(*h*) Hot, annual temperature above 18°.
(*i*) Isothermal, difference between extreme months less than 5°.
(*k*) Cold winter, annual temperature below 18°, warmest month above 18°.
(*k'*) The same, excepting warmest month below 18°.
(*m*) Monsoon rains, primeval forest in spite of one dry period.
(*n*) Frequent fogs.
(*n'*) Infrequent fogs, but high humidity accompanied by lack of rainfall, and relatively cool (summer below 24°).
(*p*) The same, with a higher temperature (summer above 28°).
(*p'*) The same, but with summer temperatures 24° to 28°.
(*s*) Dry season in summer of that hemisphere.
(*w*) Dry season in winter of that hemisphere.
(*s' w'*) The same, but rainy season delayed after autumn.
(*s'' w''*) The same, but rainy season overlapping with small dry season introduced.
(*u*) Sudan temperature course, coldest month after turn of the sun.
(*v*) Cape Verde course of temperature, warmest month in autumn.
(*x*) Transition type with early summer rain.
(*x'*) The same with infrequent but intense rain at all times of the year.

L. F. RICHARDSON ON WEATHER PREDICTION BY NUMERICAL PROCESS.

By EDGAR W. WOOLARD.

[Weather Bureau, Washington, D. C., March 15, 1922.]

Weather forecasting as conducted by the chief meteorological services of the world for many years past is completely empirical. Yet it can not be doubted that the processes of weather are simply examples of the operation of ordinary physical laws, although special methods may be required for the treatment of the special problems involved. The ultimate object of all meteorological work is to lead up to an insight into the physical processes which effect changes in weather—all our forecasting is the anticipation of these changes. The method of forecasting by empirical rules and past experience is simply a stage in the classification of the physical processes; it leads, as we know, to excellent results in the hands of the experienced, but its capacity is limited, and the limit is very soon reached. To carry it further, or to make out the true inwardness of its application in special cases, we must depend upon our knowledge of the dynamics and physics of the atmosphere.

In the present position of meteorological science, there are two extremes of opinion, both of which ought to be, and undoubtedly are by most meteorologists, avoided: Either to think the penetration into the secrets of the subject to be so difficult that we must be content to forego the attempt and deal with what we have; or to think it so easy that only observations are required, and the training of our brains of no account. As a matter of fact, brains without observations are certainly of no avail at all in any problem dealing with Nature; and observations, however numerous and widely distributed, will not exonerate us from the use of highly trained intelligence.[1]

Meteorology becomes exact only to the extent that it develops into a physics of the atmosphere. The ancients had a not inconsiderable knowledge of both meteorological facts and certain branches of physics, but no one dared to combine this knowledge in order to explain, for example, the monsoon winds. The growth of meteorological and of physical knowledge during and after the Renaissance prepared the way for some investigating spirit to perceive, sooner or later, the relationship between meteorological phenomena and physical laws; this relationship between the two sciences first came to be recognized, and the first step taken toward the development of a physics of the atmosphere, in the work of Halley and of Hadley, just following the great revolution in astronomy. However, by one stroke astronomy became an exact science, while meteorology took only a step in that direction. The transformation of meteorology into an exact science necessarily, from the transcendent complexity of the problems involved, called, and still calls, for extensive further development of both theoretical physics and observational meteorology.

[1] *Cf.* Sir Napier Shaw, "The Outlook of Meteorological Science," MO. WEATHER REV., 48, 34, 1920; *Quar. Jour. Roy. Met. Soc.*, 45, 95, 1919.

