual rocks in the channel on maps, and so some record is available. The record is probably too crude to be acceptable for studies of rates of lateral dispersion of point sources. Also, rocks tend to move toward the inside or convex bends of channel curves so this is also a limitation. When rocks have moved around several bends in the channel during the downstream transportation of a mile, lateral position in the channel is not governed by dispersion theory, for factors other than random are overpowering.

G. B. Maxey. What is the value to your studies of historical data, photos, surveys, and questioning of long-time residents in the immediate vicinity of the stream?

L. B. Leopold. All historical information that has quantitative significance should be utilized. Surveys for railroads, highways, and early maps are often good sources. Old photographs that may be retaken from the same place show changes, but it is very difficult to make quantitative assessment of those changes from photographs. Also photography so far gives only a few years of time span for comparison. An example of the use of photographs and old records is the paper "Vegetation of southwestern watersheds during the nineteenth century" by L. B. Leopold, *Geographical Review* (*circa* 1952).

M^lle^ A. R. Hirsch. La communication du D^r^ Leopold m'a vivement intéressée car, parmi les recherches faites au Centre de géographie appliquée de Strasbourg, nous avons été amenés à étudier de nombreux cours d'eau. Nous avons également cherché à avoir des méthodes simples. Nous employons aussi la méthode des « mires » pour étudier le déplacement des alluvions. En plus de la méthode des traceurs radio-actifs des particules fines, nous avons procédé à des repérages très précis par photographies que nous repérons à intervalles réguliers.

Pour ce qui est du recul des berges et de l'évolution des ravinements, nous employons également la méthode des photos-repères, appuyée par des levés topographiques qui peuvent nous donner des précisions de l'ordre de 50 cm.

RELATIONS DES FLUCTUATIONS CLIMATIQUES AVEC L'HYDROLOGIE, L'AGRICULTURE ET L'ACTIVITÉ HUMAINE EN AFRIQUE DU NORD

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INTRODUCTION

Depuis le début de l'époque néolithique, les hommes ont fait des tentatives pour prévoir le temps. La première tentative scientifique a été faite dans la zone aride par les astrologues chaldéens, et Ptolémée en a donné un exposé [1].

Il ne paraît pas inutile d'examiner ici les raisons de son échec. Ptolémée constate que chacun des événements de l'univers a une action sur l'ensemble des événements du reste de l'univers. En particulier, le groupe des événements extraterrestres a une action sur le groupe des événements terrestres. Connaissant les uns, on doit pouvoir déduire les autres, si on a observé un nombre suffisant de coïncidences. Or, les événements les mieux connus à l'avance semblaient être les événements astronomiques, dont on pouvait prévoir le retour plusieurs années à l'avance. Même en faisant abstraction de l'astrophysique, à peu près inconnue à l'époque, le groupe des événements astronomiques se révélait d'une complexité inouïe bien que moindre apparemment que celle du groupe des événements terrestres. Il fallait, pour s'attaquer à ce problème, une forte dose d'optimisme scientifique. L'optimisme fut dans ce cas tellement exagéré qu'il conduisit au discrédit de la science et fut une des causes de la stagnation constatée à partir du début du premier millénaire de notre ère.

Il est clair que les facteurs fondamentaux du climat et de l'évolution du temps n'étaient pas soupçonnés, et on faisait abstraction de ceux qui intéressaient directement le substratum des événements à prévoir. Les connaissances de base étaient insuffisantes.

Ces considérations peuvent paraître oiseuses. Je voudrais cependant être persuadé que certaines méthodes modernes de prévision à longue échéance, soit en météorologie, soit en hydrologie, ne présentent pas un caractère utopique de base du même type que celui relevé dans le système des astrologues.

D'autre part, une remarque fondamentale s'impose : le problème des variations du climat dans leurs rapports avec l'activité humaine est un problème historique, en raison du jeu des facultés d'adaptation des règnes de la nature et de l'homme lui-même. Si l'histoire avait été différente, l'humanité aurait évolué différemment. La situation actuelle est un événement unique et la situation qui se présentera, dans cent ans ou mille ans, sera aussi un événement unique, intégrant tout le passé. Comment surmonter les difficultés dues à l'historicité du problème ?

Le fait nouveau du XX^{e} siècle, est l'activité scientifique et technique de l'homme. L'évolution rapide de ses moyens de connaissance de la nature et de ses moyens d'action.

Ces considérations amènent à délimiter comme suit les champs d'investigation efficaces en matière de variabilité du climat.

1. En raison du développement rapide des moyens de connaissance on commence à dégager des facteurs d'évolution fondamentaux. Certains phénomènes physiques et astrophysiques efficaces ont un déroulement assez rapide pour qu'on puisse effectivement en observer les modifications pendant un petit nombre de générations : fluctuations des glaciers, niveau des mers, etc. Il est évident que ce champ d'investigation s'étendra énormément avec la précision des méthodes de mesure et avec le perfectionnement des méthodes de datation des événements passés dont la trace subsiste.
2. Étant donné la puissance des moyens d'action de l'homme, on peut déjà commencer à dégager des facteurs de modification du climat qui peuvent être à sa portée ; modification des états radiatifs de la biosphère, et des couches extérieures ; modification de l'état de surface des continents, augmentation du taux d'anhydride carbonique de l'air, etc.
3. Il est possible enfin d'examiner les fluctuations du climat actuel dans leurs rapports avec l'hydrologie,

1. Voir Ptolémée. *Tetrabiblion*. London, Heinemann. (Loeb Classical Library.)

l'agriculture et l'activité humaine. Le climat actuel est en effet caractérisé non seulement par les valeurs moyennes de ses éléments, mais encore par les fluctuations autour de ces valeurs.

Je me limiterai à quelques remarques sur le troisième champ d'investigation, en me référant principalement aux régions arides d'Afrique. Le caractère principal du climat de ces régions est non seulement la sécheresse, mais l'importance relative des fluctuations autour des éléments du climat moyen.

LA STABILITÉ DU CLIMAT EN AFRIQUE DU NORD AU COURS DE LA PÉRIODE HISTORIQUE

Les renseignements historiques les plus anciens pour notre sujet sont fournis par Hérodote (450 av. J.-C.). Dans une étude en cours de publication (Tixeront, 1962), nous avons procédé à une revision de l'interprétation du texte d'Hérodote et nous avons cherché à localiser les principales limites bioclimatiques en fonction de cette interprétation: *a*) limite de culture sèche dans le domaine méditerranéen pour l'olivier: isohyète de 180 à 200 mm ; *b*) limite de la zone forestière et de la zone steppique caractérisée par la végétation et la faune: zone à sangliers et zone à gazelles.

Les limites repérées d'après Hérodote concordent avec les limites actuelles.

D'autre part, les genres de vie décrits par Hérodote coïncident géographiquement avec ceux qui ont été décrits pour l'époque actuelle par Capot-Rey dans une étude sur le nomadisme présentée au colloque de l'Unesco en 1960.

Ces modes de vie étaient établis bien antérieurement à Hérodote. Les méthodes de culture sèche méditerranéenne ont été mises au point avant le deuxième millénaire en Orient, et leur introduction en Tunisie doit dater de la fin de ce millénaire.

Nous nous sommes crus autorisés à conclure que le climat, avec son aridité et son régime de fluctuations, ne s'était pas modifié en Tunisie depuis le début du premier millénaire avant notre ère.

Les mêmes conclusions peuvent être tirées des auteurs postérieurs à Hérodote, en particulier de Salluste (premier siècle avant notre ère), et de toute une série d'autres arguments: l'espacement des oliviers qui convenait à la culture sèche à l'époque romaine est le même que celui qui convient actuellement; les espèces de plantes cultivées sont les mêmes, mises à part les introductions d'espèces postérieures à l'époque romaine; les puits et les captages d'eau romains peuvent être remis en fonctionnement; c'est ainsi qu'on a remis en fonctionnement les captages de Zaghouan et l'acqueduc d'adduction à Carthage, les galeries de captage de Feriana, El Djem, etc.

LE CLIMAT ET LA VÉGÉTATION

La couverture végétale naturelle s'adapte à la balance des précipitations et de l'évapotranspiration, en tenant compte de la capacité du sol pour les réserves d'eau et d'éléments fertilisants. Les sols eux-mêmes résultent du jeu combiné du climat et du substratum.

Nonobstant cette complexité, la couverture végétale ne peut être que discontinue dès que la pluie est inférieure à l'évapotranspiration potentielle. Cette discontinuité peut se produire dans le temps et dans l'espace, et les plantes de la zone aride se sont adaptées à ce régime au cours de l'évolution. Elles se sont aussi adaptées au régime des fluctuations climatiques.

Les graminées, en particulier, couvrent le sol une partie de l'année quand la pluie a été suffisante. A la fin de la saison pluvieuse elles se flétrissent et laissent leurs graines dans le sol. Si la pluie est toujours suffisante, elles recommencent au début de la saison pluvieuse suivante leur cycle végétatif. Si elle est insuffisante, beaucoup de graines resteront dans le sol sans germer pendant une ou plusieurs années. Revienne une période d'abondance, et la couverture se reconstituera par germination des graines mises en réserve ou par dissémination à partir des lieux de refuge constitués par les zones les plus humides.

La végétation broussailleuse et arbustive lutte contre les fluctuations par son profond système radiculaire qui explore un grand volume de sol. Elle lutte aussi par la variation de turgescence des feuilles, et la variation de leur orientation. Lors des sécheresses exceptionnelles (comme ailleurs après les périodes de gelées ou d'inondations exceptionnelles), les feuilles des oliviers tombent. La vie se retire dans les racines, les troncs et les grosses branches, d'où le feuillage se reconstituera par bourgeons à la reprise des pluies normales.

Les plantes disposent ainsi d'une plasticité naturelle acquise, vis-à-vis des fluctuations climatiques, et leurs moyens d'adaptation sont complétés par ceux des animaux et ceux des hommes.

Les plantes cultivées doivent de toutes façons s'adapter à ce régime: le blé, par exemple, d'après les mesures du Service botanique de Tunisie, a besoin pour sa végétation normale de 350 mm d'eau par an. Sa culture sans concentration d'eau n'est donc possible en Tunisie qu'au-dessus de l'isohyète de 350 mm en rendement normal.

La culture des arbres rencontre une autre limite, qui a été déterminée pratiquement depuis un temps très reculé dans les régions méditerranéennes, mais qui peut se justifier par un raisonnement hydrologique schématisé comme suit: soit un olivier dont le feuillage couvre une surface de 50 m^2, chiffre normal de la région de Sfax. Son besoin d'eau est de l'ordre de 1,40 m par mètre carré de surface. Il est à prélever sur le volume de pluie utilisable, qui tombe sur l'impluvium réservé à l'arbre.

Malgré toutes les façons culturales pratiquement réalisables, l'évaporation par le sol ou les mauvaises herbes ne peut être complètement évitée. Elle constitue un seuil qui est de l'ordre de 80 mm dans les sols de la région de Sfax. On peut évaluer en conséquence la surface d'impluvium nécessaire aux arbres et leur espacement:

Pluie annuelle (mm)	Pluie utile annuelle (mm)	Superficie d'impluvium (m^2)	Espacement des arbres (m)
80	0		
150	70	1 000	32
200	120	600	24
250	170	400	20

Or, au-dessus d'un certain espacement de l'ordre de 25 m, l'olivier n'arrivera plus à prospecter par ses racines la superficie nécessaire, et les façons culturales deviendront prohibitives.

La limite pratique de la culture sèche de l'olivier sur l'isohyète 180 à 200 mm est ainsi justifiée pour le sud de la Tunisie.

Le fait qu'Hérédote, dans son énumération des tribus côtières de Tripolitaine et de Tunisie, place la limite des nomades et des agriculteurs au point où se rencontre actuellement cette limite est à mon sens une des plus fortes présomptions de la permanence du climat depuis le premier millénaire avant notre ère.

Au-dessous de cette limite, l'agriculture sans concentration d'eau n'est plus possible. Le territoire ne peut être mis en valeur que par l'élevage, qui fait intervenir la plasticité de l'animal, ou par les techniques de concentration d'eau: dérivation des eaux de crue ou irrigation par eaux souterraines.

CLIMAT, ÉROSION ET SÉDIMENTATION

Les résultats des observations sur le débit solide des cours d'eau en Algérie et en Tunisie ont été présentés aux réunions du congrès de l'UGGI à Helsinki en 1960 (Tixeront, 1960). Nous nous bornerons à reprendre ici quelques remarques fondamentales pour une application correcte des données géomorphologiques à la climatologie.

La teneur des eaux de ruissellement en matières en suspension en régime méditerranéen est d'autant plus forte que l'aridité est grande. La moyenne annuelle varie de 1 à 50 kg par mètre cube d'eau, le maximum étant atteint dans les bassins à pluviosité moyenne de moins de 400 mm, et le minimum dans les bassins les plus arrosés. Par contre, les taux d'abrasion sont beaucoup moins variables: de 500 à 1 500 T/km^2 par an, pour des bassins à pluviosité comprise entre 400 et 1 500 mm par an.

Un examen superficiel du terrain peut conduire à des conclusions trop hâtives, en surestimant l'abrasion dans les zones sèches par rapport à ce qu'elle est dans les zones humides. Dans ces dernières, les traces d'érosion sont rapidement et continuellement effacées après arrêt des ruissellements par l'activité végétale, par l'activité des organismes animaux et par les labours. Dans les premières, au contraire, les traces d'érosion peuvent rester fraîches très longtemps. Pensons que les traces des engins blindés de la campagne de 1943 sont encore très nettement visibles dans le Sud tunisien.

La principale cause climatique du déchaînement de l'érosion en l'absence d'action humaine est l'existence d'un arrêt végétatif, avec diminution massive, ou même totale, de la couverture végétale au moment des pluies de début de saison qui peuvent être des pluies orageuses très violentes. Cela se produit aussi bien en climat méditerranéen à saison sèche chaude, qu'en climat tropical à saison sèche froide. C'est donc la répartition saisonnière des précipitations qui joue le principal rôle dans l'érosion, plutôt que la moyenne, tout au moins dans les zones à hauteur de précipitations supérieure à 200 mm, les seules pour lesquelles nous disposons d'observations régulières.

Si on fait un barrage réservoir sur un cours d'eau, la principale masse des sédiments qui viennent s'y déposer est constituée par des éléments fins. Par contre, le lit des cours d'eau non barrés est en général constitué par des sédiments beaucoup plus grossiers. En remontant vers l'amont, les sédiments deviennent plus grossiers, et l'on constate des développements très étendus de colluvions à éléments grossiers.

Dans les lits d'oued les éléments grossiers sont en réalité des résidus de lavage, et ne peuvent par suite donner une idée suffisamment exacte de l'abrasion. Il en est de même des colluvions.

Au cours d'une vaste durée géologique sans mouvements tectoniques, la surface des bassins et le profil des cours d'eau tendent à se régler sur des pentes dites d'« équilibre », le long desquelles l'érosion est minimum. Les fortes pentes se trouvent sur les parties de bassins constituées par des roches dures, et l'érosion y est très faible. Dans de telles situations il est impossible d'imaginer comment peuvent se constituer les colluvions à éléments grossiers. Il n'en est pas de même en périodes d'activité tectonique, où des couches peu résistantes en voie de surrection peuvent donner lieu à des démantèlements puissants responsables des colluvions dont nous cherchons l'origine. Ces couches ne se conservent que si elles sont protégées par un revêtement extérieur. Nous avons fait remarquer dans l'étude visée en référence qu'en Algérie, les bassins où l'abrasion est la plus forte sont justement des bassins en état d'instabilité (tremblements de terre, et inversion de relief par rapport à la dureté des roches). On y trouvera également des exemples de l'influence du substratum. D'autres faits mettent en évidence l'importance d'une activité tectonique pendant toute la période quaternaire: *a*) sédiments de Gafsa redressés à plus de 30° et contenant une industrie paléolithique; *b*) formation des sources de Tozeur et de Nefta par érosion du toit d'une nappe souterraine contemporaine du plissement de ce toit; *c*) exceptions nombreuses au principe eustatique dans les mouvements du niveau des mers, mené à l'époque quaternaire: plages surélevées, datées d'une époque depuis laquelle le niveau de la mer n'a pu que s'élever; *d*) fosses de subsidence et aires de sédimentation encore actives (plaine de Kairouan par exemple).

Il paraît par suite impossible de tirer, pour les paléoclimats, des déductions sûres et générales des observations d'érosion et de sédimentation sans considérer dans chaque cas la nature du substratum et la situation tectonique.

CLIMAT ET ÉCOULEMENT

Les répercussions du climat sur l'écoulement des bassins commencent à être connues quantitativement. Comme la végétation, les écoulements sont sous la dépendance de la pluviosité, de l'évapotranspiration potentielle et du substratum.

Dans les régions désertiques, les coefficients d'écoulement varient dans de très larges limites suivant le substratum et la répartition des averses. Pour fixer les idées, ils peuvent varier de 0 à plus de 50 %, les plus forts coefficients ayant, à ma connaissance, été mesurés sur sols squelettiques gréseux dans le massif de l'Ennedi (Off. rech. sci. techn. outre-mer, 1957, 1958). Cependant, sur de très grands bassins, avec prépondérance de substratum imperméable et de sols bien constitués, les coefficients sont très faibles. Pour ce genre de bassins, nous avons établi en Tunisie une relation entre l'écoulement, la hauteur de pluie annuelle et la hauteur d'évapotranspiration annuelle. Cette relation serait bien entendu en défaut pour une région à été pluvieux.

Quoi qu'il en soit on peut, semble-t-il, aborder maintenant quelques problèmes de paléoclimatologie en se basant sur les écoulements.

Prenons le cas du Sahara septentrional, on a de nombreuses raisons de croire qu'il était avant le deuxième millénaire avant notre ère nettement plus pluvieux qu'actuellement. Il devait donc alimenter des cours d'eau plus puissants capables de parvenir à la dépression des chotts du Sud algéro-tunisien. On peut tâcher de délimiter, par des recherches sur le terrain, l'extension des lacs ainsi formés, et remonter à la pluviosité annuelle.

Au sud du Sahara, un bassin tropical de 600 000 km^2 recevant une moyenne de 1 100 mm de précipitation alimente un plan d'eau de l'ordre de 10 000 km^2 dans la dépression du Tchad, avec un ruissellement de l'ordre de 60 mm, mais il s'agit d'une zone chaude, à été pluvieux. Les formules tunisiennes appliquées au Sud algéro-tunisien donneraient, avec le régime méditerranéen, pour un bassin et un lac ayant les mêmes superficies, une moyenne de l'ordre de 500 mm de précipitation avec un ruissellement de l'ordre de 40 mm. Le ruissellement actif proviendrait bien entendu des plus hauts reliefs du bassin avec des hauteurs de précipitation avoisinant 1 000 mm.

Cet exemple a simplement pour but d'attirer l'attention sur des recherches hydrologiques susceptibles de recouper les résultats obtenus par les autres méthodes pour la paléoclimatologie.

L'ADAPTATION DE L'AGRICULTURE AU CLIMAT

La culture des céréales et l'élevage des animaux domestiques ont vraisemblablement vu le jour dans les régions semi-arides entourant la Mésopotamie[1]. Ces inventions ne furent possibles qu'à un stage avancé et relativement récent de l'évolution humaine. Elles constituèrent le pas capital dans la voie de la maîtrise de la nature. Elles permirent une vie stable dans les régions arides, où il fallait adapter une production de ressources permanentes à un cycle climatique comportant un long arrêt végétatif.

Elles se transmirent rapidement à toute la zone aride et nous voyons la Tunisie, dès le deuxième millénaire avant notre ère, en possession des techniques de culture sèche. La culture des oasis avait même peut-être précédé la culture sèche. Ces techniques se sont conservées jusqu'à nos jours.

Il est tentant d'essayer de les confronter avec les acquisitions de l'hydrologie scientifique. Cette confrontation révèle une excellente adaptation au climat et à ses fluctuations (Tixeront, 1961).

Nous avons fait état plus haut d'un seuil de pluie annuelle de 200 mm au-dessous duquel on ne peut pratiquer que l'élevage et la culture par concentration des écoulements. Les figures 1 à 4 donnent des exemples de culture par concentration des eaux de ruissellement. La figure 1 montre des cultures de thalweg par barrages en escalier dans la montagne de Tatahouine en un point où la pluviosité est évaluée à moins de 200 mm par an. Les oliviers sont énormes. Si on fait le calcul de leur évaporation, les impluviums se révèlent de qualité excellente, constitués par des bancs calcaires très squelettiques. Les taux de ruissellement sont de l'ordre de 10 %. Cette technique de culture est parfaitement adaptée aux conditions climatiques et hydrologiques. Sur le versant saharien des monts Matmatas, elle se pratique jusqu'à une ligne de 120 à 150 mm de hauteur de précipitations.

La figure 2 est relative à des cultures de céréales. Les impluviums sont, comme ceux de la figure 1, excellents, mais les céréales s'accommodent beaucoup plus difficilement que l'olivier des fluctuations climatiques. Aussi les méthodes de culture sont adaptées à cette contingence. Les superficies ensemencées dépendent des pluies de septembre à novembre. Les semailles sont faites très claires, à la dose de 25 à 40 kg à l'hectare. On profite ainsi de la plasticité de la céréale. Si les pluies sont insuffisantes, la récolte de grain sera nulle et on fera

1. Voir la communication de R. J. Braidwood, p. 251.

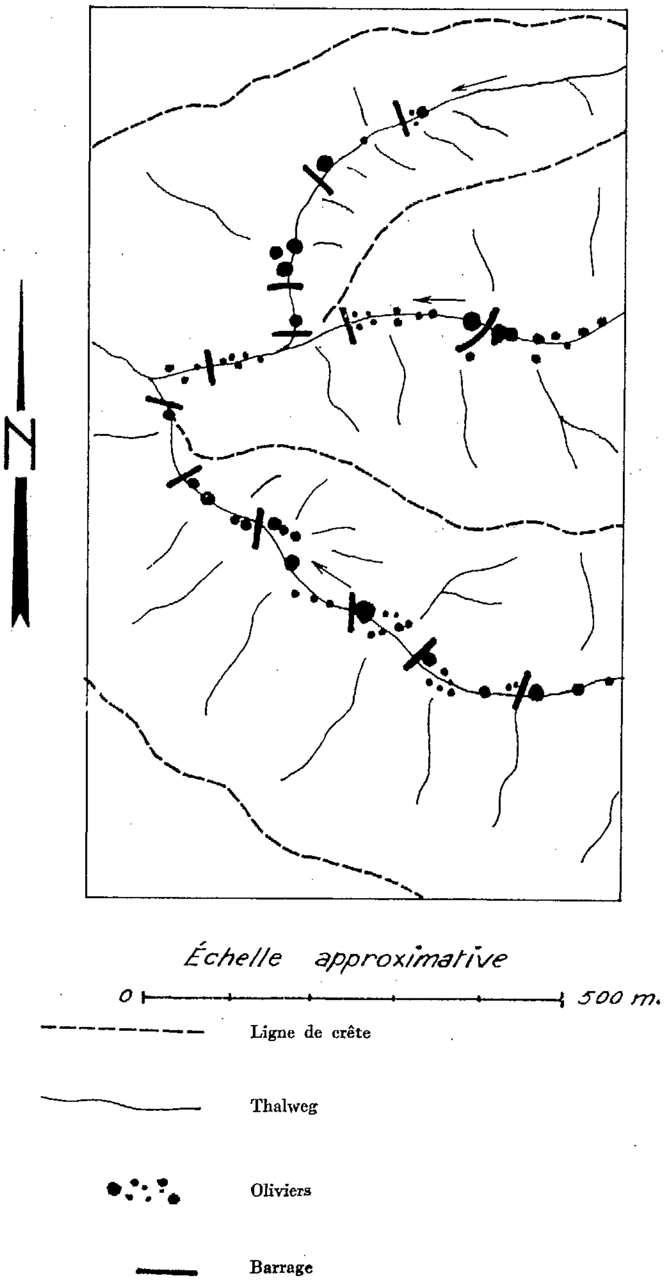

FIG. 1. Cultures d'oliviers en thalwegs dans les Matmatas (Tunisie).

pâturer le blé qui aura pu germer. Si la pluie augmente, le rendement augmentera. Si elle augmente toujours, chaque grain émettra plusieurs tiges qui porteront 10 épis et plus, et on atteindra les rendements de 100 pour 1, célèbres dans les annales des zones arides, avec des productions de grains par hectare du même ordre que sur les bonnes terres des régions humides.

Passons à l'élevage, seul possible dans la zone à pluviométrie inférieure à une centaine de millimètres. Il

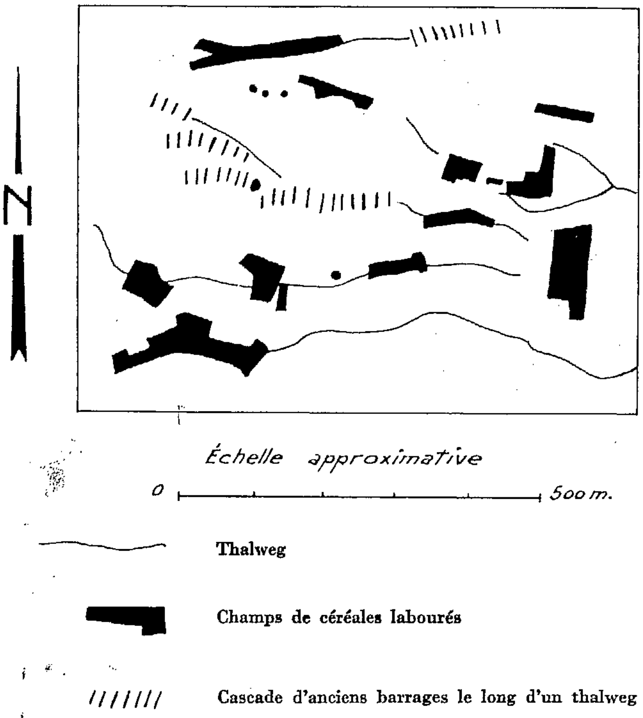

FIG. 2. Cultures de céréales en thalwegs dans les Matmatas.

est organisé de façon à utiliser la plasticité de l'animal et du végétal. Cette plasticité est surtout grande pour les animaux à vie courte et à cycle de reproduction rapide tels que le mouton et la chèvre. En cas de sécheresse, le bétail tire le parti maximum des végétaux à sa disposition. Il consomme d'abord la végétation aérienne vivante ou flétrie consommable et jusqu'à ses racines superficielles. Passé ce stade, le troupeau est obligé de se déplacer ou de diminuer d'effectif. Vienne une période pluvieuse, la couverture végétale se reconstituera rapidement grâce aux graines et aux racines profondes. Le troupeau se reconstituera vite grâce à son cycle de reproduction rapide. Le problème du chameau est différent. Son cycle de reproduction est plus long, mais il s'est adapté à la consommation des plantes salées qui habitent les bas-fonds et sont résistantes à la sécheresse.

L'élevage est non moins obligatoire que la culture par concentration des écoulements dans la zone aride. Supposons que le territoire se répartisse en 100 hectares d'impluvium pour 1 hectare de cultures. Comment va-t-on utiliser les impluviums ? La seule possibilité est d'y mettre du petit bétail rustique. Si on n'en met pas, non seulement on perdra son produit, mais la végétation naturelle augmentera de densité tout en restant inutilisable, et l'on devra réduire à moins de 1 hectare les cultures qui recevront moins d'eau. Nous sommes très loin de la notion « combattre la désertification par la suppression des moutons et des chèvres ». Les méfaits

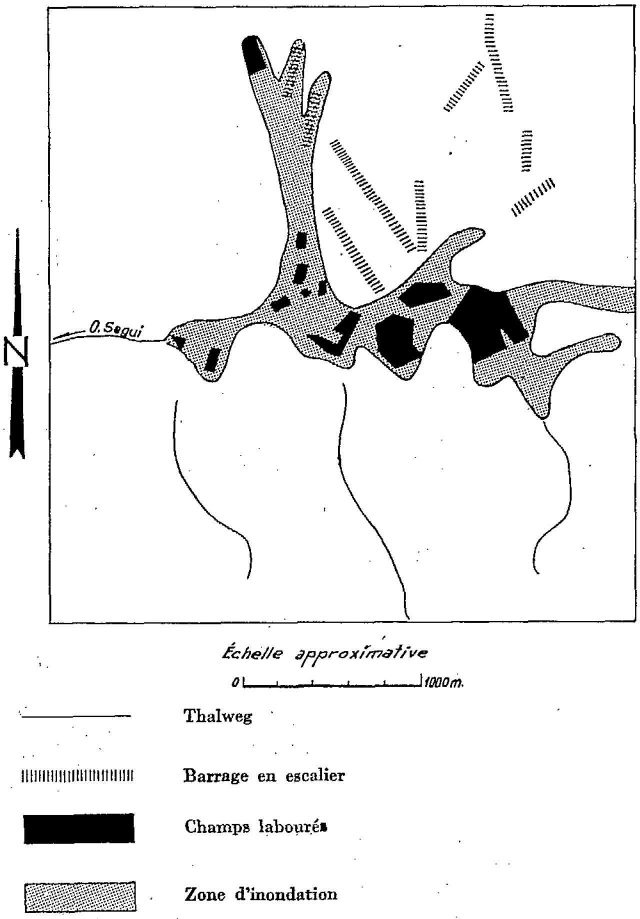

FIG. 3. Cultures de céréales en thalwegs : Oued Segui (amont).

de ces animaux sont, certes, très réels, mais ils paraissent cependant constituer un mal nécessaire dans les régions très arides.

Les procédés traditionnels témoignent donc d'une adaptation étroite de la nature et de l'homme au climat. Il est nécessaire d'analyser et d'apprécier les pratiques traditionnelles fondées sur une longue expérience. Ne pas en tenir compte entretient entre les populations et les experts des incompréhensions dont on a signalé de nombreux cas, et qu'on attribue un peu trop vite à l'esprit routinier des intéressés. Il n'entre pas dans mon propos d'étudier les moyens d'amélioration dont on dispose maintenant du fait du progrès des sciences et des techniques.

LES ASPECTS SOCIAUX DE LA VARIABILITÉ DU CLIMAT

Dans les cas examinés plus haut, l'utilisation maximum des ressources nécessite une population permanente et une population flottante. Les variations dans la distribution géographique de la pluie entraînent la nécessité de déplacements à l'intérieur de vastes régions. Une augmentation de la pluviosité, dans le cycle des fluctuations climatiques, appelle vers les zones arrosées au cours de l'année pluvieuse une foule de paysans venus des régions voisines où existent un minimum de ressources permanentes : oasis, villes, terres moins désertiques. Les années de sécheresse, cette population flottante se rétracte vers ses refuges et a recours à d'autres moyens de stabilisation qui ressortissent principalement au problème général des réserves. Ce problème, que j'ai eu l'occasion de signaler ailleurs (Tixeront, 1955), est immense et ne peut être abordé ici. Les terres à céréales représentées aux figures 3 et 4, par exemple, attirent, les années très pluvieuses, une population qui vient de 100 km à la ronde, des oasis de Gafsa, Kebili, Gabès et de toutes les terres de parcours du Sud.

L'existence même de la population flottante a joué dans le passé un rôle capital dans la transmission des civilisations de foyer en foyer à partir des lieux d'origine de l'agriculture. Elle explique la rapidité de transmission de la civilisation : *a*) par le Sahara, vers l'Afrique du Nord, l'Europe méridionale, le bassin du Niger ; *b*) par les déserts de l'Asie centrale, vers l'URSS, la Chine et

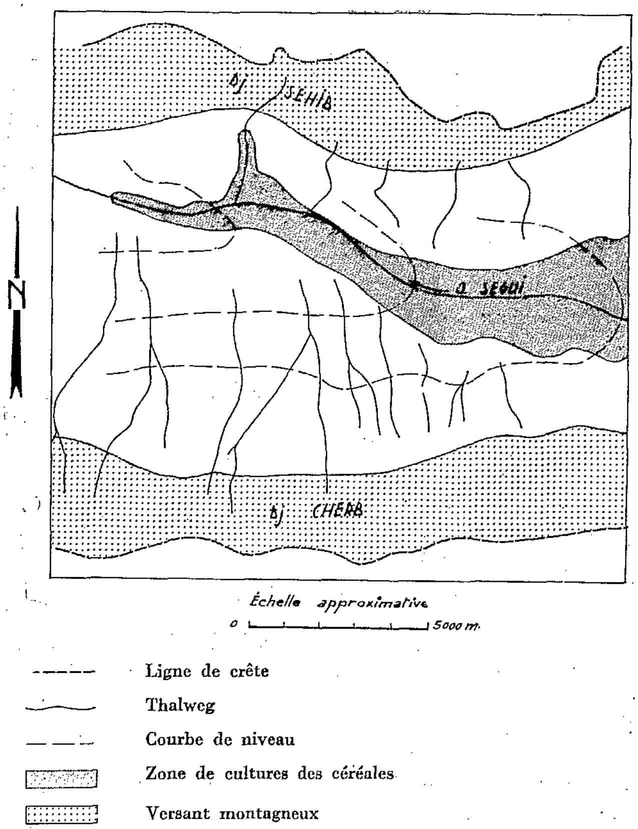

FIG. 4. Cultures de céréales en thalwegs : Oued Segui (aval).

l'Amérique ; *c*) par les déserts de l'Indus, vers l'Inde et le Sud-Est asiatique.

Les plus anciennes civilisations se groupent en fait autour des déserts ; mais, pour la rapidité des transmissions, un minimum d'humidité est nécessaire. L'expérience historique montre que ce minimum est très bas. Un désert tout à fait sec n'était guère franchissable avant notre ère. Les archéologues s'accordent en général sur une humidité du Sahara plus grande que de nos jours avant le deuxième millénaire avant notre ère. A cette époque, il était régulièrement et abondamment parcouru comme le montrent les gravures rupestres.

On a parfois affirmé que l'activité humaine était réduite sous les climats chauds par l'alimentation insuffisante des populations et, certes, les populations moins alimentées sont moins capables d'efforts, surtout physiques, que les populations bien alimentées, mais il ne faudrait pas que cela laisse sous-estimer l'influence du climat sur l'activité des hommes. Je sais par expérience que l'activité tant physique qu'intellectuelle est nettement diminuée par la chaleur dans les territoires du Sud tunisien. Le remède est ici du ressort de la technique moderne. C'est le conditionnement du climat. Il faut espérer que les sources d'énergie à bon marché permettent de le diffuser auprès du plus grand nombre possible de travailleurs. Ainsi aura-t-on l'espoir de tirer un bien meilleur parti, sinon du Sahara, tout au moins des régions tropicales et équatoriales peu peuplées où la pluie et la radiation nécessaires à la photosynthèse, ainsi que les ressources énergétiques, sont abondantes. On dit que ces régions ne sont pas propices à la conservation de la fertilité des sols cultivés, mais n'est-il pas pensable qu'avec le conditionnement systématique du climat, les chercheurs scientifiques qu'on envoie travailler sur place et qui sont écrasés par la chaleur comme les habitants du pays, n'arriveront pas à résoudre beaucoup plus rapidement les problèmes de l'agriculture?

Les facultés d'adaptation de l'homme sont soumises à une rude épreuve dans la zone aride, où la vie humaine est particulièrement menacée. Doit-on mettre au compte de l'adaptabilité ce moyen de défense inconscient que constitue un taux élevé de natalité ? Ce taux élevé perd de son intérêt lorsque la sécurité d'existence est établie. Dans ce cas, au contraire, si ce taux ne domine pas, il crée des conditions d'instabilité politique et sociale dont on peut trouver des exemples en Afrique méditerranéenne pendant l'Empire romain et postérieurement[1].

CONCLUSION

Quoi qu'il en soit, la science et la technique modernes multiplient les facultés d'adaptation de l'homme. Elles permettent ou permettront de prévoir certaines évolutions du climat, de préparer les réponses à ces évolutions et surtout de préparer des organisations internationales propres à remédier aux variations de climat. Ces variations peuvent avoir l'un des effets suivants : *a*) augmentation ou diminution des fluctuations du type envisagé dans cette note ; *b*) modifications climatiques entraînant un changement dans la répartition géographique des ressources sans changer la ressource globale ; *c*) modification du climat susceptible d'augmenter ou de diminuer la masse de la ressource globale.

Il est clair que les mauvais effets du premier type de variation doivent être combattus par une bonne organisation des réserves et des échanges.

Le deuxième type implique des recherches plus difficiles sur l'organisation des échanges et la répartition des tâches entre les diverses fractions de l'humanité.

Le troisième type implique surtout des recherches sur la manière d'obtenir la ressource maximum dans un climat donné.

Dans tous les cas, les problèmes démographiques nécessitent une prise de conscience assez claire pour permettre de les aborder scientifiquement.

1. Au sujet des aspects religieux et sociaux, voir l'œuvre de saint Augustin et sa lutte contre le donatisme. Pour l'aspect non chrétien, voir Rostovzeff : *Economic history of the Roman Empire* (chapitres sur l'Égypte et l'anachorétisme).

SUMMARY

Effects of climatic fluctuations on the hydrology and economy of arid regions (J. Tixeront)

In Tunisia, climatic changes closely condition agriculture, animal husbandry and the economy. The climate has been stable for three thousand years, with a succession of fluctuations similar to those of the present climate. The present paper studies the influence of these fluctuations.

The plant covering adapts itself to a specific arid climate and shows a certain degree of plasticity with regard to climate fluctuations. Dry farming must be adapted to these fluctuations.

Climatic variations produce concomitant variations in the supply of ground-water and in drainage above or below ground. This influence is complicated by the effects of the geological substratum, tectonic movements and soil formations. Abrasion depends on the same factors.

Like plants and animals, men adapt themselves to the climate and its fluctuations, they do so in their manner of life and their methods of farming and of animal husbandry, which have been developed in the course of the thousands of years that have followed the discovery of agriculture and the domestication of animals. Initially, these discoveries were closely bound up with the fact that the climate was characterized by aridity and variability. Variability in the climate has immense consequences for the development of mankind. The present paper very briefly examines a few relationships with demography, the problem of reserves and planning.

An analysis of these processes in the course of the past few thousand years is needed in order to provide a basis on which the resources of science and technology can rest.

DISCUSSION

R. J. Braidwood. The proposition for the diffusion of "civilization"—*if* this means *primary agriculture*—from South-west Asia to Further Asia, would not be universally accepted by archaeologists. As far as we know the earliest cultigens and their probable associated artifactual types from China (Yang shao phase) are not those of South-west Asia. *If* by "civilization" we mean the appearance of a literate proto-urban society, the matter of diffusion may be otherwise, but even here the interpretation of the available evidence differs from one authority to another.

J. Tixeront. Le terme « civilisation » que j'ai employé est bien relatif à la civilisation agricole. Cependant, dans cette civilisation, à l'agriculture est associé un état mental, social, et religieux de l'humanité qui en est inséparable. J'avoue ma grande ignorance des choses de la Chine et remercie M. Braidwood de ses commentaires. J'avais postulé le lien entre Asie du Sud-Ouest et Chine du fait que les vieux auteurs classiques chinois semblent situer l'origine des premières dynasties à l'amont du fleuve Jaune, au point d'aboutissement de la voie steppique du Turkestan qui relie les deux zones.

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EFFECTS OF CLIMATIC CHANGE IN AN ARID ENVIRONMENT ON LAND-USE PATTERNS

by

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SCOPE OF INVESTIGATION

When classifying a certain region as arid, one is applying to it an objective measure which can be expressed in quantitative terms. But at the same time in the mind of most men "arid" expresses a value judgement as well, arid regions being regions in which there is a permanent deficit-balance of water. Actually, in arid regions proper in most years the amounts of rainfall are so low that any deviation exceeds the range of the most frequent values to such an extent that averages or normals lose entirely the meaning they have in humid climates.

Whereas the preceding remarks refer to what sometimes is called the "fully arid" region it is obvious that there is a considerable range of arid climates. When discussing the effects of changes of climate on patterns of land-use in arid regions, one must, therefore, consider these various shades of climate all of which are arid.

This discussion is limited to instabilities of climate as affecting human occupancy. For technical reasons we have to restrict ourselves to changes within historical times, with particular emphasis on the present and near future. We do not, therefore, discuss *changes* of climate but *instability* or, at the most, *minor* changes of climate only.

There is another limitation to the scope of this paper. As its purpose is to discuss the effect of climatic instability on land-use, one has to appreciate the different types of land-use in the major divisions of the arid zone, in order to appreciate the influence of climatic instability on them.

TYPES OF ARID ZONE OCCUPANCY

The arid zone consists of two major regions: the arid zone proper and the semi-arid zone. The arid zone can be defined by the human geographer as having a climate so arid and a rainfall so unreliable that it does not sustain agricultural crops. Consequently, settlement here is of one of the following types: (a) service to regional routes of transportation—surface or air; (b) exploitation of mineral resources for use outside the arid zone; and two types of land-use which are essentially newcomers and characteristic of the present century only, i.e. (c) recreational land-use of the clear sunny and dry climate and the wild beauty of arid lands; (d) the use of the wide empty spaces of the desert for special purposes which require such vast lands, e.g. nuclear testing grounds; (*e*) agricultural use. Land-use in a desert is always geographically discontinuous, it is of the oasis type. With respect to agriculture we can distinguish four types of locational and distributional pattern, as follows.

1. Groundwater oases, either single villages or a small area which maintains a number of oasis villages. Their location is definitely determined by groundwater geology, generally natural, sometimes artificially developed by man, i.e. artesian wells.
2. River oases along a river the sources of which are *outside* the arid region.
3. Mountain oases where desert land rises to elevations sufficient to create some precipitation, generally very moderate in amount. Their importance is often no less in the recharge they provide for a locally strictly limited aquifer than in the direct benefit crops derive from the rainfall and general mitigation of aridity.[1]
4. Grazing by nomads or semi-nomads on the fringes of the three regions mentioned above or the fringes of the arid region in general during the appropriate season. This is always very extensive land-use whereas land-use in the three types of oases might be quite intensive.

1. A variant of this type of oasis is located not at high altitudes in mountain areas but at the border of the mountains and adjacent low lands. They are dependent on surface or ground water from springs, fans or shallow groundwater horizons and sometimes even on streams. In northeastern Brazil this is called Pé da Serra cultivation (James, 1953), a very fitting appellation indeed. Oases of the Pé da Serra type are found the world over adjoining arid and semi-arid mountain areas.

LIMITATIONS AND CHANGES OF ARID ZONE OCCUPANCY

One must appreciate that water is by no means the only factor limiting agriculture of fully arid lands to oases. Outside the oases agricultural soil is no less at a premium than water, as most of the land is either rocky or of excessive salinity. In river oases the water and its sediment bring about the amelioration of soil, the same applies to groundwater oases but to a more limited degree. The soil of altitude oases is the result of their reduced aridity of climate.

Among the types of arid zone occupancy mentioned above the non-agricultural types (*a-d*) are not necessarily dependent on a local water supply. The demand for the maintenance of a settlement here is so overriding that it justifies a water supply at excessively high costs. The 520 km. of water pipeline from the Darling Range to the gold-fields of Kalgoorlie in West Australia is a striking example. The high value-economy served by this type of settlement makes it therefore less sensitive to climatic fluctuations. These may increase the *price* of water but not critically decrease in volume the supply of this essential commodity.

As for the influence of climatic instability on agricultural settlement the types most affected are groundwater oases and altitude oases. In both of these settlement is rather low in volume. However, such changes as they have experienced in groundwater supply are generally the result of an improper use of the groundwater resources, i.e. withdrawal above the replacement level.

Both in this case and in the case of trade routes crossing deserts, it has been argued repeatedly that a critical diminution—and sometimes even failure—of water resources as the result of increasing aridity have resulted in the cessation of settlement or in the forced abandonment of the route. This argument can hardly be substantiated.

Neither the great silk road of Inner Asia nor the trans-Saharan routes—along which salt and other valuable merchandise and, later, slaves were traded—were abandoned as a result of climatic change. Of more decisive importance than these were changes in commodity exchange and possibly more important, changes in transportation technology, which made it possible to bypass the deserts successfully—by ship, railroad or airplane.[1]

Whatever type of man-induced change brought about the abandonment of trade routes, mining areas, or border settlements established for security reasons,[2] it resulted in a regression typical of arid lands. This is not a gradual decline but rather the abandonment of settlement. A large part of the population or most of it will leave the area when the one reason for its occupation ceases to exist. Owing to the physical limitations of the arid environment these people cannot readjust themselves to another resource base as would be the case in humid areas.

One special type of climatic change might indirectly be involved here. It has been claimed (e.g. Murray, 1949; Schiffers, 1951) that in certain arid areas there are fossil groundwater resources, which are relicts of a Pleistocene climate moister than the present one. Such resources would diminish under use. However, no such case has been proven to satisfaction. Obviously, many of these groundwater bodies are at present at a lower recharge level than in Pleistocene times. Still, with proper resource management no critical diminution of supply would occur.

Here, then, is a basic factor in arid zone occupancy. Life in an arid region is life in a submarginal environment, or to put it differently, an environment where nothing is easier than to overuse the natural resource-base and cause permanent damage to it. This obviously requires arid zone management to be technically highly competent. Actually, many populations of the arid zone have such competence within the framework of their tradition and experience only. Abnormal conditions of strong population or livestock pressure, drought etc., bring about either an excessive use of resources, water and pasture, or create inroads into the adjacent semi-arid lands in an effort to use these as alternative areas.

LAND OCCUPANCY IN SEMI-ARID AREAS

Conditions of occupancy and land use are different in the semi-arid region, as here they are no longer submarginal, but marginal. Obviously, a marginal environment is much more amenable to improvement and management. Here we find more rainfall and a reduced degree of fluctuation as well as—at least seasonally—lower rates of evapotranspiration. It is no less important that the lesser aridity of the semi-arid region does not, in general, impose limitations in soil quality, and only in exceptional cases does salinity in soils occur. Most semi-arid areas benefit—again, at least seasonally—from important climatic advantages such as, for example, high heat rates conducive to early maturing and permitting of multiple cropping, provided water is available in sufficient quantity. Furthermore they do not suffer from excessive moisture, an impediment to easy and regular harvesting as well as to pest control. These reasons of climate and of satisfactory and some-

1. This has been stated repeatedly, and not less often been neglected. To cite but one source, Lucien Febvre clearly states (Febvre, 1932) that the disappearance of caravans of 10,000 to 15,000 camels crossing the Sahara was due not only to the eradication of the slave trade. A more important reason was that the technological developments in shipping "dethroned the ship of the desert". A caravan of 15,000 camels could carry nearly 1,500 tons of net weight, with great hardship, loss, a low speed, and therefore at considerable cost. The development of the modern 10-20,000 ton cargo boat with speeds of 15-20 knots made the earlier form of transportation obsolete.
2. For example, settlement along many arid sections of the *limes* of the Roman Empire.

times good soil quality, make semi-arid lands desirable areas for settlement.

One must remember that it is the semi-arid regions which matter most in a discussion of important interactions of man and environment. As man in appreciable numbers is inhabiting only semi-arid lands, whereas the arid area is generally anoicumene, any influence the arid environment exerts on its few groups of inhabitants is of rather academic interest.

"SUBFOSSIL" FORESTS

Again there is an obvious type of climatic change which has affected semi-arid lands, the effect of which has often been misinterpreted. During the moister periods of the Pleistocene the climatic environment created higher-grade vegetation than that found today. When Man, during the early stages of his settlement, destroyed this vegetation, e.g. the primeval Mediterranean forest, the next climax vegetation was of a definitely inferior type. The reason being of course that the primeval forest represented a fossil element in a landscape adjusted to Late Pluvial conditions. Under the changed climatic conditions of the Recent it cannot regenerate to the primeval type met with by man's earliest ancestors. The appearance of inferior vegetation types has often been interpreted as evidence of progressive and continuous deterioration of climate. It proves, however, to be no more than the after-effect of the change from Pluvial to Recent climate.

FLUCTUATIONS OF RAINFALL AND MARGINS OF ADJUSTMENT

Semi-arid areas all over the world are affected by fluctuations of climate. The more one approaches the border of aridity the more severe their effect on man and his economy. The nearer to the arid area proper the lower the total amount of rainfall will be. The lower the average rainfall, the easier and the earlier a given percentage fluctuation in rainfall will, on its negative side, decrease rainfall to below critical values thus creating conditions of drought. A 30 per cent negative deviation from a rainfall of 600 mm. will still leave an area with 420 mm., an amount which might produce sufficient yields. But a 30 per cent negative deviation from 300 or 250 mm. will produce only 210 or 175 mm., an amount spelling drought. For such areas a negative fluctuation of 100 mm. or even less might prove critical. In conclusion, the lower the average rainfall of a semi-arid area the narrower is the margin of negative deviation it can endure.

Returning for an instant to the arid area proper, it is important to bear in mind that the arid-land farmer has an even lesser margin of adjustment than his colleague in the semi-arid zone. With land and water at a premium, arid zone landholdings are very often *minifundia*. Any sizeable reduction of their yield spells want and possibly famine. The *minifundium* farmer, therefore, cannot voluntarily reduce the area he is cultivating or irrigating.

The very mechanism of climatic fluctuations tends to aggravate the effects of negative deviations in rainfall. These generally come in sequences of years.[1]

The result is not only the direct negative effect on crops but the negative effect on the replenishment of groundwater resources as well. The influence of a series of deficiency years on groundwater resources will be delayed as against the subnormal years themselves. As a result the area will be affected in two ways: immediately by insufficient rainfall for the crops, and by a delayed-action effect on its water resources. These two effects—with a certain overlap—will come one after the other, aggravating the situation of those peasants dependent on a groundwater supply.

Not only negative deviations of climate have an injurious effect on land-use; the damage caused by positive excesses is no less severe. This affects both semi-arid and arid regions. Natural drainage lines in the arid zone are not fitted to discharge excessive amounts of water. But the very mechanism of arid climates brings about high positive concentrations of rainfall, both in single instances (often less than one hour) and over a period of years. The result might be the creation of swamps in semi-arid lands and catastrophic damage by the rare heavy rains characteristic of arid areas, including those of extreme aridity. The Pontine marshes in central Italy and the Plain of Sharon in central Israel before World War I suitably illustrate the damage resulting from insufficient drainage in semi-arid coastal plains. The literature on desert travel provides numerous examples of the effects of cloudbursts and floods in fully arid localities.

1. As an example, the rainfall record of Jerusalem may be cited (Rosenan, 1955). This station has consecutive rainfall records for 112 years, since 1846-47. Before 1924-25 no two or more consecutive years were recorded with a rainfall of 15 per cent or more below average (average 560 mm.). But since then two periods have shown such deficiencies, one very long and the other including the extreme negative value recorded so far. Details are as follows:

Negative deviation from average

Year	(%)	*Year*	(%)
1924/25	50	1932/33	56
1925-26	15	1933/34	33
1926/27	11	1934/35	14
1927/28	33	1935/36	38
1928/29	1		
1929/30	21	1957/58	38
1930/31	23	1958/59	25
1931/32	43	1959/60	63

The period 1924-25 to 1935-36 as a whole had, therefore, a cumulative rainfall deficit of 28 per cent, including a deficit of 35 per cent for 1929-30 to 1933-34 and of 44 per cent for 1931-32 to 1933-34. For the three-year period 1957-58 to 1959-60 the cumulative rainfall deficit amounted to 58.6 per cent!

EFFECTS OF CLIMATIC FLUCTUATIONS —PAST AND PRESENT

As for the effects of climatic fluctuations on farm populations in many countries there is a considerable difference between past and present conditions.

In the quite recent past, the major part of agriculture did not employ irrigation. Because of this, the peasant population was especially susceptible to fluctuations in climate. These affected not only the harvest of individual years but, whenever a series of dry years occurred, severely taxed the economic staying power of the peasant population. The low economic standard of the majority of peasant populations in semi-arid lands enabled them to weather a bad crop year, or even two with a certain degree of hardship. But a series of dry years (such as the dry spells mentioned in the footnote on p. 441) would tax their reserves beyond the limits of endurance and bring them to either starvation or indebtedness, or most probably both. In many areas a series of dry years brings about large-scale migrations of the population in search of work in other areas, sometimes at a great distance. Outstanding examples of this are the recurrent migrations of drought-stricken people from the Polígono das Sêcas into happier areas of Brazil.

A different type of pressure is exerted in dry years on the peasants in most of the arid lands in the eastern hemisphere: pressure by nomads. The nomads suffer even more from deficiencies in rainfall than the sedentary farmer. If the nomad finds no pasture for his flocks and if his water resources fail him, he has little choice but to look for pasture where he can find it, i.e. to trespass on the fields of the farmer. This creates the eternal antagonism between "the Desert and the Sown". The history of all the fringe-lands of sedentary and nomad populations abounds in stories of mutual enmity and clashes. In the absence of a strong central power which firmly enforces law and order, the nomads generally are apt to be the more successful in this contest as theirs is the triple advantage of mobility, surprise and concentration of forces.

The combination of all these factors: security- and climate- induced pressure on the semi-arid fringe, the general state of security and of the economy, and climatic fluctuations or an aggravation of climatic conditions, may bring about fluctuations of the border of settlement, its expansion or contraction. (For one example among many, see Amiran, 1953.)

ADJUSTMENT TO CLIMATIC INSTABILITY: IRRIGATION FARMING

Significant changes have occurred in the present century. Fewer and fewer farmers are willing to live in the semi-arid areas, let alone on the arid fringe, leaving it to the mercy of God and the climate to determine whether they will harvest a decent crop from their investment of effort and labour. The farmer of today is no longer willing to put up with an uncertain livelihood which depends on the vagaries of rainfall. A reliable income from farming in semi-arid areas is obtainable only by basing it essentially on irrigation. This may mean the cultivation of a smaller, and more compact, area possibly located at a considerable distance on the humid side of the border of aridity.

Reliance on irrigation as against rainfall agriculture makes man less sensitive to fluctuations of climate—provided the volume and extent of irrigation agriculture has been properly planned, i.e. based on average minimum values. A reduction in rainfall during the lower part of a fluctuation and a subsequent reduction in groundwater supply will increase the cost price of agricultural products. It may even squeeze out marginal producers and products, but it will not bring about a major physical dislocation of farming.

However, there are two aspects in which the more sophisticated present-day farmer of semi-arid lands with his farming securely based on irrigation is more affected by excessive negative climatic fluctuations than was his simpler predecessor. First, his higher standard of living narrows his range of economic endurance. He can no longer subsist during a prolonged dry period at a lower economic level: he has to go on relief, to change to non-agricultural employment, or to migrate if his water supply fails and if it is impracticable to substitute an alternative supply for it. Second, the irrigation farmer requires a fixed minimum amount of water. In irrigation agriculture land holdings tend to be small and farmers have no large margin. Even in subnormal years, therefore, with long periods of negative deviation of rainfall, the farmer can only reduce the area he cultivates and irrigates by a very limited amount. Unless controlled by a proper water authority this might lead to the withdrawal of groundwater beyond the safe replacement rate. Under certain conditions this might in turn lead to an increasing salinization of the groundwater resource, causing permanent damage which does not pass as the dry spell gives way to better and wetter years.[1]

MAN'S INFLUENCE ON ARID LANDS

Finally, one will do well to place the whole problem of present-day climatic instability and its influence on man's economy in the arid zone into proper perspective, especially the perspective of the twentieth century with its powerful tools of mechanized agriculture. The man-land relationship is such that, although nature is imposing certain very definite limitations on arid-land occupancy and its patterns, man is the more powerful

1. We have not discussed in this paper the effect of changes in the seasonal distribution of rainfall and other climatic elements which might be very important indeed.

agent. This often reaches critical values on the negative side if by neglect, or much more frequently by ignorance, man mismanages his land. Witness, those arid and more particularly semi-arid areas which have been damaged by excessive soil erosion. Or a more frequent type of damage, the wanton removal of natural—though subfossil—forest in semi-arid areas which takes a most important link out of the hydrological cycle and speeds up the run-off of water, at least in areas of impervious rock.

In summing up, it would appear that these man-induced changes of environmental conditions are by now exceeding in magnitude at least the changes of microclimatic conditions resulting from the processes of climatic change.

RÉSUMÉ

L'influence des changements de climat sur la colonisation des terres arides (D. H. K. Amiran)

En règle générale, plus le volume des précipitations qui surviennent dans les régions arides et semi-arides est bas, plus sa variabilité annuelle est grande. C'est pourquoi il importe que toute forme de colonisation — agricole ou autre — qui est tributaire des ressources locales ou régionales en eau soit conçue en fonction de ces variations et changements.

Lorsqu'il s'agit de colonisation agricole, il ne faut pas oublier que ce sont les régions marginales de la zone aride qui entrent en ligne de compte et, plus particulièrement, les terres semi-arides. Aussi faut-il se garder de tirer des conclusions en se fondant sur l'exemple des oasis du désert, qui ne constituent en aucune façon des cas typiques.

Il existe deux formes principales de colonisation agricole dans les terres semi-arides et arides : l'une, qui fait appel à l'irrigation, est notamment pratiquée dans toutes les exploitations agricoles des régions complètement arides ; l'autre repose, en tout ou en partie, sur le système de la culture sèche. De toute évidence, la colonisation agricole qui repose sur l'irrigation aboutit à créer d'importantes concentrations de population et de culture dans les régions strictement limitées et isolées les unes des autres. Là où l'on pratique la culture sèche, au contraire, le schéma de l'occupation des terres et de la répartition des exploitations agricoles est beaucoup plus régulier et la densité de la population est faible. Ces deux modes de colonisation agricole subissent fortement l'influence des fluctuations climatiques ; cette influence, qui se manifeste sous des formes différentes et à des moments différents, est analysée en détail dans le présent article.

Dans un grand nombre de régions arides, il existe un troisième mode d'utilisation des terres : celui qui est pratiqué par les pasteurs nomades. L'influence des fluctuations climatiques n'est pas moins sensible et il arrive souvent qu'elle se fasse également sentir dans les exploitations de type sédentaire. Dans l'ensemble, cependant, le nomadisme est en voie de régression, tant sous l'influence de l'acculturation des nomades que de la mécanisation, qui réduit les besoins en animaux de trait.