Parallel with the subsequent steady progress of experimental and theoretical physics and of pure mathematics, was a growth of knowledge of climatology and descriptive meteorology. The combination of meteorological and physical facts has resulted in many excellent studies of theoretical meteorology, particularly since the time of Ferrel's pioneer work on the mechanics of the earth's atmosphere. Such studies are of the utmost importance to the practical problem of forecasting, since they help toward a better understanding of the phenomena of the atmosphere. Furthermore, in addition to having their scientific importance and interest, they bring us nearer the ultimate goal of the possibility of making forecasting a science instead of an art. With complete observations available from an extensive portion of the free air, the problem is to apply the equations of mathematical physics to the actually existing atmospheric conditions, and to compute the conditions that will follow. An objection usually urged against this idea is, "How can this be of any use? The calculations must require a preposterously long time. Under the most favorable conditions it will take the learned gentlemen perhaps three months to calculate the weather that Nature will bring about in three hours. What satisfaction is there in being able to calculate to-morrow's weather if it takes us a year to do it?" However, in the words of Bjerknes,[2] "If only the calculation shall agree with the facts, the scientific victory will be won. Meteorology would then have become an exact science, a true physics of the atmosphere. When that point is reached, *then* the practical results will soon develop. It may require years to bore a tunnel through a mountain. Many a laborer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed."

Contemporary research in this field is being carried on largely by V. Bjerknes, of Norway, and L. F. Richardson, of England. It is to the latter that we owe the remarkable work now before us, *Weather Prediction by Numerical Process.*[3] Previous investigations have considered but one or two phases of the general problem—usually the purely dynamical—and have frequently been limited to more or less idealized conditions. Mr. Richardson, however, has dared to begin the discussion of the motions and phenomena of the *actual* atmosphere under the combined influences of *all* the principal factors, including radiation and absorption, evaporation and condensation, eddy motions or turbulence in the lower atmosphere, etc., gathered into one set of systematic mathematical equations, and to attempt to utilize this

[2] V. Bjerknes, "Meteorology as an Exact Science," MO. WEATHER REV., 42, 14, 1914.
[3] Lewis F. Richardson. *Weather Prediction by Numerical Process*, Cambridge Press 1922. 4to, xii, 236 pp. The manuscript was completed in 1916, but was revised, and a numerical example worked out, in France during intervals of transporting wounded, 1916–1918. Upon being sent to the rear in 1917 the working copy was lost, to be rediscovered some months later under a heap of coal. It was again revised in 1921.

scheme in computing future conditions—an undertaking which is the first step toward fulfilling a hope and desire expressed by the late Cleveland Abbe.[4]

To quote from the *Preface:*

The process of forecasting, which has been carried on in London for many years, may be typified by one of its latest developments, namely, Col. E. Gold's *Index of Weather Maps.* It would be difficult to imagine anything more immediately practical. The observing stations telegraph the elements of the present weather. At the head office these particulars are set in their places upon a large-scale map. The index then enables the forecaster to find a number of previous maps which resemble the present one. The forecast is based on the supposition that what the atmosphere did then it will do again now. There is no troublesome calculation, with its possibilities of theoretical or arithmetical error. The past history of the atmosphere is used, so to speak, as a full-scale working model of its present self.

But—one may reflect—the *Nautical Almanac,* that marvel of accurate forecasting, is not based on the principle that astronomical history repeats itself in the aggregate. It would be safe to say that a particular disposition of stars, planets, and satellites never occurs twice. Why then should we expect a present weather map to be exactly represented in a catalogue of past weather? Obviously the approximate repetition does not hold good for many days at a time, for at present three days ahead is about the limit for forecasts in the British Isles. This alone is sufficient reason for presenting, in this book, a scheme of weather prediction, which resembles the process by which the *Nautical Almanac* is produced, in so far as it is founded upon the differential equations, and not upon the partial recurrence of phenomena in their ensemble.

The scheme is complicated because the atmosphere is complicated. But it has been reduced to a set of computing forms. These are ready to assist anyone who wishes to make partial experimental forecasts from such incomplete observational data as are now available. In such a way it is thought that our knowledge of meteorology might be tested and widened, and concurrently the set of forms might be revised and simplified. Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream.