DISCUSSION

K. N. Rao. The author has given two instances of consecutive years of negative departures in rainfall (see footnote, page 441). Can we conclude from these two instances even in a general way that negative deviation occurs in sequences in all such areas? Actually if the limit of 15 per cent is taken, the first instance would be for five consecutive years only. The author's statement would also raise the questions of trends in rainfall and the independence of successive observations.

D. Amiran. In the first session of this symposium ample evidence was presented for the trough and crest character of climatic fluctuations. The case cited in my paper was restricted to *large* variations, in excess of 15 per cent, and furthermore to those where such variations occurred for more than two consecutive years.

H. Bobek. Would Professor Amiran explain what exactly he understands by "fossil" or "subfossil" forest. To me, the vegetation appears to be the element which would react most quickly to all changes of climate.

D. Amiran. I believe the argument will resolve itself if we define our terms. Applying *geological*-time scales, Professor Bobek will certainly be correct in stating that vegetation adapts itself "very quickly" to changes of climate ; but if one applies the time scale of recorded human history this adaptation will be quite slow and occur with a considerable time-lag. It so happened that early man appeared at a time where forest became unadapted to the changed climate.

Furthermore, it would appear that the adaptation of a vegetation, and more particularly forest vegetation, to a change in climate will depend to a certain extent on the magnitude of such change or on whether it occurs near critical threshold values. No one will dispute that such adaptations will be drastic in the case of major changes of climate. But small or medium scale changes will not remove a forest, but only impoverish its composition, especially with respect to critical species, and will prevent its regeneration once removed.

C. C. Wallén. As regards both Professor Amiran's and Professor Tixeront's very interesting contributions it was extremely encouraging to see that both stressed the importance of the variability of rainfall to agricultural conditions in semi-arid regions. In dealing with the agroclimatological project in the Near and Middle East jointly sponsored by FAO, Unesco and WMO, we have been able to show the great importance of this factor to the limitations for agriculture in semi-arid regions. I therefore hope that in all such areas more attention should be paid by climatologists to variability itself and to the changes of this factor. I believe that in relation to agriculture this variability is often more important than the amount itself. If it is appropriate to make some propaganda for the above-mentioned project I should like to stress that a thorough study of the actual climatic conditions, as is done in this project, must always form the basis for investigations of fluctuations of climate in relation to agriculture and man's other activities.

D. Amiran. I can only endorse Dr. Wallén's statement. As regards climatic limitations, below a certain level of rainfall, or rather above a certain level of potential evapotranspiration, variability of rainfall is a more important parameter than quantity. Any research designed to obtain more precise data on this parameter will be most important and helpful in planning any settlement project and advising on its implementation.

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A REVIEW OF EVIDENCE CONCERNING CHANGES OF CLIMATE IN INDIA DURING THE PROTOHISTORICAL AND HISTORICAL PERIODS

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INTRODUCTION

The regions of the Indo-Pakistan subcontinent most significantly affected by presumed changes of climate and demonstrable changes of vegetation during the last five millennia comprise the western and north-western states, more especially Baluchistan, the Indus Valley, Punjab and Rajasthan. It is with these regions, their archaeology and history, physiography and drainage, flora and fauna, that we will be principally concerned here, but evidence emanating from other parts of India, notably the upper Gangetic valley and important archaeological sites in the eastern, central and southern regions, will also be used to throw light on the vexed problem of climatic change.

PRESENT CLIMATE

This may be briefly summarized as follows:

Punjab. In the northern and eastern parts the average rainfall is of the order of 23 inches, mostly received from the south-west monsoon during July and August. The maximum temperatures may rise to 119° F. and the minima fall to 30° F. The mean maximum, minimum and average temperatures are of the order of 90°, 54° and 76° F. In the western and south-western portions the average rainfall is 10 inches. The temperatures are higher, the absolute maximum rising to 121° F., the absolute minimum going down to 27° F. and the means being about 92°, 61° and 76° F.

Sind. This is the driest subdivision with an average rainfall of about 5 inches received in a short wet season. The annual mean maximum temperatures may be 95° — 96° F., the absolute maximum shooting sometimes up to 127° F. The mean minimum is about 67° F.

Rajasthan. The average annual rainfall is about 11 inches in the western portion, considerably less in the Thar desert. The absolute maximum rises to 122° F., the absolute minimum approaches 25° F., and the means are of the order of 95°, 67°, and 78° F. respectively. The eastern portion of Rajasthan, east of the Aravallis, is quite a different type of area with about 27 inches of annual rainfall.

Saurashtra. The average annual rainfall of the south-western arid zone is not more than 14 inches, received in a few violent downpours. The absolute maximum may go up to 113° F., the absolute minimum down to 38° F. and the means are about 92°, 68°, and 80° F.

Recent investigations into the climate of India, with particular reference to rainfall, show that in general there is no tendency for increase or decrease in rainfall. In the arid and semi-arid regions of north-west India there is a slight deficit, whereas there is a slight excess in the north-east (Puri, 1945). No significant change is occurring in the rainfall of Rajasthan, the values of coefficient of variation showing a marked correlation with the amount of dryness (Rao, 1958). With regard to temperature, it is again apparent that there is no general tendency for a systematic increase or decrease in maximum and minimum temperatures but at some places there are variations of an oscillatory character within a period of 30-40 years (Pramanik and Jagannathan, 1953). The amplitude is 12-15° F. along the Gangetic plains and over 20° F. in the extreme north-west (Jagannathan, 1957). Similar conclusions have been arrived at with regard to humidity and wind movements. An exhaustive summary of climatic characteristics of the arid and semi-arid regions is given by Khan (1959).

PRESENT VEGETATION

Punjab. The characteristic trees of the dry plains are stunted *Acacia modesta, Acacia arabica, Zizyphus mauretiana, Capparis aphylla,* occasional *Tecomella undulata,* etc. In the salt plains, *Tamarix, Salvadora, Prosopis spicigera, Acacia modesta, Capparis aphylla,* etc. occur (Puri, 1960).

Sind. The desert region has some *Acacia arabica, Prosopis spicigera, Zizyphus* and *Tamarix* spp., *Acacia* *senegal, Salvadora oleoides, Euphorbia* spp. and usual associates.

Rajasthan. The vegetation of the driest tract west of the Aravallis contains, as the chief species, *Anogeissus pendula, Euphorbia* spp., *Acacia senegal, Zizyphus rotundifolia, Acacia jacquemonti, Tecomella undulata, Capparis aphylla, Salvadora oleoides, Prosopis spicigera, Calotropis, Calligonum polygonoides, Laptadenis spartium, Crotalaria burhia, Aerua tomentosa, Elyonurus hirsutus, Panicum turgidum, Cenchrus catharticus, Tamarix articulata* and *Phoenix* (Puri and Jain, 1960).

The vegetation of north-west India, Pakistan and Sind has a number of Arabian and African elements. An analysis of the flora of Sind shows that the western component is influenced by the western deserts whereas the eastern portion is a continuation of the Rajputana desert (Das and Sarup, 1951). The establishment of the Arabian and African species was probably facilitated by clearing of the indigenous vegetation and in course of time, owing to the prevailing winds and other climatic factors, the western element will increase still further in the Sind flora (Sabnis, 1929).

The Rajputana flora is, however, by no means poor as is evident from the numerous descriptions prepared in the past. Over five hundred species of plants including about fifty exotics have been recorded (Duthie, 1886; King, 1889). Therophytes amount to 41 per cent of the flora and when plants are considered in relation to climate, the ressemblance of the area to the Libyan desert and Cyrenaica is apparent (Das and Sarup, 1951).

EVIDENCE FROM THE PAST

HARAPPAN PERIOD (*circa* 3000 B.C. to *circa* 1500 B.C.)

As a result of excavations carried out during the last forty years it has been revealed that the Indus valley was the seat of a highly evolved chalcolithic culture in proto-historic times during *circa* 3000 B.C. to *circa* 1500 B.C. The main features of Harappa culture (as it is called from the present name of the village occupying the site of its northern metropolis on the Ravi river in the Punjab) or the Indus civilization (so-called from its main axis which lies along the Indus with the southern capital at Mohenjodaro) in which we are interested are those which throw light on the climate and vegetation prevailing in the Indus valley in its heyday.

The known remains of this culture occupy a huge irregular triangle, from the foot of the Himalyas to the Makran coast, Kathiawar and Gujarat, Bahawalpur and north-western Rajasthan, measuring 950 by 700 by 550 miles. With rare exceptions, they are towns or villages of the plains, mostly clinging to present or former courses of rivers, still flowing or long since vanished, and belonging to the Indus and western Gangetic systems.

Agriculture

The Harappans cultivated the following crops, more or less the same as their Sumerian colleagues with the notable exception of cotton, three species of which still occur wild in the region (rice was apparently unknown): Breat wheat (*Triticum compactum* and *sphaerococcum*); barley (*Hordeum vulgare* and *hexastichum* variety); peas (*Pisum arvensis*) *Brassica* (perhaps *juncea*); sesamum, melons and cotton (*Gossypium arboreum*). Among fruit trees, dates and bananas may be mentioned (Piggott, 1950; Wheeler, 1953). Although none of the species mentioned above required the degree of irrigation which rice culture demands (especially if a more humid climate is postulated in protohistoric times) a well-developed irrigation system might be expected to accompany an organized agrarian economy. Due to the nature of the country and the continuously aggrading character of the Indus system, no direct evidence is likely to be found. The periodical floods to which these mighty rivers are subject must have obliterated any remnants long ago.

However, it is quite likely that there are some references to earthen dykes in the Rigveda hymns. That some of these refer to protective embankments, such as we know skirted the cities of Harappa and Mohenjodaro, is quite certain but veiled allusions to irrigation dykes may also be suspected. Again embankments must have been necessary to protect cultivation from the ravages of the meandering streams and their rampage during floods. Thus (Griffith, 1896-97)

> O Indra, him who lay at length staying thy copious waters, thou
> In his own footsteps smotest down
>
> [Rigveda VIII(6)

and,

> There as he lies like a bank bursting river,
> the waters taking courage flow above him.
> The dragon lies beneath the feet of torrents,
> which Vritra with his greatness has encompassed
> . . . . . .
> The waters bear off Vritra's nameless body.
>
> [Rigveda I(32)]

and,

> Then did'st thou set the obstructed rivers flowing
> and win the floods that were enthralled by Dasas.
>
> [Rigveda VIII(85)]

In Baluchistan, however, Sir Aurel Stein (see Piggott, 1950) was able to identify stone-built dams and terraces to aid irrigation. These barrages and dams reflect not only a greater rainfall requiring storage, but prosperous agricultural communities in prehistoric times, as contrasted with the barren nature of the terrain at the present day and the precarious nomadism of the population. The abandoned tells of past settlements, 100 feet or more in height, tell the same story.

Domesticated animals

The Harappans possessed both zebu and humpless cattle (*Bos indicus*), buffalo (*Bubalus bubalis*), goat (*Capra aegagrus* race *indicus*), sheep (*Ovis vignei* race *domesticus*), pigs (*Sus cristatus* var. *domesticus*), dogs, cats and fowls (Piggott, 1950; Wheeler, 1953).

The elephant, horse, ass and camel were also domesticated in all probability, although the bone evidence is not conclusive for the camel and is absent for the ass or mule. It is conjectural if the elephant was tamed.

These facts tend to establish that the climate, although not arid, was certainly dry. Forest and marshland must have constituted the original habitat of elephant and buffalo but the forest need not have been very moist provided sufficient marshland existed to provide rough grazing.

Flora

The use of timber and wood on quite a large scale is attested by the following facts.

Enormous fortifications with burnt-brick revetments were raised around the metropolises of Harappa and Mohenjodaro. Kiln-fired bricks were also used for building purposes. However, in general their use was more common in the cities and larger settlements along the watercourses—at the smaller sites burnt bricks are not so ubiquitous, their place being taken by mud bricks and stones (Piggott, 1950; Wheeler, 1953).

The use of kiln-fired bricks in stupendous quantities implies two things; firstly the fuel required for burning the bricks should have been available relatively easily and in close proximity, and secondly the climate demanded something more durable than the mud bricks universally used in the empires of the ancient East. From these arguments and from the complementary evidence of elaborate systems of paved drains, it is postulated that rainfall was more frequent as well as more considerable and consequently the timber resources far more abundant than the present tamarix and scrub (Piggott, 1950).

This view is, however, not shared by all archaeologists. Childe (1942) draws a parallel between the Mesopotamian, Egyptian and Indian civilizations, all of them islands of culture in a desert scrub, dependent upon inundations of a mighty river, and observes that while low rainfall and lack of building timber were common characteristics, the Harappan environment differed in vaster expanse, in the régime of the flood, in its scrub of ugly useless trees and in the animals sheltered by them. The stupendous quantities of fuel required for firing the bricks were presumably gathered laboriously from the ugly trees that even now disfigure the desert.

Timber was used in the construction of dwellings and the following species have been noted: beams of deodar (*Cedrus deodara*); charred remains of pine rafters (*Pinus roxburghii*) and bamboo (roofing?) in the uppermost Harappa strata on the citadel mound; beams of sisu (*Dalbergia sissoo*?) at Mohenjodaro (Piggott, 1950).

Other uses of timber which have come to light are the following (Chowdhury and Ghosh, 1951); shisham (*Dalbergia latifolia*) and deodar (*Cedrus deodara*) for sides and top respectively of a coffin; ber (*Zizyphus* sp.) from remains of a wooden mortar from the grain-pounding platforms; elm (*Ulmus* app. *lancifolia*) from the surface deposits at the same site.

The wood remains belong to two distinct classes —those that were transported among which pine, deodar and elm should be certainly included and possibly shisham also and those which might be assumed to have been gathered locally, e.g. ber. In so far as the coniferous timbers are concerned it is not difficult to imagine that they were transported from the Himalayas by river. The shisham, the present range of which extends up to Marwara in Rajasthan, might have been imported overland (if in fact it did not grow within the orbit of the Harappa culture in *circa* 3000 B.C.) through numerous Harappan settlements in north-western Rajasthan along the banks of the now dry Ghaggar river (e.g., Kalibangan on the ancient Saraswati). The remains of elm mostly closely match *Ulmus lancifolia* which is now confined to eastern Himalayas, and it is likely that some species allied to *U. lancifolia* might have grown in this region in protohistoric times. Some support is lent to such a view from the fossil elm discovered in the Lower Pleistocene of Karewa formations in Kashmir (Puri, 1945). *Zizyphus* occurs even now in the neighbourhood, being a species of dry and arid tracts.

The testimony afforded by extant woody remains does not support the theory that a moist forest flourished in the neighbourhood of Harappa. A vegetation of scrub, bamboo and tall grass (the latter presumably used for making flat bamboo and rush roofs covered with mud) growing in pockets of marshy land, in a climate with a somewhat heavier rainfall for a few months in the year will satisfactorily account for the known facts (Chowdhury and Ghosh, 1951). The pipal tree (*Ficus religiosa*) supposedly recognizable on some seals (Piggott, 1950) also grows at the edge of riverine marshy tracts.

Fauna

Remains of a great variety of wild animals have been recovered but an even more realistic record is available from the numerous steatite seals of this culture distributed at various sites. The delineation is of a surprising faithfulness showing long familiarity with the animals depicted. From these sources it can be established that doves, parrots, hares, squirrels, mongoose, jackals, wolves, monkeys and bears must have existed in the territory. Suitable habitats must also have existed for tiger, rhinoceros, water-buffalo and elephant, bones of all of which, except the tiger, have been found at Mohenjodaro or Harappa. Horns of the Kashmir, spotted, sambhur and hog deer have also been found (Piggott, 1950; Wheeler, 1953).

Most of the higher mammals could have thrived only in the proximity of jungle or marsh, such as no longer occur in the proximity of the chief sites. It is noteworthy, however, that the tiger can thrive under quite dry conditions and is found today in Rajasthan and sometimes in Sind. Marshy land suitable as a haunt of the rhinoceros occurred in the Peshawar valley until 1850. Apart from the records of Babar hunting them in the high grass of the swamps in the early part of the sixteenth century, a rhinoceros skull was found quite recently on the present ground surface. In the thick reed growth of the waterlogged and swampy plain, the elephant also could have had their home (Holditch, 1909).

Nor is evidence lacking as to the existence of marshes in the Indus valley proper. The two most important marshy areas created by the confinement of the whole drainage of a mighty river to a narrow tract occur along the western edge of the Indus valley from near Jacobabad to Manchhar lake and along the eastern edge from Khyrpur to a place below Umarkot. The latter is the channel considered by some to be the ancient course of the Sutlej (Medlicott and Blanford, 1879). Manchhar lake itself, lying between the Indus and the foothills of the Kirthar range near Johi is 8-10 miles in length and as much in breadth but it swells to 200 square miles in the inundation period. There are a number of prehistoric Harappan sites dotted around or islanded near the edge of its maximum extent of flooding. The reedy marshes in these areas must have harboured the elephant, buffalo and rhinoceros so deftly chiselled on the Harappan seals.

The tiger was unknown to the Rigveda Aryans (*circa* 1500 B.C.) but they did not penetrate to Sind; or due to increasing aridity it might have receded towards the east by then. The tiger is mentioned in the Atharvaveda composed when the Aryans had established themselves in the upper Gangetic plains (*circa* 1000 B.C.).

The absence of any record, glyptic or otherwise, of the lion is rather surprising. It had probably not yet migrated from Persia into India and the climate and vegetation may have become suitable for it only much later. During the mediaeval period it was fairly common in northern India.

VEDIC PERIOD (*circa* 1500 B.C. to *circa* 300 B.C.)

Detailed and accurate information about the Vedic period is lacking, and as shown later, no reliance can be placed on descriptions of forest composition. However, much evidence of a general nature is forthcoming to show that extensive forests covered the Indo-Gangetic plains and the rainfall was probably more frequent and intense. There is reference to the famous Khandawa forest between the Yamuna and the Ganges in the vicinity of Hastinapur—and the great difficulty experienced in burning it (as Indra kept on pouring rains), presumably for cultivation and pasture. By the time of the Ramayan (*circa* fifth to third centuries B.C.) much of the forest had been cleared and droughts had begun to take their familiar toll (Stebbing, 1922).

Plant remains are chiefly known from the ancient city of Hastinapur which figures so prominently in the epic literature. Woody remains obtained in recent excavation have been identified as noted in Table 1.

The Khadar and Khola (high bank) of Ganges still supports a forest essentially similar to that from which Hastinapur material would have come. The riverain vegetation contains *Dalbergia sissoo*, and *Saccharum spontaneum* and *Holarrhena* occurs in the dry miscellaneous forest. It may be surmised that in essentials, the vegetation and by inference, the climate, have not changed in any significant respect during the last 3,000 years. [Rice mentioned in the Atharva veda (*circa* 1,000 B.C.) has also been found at this site. Rice culture may have depended upon irrigation of some sort. The site is liable to floods, which destroyed the ancient settlements time and again.]

HISTORICAL PERIOD (*circa* 300 B.C. to date)

Randhawa (1952) has collated information from many sources and tried to show the extent of desiccation that has taken place in northern India in historical times. His sources are mainly literary and glyptic. Some further remarks regarding the value of such testimony will be be made here, while commenting on his findings.

His main conclusion is that northern India, particularly the region around Mathura, enjoyed a rainfall of 80 inches or more at the time of Kanishka (first to

TABLE 1

Site	Period	Species	Remarks
Hastinapur (Chowdhury and Ghosh, 1954 and 1955) (along Ganges river)	II (*circa* 900 B.C.)	*Dalbergia sissoo* (charcoal)	Common in the neighbourhood
	II (*circa* 800 B.C.)	*Saccharum spontaneum* (mud-plaster)	Common in the neighbourhood
	III (*circa* 450 B.C.)	*Holarrhena antidysenterica* (charcoal)	Found in dry deciduous forest

second centuries A.D.). The present rainfall is around 25 inches and the vegetation is mainly a dry scrub, with some pockets of trees in suitable niches.

Quoting from Mahabharata (*circa* fifth century B.C.-third century A.D.), where sal (*Shorea robusta*), tal (palm), mango (*Mangifera indica*), kadam or kadamb (*Anthocephalus indicus*), mahua (*Madhuca indica*) and arjun (*Terminalia arjuna*) are described as growing in the Dwait forests, he opines that this shows that kadamb was growing in the northern plains. In fact there are hundreds of similar lists in the epic, another example of which is the description of trees growing on Gandhamadan mountain in high Himalayas: *Mangifera indica, Spondias pinnata, Cocos nucifera, Diospyros tomentosa, Holarrhena antidysenterica, Anthocephalus indicus, Ficus carica, Punica granatum, Citrus* sp., *Artocarpus heterophyllus, A. lakoocha, Musa sapientum, Phoenix dactylifera, Aegle marmelos, Feronia elephantum, Syzygium cumini, Gmelina arborea, Zizyphus mauretiania, Ficus infectoria, F. glomerata, F. bengalensis, F. religiosa, Semecarpus ancardium, Emblica officinalis, Terminalia chebula, T. belerica, Carissa spinarum, Michelia champaca, Saraca indica, Pandanus odoratissimus, Mimusops elengi, Callophyllum inophyllum* (?), *Nerium odorum, Bauhinia purpurea, Cedrus deodura, Shorea robusta, Borassus flabellifer, Salmalia malabarica, Butea monosperma, Dalbergia sissoo*, and many others difficult to identify. A list of birds resting in these trees is equally comprehensive.

It is quite clear that these are generalized lists in which the poet has included whatever he thought beautiful and as anybody with the barest knowledge of Indian flora will see, they are devoid of any scientific value. Such a collection of trees cannot grow anywhere. This topic has been treated rather at length in view of the tendency to give a greater weight to purely literary references than they deserve.

Other similar references need not detain us as ashoka (*Saraca indica*) and kadam (*Anthocephalum indicus*) had a ritual and iconographic significance which is no index of their ubiquity in north India. However, a curious reference may throw some light on the common depiction of ashoka in Mathura and other sculptures in association with Yakshis, Shalbhanjikas and other figures. Hiuen-Tsang (see Beal, 1961) mentions "land of no-sorrow" (*a* = without; *shoka* = sorrow) as one of the names of Ceylon, which is connected so intimately with Ramayana and the *ashoka-vatika* (grove of no-sorrow) where Sita was confined. If such were the tradition, the *ashoka* tree would merely stand as a symbol of joyousness and it is significant that what has been identified as this tree nearly always occurs in scenes of festivity, joyousness and abandon associated with yakshis (a class of benevolent semi-divine beings). This might also account for the great popularity of the ashoka tree in classical India and the fact that it was largely cultivated in gardens and pleasaunces.

The existence of extensive kadamb forests in ancient times and the reported occurrence of many remnants in the present period in the region of Mathura (Drake Brockman, 1911) also seems to be based on a misconception. The people of this tract always refer to *Mitragyna parvifolia* as kadamb and indeed the tree is by no means uncommon in many localities. It belongs to the same family (Rubiaceae) and has a ball-like inflorescence only slightly smaller than that of kadamb in size. It also grows in clayey, moist, waterlogged areas or near stream banks and it is quite certain that recent references to kadamb in the Mathura region always refer to *Mitragyna*. It is indeed likely that the humble *Mitragyna* and not the stately and lush *Anthocephalus* may have been the tree beloved of Krishna.

The names of the various places of sylvan pilgrimage in the land of Vraj include palm forest, Aegle-forest, khair (*Acacia catechu*)-forest, which indicate stiff, clayey, waterlogged or dry patches (as indeed are quite frequent) rather than lush tropical vegetation thriving under 80 inches or more rainfall.

At the time of Alexander's invasion and retreat (327 B.C.), Sind (Mousikanos) was perhaps still a fertile tract although by A.D. 712 the eastward penetration of Islam was thwarted by this bulwark of desert. Southern Baluchistan had certainly reached its present aridity and Alexander's retreating army was decimated in the cheerless wastes of Makran. The Indus basin might have, however, retained a somewhat moister climate till later times. Dense forests grew near Ohind, sufficient to enable Alexander to construct the first Indus flotilla.

Arrian (see M'Crindle, 1893) has stated that the Northern Punjab between Jhelum and Chenab was covered with dense forests with lofty trees and numerous springs. Scattered sissu (*Dalbergia sissoo*) and babul (*Acacia arabica*) still occur in the southern portion of this tract. He describes the high plains and tableland west of Ravi as already bare and desolate (Stebbing, 1922).

That the climate of Kathiawar during Ashoka's reign (*circa* 240 B.C.) must have been such that precipitation required to be carefully hoarded is evident from the construction of a dam which created the Sudarshana lake near Junagadh in Girnar. Rudradaman's inscription of A.D. 150 mentions repairs to a breach in the reservoir. This dam was again breached and was repaired by Skanda Gupta's Governor in A.D. 457-58. It had, therefore, a useful life of at least six hundred years. When it was breached last is not known. Sudarshana lake exists no longer (Majumdar 1960*a*, 1960*b*).

For the early historic period, some indications regarding rainfall are available from Kautilya's *Arthashastra* (see Shamashastry, 1929). Although supposed to have been composed in the third century B.C. it probably attained its present form three or four centuries later. In the forty-first section of Chapter 24, while dealing with amounts of rain sufficient for a good harvest in different regions, he says that 16 units (*drons*) are enough in dried-up areas, 23 units in Malwa and unlimited amounts in Western Rajasthan, implying that whatever rain falls in the last tract is helpful. This would indicate definitively arid conditions and the precarious nature of rainfed agriculture. (The *dron* is a unit, the exact mesure of which is not known. It would seem to indicate about 1 to 1.5 inches of rain.)

The accounts of the Chinese travellers, Hiuen-Tsang and I-Tsing, give some information about the climate and vegetation. Hiuen-Tsang travelled throughout India during the middle years of the seventh century A.D. He records in his travel diary (see Beal, 1961) that in general the plains below the western mountains are dry and saline (Chapter 2); there are dense and shady forests and rice is cultivated near Jullunder (now a typically dry tract); *Phyllanthus emblica* is grown on a large scale near Mathura; there are good forests and rivers near Ahichhatra (near Bareilly) (Chapter 4); there are dense forests near Banaras (Chapter 7); Malwa is well forested, and finally at Broach, at Atali near Kutch and in Saurashtra and south-western Rajasthan the soil is saline and/or sandy, trees are few and many dust storms occur (Chapter 11). He had to cross a formidable stretch of desert to reach Sind from Gurjardesh (Barmer). On the other hand the soil of Multan is described as good and fertile and the climate as mild and pleasant. This indicates that while desert conditions had settled in the lower Indus valley, the south-western part of Rajasthan around Barmer and the Punjab plains from Multan to Jullundur had not been desiccated to anything like their present condition. The development of extreme aridity in many parts of Rajasthan (except for the Thar core) and in the Punjab plains is thus a comparatively recent phenomenon.

PLANT REMAINS

Various plant materials recovered during excavations have been identified at the Forest Research Institute (see Table 2).

The Maski site is of interest from many points of view. It lies in auriferous granite (gneissic) country and presents the desolate appearance characteristic of such formations. The vegetation is scrubby and similar to that deduced from the woody remains. With regard to *Acacia* sp. it is, however, not possible to say whether they are the same or similar to those still growing in the vicinity or some species with different climatic requirements, no longer represented there. *Chloroxylon swietenia* still grows in the locality. This may indicate an essentially stable climate.

The highest point in the neighbourhood is Durguda Gudda, a gaunt gneissic summit (1,911 feet) capping an outcrop 1½ miles by 5 furlongs wide, 400 feet above the level of the plains. Huge ancient ash mounds, the remains of large heaps of cow dung, imply the essentially pastoral nature of the economy.

TABLE 2

Site	Period	Species	Remarks
Maski (see Ghosh and Chowdhury, 1957)	I (1st millennium B.C.)	*Acacia* sp.	Common in neighbourhood
(near Raichur, Hyderabad)	II (2nd to 1st cent. B.C.)	*Acacia* sp.	Common in neighbourhood
	II (1st cent. B.C.)	*Acacia* sp.	Common in neighbourhood
	II (1st cent. B.C. to 1st cent. A.D.)	*Acacia* sp.	Common in neighbourhood
	II (1st cent A.D.)	*Acacia* sp. *Chloroxylon* sp.	Common in neighbourhood
	III (3rd cent A.D.)	*Acacia* sp.	Common in neighbourhood
Sisupalgarh (see Chowdhury and Ghosh, 1952) (near Bhuvaneshwar, Orissa)	(*circa* 200 B.C. to 100 A.D. First occupational period, early level.	*Soymida febrifuga*	Common in neighbourhood
		Acacia sp. *Casaeria* sp.	Common in neighbourhood
		Boswellia serrata *Holarrhena antidysenterica*, Bamboo (species unidentified)	Common in neighbourhood
Arikamedu (see Chowdhury and Ghosh, 1946) (near Pondicherry, Madras)	Pre-Arrentine (late 1st cent B.C. or early 1st cent A.D.)	*Maba* sp. *Diospyros* sp. *Heritiera* sp. Coconut and palmyra palm fruit shells	Occur in similar terrain

The pollen grains, mainly recovered from the limy deposits of Period II (*circa* second century B.C.) resemble (Mittre, 1957) those of pine, *Brassica*, *Campanula*, *Stellaria*, *Lychnis* and Juglandaceae. Some trachieds of pine have also been identified. The investigator's inference is that these remains indicate a temperate climate. The wood remains would seem to contradict this theory, but the measure of uncertainty with regard to *Acacia* spp. should be allowed for. In view of the fact that no independent testimony with regard to a temperate or even cold subtropical climatic régime having been in existence in the Deccan during the Mauryan period is forthcoming, it may be doubted whether a climatic shift of the indicated magnitude has taken place. More pollen analysis data from strata of comparable age are not available and it is difficult to reconcile the pollen evidence with other facts. However, it is likely that pine and associated cold-loving flora survived as a relict in higher frosty localities and gradually died out in the first centuries A.D.

The evidence from Sisupalgarh and Arikamedu again confirms the general impression that there has bean no significant change in the climate and the type of vegetation associated with it. A change in extent and quantity is incontrovertible; whether this has also resulted in retrogression or degradation to a more xerophytic spectrum it is impossible to say.

It has been conjectured that the great Rajput kingdoms would not have flourished were it not for the fact that even towards the beginning of the Christian era, Rajputana was forested and far less arid (Krishnan and Aiyangar, 1941). In this connexion it should, however, be noted that the great dynastic cities of the Rajputs occurred east of the Aravallis in the basin of the Ganges drained by the Chambal and its tributaries. Jaipur, Jodhpur, Udaipur, Ajmer occupy a region which has a far more favourable climate than the western desert.

It may, therefore, be safely concluded that while a certain degree of desiccation has certainly taken place, the vegetation and climate in northern India were not much different two thousand years ago from what they are now. Deforestation has proceeded apace and this has affected the local climate rather than that natural climate has changed and has caused a profound change in the climax vegetation. In fact even as late as A.D. 1017 when Mahmud of Ghazni attacked Mathura, there were forests near Mahavan (great forest) dense enough to obstruct the movement of armies (Eliot, 1909). The forests were thick but probably they comprised much the same species of trees as still grow in favourable situations in the tract.

THE RAJASTHAN DESERT

Western Rajasthan was largely occupied by a sea during the Jurassic, Cretaceous and Eocene and outcrops of Jurassic sandstone and limestone occur at Jaisalmer. It was probably raised into dry land sometime in the upper Tertiary. The sea extended up the Luni basin up to Panchbhadra and occupied the Rann and the lower portions of the Indus Valley in post-tertiary times (Blanford, 1909).

The whole central Asian region has been drying up for thousands of years (Manton, 1954) and the Indus basin and Rajasthan may well form part of the same system. The desert topography has, however, evolved within comparatively recent geological time as a result of dryness that has overcome the region since the Pleistocene. There is no high range to intercept the moisture-bearing monsoon. Intense solar action, drought, extremes of heat and cold and wind action lead to considerable mechanical disintegration. The sand is partly derived from this source but a larger portion comes from the former seashore and from the river channels, old and new, and the bed of the Indus. Powerful summer winds transport this debris, leading to the formation of sand dunes as well as the widespread loess deposits of north-west India (Wadia, 1926). The desert conditions are hence accentuated with time as the area is cut off from water circulation, except for occasional cloudbursts in the rains, and the water action of the internal drainage is too feeble to transport the blown sand to sea.

The sand hills are of great antiquity and often show signs of denudation. Wells dug at Gadra Road encountered horizontal fine-grained sandstone to a depth of 340 feet, which exactly resembles the wind-blown sand of the dunes. Some slight induration of the sand rock has occurred as a result of periodical precipitation of carbonates, silica and iron oxide (Auden, 1950). The most sandy tracts are along the edge of the Indus Valley and the depression marked by the Luni Valley. The present topography resembles a number of rocky islands jutting out of a vast sea of sand. This sea is not still —denudation and aggradation are active. The Thar desert hollows and the direction of sand ridges, which are parallel rather than at right angles to the prevailing winds, indicate that some areas were more deeply covered with sand in the past than at present (Medlicott and Blanford, 1879).

Given these conditions, that is, a dry climate, scanty rains, an inexhaustible source of sand from the former coastline, and powerful summer winds capable of raising tremendous dust storms, the formation of limitless wastes of blown and shifting sand is inevitable. If the cutting down of trees further accentuates insolation, increases evaporation, creates conditions for the development of violent winds and removes obstruction and surface drag in the path of such winds, the creep of the desert is very much accelerated and sands are blown on, deposit over, and engulf larger and larger tracts of fertile land at the edges. That something like this is happening at present is evident from the so-called advance of the Rajasthan desert, north-eastwards, in a great convex arc through Multan, Montgomery, Ferozepur, Bhatinda, Bhiwani, Aligarh and Kasganj, encroaching on fertile land at the rate of 50 square miles each year (Wright, 1945). There is another area of deposition between Phalodi and Jodhpur. The deposits are taking place in low-lying areas through the funnel between Barmer and Jaisalmer and along the courses of the Sutlej, old Ghaggar bed and between Loharu and Bhiwani. At the present day the water level in western Rajasthan is usually several hundred feet deep (Auden, 1950), indicating the paucity of recharge.

WANDERING RIVERS

Great changes have taken place in the topography of western India within comparatively recent geological times. Apart from the Rann, which was a gulf of sea until much after Alexander's invasion, and where a submergence and complementary uplift took place as late as A.D. 1819, there have been substantial changes in surface drainage which it is necessary to consider in some detail. There are many conflicting views but the following seems to have been the probable course of events.

The Indus itself has only two fixed points in its course through the plains and has been changing its channel frequently. It might originally have even been confluent with the Ganges (Wadia, 1926). The highest elevation of the Sirhind watershed between the Indus and Ganges is only 924 feet above mean sea level and a trifling change in the surface might turn the affluents of one river into the other. The response of closely allied species of *Platanista* (fresh-water porpoises) and many other animals common to the Indus, Ganges and the Brahmaputra may thus be explained (Medlicott and Blanford, 1879). It has shifted in its lower reaches by 100 miles westwards, and no longer empties in the Rann of Kutch as it did at the time of Alexander. It deserted its old course at Arur in A.D. 962. Through the deltaic flats may still be seen old channels which carried its waters to the Rann.

The streams making for Rajputana across the low watershed converge towards a large dry watercourse (Ghaggar) which runs parallel to the Sutlej and was fed by its waters. In its lower reaches (Hakra), it was probably fed by the Indus in the eighth century A.D. (*Encycl. Britan.*, 1951), the lower channel coinciding with the eastern Nara in Sind. This is, however, doubtful as the eastern Nara runs through a series of swamps which should have been filled up long ago by deposits had a great river followed this course. The Beas did not join the Indus either, but probably followed a distinct course to the Indus (Medlicott and Blanford, 1879). It now joins the Sutlej due to westering of the latter. The confluence of the two also probably shifted 150 miles up from near Bahawalpur to above Ferozepur (Chaturvedi, 1952). The Ravi and Chenab had their confluence near Multan at the time of Timur's invasion in A.D. 1398 but this has now shifted 30 miles up.

The most remarkable case is that of the Saraswati, which was a considerable river known to the Vedic Aryans and probably still followed its old course in the sixth century B.C. Now it is a minor stream between the Sutlej and Yamuna, which joins the Ghaggar, whose waters are engulfed by the sand at Bikaner (Pascoe, 1950). According to some traditions it followed an independent course to the sea but this is doubtful as there is no suitable stretch of low country between the Aravalli hills and the eastern Nara to permit a river to flow to the Rann. Another view is that it joined the Sutlej near Suratgarth when the latter followed its old Ghaggar course and then flowed independently to the sea under various names like Hakra, Sotra and Wahind, the lower portion of the channel coinciding with the eastern Nara, which was also perhaps a distributory of the Indus. However that may be, in course of time the aggradation of Saraswati's channel, either through its own deposits swollen by deforestation in its upper catchment or by the accumulating sand of Rajasthan or both, caused its waters to flow eastwards into the Yamuna (which was cutting into its deposits) which merged into the Ganges at Allahabad. The volume of the Saraswati may also have diminished by a decrease in rainfall or because of deforestation on the lower Himalayan slopes or both. This view may account for the ancient Indian tradition of three rivers, Saraswati, Yamuna and Ganges meeting at Triveni (Allahabad). Some would even say that the Saraswati received the name of Yamuna when it took an easterly course (Wadia, 1926).

Thus the Saraswati had disappeared in the early centuries of the Christian era, the Sutlej was no longer independent of the Indus in the early years of that era and by A.D. 1790 the Hakra was dead (*Encycl. Britan.*, 1951). The westering of the Indus and the northering of Sutlej have resulted in the Indus basin being permanently separated from the peninsula by vast desert spaces, in which traces of ancient river beds testify to its once fertile nature. Thus has the Indian Desert accomplished its march.

The history of these ancient channels indicates that the aggravation of desert conditions in the Rajasthan is of recent origin. Three millennia ago much of this country must have supported a more luxuriant vegetation.

It is also evident that some slight shift in climate must have taken place in Harappan or post-Harappan times—in fact increasing aridity may have been one of the causes of the decline of the Indus civilization itself—but the deleterious effects have been reinforced by deforestation on a large scale to which the Harappan brickmakers and their successors contributed largely, with the result that desert conditions had established by the middle of the first millennium A.D. and were a sufficient deterrent to Muslim invaders from the Sind.

HAS THE CLIMATE CHANGED?

Monsoon conditions are said to have been established in India after the Miocene when the Himalayas became a prominent feature. Between that period and the onset of desert conditions in geologically subrecent or recent times, the western Indian region should have enjoyed a moister climate. The protagonists of a definite climatic shift during the last four millennia claim that a relatively minor climatic adjustment would be sufficient to account for the change in the character of the environment. The following mechanisms have been suggested:

1. The Atlantic cyclones, which at one time deflected southwards to the latitude of northern Africa and extended to Arabia, Persia and India and nourished the plains of Sind, have receded northwards since the third millennium (Wheeler, 1946).
2. The edge of the south-west monsoon area has shifted eastwards: formerly the Indus was within the area of monsoon rains.
3. The northern storm belt was deflected southwards by conditions in immediately post-glacial times, and the effect persisted after the establishment of otherwise normal climatic conditions (Piggott, 1950).

The present climate of Sind is characterized by extreme aridity, the average rainfall being less than 6 inches in a year, with the maximum temperature in the neighbourhood of 120° F. and frosts in winter. That the climate was somewhat kinder in the past cannot be denied, however scanty the objective evidence may be. Even if it is conceded that the vegetation was of a scrubby type and more or less akin to its present degraded remnant, better growing conditions with ampler rainfall and lesser temperature extremes must have prevailed. The question is whether a basic climatic change of the type suggested above took place or the progressive deterioration in the environmental conditions in the Indus valley and its environs was the effect of human interference (e.g., the activities of Indus brickmakers)—an interference which caused a progressive deterioration of the local climate such that a vicious cycle was established; denudation leading to a harsher climate, the latter creating conditions unsuitable for the regeneration of plant cover, and the final reign of aridity.

The ensemble of historical and archaeological studies argues in favour of great stability of climate, at least in terms of historical time (Tixeront, 1956). There is also some evidence to the contrary, showing on the basis of C-14 dating that drastic differences must have existed in some areas less than nine millennia ago and that there have been significant cycles within this recent period (Kellogg, 1956). There have been wide swings from dry and warm to cold and wet conditions in Europe in the last two thousand years. During the tenth and eleventh centuries the climate was very dry and warm and the Arctic ice cap may have disappeared. From A.D. 984 to the fifteenth century Greenland was certainly much warmer than now (Tannehill, 1947). It is however, simpler to assume that deterioration in local conditions has been caused largely by local influences which have modified the topography, temperature and humidity régimes, infiltration and surface drainage, wind movement and insolation, and a host of interrelations of climatic elements. The evidence from Israel, Tunisia and India (Pramanik *et al.*, 1952) supports the primacy of human rather than natural climatic factors. There is wide agreement that the derelict Roman ruins in Algeria, the Central Asian ruins of Balkh and beyond point towards man rather than climate alone as the chief agent responsible for devastation.

There is a widespread belief that destruction of forests has caused a change of climate. There is no doubt that extensive forests do affect the climate to a considerable degree and may be responsible for a share of the rainfall. A barrier of trees protects the land from wind desiccation, reduces soil blow and modifies the temperature and humidity régimes. If all the vegetative cover were reduced from a large enough tract, remarkable changes are sure to follow (Tannehill, 1947). The temperature would rise steeply, the temperature differential between land and sea and land and upper atmosphere would change the pattern of wind circulation both horizontally and vertically and consequently the balance between "wet" and "dry" air currents, and upset the distribution as well as the amount of precipitation. This is undoubtedly what has happened, not in one step, but as a cumulative result of denudations over a long period of time.

CONCLUSIONS

Leaving aside the question of any change in the natural climatic zones, the process of desiccation may be brought about by the excessive utilization of vegetation covering the soil. This results in lowered productivity, decrease in surface water supply in springs, streams and wells, and diminution in underground water resources associated with a sinking water table. Desiccation under these conditions may be enhanced by proximity of desert areas from which strong dry, hot or cold winds usually blow, and which cause accelerated evaporation as welll as sand penetration (Stebbing, 1954).

It is evident that such conditions have prevailed in the Indus valley in particular during the last one or two thousand years, and that they in conjunction with a slight shift in the range of the south-west monsoon, have led to the development of extreme aridity. The region is a critical one, with innate potentialities of harsh developments such as the prevalance of strong summer winds and plenty of sand for them to lift; the destruction of even such scrubby vegetation as the area now has or had from the beginning tilts the balance in the favour of the desert. In this region at least, both climate and man appear to share the blame for the present condition.

Further east in the eastern Punjab and upper Gangetic plains, the evidence would seem to lay the major blame on man's shoulders. It is his insatiable nature and improvident actions which have degraded the vegetation and the climate.

As far as other regions of India are concerned, although the objective evidence is scanty, there is no doubt that large-scale clearing of vegetation has produced its usual effect.

PROBLEMS

Finally, there are certain problems connected with the interactions of climate and vegetation to which attention should be drawn.

1. Given the present climatic pattern, what is the minimum period of time involved for a significant permanent shift in climatic elements to materialize?
2. Assuming that large-scale changes in the pattern of vegetation affect the climate, in what ways and to what extent would the climate change, what would be the order of magnitude of the time required and the area over which such effects may be felt?
3. Are the interactions between climate and vegetation reversible? If the vegetation cover is restored over areas denuded within the protohistorical and historical period, would the climate also be restored to its original characteristics? If so, what would be the order of time and what should be the magnitude of area over which the surface cover would have to be restored to induce an appreciable improvement in the climatic pattern?
4. Could the vegetational environment have a retarding or accelerating influence on climatic shifts originating in purely climatic processes?

RÉSUMÉ

Les changements de climat dans l'Inde, analyse des données (S. K. Seth).

Les données archéologiques, historiques, littéraires, glyptographiques et scientifiques ont été soumises à un examen minutieux visant à déterminer si le climat a changé de façon démontrable dans la péninsule indo-pakistanaise au cours des périodes protohistorique et historique, si la flore s'est sensiblement modifiée, enfin si la végétation s'est adaptée à des conditions climatiques nouvelles, ou si c'est au contraire l'action exercée sur la végétation naturelle qui a entraîné une détérioration du climat.

Les données archéologiques se rapportent essentiellement à la période de la civilisation de l'Indus ; pour la période ultérieure on a puisé aux sources littéraires et historiques ; on a également tiré parti des indications fournies par les fossiles animaux et végétaux.

Les caractéristiques du désert et les modifications de son régime hydrographique ont été étudiées ; d'autre part, les théories qui se fondent sur l'hypothèse d'une régression de la zone des moussons ont fait l'objet d'un rapide examen.

La conclusion de ce travail est que, si le climat a vraisemblablement changé dans une certaine mesure, notamment dans la vallée inférieure de l'Indus et au Rajasthan, la destruction de la végétation a aussi contribué de manière sensible à la détérioration des conditions climatiques. Dans le reste du pays, c'est surtout la destruction de la végétation naturelle sur de vastes étendues qui a aggravé l'aridité du milieu et modifié la flore.

DISCUSSION

H. Flohn. Would it be possible to say something on the predominance either of winter rains of Mediterranean origin or of summer monsoon rains during this humid period of 3000-1500 B.C. in the arid area of Western India?

S. K. Seth. The plant remains recovered from horizons relating to the period 3000-1500 B.C. are so limited as to make it difficult to give a definite reply to this question. On the basis of *Dalbergia latifolia* and *Zizyphus mauritiana* specimens identified from the Harappan sites, it would appear that the summer monsoons predominated, as these species usually grow in summer rainfall areas. But this conclusion can only be treated as very tentative in view of the paucity of evidence.

H. Bobek. Would Dr. Seth be inclined to consider the probable existence and importance of a gallery forest which could have offered a suitable habitat for species like rhinoceros and elephant? As far as I know the tree species quoted are all (except *Tamarix*) non-groundwater types. However, I know from experience in the Iranian uplands that nearly all non-gallery types are apt to gather along the streambeds on their aridity limits.

S. K. Seth. This is certainly a most significant suggestion and I am inclined to think that riverine gallery forests should have been a prominent feature of the landscape; but perhaps the activities of the Indus brickmakers, among other things, soon destroyed them. Inundation forests of *Acacia arabica* and *Tamarix* even now occur in the lower Indus valley. These gallery forests must have provided suitable habitats for the rhinoceros and the elephant but even otherwise vestiges of habitats suited to such fauna occur in the reed marshes and swamps in the lower reaches of Nara river and perhaps Manchkar lake. As such it is not necessary to postulate a moist forest to account for the distribution of fauna—riverine swamps would provide the necessary forage and cover.

R. J. Braidwood. Dr. Seth is correct in not taking the older generalizations as to climatic change inferred from the Harappan materials too seriously. The matter of the "cultural filter" is at issue again, particularly as regards assessing the fauna and flora seen on the seals. These may not have been engraved at Mohenjodaro or even up-river at Harappa. The area of distribution of the Harappan assemblage has —we know from the recent work of Sankalia and Subbaroo— a distribution south into Gujarat and beyond (sites of Lothal and Nardotali, in much more moist environments), and that the inventories from these sites bear a remarkable similarity to those of the classical sites in the lower Indus valley itself. Perhaps the seals were engraved here. Finally, as to detail in the animals engraved, griffins and other mythological animals are known to have been engraved with exquisite detail.

From the apparent trend of C-14 determinations now available, it is perhaps unlikely that the Harappan assemblage began as early as 3000 B.C.

S. K. Seth. I agree that the representation of animals—and plants—on such seals and other objects can only be treated as an indirect evidence of limited value, in default of positive direct evidence in the shape of identifiable and datable animal and plant remains. Perhaps Professor Braidwood is right in supposing that the seals orginated in a moister sector of the Harappan culture complex where animals like the rhinoceros, the elephant, the water buffalo thrived in habitats which provided optimum food and cover conditions.

I have also mentioned another instance of the danger of taking sculptural and glyptic representations too seriously as evidence for the existence of particular species under natural conditions in connexion with the delineation of asoka and kadamba trees in Mathura sculptures of the Kushan period from which it is inferred that the rainfall in *circa* first and second centuries A.D. was in the neighbourhood of 80 inches, as against 25 inches or so at the present day. From other evidence, it is impossible to agree that dessiccation of such severity has occurred during historical times in the Mathura region.

Mlle A. R. Hirsch. A propos de l'interaction du climat et de la végétation, je me permet de citer un cas que j'ai pu observer en Basse Côte d'Ivoire dans la zone forestière. Les défrichements exécutés pour la culture du cacao ont eu une influence sur le climat local. La disparition de la forêt fossile a entraîné une baisse de 250 mm par an des précipitations dans la région, baisse qui se maintient depuis plus de cinq ans. La végétation actuelle est constituée par une savane arborée et les sols se sont considérablement altérés.

S. K. Seth. The information given by Mlle Hirsch with regard to the diminution of annual precipitation as a result of deforestation on the Ivory Coast is extremely interesting and is an objective confirmation of what many of us thought regarding the interactions of local climate and vegetation.

Once the climax community has been destroyed, the succession enters an irreversible phase in the majority of cases, due to attendant degradation of soil, change in microclimate and the incidence of biotic factors like fires. By itself, without the help of human agency, it is extremely unlikely that the secondary savannah can ever progress towards the primeval climax formation.

J. Namias. The idea that man's interference with vegetation has brought about climatic deterioration and drought had a number of adherents during the great "Dust Bowl" drought period over the Central Plains of the United States. However, the decade of the 1940's was one of rainfall abundance of the previously drought-afflicted area. This change appears to have been due to response of the circulation over the United States to quite marked changes in the centres of action over the Pacific and Atlantic oceans.

C. S. Christian. In considering the question of man's effect on the creation of deserts much emphasis is often placed on the tree portion of the vegetation. I would like to refer to an experience in Australia in 25 cm.-rainfall country. In one area grazed for seventy years at a high level of intensity by sheep, the ground flora was destroyed, sheet erosion was rife and the tree vegetation was killed—a desert was created in seventy years. In another area of the same region, with the same vegetation grazed at lower intensity for a shorter period, both grass and trees survived and when a proportion of the trees was removed still more grass was produced and the land surface was further stabilized. Removal of the trees did not in itself cause a major degradation. One often hears of the need to "reafforest the desert"—perhaps we might achieve more in reclaiming desert areas if we place more emphasis on repasturing the desert rather than reafforesting it.

S. K. Seth. I entirely agree that in semi-arid and arid areas where the climax vegetation at best approaches the form of an open savannah the surface vegetation is a most important constituent conferring stability on the site and preventing erosion. In developing degraded areas in such regions adequate emphasis should be placed on the proper management of the grass cover—but trees should not, on that count, be excluded from development and rehabilitation programmes in areas where trees *can* grow. In fact, what we should aim at is a balanced association of both tree and grass communities.

D. Amiran. I should like to ask permission to rephrase one statement by Mr. Christian. No one has seriously considered reafforesting or afforesting really arid areas—the deserts. One should mention afforestation only as related to semi-arid areas.

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THE SIGNIFICANCE OF CLIMATE VARIATIONS IN BRITAIN

by

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INTRODUCTION

In order to make a contribution towards the understanding of the practical significance of fluctuations in climate in so far as they affect agriculture in general and the production of food in particular, the recorded climate in Britain over the last one to two hundred years has been examined.

An attempt has been made to analyse such records in terms of the effects on farm operations and on land use. In so doing it is hoped that such a method of analysis will provide an example as to how climate can be linked to agricultural practices, so that similar methods could be used with advantage in other areas.

WINTER CLIMATE

Possibly the most striking change in British climate during the present century has been the tendency towards milder winters. If, for the sake of simplicity, the severity of the winter is defined as the mean temperature of the coldest month, whatever month that has been in any particular season, then Fig. 1 shows the ten-year means of this temperature for Kew Observatory from 1870. The mild period from 1895 to 1939 is clearly shown.

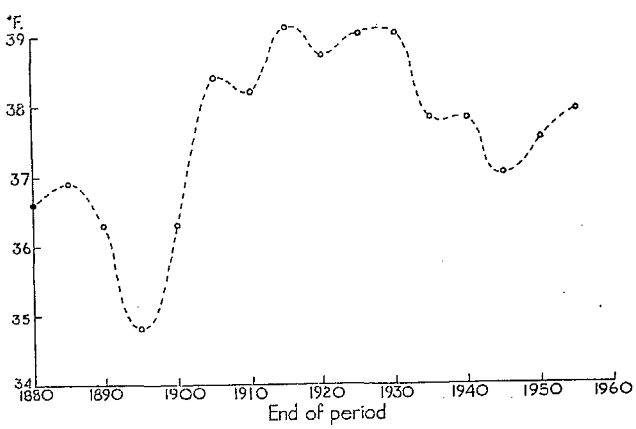

Fig. 1. Average temperature of coldest month in the year at Kew Observatory (in ten-year periods).

Kew, however, has an unorthodox exposure and has probably been affected to some extent by the westward spread of urban London. Figure 2 shows similar graphs for Stonyhurst in north-west England and Edinburgh in south-east Scotland. In both cases there is an obvious sequence of mild winters in the first half of the twentieth century. It can then be assumed that this trend was common to most of Britain and it remains to be found what effect this could have had on agriculture.

Now winter temperatures imply snow and persistence of snow cover. Examination of London records suggests the following relationship between mean monthly temperature and days of snow cover:

Mean monthly temperature	*Days of snow cover*
Above 35° F.	A week or less
32-34° F.	1-2 weeks
Below 32° F.	2-4 weeks

Snow cover affects the management of farms handling livestock, especially sheep. If its occurrence is regular, the pattern of farm management is such that adequate provisions are made. If it is sporadic, it is of minor importance if the duration in short. If it is sporadic and the periods of snow cover exceed a week, crises may occur.

Considering the Stonyhurst records and taking 34° F. as a critical "threshold value" for the mean temperature of the coldest month we obtain the data illustrated in Fig. 3: the estimated frequency of years with major snow problems since 1851, which is regarded as representative for Pennine farms up to 500 feet above mean

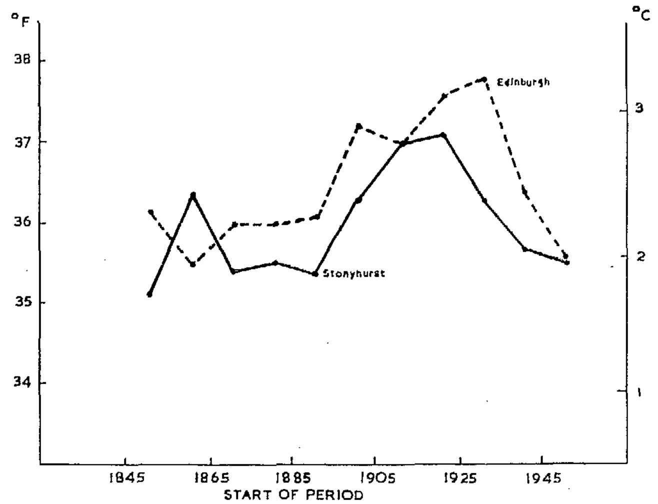

FIG. 2. Average temperature of coldest month in the year.

sea level. In the last century the frequency averaged one year in three. Then came a period between 1896 and 1939 when only one year (1929) was likely to have brought about serious conditions.

This length of period involves almost two generations of farming during which practices must have changed such that no state of preparedness existed. Furthermore the reliance on motor transport and quicker communications meant that far less food for men or beast was held on isolated farms. There was indeed a state of "false security". This climate holiday was followed by three consecutive cold winters with major snow difficulties, 1939-40, '40-41 and '41-42. The effect of these was far greater because it followed so long a period free from danger.

It might have been thought that this trend towards milder winters would have led to an increase in hill farming activity. In actual fact, because it coincided with a period of trade depression, farming receded from the hills at the very time when it would have been more profitable when considered solely from the standpoint of climate.

Normally winter temperatures in Britain are too low to permit the growth of a standard crop such as grass. During the period of milder winters the temperatures in south-west England almost rose high enough to permit continual growth throughout the year on a basis dependable enough to change the farming structure. This "threshold" was not, however, crossed and the recent recession from the mildest period has prevented any alteration in management designed to provide stocks of winter feed. The climate change was large, but not large enough and was therefore comparatively insignificant.

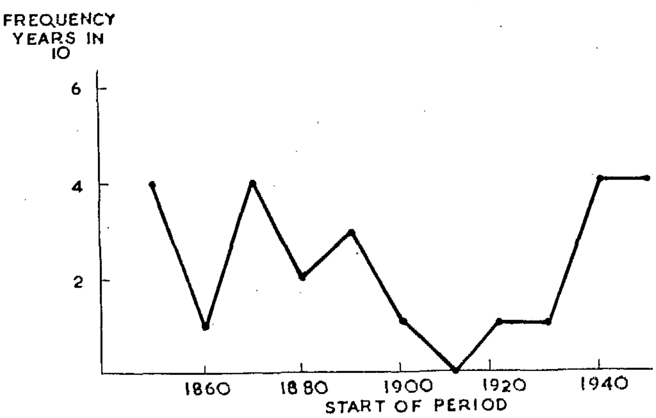

FIG. 3. Frequency of years with major snow problems in Lancashire.

SPRING TEMPERATURES

It might be thought that higher winter temperatures would be accompanied by earlier growth in spring. This is not completely true. Judging from the Oxford records, shown in Fig. 4, the curves of average coldest monthly mean temperature and average mean March temperature do not vary in a very close manner. Winters were cold in 1815-35, but March was relatively mild and, on average, above the critical temperature for grass growth (43° F.). The mildest decade of winters, 1916-25, had average March temperatures close to 42° F., when grass growth would be quite limited.