The state of the atmosphere at any point is specified by the values of seven dependent variables—the velocity horizontally toward the east, horizontally toward the north, and vertically upwards; density; joint mass of solid, liquid, and gaseous water per mass of atmosphere; temperature; and pressure. There are four independent variables—time, height above mean sea level, longitude, and latitude. Atmospheric phenomena are then completely described by seven fundamental differential equations; among these, temperature is eliminated, and the vertical velocity solved for, leaving five main equations to give the time rates of change of the remaining variables. The upper layers of the soil and sea are also taken into account.

In order to obtain a practical solution of these equations, recourse is had to the powerful Calculus of Finite Differences, using the method of Central Differences. The surface of the earth is divided into quadrilaterals by parallels and meridians, the author reaching the tentative conclusion that the parallels should be separated by 200 kilometers, and the meridians spaced uniformly at the rate of 128 to the whole equator, alternate meridians being omitted in high latitudes; the atmosphere is divided into five conventional strata at fixed heights of 2, 4.2, 7.2, and 11.8 kilometers above sea level. The fundamental equations are integrated with respect to height across these strata; special treatment has to be accorded the upper stratum. The centers of the squares are supposed to be the points for observing and recording the meteorological elements at the surface and aloft. If we imagine the squares to be colored alternately red and white like a chessboard, then those of one color should contain the pressure, temperature, and humidity, the others the density and wind velocities. To carry out the numerical solution of the equations, a piece of paper is ruled in squares corresponding to the squares on the earth's surface, and inside these squares are written the values of the dependent variables at the center. The infinitesimal differentiating operators in the equations are then replaced by the finite difference operators, and arithmetic is used instead of symbols, the increments being computed from the above tabulation; the time increment is taken as six hours. The increments of the variables with respect to time may then be computed; at the end of the process, the errors due to the finiteness of the differences may be estimated. In order to convince the reader of the reliability of this method, and to exhibit its powers and limitations, it is first applied to a simple example which is also solved analytically.

Thus we see the scheme consists of tabulating initial data of observation at certain latitudes, longitudes, and heights arranged in a pattern which, by borrowing a term from crystallography, may be called a "space-lattice," so as to give a general account of the state of the atmosphere at any instant over an extended region up to a height of, say, 20 kilometers, small scale phenomena being smoothed out; difficulties connected with lack of data over uninhabited regions, etc., may be partially overcome through the use of "normal" values at the boundaries. Then by operating upon the the tabulated numbers we obtain a new table representing approximately the subsequent state of the atmosphere after a brief interval of time; wherever in the lattice a pressure, say, is given initially, there the numerical process yields a pressure, so that we have a "lattice-reproducing process." The process can then be repeated so as to yield the state of the atmosphere after twice or thrice the same interval, and so on, but the errors accumulate of course, and besides each successive table is smaller than its predecessor, having lost a strip around the edge.

The method is applied to a very complete set of observations over middle Europe at 1910 May 20d. 7h. G. M. T., for which Bjerknes has published detailed charts. The resulting forecast is quite satisfactory, considering the amount and distribution of initial data: For of all the reasons that have determined the present distribution of meteorological stations, the nature of the atmosphere as summarized in its chief differential equations, is not one; and in the present case, errors seem to have been present in the initial wind data, also.

This book is an admirable study of an eminently important problem; being a first attempt in this extraordinarily difficult and complex field, it necessarily possesses, self-confessedly, many imperfections; and is by no means, of course, the final word; however, it indicates a line of attack on the problem, and invites further study with a view to improvement and extension. There are listed a number of problems still awaiting investigation. Perhaps the most serious handicap to studies in this field is the lack of adequate observational material. So far as the purely mathematical difficulties which the complexity of the subject introduces are concerned, they are surmountable. For the Philosophy of Mathematics teaches us that [5] the power of pure mathematics is unlimited—its development can not be stayed—it meets difficulties by a creative act which leaps over them; whence the nature of the peculiar rôle it plays in the physical sciences.[6] It is sincerely to be hoped that the author will continue his excellent work along these lines, and that

[4] Cleveland Abbe, "The Weather Map on the Polar Projection," MO. WEATHER REV. 42, 36, 1914.