The timing of the spring flush of growth is very important to the dairy industry, especially if it is planned towards spring calving. A mild March leads to good spring grass, the rains permitting, and high milk yields in April and May. Unless a cow can eat well and provide a good volume of milk at the beginning

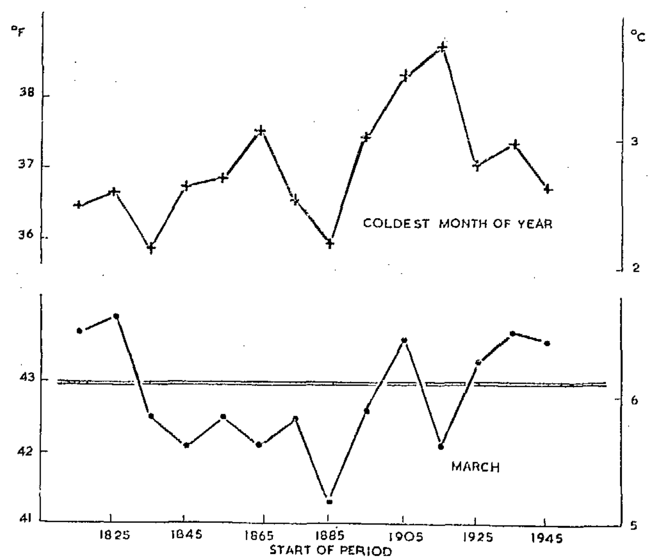

FIG. 4. Ten-year means, Oxford.

of a lactation, it cannot maintain high yields later in the summer. The normal yield in September is at a minimum and the ratio between April yields and September yields is almost constant. April yields depend largely on grass growth in March as far as climatic conditions are concerned.

SPRING RAINFALL

Apart from permanent grass, the main urgent tasks of farmers in March are the spring cultivations preparatory to sowing annual crops. Delay in sowing due to unprepared ground means reduced final yields. The "peck of March dust" is indeed worth a "King's ransom". Everything therefore turns on the March rainfall and Fig. 5 shows the ten-year means at Stonyhurst and Kew. The decrease in rain in the present century during March in the north-west is striking; a similar tendency is seen in the south-east.

The significance of this change depends on another factor and that is the rate of evaporation of moisture from the top layers of soil. This is at the rate of 1-1 ½ inches per month, so that to provide the peck of dust a rainfall not exceeding 0.8 inch is needed.

If we accept this threshold value and plot in Fig. 6 the frequency of pecks of dust the smaller change in March rainfall in the south-east is far more significant than the larger change in the north-west. The change is considerable: in the forty years between 1881 and 1920 there were only three years when a farmer in south-east England would have had good conditions for his early spring work; in the next forty years there were thirteen such occasions.

A small change in rainfall régime at a significant period of the farming year has thus had a very appreciable effect on farm management and on consequent yields of annual crops. Again we have clear proof that a small climatic change can be of the highest importance if it crosses a significant limiting value. Larger changes within a more uniform range are of far less significance. Straight-line correlations are an exception and not a general rule when linking meteorology to agriculture. They can only be used in limited ranges, and extrapolation is a dangerous practice.

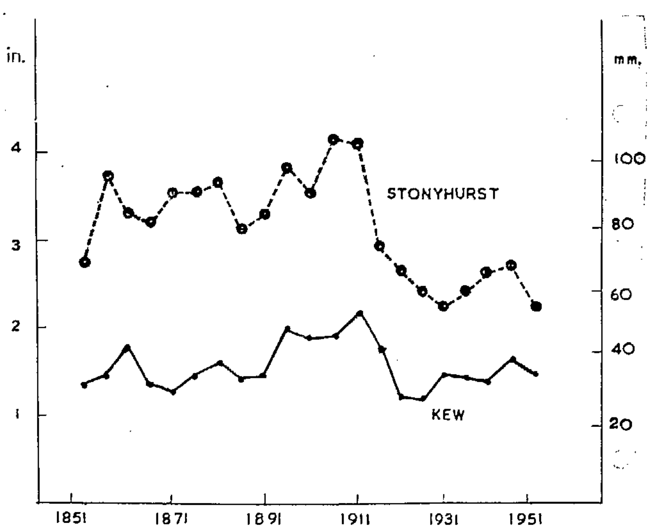

Fig. 5. March rainfall.

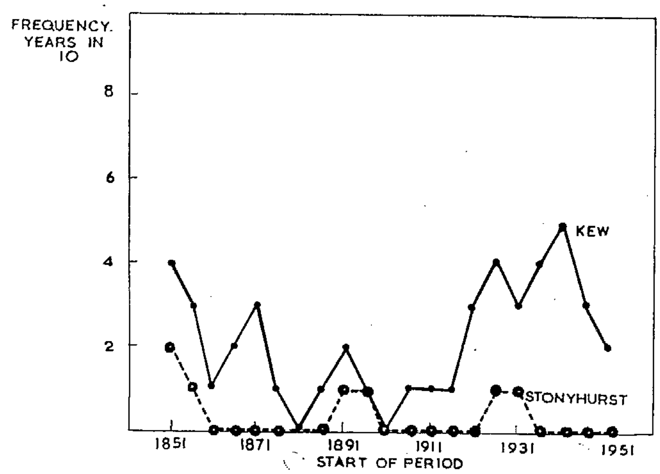

Fig. 6. Good conditions for spring cultivation.

SPRING FROSTS

The next critical period of weather is the time of spring frosts. Fig. 7 shows the ten-year averages of the data of the last spring frost at Ross-on-Wye in the West Midlands, Cambridge in East Anglia, and Tunbridge Wells in Kent. No clear pattern emerges. Cambridge shows little variation over the period, Tunbridge Wells has changed slightly for the worse, and Ross has fluctuated in a cyclic manner. The only unanimity is shown

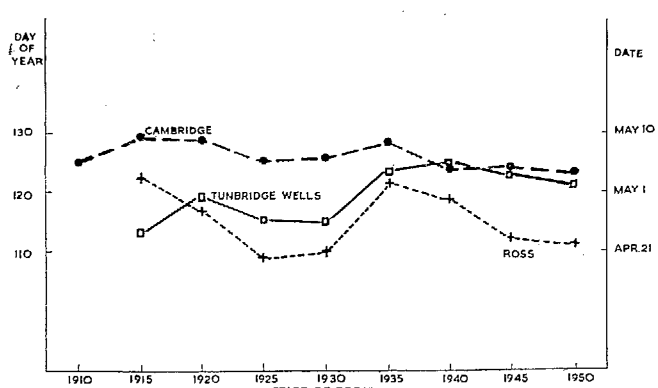

Fig. 7. Date of last spring frost.

in the 1936-45 decade, when in a period of dry springs all three stations show poor prevailing conditions. The years 1935 and 1938 were those when major damage to fruit crops was experienced. In this case the non-uniformity of record is due to the "chance" nature of frost but even so if the climate had continued in the fashion of the late thirties the fruit industry would have become increasingly uneconomic. Another threshold had been approached, but not crossed.

HAYMAKING WEATHER

Hay is a vital crop to livestock farming. Unless it is of good quality and in sufficient quantity there is a lack of winter feed and stock either has to be sold, probably on a poor market because everyone else is trying to do the same thing, or else expensive concentrates have to be imported. The simplest factor indicating good quality hay is a dry June, although to be more accurate the June sunshine should also be taken into account.

Traditional haymaking methods vary according to the climate. In the drier parts of Britain the general method is to cure the hay in wind-rows lying in the field. In Scandinavia the grass is hung up on wires something like washing out to dry. Farmers do not change their methods according to the year, so that the wind-row method will tend to be used in years better suited to the more laborious but more efficient methods of cooler and wetter climates.

Figure 8 shows the ten-year averages of June rainfall for England and Wales as a whole. It shows one dry period, 1790-1829, followed by a very wet decade. More recent years have been, in general, comparatively dry. If the general rainfall over England and Wales is 2 inches or less, it is reasonable to assume that much of the lowlands have totals of about half this country average, in which cases the traditional methods of haymaking would have been generally adequate.

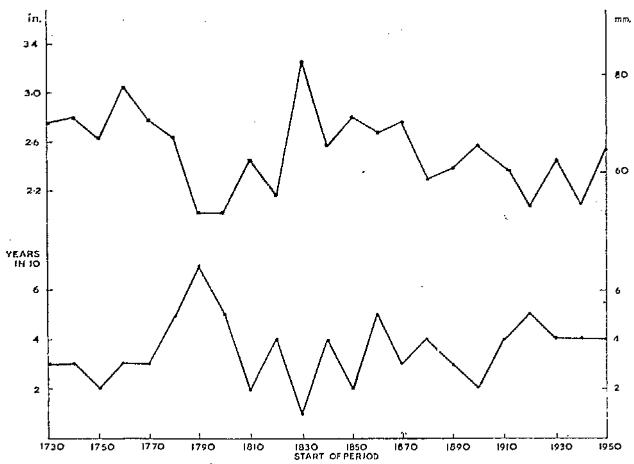

FIG. 8. Ten-year means, June rainfall, England and Wales and frequency of good hay harvest years.

Figure 8 also shows the frequency of good hay harvest years, based on this assumption. The end of the eighteenth century was obviously a good era for hay, the 1830's on the other hand were likely to be disastrous and the 1900's little better. It must be remembered that although a good hay harvest may not make a rich farmer, a succession of bad hay harvests is likely to break him.

The main significant change is clearly the 1790-1830 reversal of fortune; recent years have been far more equable. The problem of the best methods to adopt still exists, however, and in British conditions, its solution lies more in the province of medium-term forecasting than in foretelling any climate change.

DISEASE WEATHER

Many plant diseases depend to a great extent on the humidity climate, the details of which are sadly deficient and the implications of which we are just learning to interpret. Humidity, however, is closely allied to rainfall and we can make some deductions using this parameter. The important factor is that diseases can build up from year to year and a succession of years which are wet at a period critical to the disease will have a cumulative effect.

For example, the April and May rainfall is closely linked to the intensity of attacks of apple scab. Between 1931 and 1939, wet and dry years tended to alternate; between 1940 and 1947 came a succession of years which were dry during April and May, and scab was not a serious disease. This was followed by four wet late springs and as a result the disease built up to very serious proportions in the main apple-growing areas of East Anglia. Since 1955 the trend has been reversed, and dry weather has predominated.

The consequence to the fruit industry is relatively clear-cut. Wet weather in April and May—high incidence of scab—diseased and scarred fruit—poor prices. With other diseases it is not so simple. An examination of July rainfall would give a good indication of the intensity of potato blight attacks. A wet July brings an early and possibly heavy blight attack; it does not inevitably result in low yields. The reason for this is that the July rain increases the rate of bulking of the tubers and this effect is greater than the reduction due to disease. The average national yields are greater in blight years than in non-blight years.

Climate change analysis in terms of plant disease is therefore by no means simple; the most important factor is probably the sequence of unfavourable years. The second bad year in succession is serious, the third bad year may be disastrous. Admittedly an increase in frequency of bad weather increases the risk of such sequences but the distribution of bad years seems to be more due to chance then to any recognizable climate change.

The incidence and intensity of attacks of some annual diseases, such as liver fluke in sheep or lung-worm in cattle, depends to a great extent on the wetness of the summer. If, in high rainfall areas, the grass is continually wet, the life cycle of the parasites which cause such diseases can continue without check.

If, for example, we adopt a simple parameter for the liver fluke such as that each of the three months June, July and August have rainfalls with a national figure of 2.5 inches at least, thus implying rainfall of 4 inches or more each month on the hill pastures we find that the frequencies of such occurrence were:

1730-49	2	1850-69 (3 successive years, 1851-53)	9
1750-69	5	1870-89	6
1770-89	4	1890-1909	5
1790-1809	4	1910-29	5
1810-29 (3 successive years, 1828-30)	5	1930-49 (3 successive years, 1944-46	5
1830-49	7		

The mid-nineteenth century was clearly the most difficult period, but because of the build-up of the parasites from year to year, the most important facts are the occurrence of the three sequences of three "disease" years.

WEATHER FOR MILK

Milk is a perishable food and cannot easily be obtained from distant sources of supply. Milk production has pronounced seasonable variations, it is at a maximum in late spring, a minimum in late summer and is relatively constant or with a slow increase from October to March. The production problem is to avoid too large a surplus in May and a shortage in September. As indicated previously in this paper the volume of September supplies depends to a great extent on the volume of late spring supplies.

The ratio of September milk to April milk in recorded herds varies from 0.74 to 0.80 and the greater part of this variation can be related to the June and July rainfall over the country. The correlation between the two factors, the ratio and the rainfall, over an eight-year period is 0.85. The reason for this is explained by the logical sequence: early summer rain—good grass growth—plentiful food for grazing cows—a maintained diet of good quality—sustained milk yields. The June-July rainfall total is thus a good indicator of the difficulties facing the milk producers. If the September-April ratio falls below 0.75, supplies will be short in September unless the late spring peak of production was abnormally high, a state of affairs which would be unlikely in normal planning and could only be occasioned by change in a very mild and fairly wet spring.

From the regression referred to above a ratio of 0.75 is equivalent to 5.8 inches of rain over England and Wales in June and July. If the ten-year average for this parameter falls below this critical level then it may safely be deduced that milk supplies in September were low in such a decade, although if prices vary inversely with supplies it is not safe to assume that the years would have been financially bad for the producer, but only that they would have been difficult for the consumer.

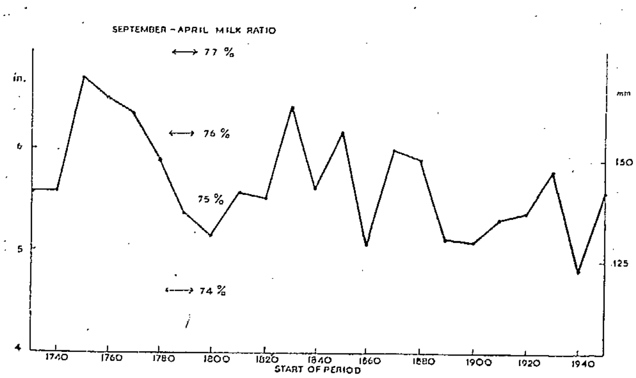

FIG. 9. June-July rainfall, England and Wales.

Figure 9 shows the plot of June-July rainfall in England and Wales with the critical values inserted. From this it will be seen that in this century there have been several decades when conditions have not been ideal for dairying. The 1940's in particular were years in which it was not easy to maintain good milk supplies in late summer on grass alone.

SUMMER RAINFALL

The consideration of summer rainfall leads towards the major problem of land use. The balance between transpiration which extracts moisture from the soil and rainfall which replaces it is a very delicate one and the margin of difference between income and expenditure is restricted by the root range of the crop and to a lesser extent by the quality of the soil.

We can calculate the average potential transpiration from meteorological data by the method due to Penman and quick monthly estimates can be made by the modified method devised by the author depending on average values and incident sunshine. If we compare average potential transpiration and average rainfall over the April to September period we find that for Britain:

Summer transpiration minus Summer rainfall	*Land use*
Over 6 inches	Main crop-cereals
3-6 inches	Mixed farming
0-3 inches	Grassland farming
Minus quantities	Upland farms with poor acid soils

The summer rainfall and summer transpirations for Kew were compared for the years 1880-1959, and the differences between the two which can be regarded as the potential soil moisture deficits are plotted in Fig. 10.

The vertical lines are the potential deficits, the disjointed line connects the ten-year averages of this parameter, and the pecked horizontal lines the critical values of 3, 6 and 9 inches. If the potential deficit exceeds 9 inches, then the summer climate that year could be described as sub-arid and major soil moisture deficiencies would be suffered by all crops including trees.

In general the conditions have been fairly steady with more dry years than human memory would have suggested and four years in eighty when rainfall exceeded transpiration. In this connexion two old sayings may be quoted. "Drought never killed the British farmer", because drought may bring light crops but prices are high and harvest conditions good; "A year good for grass is good for nothing else", for continued wet weather will make any harvesting difficult and lower the general condition of animals. In other words, British agriculture as a whole would prefer the years to be drier in summer than to be wetter, even though in such cases yields would fall due to lack of soil moisture.

Figure 11 interprets the Kew analysis in terms of the frequency of years good for grass, good for cereals, and those suffering from drought. Again the picture is one of relatively stable conditions except for a dry decade commencing 1895 and a wet period 1915-26 (with 1921 a conspicuous exception). The appearance of 1895 as a significant date is interesting. It also appears to be the start of the series of mild winters and warmer summers.

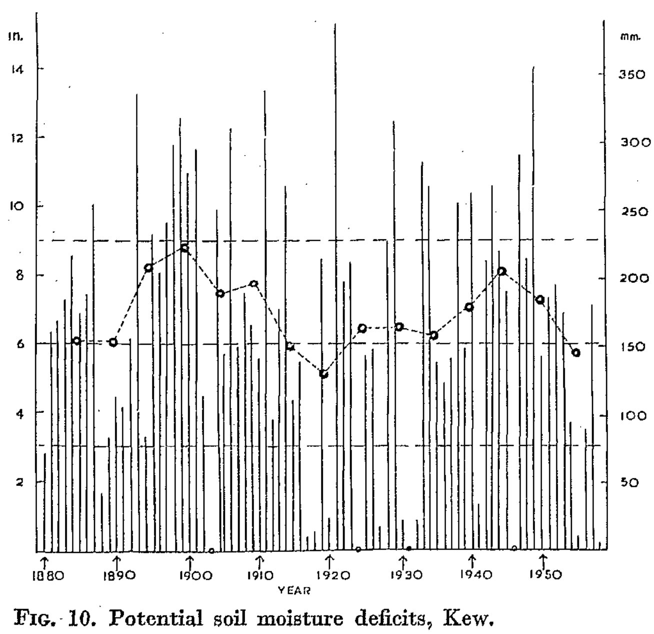

FIG. 10. Potential soil moisture deficits, Kew.

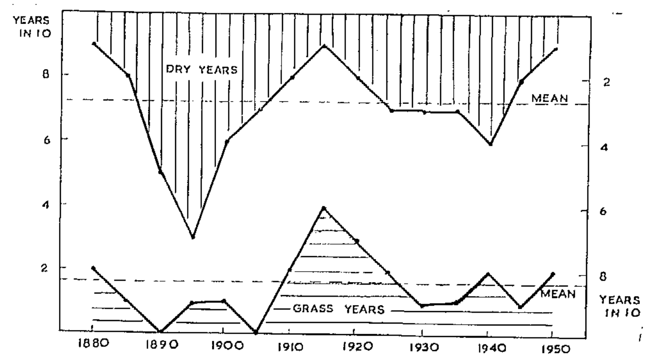

FIG. 11. Frequencies of suitable land use, Kew.

HARVEST WEATHER

No crop is safe until it has been harvested. The main harvest month for cereals is August and it has been observed that when the rainfall during this month exceeds 4 inches harvest conditions are extremely difficult even with modern equipment.

For simplicity the country averages have been used and the frequency of years in ten with an England and Wales rainfall of 4 inches or more are plotted in Fig. 12. Probably three bad harvest years in ten can be tolerated, and in the last 230 years there have been four periods when conditions have been worse than this, namely 1750-69, 1840-49, and 1950-59. The 1950's produced the worst conditions of all and were only mitigated by intensive use of combine harvesters and grain-drying equipment.

Again consecutive bad years are likely to be most serious to a farmer who has only limited capital. There have been four such sequences of three consecutive bad harvest years as judged by the rainfall criteria: 1755-57; 1877-79; 1950-52; and 1956-58.

Had it been possible to foresee the August rainfalls of the 1950's the benefit to British agriculture would have been considerable and would have had a pronounced effect on the pattern of land use.

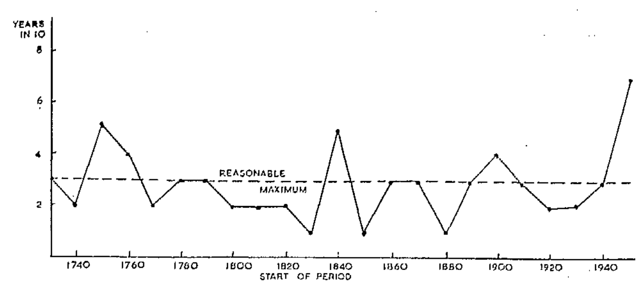

FIG. 12. Frequencies of difficult harvests, England and Wales.

SUMMER TEMPERATURES

The mean summer temperatures, averaged over the three months June, July, August, for Oxford together with a similar figure for England and Wales as a whole are shown in Fig. 13. The main impression is one of stability although there is a tendency for a warmer period towards the middle of the present century. The frequency of extreme temperature conditions, either hot or cool, is fairly constant, occurring about once a decade. The significance of these variations in regard to agriculture is very small except in relatively minor aspects of seed production. It is clear that rainfall variations are of far greater importance in summer as far as British crops are concerned.

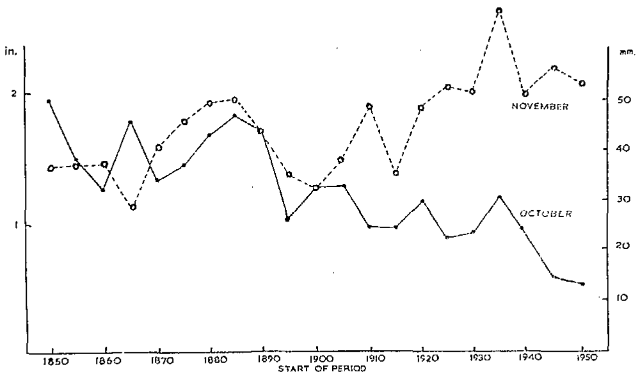

FIG. 14. Effective autumn rainfall, Kew.

AUTUMN RAINFALL

After the grain harvest, the farmer is principally concerned with autumn cultivations and autumn sowing, although he may still be engaged on the lifting of potatoes and sugar beet crops. In all cases, however, he welcomes an "open" autumn free from excessive rain and with reasonable dry sunny periods. In midland and eastern England there has been during this century a significant change in the pattern of autumn rainfall. The October rains have decreased and the November rains increased. This change cannot be found in the north-west of England or in Scotland.

In the south-east, however, the change is very significant. If we substract from the monthly rainfall totals the amount of moisture likely to be lost in evaporation and plot the resulting "effective" rainfall for Kew, we obtain the series of ten-year averages shown in Fig. 14. October has, in effect, become a relatively dry month in the last twenty years. This must have made for much easier conditions in lifting root crops and carrying out ploughing and other cultivations, especially on the heavier clay lands.

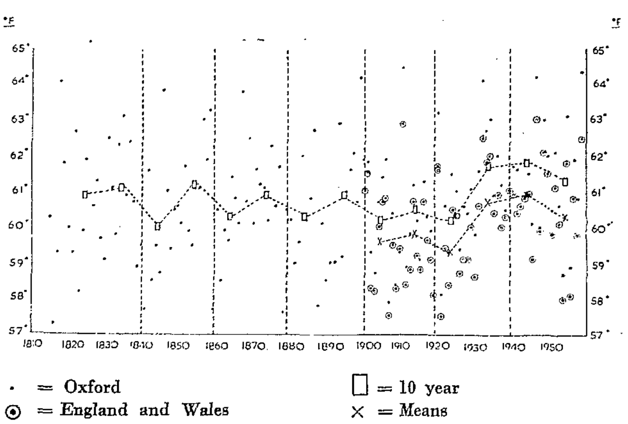

FIG. 13. Mean summer (June, July, August) temperature. Oxford; England and Wales.

A further consequence of the decrease of October rains in the south and east of England has been a decrease in the number of wet days. In the early years of this century, these averaged 15 per month, representing a likely interference of outside farm work one day in two. In recent years the average has decreased to nearly half this figure (between 8 and 9 days per month) so that the effective working hours in the fields have increased considerably.

This decrease in rainfall has often been accompanied by milder weather. In south-east England between 1850 and 1899 there were only four autumns (September-November) which could be termed dry and mild; between 1900 and 1949 there were seventeen.

WINTER RAINFALL

Winter rainfall in Britain is commonly regarded as something to be endured and the consequent water is disposed of by the quickest possible means of drainage. It is only fair to say that with the constantly increasing demand for water supplies, especially for irrigation, far more attention is now being paid to conservation and storage. At present the supply of water is limited more by the available storage facilities than by the total rainfall, but this state of affairs may change before the end of the century.

In eastern England, however, there are areas where the average winter rainfall (October-March) is 10-12 inches, so that about one year in ten the actual winter rainfall may be about half this value. This winter rain is used in three main ways; it replenishes the soil moisture, it evaporates from the soil surface and it replenishes the wells, streams and rivers.

The usual soil moisture deficit at the end of summer can be estimated as 4 inches under crops such as those grown in this area. It will only be less than this in the years with very wet summers which are relatively rare in eastern England. The winter loss by direct evaporation is of the order of 3 inches. Therefore, unless the winter rainfall exceeds 7 inches there is a danger that the soil will not be at field capacity by the beginning of the next growing season. What is more important, the soil in such circumstances will have a dry zone some 2-3 feet down. This could be disastrous for deep-rooted crops such as cereals or fruit trees and lead to sudden wilting and large drops in yield in the following summer unless it was considerably above average in rainfall.

Figure 15 shows an analysis of Cambridge rainfall carried out with these assumptions, from which it will be seen that there was a danger of this state of affairs happening in three of the twenty years, in one of which at least it is known that the drains under a field of permanent grass did not run throughout the winter, thus confirming the calculations.

It is interesting to note that crop rotations in this area have rarely favoured the taking of two cereal crops in succession on any one field. The reason for this has usually been stated to be one of fertility levels, but it is also a good insurance against insufficient soil moisture replenishment. It is suggested that many of the "dust-bowl" conditions in many parts of the world have been accentuated by this difficulty of insufficient replenishment rains and it is interesting to find that the same problem is not completely absent in a relatively wet country like Britain. The driest areas of Britain are, in fact, on the verge of semi-arid.

It is difficult to examine the incidence of such dangers in the past because of insufficient knowledge of the variation in potential transpiration, but if we examine the October-March rainfall totals alone an interesting picture emerges. Assuming that the winter rains in East Anglia are two-thirds of the national total, Fig. 16 shows the variation in this parameter since 1730.

These totals have generally increased over this period and from this it may be deduced that the dangers of insufficient winter rain have decreased. In the 1780's in particular the position must have been acute in the drier grain-growing areas.

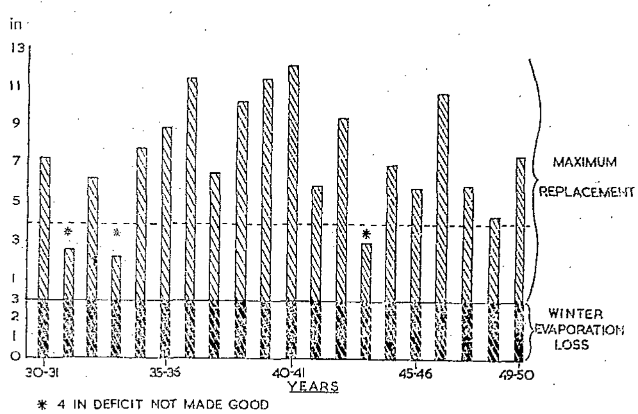

FIG. 15. Use of winter rainfall, Cambridge 1930-50.

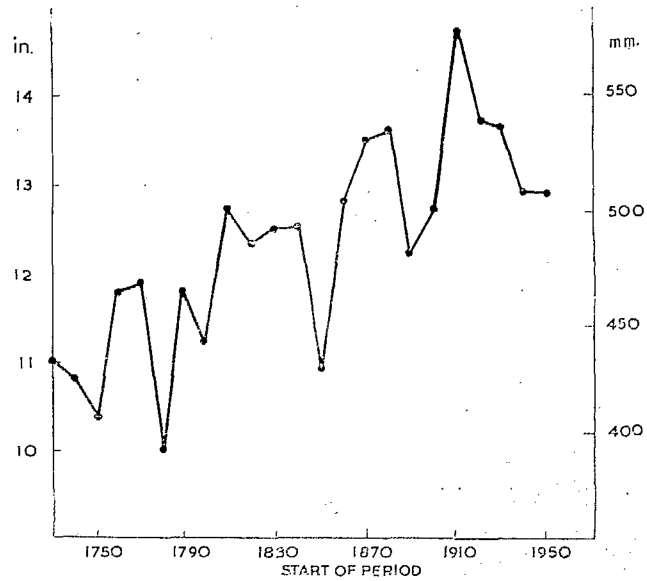

FIG. 16. Winter rainfall, East Anglia.

It is interesting to note that in south-east England there has been a big change in the character of the winters since 1850. In the last fifty years of the nineteenth century there were only nine wet mild winters (December-February); in the first fifty years of this century there were twenty-two!

CONCLUSIONS

The importance to agriculture of a fluctuation in climate does not necessarily depend on its magnitude or on its statistical "significance".

The first step in any appraisal of climate from the point of view of agriculture, forestry and horticulture, is to determine the critical meteorological elements and the critical periods of the farming year.

Secondly, the critical values of such parameters must be established or, at least, they must be estimated. The relationships between weather and crops or between weather and farming activities are not linear except within limited ranges. At the extremity of such ranges, there are "threshold values" of which the occurrence of frost is the simplest example.

It is the frequency with which such thresholds are crossed that provides the best index of the effect of climate. Chronological averages are therefore of limited use and it is the variation about such averages that becomes of the greater importance. In particular, annual averages are very poor working parameters.

If the threshold value is one of "danger" in that it relates to the failure of a crop, the inability to harvest a crop, or the probability of serious adverse effects due to disease or pests, then not only must the frequency of such dangers be considered but also the chance of failures occurring in successive years, as the cumulative effect on the economy of the farmer is very important.

The nearer a system of land use is to the meteorological limits appropriate to such a system, then the more susceptible it is to small fluctuations in climate. This fact is evident from experience in the United Kingdom, it must be of paramount importance in arid and sub-arid areas. Furthermore the period of such fluctuations that must be considered is no more than the lifetime of a single farmer.

RÉSUMÉ

Les effets des variations du climat en Grande-Bretagne (L. P. Smith)

L'auteur étudie l'influence exercée sur l'agriculture par les variations de climat enregistrées en Grande-Bretagne depuis un ou deux siècles. Il examine en particulier les points suivants: Les températures hivernales et la couverture de neige; Les températures de printemps et le début de la saison de croissance; Les pluies de printemps et les cultures printanières; Les gelées de printemps; Les pluies de juin et la fenaison; Les pluies d'été et les épiphyties; Les pluies d'été et la production laitière; Les pluies d'été et l'utilisation du sol; Les pluies d'août et la moisson; Les températures estivales; Les pluies d'automne et les cultures automnales; Les pluies d'hiver et la réhumidification du sol.

SECTION V

CONCLUSIONS OF THE SYMPOSIUM

CONCLUSIONS DU COLLOQUE

AIMS AND METHODS IN STUDIES OF CLIMATIC FLUCTUATIONS

by

C. C. Wallén

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It is a great honour and pleasure for me to have been asked to give the concluding lecture of this symposium on climatic change. However, it is certainly not an easy task, because the problem of climatic fluctuations, as we have seen from the discussion, is one of extreme complexity and one which covers many disciplines. The fact that there are so many disciplines involved, as for instance meteorology, oceanography, geography, hydrology, geology and glaciology, plant ecology and vegetation history—to mention only some—has made it impossible to work in this scientific field with common and well established definitions and methods. Investigators in various disciplines—and sometimes within one and the same—have applied methods and definitions which have often differed from each other to such an extent that comparisons between the results have been hardly possible. The main reason is that people from various disciplines are interested in fluctuations of different scale occurring at different times in the earth's history which, as we have seen, means that the same methods cannot be applied.

It has been one of the important aims of this symposium that people from various disciplines and dealing with quite different aspects of the climatic fluctuation problem have been brought together and shown each other how different are the approaches and methods that have to be applied, simply because of the great variations in the timing, scale and availability of data.

In my opinion, the aim of this last day should be to summarize the difficulties we meet in comparing work done by scientists, in various disciplines and with the use of very different methods, and to make proposals as to future activities in the field of climatic fluctuations. My review therefore will deal rather with aims and methods than results. The actual state of knowledge on climatic fluctuations is so well revealed in the papers and summaries published recently or presented at this symposium that I do not see the need to give a "summary of summaries".

It has been clearly shown in the discussion that meteorologists dealing with climatological records are —compared with scientists from many other disciplines—in a favourable position, as they can apply well-defined physical and statistical methods to the problem of climatic change even if so far no attempt to standardize these has been made.

The most radical and theoretical approach to the study of the existence of climatic fluctuations since meteorological records have been kept is that of the statisticians which was shown during our first session, by R. Sneyers, W. Hofmeyr, K. N. Rao and V. M. Yevdjevich. The basic idea in all theoretical approaches to the problem is that no fluctuation of an element varying with time should be considered as true unless it is statistically significant within the period of records available.

In dealing with the important question of statistical significance there are, however, at least two questions which have to be discussed and clarified as to our further activities within the field of climatic fluctuation. The first one deals with the theoretical aspect of the problem. It is evident that a certain trend in climate might—at least if studied with many common methods —be important if treated within a comparatively short period of record but may seem quite insignificant when studied within a long record. The development of the "recent climatic fluctuation" renders a good example as has been shown in the interesting contribution by L. Lysgaard, W. L. Hofmeyr, N. Rosenan, J. E. Buchinsky, J. Dubief and J. M. Mitchell. All authors have been able to show, by using records dating back to the end of the eighteenth century that the warming up of large parts of the world from the middle of the nineteenth century until recently has been statistically significant. However, as pointed out especially by J. M. Mitchell and also shown for sea temperatures by M. Rodewald this increase in temperature has recently declined. The decreasing trend is significant if we consider the last 20-50 years or even further back but may lose most of its significance by applying several of the statistical methods commonly used to show fluctuations during a longer period. Many other examples may be given as to how difficult our situation is because we cannot compare results from investigations where different standard periods and statistical methods have been used. This situation therefore calls for some kind of recommendation as to standard periods and statistical methods to be applied, as well as for some criteria for what shall be considered a climatic fluctuation from the theoretical point of view.

There is, however, a very important practical side also to the problem of climatic fluctuations, in recent periods of time, which certainly indicate that the importance of statistical significance should not be so exaggerated as to say that changes of climate which cannot be proved statistically significant should not be considered. As indicated by Dubief and others during the first day of discussion and many times shown by geographers, land-use specialists, plant ecologists, etc., changes of climate of a short range—such as, for instance, the recent decline—may have a great influence on vegetation, agricultural conditions and mankind as a whole, particularly in climatically regional areas of the world. Such changes therefore certainly cannot be disregarded from the practical point of view.

For instance, it seems to me—and this was confirmed by personal communication—that the short periodic and not statistically significant fluctuations, shown to have occurred recently in India by K.N. Rao, might have had important implications on the margin for agriculture in that country. We also know that the recent decline of temperature in northern latitudes has shown up in a quite considerable deterioration of the sea-ice conditions. It should be kept in mind that in marginal areas even a very small change of climate lasting for a short period may have a disastrous influence on, for instance, vegetation or may considerably change the sea-ice conditions, thus creating secondary climatic implications of great importance. I should like to emphasize, however, how complex is this problem. In many cases vegetation, fauna, glaciers, etc., which form indications of climatic changes, react by a considerable lag. It is therefore as Lysgaard has found, that many indications in vegetation and fauna of the long-periodic increase of temperature up to the 1940's are still important features in Denmark, and the recent decline seems to have influenced such factors only in very marginal areas. Great care certainly has to be shown, therefore, in interpreting evidences that react with lag to climatic changes. The excellent presentation of the influences of recent short-range changes of climate on agriculture in England given by L. P. Smith certainly stresses the importance of statistically insignificant changes in climate even in temperate latitudes. I also believe that all those interesting methods that he used could be applied in arid regions and thus help us to understand the behaviour of the margins for agriculture.

It is thus a practical necessity to study also statistically insignificant fluctuations to try to find their causes, and if possible to say how long they are going to last.

We further noted from the discussions that there is at the moment no general agreement on which are the best methods to apply to prove the occurrence of fluctuations when climatic records are available. Among the methods used, the smoothing of time series by the use of overlapping means seems to be the most common one applied, for instance by L. Lysgaard, N. Rosenan and several others. This method has been the matter of rather severe criticism in recent years due to statistical weaknesses but still is a very handy method. Others suggested are E. B. Kraus' cumulative curves, and the more sophisticated statistical trend tests by R. Sneyers and W. Hofmeyr just to mention a few of them. All authors agree that their methods have certain disadvantages and a task for the future would be to recommend the most suitable method for studies on fluctuations in climatic records. We may probably agree that the methods recommended preferably should allow for the statistical significance of the fluctuation to be studied.

The whole problem of which statistical methods and what length of record should be used in studies of climatic changes could then be looked at from either a theoretical or a practical point of view. For the purpose of facilitating comparisons between various investigations the theoretical aspect calls for some standardization to be recommended regarding the length of record which should be accepted as true. This seems to be a typical task for a working group of WMO to settle. In fact, there exists a group within the Climatological Commission which has to deal with the question of the length of standard normal periods in climatological investigations. The problem mentioned is obviously closely connected with this task. However, the practical side also has to be looked at and it seems that, if a working group should take up the problems mentioned above, it should not only lay down criteria for length of record and significance but should also propose some standard methods to be applied in studies of climatic fluctuations. In addition, it should more particularly suggest ways of treating short periodic fluctuations which may have practical implications although being statistically insignificant according to the proposed criteria for a true climatic fluctuation. There is also a third problem which has been dealt with rather carefully in recent years and which I have not found time to deal with but which should be studied carefully by such a working group. This is the important question of methods to study the homogeneity of the records used in studies of climatic fluctuations.

Before leaving this question of changes during the period of record I should like also to point out the importance of keeping all around the world a network of key stations with continuously homogeneous trends. Dr. Mitchell's work has shown the importance of keeping such a network which has already been recommended and is under study by the Commission on Climatology of WMO.

Coming to the problem of climatic fluctuations during ancient and geological periods, we are faced with much greater difficulties in laying down standardizations and criteria. We face—in dealing with the "pre-meteorological" fluctuations of all scales—at least three difficulties which do not exist for the more recent changes of climate. These are dating of the fluctuations as well as determination of their absolute magnitude and significance. In periods of climatic records, statistical methods of different kinds could be applied to establish these facts but this is generally not the case in dealing with ancient periods. For historical records without climatic data, dating and sometimes estimates of magnitude of climatic elements can be made as shown by H. H. Lamb regarding pressure, S. Manley on temperature and R. Schove on wind conditions. Such methods are extremely important as they make the fluctuations found during these old periods more or less directly comparable with the ones found from climatic records during the last 200 years. In most cases, however, only the relative and not the absolute magnitude of the fluctuations can be determined. This means that it is generally impossible to apply significance tests to values derived from historical records. We can only agree that a qualitative discussion of their significance should be made and that in any case, it is advisable that in dealing with climatic conditions in historic periods, fluctuations of climate should, if possible, be expressed in absolute or relative figures rather than discussed qualitatively. Comparisons with more recent periods will be facilitated by such an approach.

Archaeology and palaeoanthropology—particularly in old historical times—plays an important role as a means for studying climatic fluctuations both in comparatively recent time, and in very ancient periods. This has been very well shown by Braidwood, Tixeront and Wendorf in their studies of Iran, Tunisia and the United States of America. As long as we deal with historical records, we have no difficulty in fixing the time when the fluctuations occurred but going further back in history, this becomes more and more of a problem. Archaeologists will, however, especially by C-14 tests, in most cases be able to fix the time within a certain limit, but we face the problems of expressing our results quantitatively and discussing their significance even more than in the case of historical records.

Quite often and especially in the semi-humid or semi-arid parts of the world where ancient cultures flourished, changes in vegetation and agricultural conditions are used to prove the existence of climatic fluctuations during a period studied by archaeological methods. As will be discussed more extensively later, changes in vegetation conditions and agricultural habits are often a result of the influence of man, and therefore great care should be taken in interpreting such changes as caused by climatic influences.

Other methods which may be used for both recent changes of climate and such ones occurring far back in the Pleistocene are dendrochronology and pollen analysis. The tree-ring method discussed in its modern form by H. Fritts has the obvious advantage of archaeological methods in that it often makes it possible to establish a quantitative index to allow for a direct comparison of a fluctuation with criteria for recent fluctuations. One of several problems with this method is that it is often difficult or impossible to be sure which is the climatic factor that has caused the ancient fluctuations in the density of the rings. In certain parts of the world it may be possible to find out by modern methods of correlation which factor in recent time has played the most important role in the development of trees, but this does not necessarily mean that the same factor was predominant in ancient time. It has been shown by Fritts how complex is the problem of applying correct statistical methods in studies of fluctuations in the density of tree-rings but the careful method applied nowadays seems to be very promising for future application to ancient periods. In applying dendrochronology to ancient periods of time it is valuable if results are supported by evidence pointing in the same direction but derived by geomorphological, pollen analytical, archaeological or other methods.

Pollen analysis is another method that can be used over a wide range of time. It has the great advantage of telling us both the time-scale and the relative order of magnitude of a fluctuation. By comparisons with recent vegetation conditions and climatic limits for actual vegetation, it is sometimes also possible to establish rather well the absolute order of magnitude of the fluctuations. This method is, of course, the one generally used to investigate postglacial fluctuations of climate in temperate latitudes, but it is encouraging to see how well it has recently been applied to both ancient and recent fluctuations in arid and semi-arid regions, as demonstrated by E. Leopold and P. Quezel. It may be of particular help in these areas even for recent periods, as climatic data generally do not exist until the last few years.

Among methods which are used for studies of both recent fluctuations and those of ancient times, I also wish to mention briefly the glaciological ones. In studies of historical climatic changes data on the stand of a glacier's margin have frequently been used, and for investigations of the relation between recent fluctuations of temperature and precipitation on one hand and glacier variations on the other, more detailed methods of studying the whole régime of a glacier have been used.

The glacial-meteorological investigation of the causes of fluctuations of recent glaciers forms an important complement to the study of climate records. A detailed study of the atmospheric circulation conditions under which glaciers are actually retreating may give us many interesting hints as to the causes of the disappearance of the inland-ice and has in some cases even made possible a quantitative estimate of climatic conditions during the ice-ages.

In their application of geological, geomorphological and pedological methods to periods far back in the Pleistocene and mainly within arid and semi-arid parts of the world, W. Kubiena, K. W. Butzer, C. Voûte, H. Bobek have shown us how it is possible to determine, at least qualitatively, fluctuations in both wind and precipitation conditions, through studies of, for instance, the stand of ancient lakes, sediments in layers of various ages and palaeontological evidences.

By establishing the ancient wind and general circulation conditions on geomorphological evidences and comparing them with what we know about the general circulation and its changes in our times it has even been possible to reach conclusions regarding the climate and the circulation in those remote periods of time as demonstrated among others by Butzer. The main difficulty with the geomorphological, geological and pedological methods is again that they generally do not give us any idea of the order of magnitude of a climatic change neither as far as the fluctuation of the climatic elements is concerned nor of the area covered by the change.

The weaknesses involved in the above-mentioned methods generally are to a certain extent overcome by additional use of methods which render more quantitative results. Apart from archaeology, dendrochronology and pollen analysis, new methods for this purpose have recently been derived from oceanography and hydrology. I am thinking mainly of studies of ocean-bottom sediments which could give interesting information relating to sea temperature at the time of the deposition of the sediments. The time-scale is obtained either from radioactive dating or from knowledge of the sedimentation speed. In a contribution not read, Dr. Wiseman has given a critical and important analysis of these methods. R. W. Fairbridge has demonstrated in our discussions how well secular eustatic changes of sea-level could be used to give world-wide information on the order of magnitude of Pleistocene and post-glacial climatic fluctuations, and has even been able to present a complete, but highly tentative, scheme of these fluctuations.

A final word should be mentioned regarding the use of modern radioactive methods in studies of climatic fluctuations. For fixing an absolute time-scale, these methods have proved to be of great value and could be applied not only to archaeological periods but even to rather remote periods of time, particularly in connexion with studies of sediments in lakes and oceans. It was encouraging to hear the valuable results achieved by M. Rubin in his studies of the timing of glacial periods by the use of radioactive methods in lake and sea sediments. It also seems that investigations on the age and run-off of groundwater in semi-arid regions, which will be applied in the near future by the International Atomic Energy Agency, could reveal many interesting results with bearing upon fluctuations in ancient and recent climate.

The future development in the scientific field of climate fluctuations during prehistoric periods specially calls, as emphasized by L. Leopold, for new methods to analyse quantitatively the geomorphological evidences. The morphometric method of studying the shape of gravels as discussed by Dr. Butzer is one method to to develop, and I was particularly interested to note the activities by Dr. Leopold in the United States to create methods for quantitive analysis of the aggradation or degradation processes in a river bed. We might be able by such quantitative methods to arrive also at quantitative measures of ancient changes in precipitation by comparison with evidences from landforms and soils formed during periods of known rainfall conditions.

Several speakers have also emphasized the great need for inter-disciplinary work in this field of science. I wish to underline this point particularly and to draw your attention to the great value of such investigations as that of Quezel, of Braidwood, and of Wendorf and the two Leopolds, where different scientific methods to study climate conditions are applied to one and the same area and period. By such an approach it will be possible not only to make comparisons between the validity of the different methods applied, but also to see if they render results which point in the same direction and thereby support each other.

Generally speaking, it seems, from the contributions given to the symposium, that the recent development of geomorphological methods supported by plant-ecological evidences, pollen analyses, dendrochronology, archaeology, radioisotope dating, etc., has helped us during the last fifteen years to get a clearer, but of course still only qualitative picture of the large-scale fluctuations in climate during the Pleistocene and Holocene. Many points, however, are still controversial and great difficulties remain in obtaining quantitative values and exact dating.

It would be interesting to discuss the possibility of reaching an agreement on some criteria for climatic changes where the relative magnitude of the fluctuation is related to the accuracy of the method used to establish its existence.

From a scientific point of view the most intriguing question in relation to both long-periodic climatic fluctuations in geological times and short-range ones in historical times is what causes them. Even from a practical point of view, this question gains more and more interest as man's attempt to foresee the development of climate, and if possible to make large-scale influences upon it, increases.

If many attempts to establish the existence of climatic fluctuations have been made, there has been an even greater number of attemps at discovering their causes. Milankovitch's mathematical and astronomical approach to the influence of the sun's radiation, disand is under study by the Commission on Climatology of WMO.

Coming to the problem of climatic fluctuations during ancient and geological periods, we are faced with much greater difficulties in laying down standardizations and criteria. We face—in dealing with the "pre-meteorological" fluctuations of all scales—at least three difficulties which do not exist for the more recent changes of climate. These are dating of the fluctuations as well as determination of their absolute magnitude and significance. In periods of climatic records, statistical methods of different kinds could be applied to establish these facts but this is generally not the case in dealing with ancient periods. For historical records without climatic data, dating and sometimes estimates of magnitude of climatic elements can be made as shown by H. H. Lamb regarding pressure, S. Manley on temperature and R. Schove on wind conditions. Such methods are extremely important as they make the fluctuations found during these old periods more or less directly comparable with the ones found from climatic records during the last 200 years. In most cases, however, only the relative and not the absolute magnitude of the fluctuations can be determined. This means that it is generally impossible to apply significance tests to values derived from historical records. We can only agree that a qualitative discussion of their significance should be made and that in any case, it is advisable that in dealing with climatic conditions in historic periods, fluctuations of climate should, if possible, be expressed in absolute or relative figures rather than discussed qualitatively. Comparisons with more recent periods will be facilitated by such an approach.

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Quite often and especially in the semi-humid or semi-arid parts of the world where ancient cultures flourished, changes in vegetation and agricultural conditions are used to prove the existence of climatic fluctuations during a period studied by archaeological methods. As will be discussed more extensively later, changes in vegetation conditions and agricultural habits are often a result of the influence of man, and therefore great care should be taken in interpreting such changes as caused by climatic influences.

Other methods which may be used for both recent changes of climate and such ones occurring far back in the Pleistocene are dendrochronology and pollen analysis. The tree-ring method discussed in its modern form by H. Fritts has the obvious advantage of archaeological methods in that it often makes it possible to establish a quantitative index to allow for a direct comparison of a fluctuation with criteria for recent fluctuations. One of several problems with this method is that it is often difficult or impossible to be sure which is the climatic factor that has caused the ancient fluctuations in the density of the rings. In certain parts of the world it may be possible to find out by modern methods of correlation which factor in recent time has played the most important role in the development of trees, but this does not necessarily mean that the same factor was predominant in ancient time. It has been shown by Fritts how complex is the problem of applying correct statistical methods in studies of fluctuations in the density of tree-rings but the careful method applied nowadays seems to be very promising for future application to ancient periods. In applying dendrochronology to ancient periods of time it is valuable if results are supported by evidence pointing in the same direction but derived by geomorphological, pollen analytical, archaeological or other methods.

Pollen analysis is another method that can be used over a wide range of time. It has the great advantage of telling us both the time-scale and the relative order of magnitude of a fluctuation. By comparisons with recent vegetation conditions and climatic limits for actual vegetation, it is sometimes also possible to establish rather well the absolute order of magnitude of the fluctuations. This method is, of course, the one generally used to investigate postglacial fluctuations of climate in temperate latitudes, but it is encouraging to see how well it has recently been applied to both ancient and recent fluctuations in arid and semi-arid regions, as demonstrated by E. Leopold and P. Quezel. It may be of particular help in these areas even for recent periods, as climatic data generally do not exist until the last few years.

Among methods which are used for studies of both recent fluctuations and those of ancient times, I also wish to mention briefly the glaciological ones. In studies of historical climatic changes data on the stand of a glacier's margin have frequently been used, and for investigations of the relation between recent fluctuations of temperature and precipitation on one hand and glacier variations on the other, more detailed methods of studying the whole régime of a glacier have been used.

The glacial-meteorological investigation of the causes of fluctuations of recent glaciers forms an important complement to the study of climate records. A detailed study of the atmospheric circulation conditions under which glaciers are actually retreating may give us many interesting hints as to the causes of the disappearance of the inland-ice and has in some cases even made possible a quantitative estimate of climatic conditions during the ice-ages.

In their application of geological, geomorphological and pedological methods to periods far back in the Pleistocene and mainly within arid and semi-arid parts of the world, W. Kubiena, K. W. Butzer, C. Voûte, H. Bobek have shown us how it is possible to determine, at least qualitatively, fluctuations in both wind and precipitation conditions, through studies of, for instance, the stand of ancient lakes, sediments in layers of various ages and palaeontological evidences.

By establishing the ancient wind and general circulation conditions on geomorphological evidences and comparing them with what we know about the general circulation and its changes in our times it has even been possible to reach conclusions regarding the climate and the circulation in those remote periods of time as demonstrated among others by Butzer. The main difficulty with the geomorphological, geological and pedological methods is again that they generally do not give us any idea of the order of magnitude of a climatic change neither as far as the fluctuation of the climatic elements is concerned nor of the area covered by the change.

The weaknesses involved in the above-mentioned methods generally are to a certain extent overcome by additional use of methods which render more quantitative results. Apart from archaeology, dendrochronology and pollen analysis, new methods for this purpose have recently been derived from oceanography and hydrology. I am thinking mainly of studies of ocean-bottom sediments which could give interesting information relating to sea temperature at the time of the deposition of the sediments. The time-scale is obtained either from radioactive dating or from knowledge of the sedimentation speed. In a contribution not read, Dr. Wiseman has given a critical and important analysis of these methods. R. W. Fairbridge has demonstrated in our discussions how well secular eustatic changes of sea-level could be used to give world-wide information on the order of magnitude of Pleistocene and post-glacial climatic fluctuations, and has even been able to present a complete, but highly tentative, scheme of these fluctuations.

A final word should be mentioned regarding the use of modern radioactive methods in studies of climatic fluctuations. For fixing an absolute time-scale, these methods have proved to be of great value and could be applied not only to archaeological periods but even to rather remote periods of time, particularly in connexion with studies of sediments in lakes and oceans. It was encouraging to hear the valuable results achieved by M. Rubin in his studies of the timing of glacial periods by the use of radioactive methods in lake and sea sediments. It also seems that investigations on the age and run-off of groundwater in semi-arid regions, which will be applied in the near future by the International Atomic Energy Agency, could reveal many interesting results with bearing upon fluctuations in ancient and recent climate.

The future development in the scientific field of climate fluctuations during prehistoric periods specially calls, as emphasized by L. Leopold, for new methods to analyse quantitatively the geomorphological evidences. The morphometric method of studying the shape of gravels as discussed by Dr. Butzer is one method to to develop, and I was particularly interested to note the activities by Dr. Leopold in the United States to create methods for quantitive analysis of the aggradation or degradation processes in a river bed. We might be able by such quantitative methods to arrive also at quantitative measures of ancient changes in precipitation by comparison with evidences from landforms and soils formed during periods of known rainfall conditions.

Several speakers have also emphasized the great need for inter-disciplinary work in this field of science. I wish to underline this point particularly and to draw your attention to the great value of such investigations as that of Quezel, of Braidwood, and of Wendorf and the two Leopolds, where different scientific methods to study climate conditions are applied to one and the same area and period. By such an approach it will be possible not only to make comparisons between the validity of the different methods applied, but also to see if they render results which point in the same direction and thereby support each other.

Generally speaking, it seems, from the contributions given to the symposium, that the recent development of geomorphological methods supported by plant-ecological evidences, pollen analyses, dendrochronology, archaeology, radioisotope dating, etc., has helped us during the last fifteen years to get a clearer, but of course still only qualitative picture of the large-scale fluctuations in climate during the Pleistocene and Holocene. Many points, however, are still controversial and great difficulties remain in obtaining quantitative values and exact dating.

It would be interesting to discuss the possibility of reaching an agreement on some criteria for climatic changes where the relative magnitude of the fluctuation is related to the accuracy of the method used to establish its existence.

From a scientific point of view the most intriguing question in relation to both long-periodic climatic fluctuations in geological times and short-range ones in historical times is what causes them. Even from a practical point of view, this question gains more and more interest as man's attempt to foresee the development of climate, and if possible to make large-scale influences upon it, increases.

If many attempts to establish the existence of climatic fluctuations have been made, there has been an even greater number of attemps at discovering their causes. Milankovitch's mathematical and astronomical approach to the influence of the sun's radiation, discussed in the symposium in a modified form by Obuljen, studies of the upper atmosphere to investigate variation of the ozone content or the stratospheric wind conditions as influenced by variation in the sun's activity applied and discussed, for instance, by W. Godson, are some where the basic hypothesis is accepted that the ultimate cause of all climatic changes stems from the fluctuations in the sun's radiation. This hypothesis seems to have gained increasing ground in recent years but no definite proof of the influence of the sun's radiation has so far been given. Most evidence points at no change in the solar constant in recent time, which of course does not exclude changes in parts of the spectrum of the radiation from the sun.

There is a basic difference between the above-mentioned approaches, where it is hoped to find a direct relation between fluctuations of the sun's radiation and climatic elements, and those favoured by many other meteorologists today, where it is argued that the influence of the sun's radiation will be more easily found by interpreting climatic fluctuations in terms of changes in the general circulation of the atmosphere. The investigation by J. S. Sawyer forms a good modern example of this approach.

There are also investigators like H. Flohn, who have suggested the direct study of the influence of fluctuations in the radiation of the sun upon the heat and water balance of the earth. Godson has even formulated a research programme for studies of the changes in the heat balance as a basis for future research on climatic changes.

Other connexions with the sun's radiation have been argued by H. Wexler, H. H. Lamb and others. Their studies of climatic changes in historical and recent times seem to favour the idea that the radiation reaching the earth has decreased and the heat balance of the earth changed by expulsion of volcanic dust in the earth's atmosphere during periods of strong volcanic activity. Consequently, such influences must also have occurred during those periods of the earth's history when extensive mountain building occurred, which might account for the interconnexion between periods of mountain building and ice ages stressed earlier by Brooks.

Several investigations of climatic changes have in recent years referred to the increase of carbon dioxide in the earth's atmosphere during the last 100 years as a probable cause of the "recent climatic fluctuation". The theoretical implications are based on ideas originally formulated by S. Arrhenius and P. Callendar but revised recently by Plass and reviewed in this symposium by H. Flohn.

Finally, there are several meteorologists, such as Dr. Sutcliffe and Professor B. Dzerdzeevskii, who argue that fluctuations in the general circulation of the atmosphere, occurring only within the range of variability of the circulation and caused by factors which are not extraterrestrial, are enough to account for the fluctuations in climate that we know. J. Bjerknes' and J. Namias' contributions give indications in this direction and show very striking examples of the influence of feed-back mechanisms from land and sea on short-range fluctuations of the general circulation pattern and these influences seem to call for special attention as regards the interpretation of both short and long-range fluctuation of climate.

Namias' contribution also demonstrates the intimate relationship which exists between the methods used to study causes of short-range climatic fluctuations and those applied to the study of long-range forecasting of weather and climate. The original impulse to start investigations on climatic changes was certainly the hope of finding a method to extrapolate the evolution of climate into the future. In the old days this led to rather unfruitful statistical treatments of climatic cycles often in relation to sun-spots. It seems that it is now more or less clear that no simple periods of climate could be found to exist, although there is certainly some kind of quasi-periodicity in the fluctuations. The modern approach of studying, instead of statistical periods, the physical implications of changes in the general circulation and the heat balance on climatic and weather fluctuations seems to give us much more hope. The circulation conditions of the atmosphere also indicate that we shall have the best prospects with this approach both as regards explanation for climatic fluctuations and long-range forecasting in dealing with the tropics and the subtropics, which is an important conclusion as regards the arid and semi-arid regions.

Further, I wish to draw attention to certain other interrelationships which have been emphasized during this meeting and which complicate the problem of the causes of climate changes and therefore have to be taken into consideration. There are reasons to believe that there is not one ultimate cause of climatic changes, but that many of the explanations given for world climatic changes are all applicable so that they interact with each other. Milankovitch's fluctuations in radiation caused by astronomical influences; pole migrations; changes in the sun's activity; the amounts of volcanic or cosmic dust in the earth's atmosphere or increases in its carbon dioxide content; changes in the earth's level and altitudinal conditions; arbitrary fluctuations of the general circulation of the atmosphere; as well as lag-factors and feed-back mechanisms caused by heat storage at the earth's surface or in the great oceans: all these factors may have been acting in the same direction to cause the great fluctuations in the earth's climate as ice-ages on the one hand and very dry and warm periods on the other. Just one of the factors may be responsible for the short-term fluctuations that we can trace by meteorological records. It is our goal as scientists to separate the influence of these factors and to find the extent of the influence of each of the causes on climatic changes of different scales.

It seems possible to conclude from the review given that the first step to be taken in order to explain a fluctuation in a certain climatic element, which has been shown to have occurred, should, preferably be to interpret this same fluctuation in terms of changes of the general circulation over the area concerned. The next step would then be to relate the changes in the circulation to possible variations in the heat balance of the atmosphere, and follow on to see if such variations have any relation to the sun's radiation conditions. It is true that the clue to the cause of changes in the earth's climate might be found in studies of the heat balance by itself, but it must be admitted that it would be even more interesting to know also how a certain change in the heat balance would influence the general circulation and ultimately the climatic elements. No doubt the new possibilities with electronic computers in statistical treatment of changes in the general circulation on one side and data obtained from satellites will play a dominant role in the future development of studies of the causes of climatic changes as related to the general circulation, as shown by Namias, Kraus and Lorenz.

It would be interesting to have opinions expressed in today's discussion on this proposed step-by-step approach to the causes of short-range and long-range climatic fluctuations and to the whole question of the best ways to continue our studies of the causes of climatic change.

On several occasions during this symposium and this lecture the significance of climatic changes to vegetation, fauna and man's activity has been referred to. Most meteorological scientists dealing with the problem have, of course, no particular reason to consider this aspect. However, in the last fifteen years geographers interested in the relation between man and nature, as well as international organizations working for the benefit of mankind, have shown a growing interest in this side of the problem. As mentioned, the implications to vegetation, fauna, agriculture, fishery and sea-trade of the "recent climatic fluctuations" have been enormous.

In connexion with its arid lands programme, Unesco has become increasingly interested in climatic fluctuations in arid and semi-arid parts of the world. Many of those areas, where we are now trying to extend settlement and agriculture, are considered by many to have been fertile and used for dry-farming or irrigated agriculture in ancient time. A highly interesting aim of future development within the field of climatic fluctuations will, therefore, be an attempt to establish the changes of the margin of the arid and semi-arid lands which have occurred in historical and prehistorical times.

It has been clearly shown how complex is the problem of climatic change in arid regions in interesting contributions by J. Tixeront for Tunisia, D. Amiran for Israel, C. Voûte for Iraq and H. Bobek for Iran, and more completely by K. W. Butzer in his recently published summary for the semi-arid regions since the time of man's settlement. One difficulty is mainly due to the fact that we may be able to establish, by geomorphological, pollen-analytical or archaeological methods, that a certain change in vegetation and soil conditions has taken place at a certain time, but are usually not able to say what has been the ultimate cause of this change. In large parts of the world within temperate latitudes, changes of plant-ecological and soil conditions in old times can hardly have been due to anything but large-scale fluctuations in the general circulation and therefore must have been connected with true climatic fluctuations. However, in areas of rather dense population—many semi-arid regions were in the old days—one cannot neglect the influence of man and his animals on soil and vegetational conditions that we use in order to establish the character of the ancient climate. It has been emphasized by R. Veryard, and discussed in detail earlier by J. M. Mitchell, that when we deal with local climate or microclimate, we are always faced with great difficulties in trying to determine whether what seems a certain climatic fluctuation is caused by changes in the large-scale atmospheric conditions or by, so to speak, artificial influences by man and animal such as deforestation, soil erosion, urbanization and grazing. I should like to emphasize, however, that we cannot be certain on this point even in the case of macroclimatological changes, unless they can be proved to have covered quite a large area. We are not able to say today how large a change of the microclimate or the local climate would constitute a change also in a broader sense, i.e. of the macroclimate.

Even if we accept the idea most common at present that the change in agricultural conditions in arid and semi-arid regions of the world since the time of flourishing culture has been mainly due to man's influence, the problem of the secondary influence of man's activity on climate remains to be solved. For instance, the idea accepted by many investigators at present seems to be that a vast deforestation in semi-humid and semi-arid lands may not only increase soil erosion and thereby extend desert conditions, but may also influence directly the climate. This, however, is denied by others and still has to be proved. Irrigation, as we know, has a clear influence upon the small-scale climate, but, if applied on a large scale, may have far reaching consequences even to the macroclimate. As far as grazing is concerned, it is well known that it has a wide influence upon vegetation conditions and therefore has to be taken into account whenever we establish climatic conditions by plant-ecological methods. In our discussions H. Flohn has drawn attention to the possible important influence of changes in vegetation and plant cover upon the evapotranspiration in subtropical and tropical climates and thereby indicated the possibility of essential influence of man upon climate.

The interrelation between true changes of climate caused by extra-terrestrial influences or large-scale fluctuations in the general circulation of the atmosphere on the one side and on the other the influence of man on natural vegetation and soil erosion conditions, which may seem as caused by a true change in climate, is a basic problem that we have to face in dealing with all practical consequences of climate fluctuations both in ancient and recent times.

In order to investigate this interrelation, it is first of all essential to know the present climatic situation and in which way natural vegetation, agriculture and climate are related to each other. The joint WMO/Unesco/FAO project to study the agroclimatic conditions of the semi-arid parts of the Near and Middle East will give a firm basis to the understanding of the agroclimatic conditions in that part of the world. I feel that this project should be followed up in at least one pilot area within the region by a contemporary study of the climate development and man's influence upon climate by reafforestation and irrigation. This is a long-term project which has to go on for a considerable time, but it will be the only possibility of obtaining an idea of the order fo magnitude of the changes caused by man in relation to those caused by true fluctuations in climate. This suggestion is related to the proposal by Leopold in his opening address that a world-wide network of small watersheds be erected for studies of the run-off conditions as influenced by the development of climate and the influence of man. Projects of this kind could preferably be carried out on a national basis, but under the supervision of, and with the support of international organizations. It seems that the whole question of the interrelationship of man's influence and climatic changes in arid and semi-arid regions needs much further discussion. The question may be so wide that there is need for a special symposium on this question at a later stage.

In this symposium we have not been able to treat the controversial question of man's possibilities to foresee the future development of or to influence climate by artificial means. So much may be said today that it seems unlikely with our actual knowledge about the general circulation of the atmosphere that large-scale changes of climatic conditions will be possible by artificial means, but I wish to emphasize that we do not know how large can be the consequences of smaller influences induced by man. It is obvious that a better knowledge of the interrelation between climatic conditions and man's influence on vegetation and soil, as well as how changes in the general circulation and the heat balance of the atmosphere are coupled with climatic fluctuations, forms a necessary condition to make it possible for man to learn how to forecast and influence climate.

Finally, I wish to present a list of proposed items for our discussion during the rest of this session:

1. How should we be able to reach some kind of standardization of methods to show the existence of climatic fluctuation within the time of climatic records, including the questions of significance and criteria for such fluctuations? Could any recommendation be given for methods of studying the homogeneity of records? Could we arrange for the erection of special networks and special publications of data for the purpose of studying climatic changes? (Flohn.)
2. Could any direct recommendations be suggested for the best approach to studies of climatic fluctuations during the Pleistocene and Holocene periods, including which are the most important problems to be tackled? Are there any possibilities for arranging on an international basis interdisciplinary studies of ancient and actual processes which are of importance for studies of climatic change?
3. Which is the most reasonable approach to be taken to the future scientific investigation of the causes of climatic change? (Godson.)
4. Could any international arrangements be made for establishing interdisciplinary investigations on the relationship between the development of climate and land forms by natural factors on the one hand, and man's activity on the other hand?

OBJECTIFS ET MÉTHODES DES ÉTUDES SUR LES FLUCTUATIONS CLIMATIQUES

par

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C'est pour moi un grand honneur et un grand plaisir d'avoir à tirer une conclusion des débats de ce colloque sur les changements de climat. Pourtant, ce n'est certainement pas une tâche facile, car les fluctuations climatiques, nous l'avons vu pendant les débats, posent un problème d'une grande complexité et qui intéresse de nombreuses disciplines. Le fait même qu'il y avait tant de disciplines en cause — météorologie, océanographie, géographie, hydrologie, géologie et glaciologie, écologie végétale et histoire de la végétation, pour n'en citer que quelques-unes — a empêché de travailler dans ce domaine scientifique à partir de définitions et avec des méthodes communes et bien établies. Des chercheurs appartenant à des disciplines différentes et quelquefois à la même ont employé des méthodes et des définitions souvent si différentes les unes des autres que toute comparaison entre les résultats était pratiquement impossible. La raison principale en est que les représentants de disciplines différentes s'intéressent à des fluctuations d'un ordre de grandeur différent, appartenant à des époques différentes de l'histoire de la terre, ce qui fait, nous nous en sommes rendu compte, qu'il n'est pas possible d'appliquer les mêmes méthodes.

L'un des objectifs importants de ce colloque était de réunir les représentants de disciplines diverses s'occupant d'aspects entièrement différents du problème des fluctuations climatiques, pour leur permettre précisément de s'exposer mutuellement ces disparités entre les méthodes et techniques, tenant simplement à la grande variété des époques, des ordres de grandeur et des données disponibles.

A mon avis, cette dernière journée doit être employée à résumer les difficultés que nous avons à comparer les travaux dus à des représentants de disciplines différentes employant des méthodes très différentes, à formuler des propositions touchant les activités futures dans le domaine des fluctuations climatiques. Mon exposé portera donc plutôt sur les objectifs et les méthodes que sur les résultats. L'état actuel des connaissances relatives aux fluctuations climatiques est si bien précisé par les exposés et résumés publiés récemment ou présentés au cours de ce colloque que je ne vois pas l'intérêt de faire un « résumé de résumés ».

Il ressort nettement des débats que les météorologues s'occupant de relevés climatologiques sont, par rapport aux représentants de maintes autres disciplines, dans une situation favorable, car ils peuvent appliquer des méthodes bien définies d'ordre physique et statistique au problème des changements de climat, même si rien n'a été fait encore pour tenter de les normaliser.

La manière la plus radicale et la plus théorique d'aborder le problème de l'existence de fluctuations climatiques depuis que se font des relevés météorologiques est celle des statisticiens, qui a été exposée à notre première séance par R. Sneyers, W. Hofmeyr, K. N. Rao et V. M. Yevdjevich. L'idée qui est à la base de toutes les méthodes théoriques d'étude du problème, c'est qu'aucune fluctuation d'un élément variant dans le temps ne devrait être considérée comme exacte si elle n'a pas, du point de vue statistique, de valeur significative pour la période au sujet de laquelle on dispose de relevés. Toutefois, en ce qui concerne cette importante question de la valeur significative du point de vue statistique, il y a deux problèmes au moins qui méritent d'être discutés et élucidés, en prévision de nos activités futures dans le domaine des fluctuations climatiques.

Le premier se rapporte à l'aspect théorique de la question. Il est évident qu'une certaine tendance climatique peut, du moins si on l'étudie avec un certain nombre des méthodes habituelles, se révéler importante quand elle est considérée sur une période relativement courte, mais paraître tout à fait insignifiante quand on l'étudie sur une longue période. Un bon exemple en est fourni par la formule de la « fluctuation climatique récente », ainsi que l'ont montré les intéressantes communications de L. Lysgaard, W. L. Hofmeyr, N. Rosenan, J. E. Buchinsky, J. Dubief et J. M. Mitchell. Tous les auteurs ont pu montrer, en s'appuyant sur des relevés qui remontent jusqu'à la fin du XVIII^e siècle, que le réchauffement de grandes parties du globe depuis le milieu du XIX^e^ siècle jusqu'à une époque récente a été statistiquement significatif. Cependant, comme l'a indiqué en particulier J. M. Mitchell et comme l'a démontré aussi M. Rodewald pour les températures de la mer, cette augmentation de température s'est récemment atténuée. La tendance décroissante est significative si l'on considère les vingt ou cinquante dernières années ou même une période plus longue, mais elle pourrait perdre la plus grande partie de sa signification si plusieurs des méthodes statistiques communément employées étaient appliquées pour dégager les fluctuations sur une période plus longue. On pourrait donner de nombreux autres exemples de la situation difficile où nous sommes du fait que nous ne pouvons comparer les résultats de recherches qui ont été faites concernant des périodes types différentes et avec des méthodes statistiques différentes. Il importe donc de formuler des recommandations quant au choix des périodes types et des méthodes statistiques ainsi que de certains critères de ce que l'on peut considérer, du point de vue théorique, comme une fluctuation climatique.

Le second point concerne un aspect pratique très important de la question des fluctuations climatiques au cours des périodes récentes, qui montre certainement qu'il ne faut pas exagérer l'importance de la signification statistique au point de prétendre que des changements de climat dont on ne peut prouver la signification statistique ne méritent pas une étude. Comme l'ont indiqué Dubief et d'autres le premier jour de nos débats, et comme l'ont montré bien des fois des géographes, des spécialistes de l'utilisation du sol, des spécialistes de l'écologie végétale, etc., les changements de climat d'une faible durée, comme par exemple le déclin récent, peuvent exercer une grande influence sur la végétation, la situation de l'agriculture et l'humanité même, en particulier dans des zones du monde qui sont climatiquement « régionales ». Des changements de ce genre ne peuvent manifestement pas être négligés du point de vue pratique.

Il me semble, par exemple, et des communications personnelles me l'ont confirmé, que les fluctuations à courte période et statistiquement non significatives qui se sont produites récemment en Inde, comme V. N. Rao l'a démontré, ont pu avoir des conséquences importantes sur la place faite à l'agriculture dans ce pays.

Nous savons aussi que la baisse récente de la température aux latitudes septentrionales s'est manifestée par une détérioration considérable des conditions de glaciation de la mer. Il faut à cet égard se souvenir que, dans les régions marginales, un changement de climat même très faible et de brève durée peut avoir une influence désastreuse sur la végétation; par exemple, on peut modifier beaucoup les conditions de glaciation de la mer, provoquant ainsi des phénomènes climatiques secondaires d'une grande importance. Je voudrais insister sur la complexité de ce problème. Dans bien des cas, la végétation, la faune, les glaciers, etc., qui apportent des indications sur les changements de climat, réagissent avec un retard considérable. Ainsi Lysgaard a constaté que les nombreuses conséquences qu'a eues pour la végétation et la faune la longue période de hausse des températures allant jusque vers 1940 sont encore importantes au Danemark, alors que la baisse récente semble n'avoir exercé d'influence sur les facteurs de ce genre que dans des régions très marginales. Il faut donc certainement apporter la plus grande prudence à interpréter des indices qui réagissent tardivement aux changements de climat. L'excellent exposé qu'a fait L. P. Smith des influences exercées en Angleterre sur l'agriculture par de récents changements de climat de brève durée établit à n'en pas douter l'importance de changements statistiquement insignifiants du climat même aux latitudes tempérées. Je crois aussi que toutes les méthodes intéressantes qu'il a utilisées pourraient être appliquées dans les régions arides et aider ainsi à comprendre le comportement des régions marginales pour ce qui est de l'agriculture.

Il est donc nécessaire en pratique d'étudier aussi les fluctuations qui statistiquement sont insignifiantes pour tâcher de découvrir leurs causes et si possible d'apprécier le temps qu'elles vont durer. Nous avons noté en outre au cours des débats qu'il n'existe pas actuellement d'accord général quant aux meilleures méthodes à employer pour prouver l'existence de fluctuations lorsqu'on dispose d'observations climatologiques. Parmi les méthodes utilisées, le lissage des séries chronologiques par l'emploi de moyennes imbriquées semble être celle qui est le plus communément suivie, notamment par L. Lysgaard, N. Rosenan et plusieurs autres spécialistes. Cette méthode a été l'objet de critiques assez sévères au cours des dernières années en raison de faiblesses statistiques, mais elle reste encore très commode. D'autres méthodes suggérées sont celle des courbes cumulatives, d'E. B. Kraus, et celle des tests plus complexes de la tendance statistique, de R. Sneyers et W. Hofmeyr, pour n'en citer que quelques-unes. Tous les auteurs reconnaissent que leurs méthodes ont certains inconvénients et une tâche qui s'offre pour l'avenir serait de recommander la méthode convenant le mieux à l'étude des fluctuations d'après les relevés climatiques. Nous sommes probablement d'accord pour penser que les méthodes à recommander devraient de préférence permettre d'étudier la signification statistique de la fluctuation.

Le problème global du choix des méthodes statistiques à utiliser et de la durée de relevés à retenir pour les études sur les changements de climat pourrait alors être abordé, soit d'un point de vue théorique, soit d'un point de vue pratique. Pour faciliter les comparaisons entre enquêtes différentes, il conviendrait, du point de vue théorique, de recommander une certaine normalisation en ce qui concerne la durée des relevés à admettre comme exacte. Il semble qu'il serait tout indiqué de confier cette tâche à un groupe de travail de l'OMM. En fait, il existe au sein de la Commission de climatologie un groupe chargé de la question de la longueur des périodes types normales dans les enquêtes climatologiques ; le problème en question est évidemment en relation étroite avec cette tâche. Il faut cependant considérer aussi le côté pratique ; dans le cas où un groupe de travail étudierait les problèmes mentionnés ci-dessus, il ne devrait pas seulement, semble-t-il, établir des critères touchant la durée des relevés et la valeur significative des observations, mais aussi proposer des méthodes normalisées pour l'étude des fluctuations climatiques. En outre, il devrait plus particulièrement suggérer des moyens de s'en tirer avec les courtes fluctuations périodiques qui peuvent avoir des conséquences pratiques tout en étant statistiquement insignifiantes selon les critères proposés pour une véritable fluctuation climatique. Il est encore un troisième problème dont on s'est assez occupé au cours des dernières années et que je n'ai pas eu le temps de traiter moi-même, mais qui devrait être étudié avec soin par un groupe de travail de ce genre. C'est le problème important des méthodes à employer pour étudier l'homogénéité des observations utilisées dans les recherches sur les fluctuations climatiques.

Avant d'en terminer avec cette question des changements intervenus pendant la période des observations, je voudrais aussi insister sur l'importance qu'il y a à organiser tout autour du monde un réseau de stations clés faisant des relevés continuellement homogènes. L'ouvrage de J. M. Mitchell a montré l'importance que présente l'organisation d'un réseau de ce genre, qui a d'ailleurs été déjà recommandée et qu'étudie actuellement la Commission de climatologie de l'OMM.

Quand on arrive au problème des fluctuations climatiques au cours des périodes anciennes et géologiques, on se trouve en face de difficultés beaucoup plus grandes encore pour l'établissement de normes et de critères. En étudiant les fluctuations « prémétéorologiques » de toute ampleur, on rencontre au moins trois difficultés, qui n'existent pas quand il s'agit des changements de climat plus récents. Elles concernent le datage des fluctuations, la détermination de leur grandeur absolue et celle de leur signification. Pour les périodes où l'on dispose de relevés climatiques, on peut recourir à des méthodes statistiques pour établir les faits, mais ce n'est généralement pas le cas lorsqu'on s'occupe des périodes anciennes. Si l'on dispose de documents historiques sans données climatiques, on peut dater les éléments climatiques et parfois même estimer leur valeur, comme l'ont montré H. H. Lamb pour la pression, S. Manley pour la température et R. Schove pour les vents. Les méthodes de ce genre sont d'une extrême importance car grâce à elles les fluctuations découvertes au cours de ces périodes anciennes sont plus ou moins directement comparables à celles qui se déduisent des relevés climatiques des deux cents dernières années. Dans la plupart des cas, toutefois, on ne peut déterminer que l'ampleur relative et non l'ampleur absolue des fluctuations. Aussi est-il généralement impossible d'appliquer des tests de signification aux valeurs dégagées de documents historiques. On peut seulement admettre qu'il faudrait discuter qualitativement de leur signification mais qu'en tout cas il est préférable, lorsqu'on s'occupe des conditions climatiques pendant les périodes historiques, d'exprimer si possible les fluctuations du climat en chiffres, absolus ou relatifs, plutôt que d'en discuter qualitativement. Cette méthode facilitera les comparaisons avec des périodes plus récentes.

L'archéologie et la paléoanthropologie, en particulier quand il s'agit des périodes historiques anciennes, jouent un rôle important dans l'étude des fluctuations climatiques, à la fois pour des périodes relativement récentes et pour des périodes très anciennes. Braidwood, Tixeront et Wendorf l'ont très bien montré dans leurs études relatives à l'Iran, à la Tunisie et aux États-Unis d'Amérique. Tant que l'on dispose de documents historiques, on n'a pas de difficultés pour fixer l'époque où s'est produite une fluctuation, mais en reculant dans le temps la question pose un problème de plus en plus délicat. Les archéologues, toutefois, seront en mesure dans bien des cas, surtout par l'emploi de tests au carbone-14, de fixer certaines limites à cette époque, mais il se pose alors, plus encore que dans le cas des documents historiques, le problème de l'expression quantitative des résultats obtenus et de la discussion de leur signification.

Assez souvent, et en particulier dans les régions semi-humides ou semi-arides du monde où des cultures anciennes se sont développées, les changements de la végétation et des conditions agricoles servent à prouver l'existence de fluctuations climatiques pendant une période étudiée par des méthodes archéologiques. Comme il en sera discuté plus en détail ultérieurement, les changements survenus en matière de végétation et d'habitudes agricoles résultent souvent de l'activité humaine et il faut apporter la plus grande prudence à interpréter ces changements comme étant le résultat d'influences climatiques.

D'autres méthodes qui peuvent être employées à la fois en ce qui concerne les changements de climat récents et ceux qui se sont produits au cours de la période du pléistocène sont la dendrochronologie et l'analyse pollinique. La méthode fondée sur l'examen des couches annuelles des arbres, qu'a étudiée sous sa forme moderne H. Fritts, présente l'avantage manifeste des méthodes archéologiques en ce qu'elle offre souvent la possibilité d'établir un indice quantitatif qui permet de comparer directement une fluctuation avec les critères des fluctuations récentes. Un des nombreux problèmes que pose cette méthode tient à ce qu'il est souvent difficile, sinon même impossible, de déterminer avec certitude le facteur climatique qui a été à l'origine des anciennes fluctuations dans la densité des couches. En certaines régions du monde, on pourra peut-être découvrir par les méthodes modernes de corrélation le facteur qui à une époque récente a joué le rôle le plus important dans le développement des arbres, mais il ne s'ensuit pas nécessairement que le même facteur ait été prédominant à une époque ancienne. H. C. Fritts a montré la complexité du problème posé par l'application de méthodes statistiques correctes à l'étude des fluctuations de la densité des couches annuelles, mais les méthodes précises qui sont appliquées de nos jours semblent être très prometteuses pour ce qui est de leur emploi futur au sujet de périodes anciennes. Si l'on applique la dendrochronologie à des périodes anciennes, il est utile de confirmer les résultats obtenus par des indices suggérant des conclusions analogues, mais dérivés des méthodes de la géomorphologie, de l'analyse pollinique, de l'archéologie, etc.

L'analyse pollinique est une autre méthode qui peut être employée pour des périodes très diverses. Elle a le grand avantage d'indiquer à la fois la durée et l'ordre de grandeur relatif d'une fluctuation. Par des comparaisons avec l'état récent de la végétation et les limites climatiques de la végétation actuelle, il est quelquefois possible également d'établir avec une certaine précision l'ordre de grandeur absolu des fluctuations. Cette méthode est naturellement celle qui sert généralement à étudier les fluctuations postglaciaires du climat aux latitudes tempérées, mais il est encourageant de voir avec quel succès on vient de l'appliquer aux fluctuations anciennes et récentes dans des régions arides et semi-arides, comme l'ont montré E. Leopold et P. Quezel. Elle peut être particulièrement utile dans ces régions pour des périodes même récentes, car on ne possède généralement pas de données climatiques antérieures à ces dernières années.

Parmi les méthodes utilisées pour l'étude des fluctuations, tant récentes qu'anciennes, je voudrais aussi mentionner brièvement les méthodes glaciologiques. Dans les études sur les changements historiques de climat on s'est souvent servi de données relatives au niveau de la rive d'un glacier ; pour les recherches sur les relations entre les fluctuations récentes des températures et des précipitations d'une part, et les variations du glacier d'autre part, on a eu recours à des méthodes plus détaillées comportant l'étude du régime d'ensemble du glacier.

Les recherches glacio-météorologiques sur les causes des fluctuations des glaciers récents fournissent un notable complément à l'étude des relevés climatiques. Un examen détaillé des éléments de la circulation atmosphérique qui correspondent au recul actuel des glaciers pourrait donner de nombreuses et intéressantes indications sur les causes de la disparition des glaces à l'intérieur des terres ; des études de ce genre ont même permis dans certains cas de faire une évaluation quantitative des conditions climatiques pendant les périodes glaciaires.

En appliquant à des périodes anciennes du pléistocène les méthodes de la géologie, de la géomorphologie et de la pédologie, principalement dans des régions arides et semi-arides du monde, W. Kubiena, K. W. Butzer, C. Voûte et H. Bobek nous ont montré qu'il est possible de déterminer au moins qualitativement des fluctuations du vent et des précipitations, par des études portant par exemple sur le niveau des anciens lacs, les sédiments dans des couches de terrain d'âges divers et les indices paléontologiques.

En déterminant d'après des indices géomorphologiques le régime ancien des vents et de la circulation atmosphérique générale, et en le comparant avec ce que l'on sait de la circulation générale et de ses modifications à l'époque actuelle, il a même été possible d'arriver à des conclusions touchant le climat et la circulation en ces périodes anciennes, comme l'a démontré notamment K. W. Butzer. Avec les méthodes de la géomorphologie, de la géologie et de la pédologie, la difficulté principale tient, là encore, à ce qu'elles ne donnent généralement aucune idée de l'ordre de grandeur d'un changement de climat, en ce qui concerne la fluctuation des éléments climatiques ou la zone intéressée par le changement.

On arrive généralement à remédier quelque peu aux faiblesses des méthodes susmentionnées en recourant en même temps à des méthodes qui donnent des résultats plus quantitatifs. En dehors de l'archéologie, de la dendrochronologie et de l'analyse pollinique, de nouvelles méthodes ont été récemment tirées à cette fin de l'océanographie et de l'hydrologie. Je pense surtout à des études sur les sédiments du fond de l'océan, qui pourraient renseigner utilement sur la température de la mer à l'époque du dépôt de ces sédiments. On établit la chronologie correspondante soit en recourant au datage radio-actif, soit en recherchant la vitesse de sédimentation. Dans une communication qui n'a pas été lue, J. D. H. Wiseman a fait une intéressante analyse critique de ces méthodes. R. W. Fairbridge a montré au cours de nos débats comment les variations eustatiques séculaires du niveau de la mer pourraient fournir des informations de valeur mondiale sur l'ordre de grandeur des fluctuations climatiques du pléistocène et de l'époque postglaciaire ; il a même pu présenter, à titre de suggestion, un schéma complet de ces fluctuations.

Il reste encore à dire quelques mots sur l'emploi des méthodes radio-actives modernes dans l'étude des fluctuations climatiques. Pour fixer une chronologie absolue, ces méthodes se sont révélées d'une grande valeur ; elles pourraient être appliquées non seulement aux périodes archéologiques, mais même à des périodes plus anciennes, en liaison notamment avec des études portant sur les sédiments des lacs et des océans. Il a été encourageant d'apprendre les utiles résultats obtenus par M. Rubin dans ses recherches sur la chronologie des périodes glaciaires, par l'application des méthodes radio-actives aux sédiments lacustres et maritimes. Il semble également que les recherches sur l'âge et l'écoulement des eaux souterraines dans les régions semi-arides, auxquelles procédera dans un proche avenir l'Agence internationale de l'énergie atomique, pourraient donner de nombreux et intéressants résultats relativement aux fluctuations des climats tant anciens que récents.

Le progrès futur de l'étude scientifique des fluctuations climatiques aux périodes préhistoriques nécessite particulièrement, comme l'a souligné L. B. Leopold, l'intervention de méthodes nouvelles permettant d'analyser quantitativement les indices géomorphologiques. La méthode morphométrique d'étude de la forme des cailloux, telle qu'elle a été exposée par le Dr Butzer, est une méthode à perfectionner, et j'ai été particulièrement intéressé d'entendre parler des activités entreprises par le Dr Leopold aux États-Unis, visant à mettre au point des méthodes d'analyse quantitative des processus d'accumulation ou de creusement dans le lit d'une rivière. On pourrait aussi, grâce à des méthodes quantitatives de ce genre, arriver à des mesures quantitatives de changements anciens dans les précipitations en procédant par comparaison avec des indices tirés des formes de terrain et des sols datant de périodes dont la pluviosité est connue.

Plusieurs orateurs ont aussi souligné l'urgent besoin de travaux interdisciplinaires dans ce domaine de la science. Je voudrais insister particulièrement sur ce point et attirer votre attention sur la grande valeur de recherches comme celles de Quezel, de Braidwood, de Wendorf et des deux Leopold, où des méthodes scientifiques différentes pour l'étude des conditions climatiques sont appliquées à une zone et à une période déterminées. De cette façon, il sera possible non seulement de comparer la validité des différentes méthodes appliquées mais aussi de se rendre compte si elles donnent des résultats concordants et par conséquent s'appuient mutuellement.

Il semble en général, d'après les communications faites au cours du colloque, que les progrès récents des méthodes géomorphologiques complétées par des indices tirés de l'écologie végétale et de l'analyse pollinique, de la dendrochronologie, de l'archéologie, du datage aux radio-isotopes, etc., ont permis, au cours des quinze dernières années, de se faire une idée plus claire mais, bien entendu, seulement qualitative encore, des fluctuations à long terme du climat pendant le pléistocène et l'holocène. Cependant, de nombreux points sont encore controversés et il reste très difficile d'obtenir des valeurs quantitatives et des datages exacts.

Il serait intéressant d'arriver si possible à un accord sur certains critères relatifs aux changements de climat où la grandeur relative de la fluctuation soit en rapport avec la précision de la méthode suivie pour établir son existence.

Du point de vue scientifique, la question la plus mystérieuse, en ce qui concerne les fluctuations climatiques à long terme des temps géologiques et les fluctuations à court terme des temps historiques, est celle de leur cause. Même d'un point de vue pratique, cette question devient de plus en plus intéressante à mesure que l'homme s'efforce de plus en plus de prévoir l'évolution du climat et, si possible, d'exercer sur lui une influence réelle.

En fait, si l'on a tenté bien des fois d'établir l'existence de fluctuations climatiques, on s'est efforcé encore plus souvent de découvrir leurs causes. La méthode mathématique et astronomique de Milankovitch relative à l'influence de la radiation solaire, qui a été discutée au cours du colloque par Obuljen sous une forme modifiée, les études de l'atmosphère supérieure portant sur les variations de sa teneur en ozone ou sur les vents stratosphériques qui subiraient l'influence des variations de l'activité solaire, études qu'a exposées et discutées par exemple W. Godson, sont de celles qui admettent l'hypothèse fondamentale selon laquelle la cause ultime de tous les changements de climat réside dans les fluctuations de la radiation solaire. Cette hypothèse semble avoir gagné du terrain au cours des dernières années mais on n'a jusqu'à présent établi aucune preuve véritable de l'influence de la radiation solaire. La plupart des indices ne révèlent aucune modification de la constante solaire à une époque récente, ce qui n'exclut pas, bien entendu, des modifications de certaines parties du spectre de la radiation solaire.

Il existe une différence fondamentale entre les méthodes susmentionnées, qui visent à découvrir une relation directe entre les fluctuations de la radiation solaire et les éléments du climat, d'une part, et d'autre part la méthode préconisée actuellement par nombre d'autres météorologues, qui soutiennent que l'on découvrira plus facilement l'influence de la radiation solaire en interprétant les fluctuations climatiques d'après les modifications de la circulation générale de l'atmosphère. Les recherches de J. S. Sawyer offrent un bon exemple moderne de l'application de cette méthode.

Il y a aussi des chercheurs, comme H. Flohn, qui ont proposé que l'on étudie directement l'influence des fluctuations de la radiation solaire sur les bilans calorique et hydrique de la terre. W. L. Godson a même dressé un programme de recherches pour l'étude des modifications du bilan calorique qui servirait de base à des recherches futures sur les changements de climat.

H. Wexler, H. H. Lamb et d'autres spécialistes ont soutenu qu'il existait d'autres rapports avec la radiation solaire. Leurs études sur les changements de climat aux époques historiques et récentes semblent confirmer l'idée que la radiation atteignant la terre a diminué, et que le bilan calorique de la terre a été modifié par l'expulsion de poussières volcaniques dans l'atmosphère au cours des périodes d'activité volcanique intense. Par conséquent, ces influences ont dû aussi se manifester au cours des périodes de l'histoire de la terre où se sont produits d'importants plissements montagneux, ce qui pourrait rendre compte de l'interconnexion des périodes de plissements montagneux et des périodes glaciaires signalées antérieurement par Brooks.

Plusieurs spécialistes des changements de climat ont, au cours des dernières années, indiqué que l'augmentation de la teneur en anhydride carbonique de l'atmosphère terrestre au cours des cent dernières années était probablement une cause de la « fluctuation climatique récente ». Les éléments théoriques de leurs études sont fondées sur des idées formulées à l'origine par S. Arrhenius et P. Callendar mais revues récemment par Plass et exposées au présent colloque par H. Flohn.

Il y a enfin des météorologues, comme le Dr Sutcliffe et le professeur B. Dzerdzeevskii, pour qui les fluctuations dans la circulation générale de l'atmosphère qui se produisent entre des limites de la variabilité de cette circulation et résultant de facteurs qui ne sont pas extraterrestres suffisent à appliquer les fluctuations climatiques que nous connaissons. Les communications de J. Bjerknes et de J. Namias donnent des indications qui vont dans le même sens, et citent des exemples très frappants de l'influence exercée par les mécanismes de rétroaction de la terre et de la mer sur les fluctuations à court terme de l'état général de la circulation; ces influences semblent appeler particulièrement l'attention pour ce qui est d'interpréter les fluctuations climatiques à court et à long terme.

La communication de Namias montre également les relations étroites qui existent entre les méthodes utilisées pour étudier les causes de fluctuations climatiques à court terme et celles que l'on applique à l'étude de la prévision à long terme du temps et du climat. A l'origine des recherches sur les changements de climat il y avait certainement l'espoir de découvrir une méthode permettant d'extrapoler l'évolution du climat dans l'avenir. On a ainsi été amené autrefois à soumettre à des traitements statistiques assez infructueux les cycles climatiques, étudiés souvent dans leurs relations avec les taches solaires. Il semble maintenant plus ou moins évident que l'on ne pourra pas découvrir l'existence de périodes climatiques simples, bien qu'il existe certainement une sorte de quasi-périodicité des fluctuations. La méthode moderne qui consiste à étudier, au lieu de périodes statistiques, les incidences physiques de changements dans la circulation générale et le bilan calorique sur les fluctuations du climat et du temps semble bien plus prometteuse. Les conditions de la circulation de l'atmosphère indiquent également que cette méthode ouvre de meilleures perspectives, en ce qui concerne à la fois l'explication des fluctuations climatiques et la prévision à long terme dans l'étude des zones tropicale et subtropicale, ce qui est important pour le cas des régions arides et semi-arides.

Je voudrais en outre signaler certaines autres interrelations sur lesquelles on a insisté au cours de cette réunion et qu'il faut prendre en considération, car elles viennent encore compliquer les problèmes posés par les causes des changements de climat. On a de bonnes raisons de croire que les changements de climat n'ont pas une seule cause première mais que beaucoup des explications données touchant les changements de climat dans le monde sont applicables simultanément de sorte qu'elles réagissent les unes sur les autres. Les fluctuations de la radiation dues à des influences astronomiques, dont parle Milankovitch, le déplacement des pôles, les modifications de l'activité solaire, les quantités de poussière volcanique ou cosmique existant dans l'atmosphère terrestre ou les augmentations de sa teneur en anhydride carbonique, les changements dans les conditions régnant au niveau de la terre et en altitude, les fluctuations arbitraires dans la circulation générale de l'atmosphère, ainsi que les facteurs de retard et les mécanismes de rétroaction résultant de l'emmagasinage de chaleur à la surface de la terre ou dans les grands océans; ce sont là autant de facteurs qui ont pu agir tous dans la même direction pour causer les grandes fluctuations du climat de la terre, comme les périodes glaciaires d'une part et les périodes très sèches et chaudes d'autre part. Un seul de ces facteurs peut être responsable des fluctuations à court terme qui permettent de repérer les relevés météorologiques. C'est notre objectif en tant qu'hommes de science de distinguer les influences de chacun de ces facteurs et de découvrir l'importance de l'effet exercé par chacune des causes sur les changements de climat de durée différente.

On peut, semble-t-il, conclure de tout cela que la première mesure à prendre pour expliquer une fluctuation d'un certain élément climatique dont l'existence a été démontrée serait, de préférence, d'interpréter cette fluctuation comme une conséquence des modifications de la circulation générale au-dessus de la région intéressée. La mesure suivante serait d'établir un rapport entre les changements de la circulation et les variations possibles du bilan calorique de l'atmosphère pour voir ensuite si ces variations ont un rapport quelconque avec l'évolution de la radiation solaire. Il est vrai que des indices concernant la cause des changements du climat de la terre pourraient être découverts par des études du bilan calorique considéré isolément, il serait encore plus intéressant, on doit bien le reconnaître, de savoir aussi comment une modification donnée du bilan calorique agirait sur la circulation générale et finalement sur les éléments du climat. Sans doute, les nouvelles possibilités qu'offrent les calculatrices électroniques pour le traitement statistique des changements de la circulation générale d'une part, et les données obtenues par des satellites d'autre part, joueront un rôle capital dans l'évolution future des études sur les causes des changements de climat dans leur rapports avec la circulation générale; c'est ce qu'ont bien indiqué Namias, Kraus et Lorenz.

Il serait intéressant de recueillir au cours de ce débat d'aujourd'hui des opinions sur cette méthode, qui consiste à aborder progressivement les causes des fluctuations climatiques à court et à long terme, ainsi que sur l'ensemble de la question des meilleurs moyens de continuer l'étude des causes des changements de climat.

A plusieurs reprises pendant le colloque, et dans le cours même de cette allocution, l'importance des changements de climat pour la végétation, la faune et l'activité de l'homme a été évoquée. La plupart des spécialistes de la météorologie qui s'occupent du problème des variations climatiques n'ont bien entendu aucune raison particulière d'en envisager cet aspect. Cependant, au cours des quinze dernières années, des géographes qui s'intéressent aux relations entre l'homme et la nature ainsi que des organisations internationales qui travaillent pour le bien de l'humanité ont manifesté un intérêt croissant à l'égard de cet aspect du problème. En fait, on l'a mentionné, l'influence des « fluctuations climatiques récentes » sur la végétation, la faune, l'agriculture, la pêche et le commerce maritime, a été énorme.

Au titre de son programme relatif aux terres arides, l'Unesco s'est de plus en plus intéressée aux fluctuations climatiques dans les régions arides et semi-arides du monde. Maints spécialistes considèrent que bon nombre de ces régions, où l'on s'efforce actuellement de développer la colonisation humaine et l'agriculture, étaient fertiles et utilisées pour la culture sèche ou l'agriculture irriguée, à des époques très anciennes. Un objectif fort intéressant des études futures concernant les fluctuations climatiques sera donc de déterminer les changements dans les limites des terres arides et semi-arides qui se sont produits au cours des temps historiques et préhistoriques.

La complexité du problème des changements de climat dans les régions arides ressort nettement des intéressantes communications de J. Tixeront en ce qui concerne la Tunisie, de D. Amiran pour Israël, de C. Voûte pour l'Irak et de H. Bobek pour l'Iran ; elle l'a été d'autre part plus complètement par K. W. Butzer dans son résumé récemment paru concernant les régions semi-arides depuis l'époque de l'établissement de l'homme. Une des difficultés de ce problème tient principalement à ce que, s'il semble possible de prouver, au moyen de méthodes empruntées à la géomorphologie ou à l'archéologie, ou par l'analyse pollinique, qu'un certain changement de la végétation et de l'état du sol s'est produit à une période donnée, on ne pourra généralement pas dire quelle a été la cause première de ce changement. Dans de vastes régions du monde situées à des latitudes tempérées, des changements intervenus en des périodes anciennes dans les conditions de l'écologie végétale et du sol ne peuvent guère résulter que de très grandes fluctuations de la circulation générale et doivent donc avoir été liés à de véritables fluctuations climatiques. Cependant, dans les régions de population assez dense, ce qui était anciennement le cas de nombreuses régions semi-arides, on ne peut pas négliger l'influence de l'homme et de ses animaux sur l'état du sol et de la végétation, dont on tire parti pour établir le caractère du climat ancien. Comme l'a souligné R. Veryard, et comme l'avait exposé antérieurement en détail J. M. Mitchell, quand on s'occupe d'un climat local ou d'un microclimat, il est toujours très difficile de déterminer si ce qui semble être une certaine fluctuation climatique résulte de changements dans les conditions atmosphériques générales ou, pour ainsi dire, d'influences « artificielles » de l'homme et des animaux comme celles que constituent le déboisement, l'érosion du sol, l'urbanisation, l'irrigation et le pâturage. Je voudrais d'ailleurs souligner que l'on ne peut obtenir de certitude sur ce point, même dans le cas de changements macroclimatologiques, à moins de prouver que ces changements ont intéressé des régions très étendues. Nul n'est actuellement en mesure de dire quelle est l'importance d'un changement du microclimat ou du climat local qui constituerait également un changement d'un ordre plus général, celui du macroclimat.

Même si l'on accepte la théorie, très répandue à l'heure actuelle, selon laquelle le changement des conditions de l'agriculture dans les régions arides et semi-arides du monde depuis le temps où des cultures y florissaient est dû principalement à l'influence de l'homme, le problème de l'influence secondaire de l'activité de l'homme sur le climat demeure sans solution. Par exemple l'idée admise aujourd'hui par de nombreux chercheurs serait qu'un déboisement important dans des terres semi-humides ou semi-arides peut non seulement augmenter l'érosion du sol et par conséquent étendre le champ des conditions désertiques, mais aussi exercer une influence directe sur le climat. D'autres cependant le nient, pensent que cela reste encore à prouver. L'irrigation, nous le savons, a un effet manifeste sur le microclimat mais si elle est pratiquée à grande échelle, elle peut avoir des conséquences étendues même sur le macroclimat. Pour ce qui est du pâturage, il est bien connu qu'il exerce une influence importante sur la végétation et que, par conséquent, on doit en tenir compte lorsque l'on étudie des conditions climatiques par des méthodes tirées de l'écologie végétale. Au cours de nos débats, H. Flohn a signalé l'effet important que peuvent avoir des changements de la végétation et de la couverture végétale sur l'évapotranspiration dans les climats subtropicaux et tropicaux et, par voie de conséquence, il a envisagé la possibilité d'une influence capitale de l'homme sur le climat.

L'interrelation des véritables changements de climat dus à des influences extraterrestres ou à des fluctuations importantes de la circulation générale de l'atmosphère, d'une part, et, d'autre part, de l'influence de l'homme sur la végétation naturelle et l'érosion du sol, qui peut sembler tenir à un changement véritable du climat, posent un problème fondamental auquel il faut s'attaquer lorsqu'on s'occupe de toutes les conséquences pratiques des fluctuations climatiques aux époques anciennes et récentes.

Pour étudier cette interrelation, il est tout d'abord essentiel de connaître la situation climatique actuelle, et de savoir quels sont les rapports mutuels entre la végétation naturelle, l'agriculture et le climat. Le projet mixte OMM-Unesco-FAO visant à étudier les conditions agroclimatiques régnant dans les régions semi-arides du Proche-Orient et du Moyen-Orient donnera une base solide à la détermination des conditions agroclimatiques dans cette partie du monde. J'estime que ce projet devrait être suivi d'un autre, à exécuter au moins dans une zone pilote de l'intérieur de la région, comportant une étude moderne de l'évolution du climat et de l'influence exercée par l'homme sur le climat du fait du reboisement et de l'irrigation. Il s'agit là d'un projet à long terme dont l'exécution prendra un temps considérable, mais qui offre la seule possibilité de se faire une idée de l'ordre de grandeur des changements dus à l'homme par rapport à ceux qui résultent de véritables fluctuations du climat. Cette suggestion se rapproche de la proposition énoncée par Leopold dans son allocution d'ouverture, visant à l'établissement d'un réseau mondial de petits bassins d'écoulement où seraient étudiées les conditions du ruissellement superficiel et les influences qu'elles subissent du fait de l'évolution du climat et de l'action de l'homme. Il serait préférable que des projets de ce genre soient exécutés à l'échelon national, mais sous la surveillance d'organisations internationales et avec leur aide. L'ensemble de la question de l'interrelation entre l'influence de l'homme et les changements de climat dans les régions arides et semi-arides nécessite encore bien des recherches. Cette question est suffisamment vaste, semble-t-il, pour justifier l'organisation d'un colloque spécial qui aurait à l'étudier à une date ultérieure.

Au cours du présent colloque, nous n'avons pas pu traiter la question controversée des possibilités qu'aurait l'homme de prévoir l'évolution future du climat ou d'agir sur ce dernier par des moyens artificiels. Il semble peu probable, dans l'état actuel des connaissances sur la circulation générale de l'atmosphère, qu'il soit possible de provoquer des changements importants des conditions climatiques par des moyens artificiels, mais je voudrais souligner que l'on ne sait pas non plus quelle peut être l'importance des conséquences d'influence plus limitée dues à l'homme. Il est évident qu'une meilleure connaissance de l'interrelation entre les conditions climatiques et l'influence de l'homme sur la végétation et le sol, ainsi que des rapports entre les modifications de la circulation générale, le bilan calorique de l'atmosphère et les fluctuations climatiques, est une condition nécessaire pour permettre à l'homme d'apprendre à prévoir le climat et à le modifier.

Pour terminer, je voudrais présenter une liste de questions proposées à l'examen de notre colloque pour le reste de cette session :

1. Comment arriver à quelque forme de normalisation des méthodes visant à démontrer l'existence de fluctuations climatiques depuis l'époque où l'on dispose de relevés climatiques, et à étudier notamment la signification et les critères de ces fluctuations ? Serait-il possible de formuler une recommandation touchant les méthodes d'étude sur l'homogénéité des observations ? Pourrions-nous prendre des dispositions en vue de la création de réseaux spéciaux et la publication spéciale de données pour l'étude des changements de climat ? (Flohn.)
2. Quelles recommandations directes serait-il possible de formuler concernant la meilleure méthode à appliquer pour l'étude des fluctuations climatiques pendant les périodes du pléistocène et de l'holocène, et notamment pour la détermination des problèmes les plus importants à résoudre? Serait-il possible d'organiser à l'échelon international des études interdisciplinaires sur les processus anciens et actuels qui présentent de l'importance pour l'étude des changements de climat ?
3. Quelle est la méthode la plus raisonnable à adopter pour les recherches scientifiques futures sur les causes des changements de climat ? (Godson.)
4. Des dispositions internationales pourraient-elles être prises en vue d'organiser des recherches interdisciplinaires sur les relations entre l'évolution du climat et des formes de terrain due aux facteurs naturels, d'une part, et celle qui est due aux activités de l'homme, d'autre part ?

DISCUSSION

H. Flohn. The most urgent need for research workers in the field of climatic fluctuations—including basic investigations for long-range forecasting—is the availability of data, especially monthly averages for individual months. This could perhaps be done by an implementation of *World Weather Records*, but other, less expensive, ways of publication might prove more advantageous.

The following data are needed (for individual months and years, as far back as possible):

1. Area-averaged, homogeneous data for precipitation—perhaps including precipitation frequency—and temperature, for areas with rather uniform climate in the order of 1-5 $\times$ 10^6 km.

2. Temperature, precipitation, pressure and (perhaps) wind distribution for representative high-level stations.

3. Temperature of air and sea, precipitation frequency, cloudiness and wind distribution for selected grid areas of the oceans.

4. World-wide grid-point data for pressure (surface since 1881, northern hemisphere) and 500 m.-topography (since about 1935).

I should suggest that in those countries where the relevant data is available but not the personnel, Unesco might provide financial support for the evaluation of data under 1 and 2. I am aware of the fact that there is some data available but, especially in the tropics and in the southern hemisphere, much more is wanted.

M. Schüepp. I would like to suggest that an information centre be established to receive papers and publish a yearly bulletin summarizing the information received and including bibliographies.

I think we should invite Dr. Veryard to accept such a task.

C. C. Wallén. This is an excellent idea.

V. M. YEVDJEVICH. Some general remarks on the studies as to whether there have been or have not been climatic changes in recent years (100 to 150 years) may be advanced:

1. The last three of four decades have produced many studies on the fluctuations of annual precipitation, river flow, lake level, sediment deposits, etc., which used the harmonic analysis in order to find the hidden periodicities and cycles longer than one year. It seems that those efforts have not produced any consistent results on the world-wide basis, and the determined hidden periodicities have not been usually proved by the further observations.

2. The available data of climatic factors or other factors related to the climate contain generally the inconsistency defined as systematic errors, jumps or trend, and the non-homogeneity defined as man-made effects. In this way the true or virgin values of a time-series are different from the series which are available on our desks. It can be proved stastistically that the inconsistency and non-homogeneity in data introduce on the average a dependence or serial correlation in a time-series. In many cases these effects are not negligible.

3. In order to determine if there have been or not some climatic changes on an annual basis in the last 100-150 years, some standard or bench-mark series are needed. It seems that the properties of random time-series and the series derived by stochastic processes should be bench-mark series. The actual development of the theories of random variables, and of stochastic processes give us powerful tools for the analysis of climatic fluctuations.

4. The use of running overlapping means should be carried out in the light of the Slutsky-Yule studies and effects. The use of moving average in pure random series may show the same ups and downs (cooling off, or warming up) as are often shown in the smoothed time-series of temperature.

5. When a significant difference is detected between a climatic time-series derived by stochastic process, and when that difference is not caused by the inconsistency or non-homogeneity in data, and only then do we have the right to talk of a climatic change. If, however, we detect that the recent time-series are close to some series obtained by stochastic processes, then we are forced to talk of probability of future climatic fluctuations. The probability that a wet or hot period of 20-30 years occurs in a period of some hundred years is not small.

6. The storage of heat or water in oceans, atmosphere and soil, and the feed-back process can be very well approximated by some regressional or moving average stochastic processes, applied to random fluctuations.

7. Apart from using the point observations of climatic factors, the use of the integrated effects of climate, as for instance the effective annual precipitations on river basins (defined as precipitation minus evaporation, and determined from river flows), may give a better insight as to whether there are climatic changes in the recent 100-150 years or not.

8. There is a need for further studies of the best methods to be used in the analysis of climatic time-series.

9. A net of some hundreds of river-gauging stations from all around the world would give a very useful data for the studies of climatic influences on water resources, but also they may give the data for studying the climatic fluctuations themselves.

R. G. VERYARD. I would like to urge that consideration be given to the setting up of some machinery whereby the experts in various disciplines keep in touch with each other. The need for close contact has been revealed several times during the discussions at this symposium.

D. AMIRAN. With reference to Dr. Wallén's suggestion for regional investigations of man's influence on changes of climate: these should be carried out by interdisciplinary teams. The problem is of a very complex nature and specialists in a number of fields are required in order to isolate the various elements and their influence.

It should be worth while, furthermore, to refer to the material included in *Man's Role in Changing the Face of the Earth* published in 1955.[1]

H. H. LAMB. One possible way in which regular contacts between meteorologists and those in other disciplines concerned in studying climatic change would be for meteorological research centres, possibly WMO, to become associated with INQUA (the International Association for Quaternary Research). Local contacts between individual workers in the different disciplines are also to be commended and encouraged.

R. FAIRBRIDGE. In supporting the sentiments expressed by Dr. Veryard and Dr. Lamb in favour of our extended international liaison on an interdisciplinary basis, it is felt that INQUA is not quite suitable, since meetings are held only every four years in varied centres and there is no permanent Secretariat. While a relationship with INQUA should be maintained, another permanent mechanism should be developed.

O. M. ASHFORD. With regard to Dr. Wallén's first question, I should like to mention that there have already been discussions with WMO concerning the establishment of a working group to recommend standard methods for analysing climatological data for studies of climatic fluctuations. It was decided to postpone a decision on this matter until after the present symposium. I have no doubt that the President of the WMO Commission for Climatology will now reconsider the suggestion in the light of the discussions which have taken place here in Rome.

J. TIXERONT. La question 1 est relative aux fluctuations à courte échéance. Certaines conséquences climatiques donnent des index encore plus sensibles que les éléments même du climat, notamment les écoulements d'eau et la production agricole. Celle-ci est particulièrement sensible dans les régions arides. Une part très importante dans l'étude de cette question devrait être réservée aux écologues, aux agronomes et aux hydrologues.

La question 2, relative aux fluctuations pendant l'époque glaciaire, donne lieu à une observation analogue. Une part très importante devrait être réservée aux tectoniciens dans les études envisagées, au sujet desquels on entend surtout les géomorphologues au cours de discussions où l'aspect tectonique et dynamique n'est jamais exposé avec assez de précision.

H. BOBEK. I should like to make a suggestion concerning item 2. Up to now investigation is carried out individually, in a random way, generally not in the best possible way and without the necessary co-operation of other scientists

1. W. L. Thomas, Jr. (ed.) 1955. *Man's Role in Changing the Face of the Earth*, published for the Wenner-Gren Foundation for Anthropological Research and the National Science Foundation, Chicago, The University Press, 1,193 p.

concerned. It may be an all too ambitious idea and not very realistic but I could conceive the launching of a series of international expeditions, preplanned by a group of co-operating scientists interested in different disciplines, to investigate the crucial areas in a peaceful way so as to achieve the greatest progress within a given time.

E. B. Kraus. We should not commit ourselves narrowly to any standard method or to any standard period. Different methods have different purposes—for example curves of cumulative deviations cannot be used to show statistical significance, but they are a powerful statistic tool.

Standard periods can be ignored by nature. Change may be discontinuous for all we know. The climate may remain stationary for long periods and then vary rapidly. Restriction to standard periods would possibly submerge this type of change.

The same need for a multiplicity of methods applies to the study of earlier ages. Much of the geological and biological evidence produced here may well be indicative of certain seasons or perhaps even of certain catastrophic events—floods or droughts—rather than of the total climate. We need different methods that are well established in their own right and which not only support each other, but which also produce different, contrary evidence. This only may allow us to learn something about a past climate and its range as a whole.

C. C. Wallén. I certainly do agree that no standard method should be recommended for exclusive use. My intention rather was to recommend that some very useful standard methods be applied to a standard period in connexion with any other method suggested by authors. This would allow for a comparison as to the significance of the fluctuations studied. Used in this way a standard criterion and clear definitions would not stop the development of new methods in the field.

R. G. Veryard. Whilst I agree, Sir, with your view that action should be taken to standardize and amplify statistical methods for the determination of climatological fluctuations and their effects I would like to emphasize the importance of the dynamical approach. Even if we had a good network of observing stations with long-period records and homogeneous data thus enabling us to determine climatic fluctuations more precisely there is still the need to know how these changes came about, as you have pointed out yourself, Sir. After all, everyone wants to know what changes may be expected in the future—has, for example, the warming of the early part of this century really come to an end or not? I would therefore urge, and I am sure Dr. Sutcliffe would agree with me, that there should be many more studies of the kind presented to us by Dr. Bjerknes, Dr. Kraus, Dr. Namias, and others. To my mind it is only by means of such studies that we can hope to interpret the findings of the climatologists in terms of physical and dynamical principles. Perhaps the WMO Commissions for Aerology and Climatology could be invited to encourage and effect the co-ordination of such studies.

C. C. Wallén. I cannot agree more to the suggestion made by Dr. Veryard that the dynamical approach to the problem of climatic fluctuation is at least as important as any statistical one. It was therefore why I suggested that the first step to investigate a climate fluctuation, once it is established by statistical methods, should be to study its causes in relation to the general circulation of the atmosphere.

J. Namias. Regarding item 3, it would be presumptuous of me to suggest the best approach to the solution of causes of climatic fluctuations because of our present state of ignorance. But I would like to suggest two items of concern:

1. The problem of specifying climate and weather according to aspects of circulation has now passed from the qualitative stage, and such studies (statistical and synoptic, with the help of computers) would be appropriate and rewarding for all areas of the world.

2. A new group of students of the general circulation working with high-powered mathematical-physical techniques and computers has developed over the past decade. The ultimate aim of this group is to test theories of climatic fluctuations and even modification. Such a group will be helped in their work at some point if they are informed of the empirical evidence for climatic fluctuations on all time-scales, and our group meeting here might assist in doing this.

L. A. Ramdas. With regard to human interferences or influences on Nature, we all realize that man is perhaps the most efficient "pest" in Nature ! There may be situations which are "unstable" where such human interference may lead to progressive and disastrous deterioration of the plant-cover that would result in man-made deserts.

Another point: during the last fifteen or twenty years many agricultural or bio-meteorologists have been engaged in studying the effect of specified plant cover on the micro-climate. This is done by comparing the temperature, humidity, etc. in a plant-covered area with simultaneous observations at similar levels in an adjoining "open" space. A dense plant community with a canopy produces the largest deviations from the climate of an open space often exceeding 20° C. in air temperature. The border effect is confined to a few rows at the border of the plant community and the local climate is fully established as soon as the plant community is established. This body of information should be made available to workers in other fields by the Commission for Agricultural Meteorology of WMO.

J. Murray Mitchell. With reference to item 1, I should merely like to suggest that consideration also be given to standardization of terminology used in describing the time-scale of climatic variation. For example, the climatologists' usage of the word "secular" bears little resemblance to the geologist's usage of it. If a working group on this item 1 is established by WMO, this matter of terminology should I believe be recommended as one of its terms of reference.

G. B. Maxey. The geological and pedological information presented at this symposium has not been representative of the contributions that have been made by members of the Earth Science. Therefore I would suggest that the recent literature of that science be consulted before conclusions regarding items 1, 2, and 4 (actually all four items) are made.

R. J. Braidwood. With reference to item 1 and the matter of usage: to the archaeologist, for example, such a word as "neolithic" communicates many (often opposing) ideas, to me it generally communicates nothing.

With reference to item 4: my paper was purposely negative for reasons of emphasis, but I should like to say that very good archaeology *is* being done today. As an example of a site report in which the reclamation and interpretation of the evidence is used to really good advantage in all categorie (artifactual and non-artifactual), I suggest J. G. D. Clark's *Star Carr*, 1954, report.

L. P. Smith. In considering how best we can treat the problems of climate change there must be a dual approach:

1. The search for truth; this includes the estəblisment of true facts and the true explanations of such facts based on the laws of physics and chemistry.
2. The urgent need for a good working answer which is the nearest approach to the truth available at the present stage of incomplete knowledge.

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