[5] See, e. g., J. B. Shaw, *Lectures on the Philosophy of Mathematics,* Chicago, 1918.

[6] R. D. Carmichael, "The Provision made by Mathematics for the Needs of Science," *Science* (N. S.), 45, 465, 1917.

other investigators will be attracted to the field which he has opened up. The results can not fail to be of direct practical importance as well as of immense scientific value.

At the end of the book is a full explanatory list of notation in English and Ido. The mechanical execution of the work conforms to the usual high standard of the Cambridge University Press.

METEOROLOGY ON CAPTAIN AMUNDSEN'S PRESENT ARCTIC EXPEDITION.

By H. U. SVERDRUP, *in charge of the scientific work.*

Captain Amundsen's expedition left Norway in July, 1918. The plan was to follow the coast of Siberia eastward to the vicinity of Bering Strait, thence proceed to the north and let the vessel, the *Maud*, especially built for this expedition, freeze in. The vessel was then to be carried with the drifting ice fields across the Arctic Sea until it was released from the grip of the ice between Spitzbergen and Greenland, where the ice masses from the Arctic are slowly drifting south to the Atlantic Ocean. The main object of the expedition was to study the physical conditions of the Arctic Sea by determining depths, temperatures, salinities, and currents. But along with the oceanographical work, a number of other observations, mostly of geophysical interest, were to be carried out, as, for instance, meteorological observations which were to be extended to the upper air by means of pilot balloons and kites, observations of solar and nocturnal radiation, of the temperature distribution in the ice, and magnetic observations in cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. However, the ice conditions forced the expedition to winter three times in different places on the coast of Siberia, and in the summer of 1921, the *Maud* had to be sailed to Seattle for repairs.

The first wintering took place close to Cape Chelyuskin, the north point of the Continent. During the sea voyage, the pressure of the air had been registered continuously, and temperature, wind, and cloudiness had been noted six times a day. Shortly after the *Maud* was frozen fast in the vicinity of Cape Chelyuskin, a meteorological hut, containing thermograph, hygrograph, thermometers, and hygrometer was placed on the ice at a distance of about 50 meters from the vessel, and an anemograph was placed on board on the main boom, with the cups 3.5 meters above the roof of the deck's hut.

The meteorological registration for this winter showed several characteristic features. Especially were the frequent storms in the months October to January of interest, because barometric pressure, wind, and temperature always changed in a similar way during the development of the storm. Falling barometer was accompanied by a southwest gale, which might reach a velocity of 50 miles per hour, and by rising temperature, but at the moment the barometer stopped falling, the wind changed abruptly to northeast, and the temperature dropped as much as 20° C. in a few hours. This change of the meteorological elements when a storm passes is similar to the one experienced here when a cold wave passes a place, but the wind directions are here different. The wind directions noted by us indicate that the progression of the cold waves in high latitudes takes place from northeast to southwest, at right angles to the direction of progress in this latitude.

As soon as the daylight returned after the dark season, every opportunity was used for sending up pilot balloons and kites. However, the wind conditions were generally not favorable for kite flights, so the results were not in proportion to the time devoted to the work, but the few successful flights showed clearly the great temperature inversion which, in the winter, is found in the lower strata of the atmosphere in the Arctic. Attempts to send up captive balloons on calm days failed, partly because the rubber balloons to be used for this purpose were too old, having been procured in 1913, partly because we had no means to overcome the difficulties arising from the low temperatures. In May and June, the work with pilot balloons and kites had to be abandoned, because the time had to be devoted to a survey of the most northerly peninsula of the Continent.

The ice held us bound for a whole year, less one day, at Cape Chelyuskin. When we left Captain Amundsen hoped to succeed in beginning the drift. He wanted, however, to send the scientific observations home, to prevent their loss in case the vessel was crushed by the ice. They were, therefore, entrusted to two men, who were to bring them to the nearest settlement, the Russian wireless station at Dickson Island, about 600 miles to the southwest. Along the coast, which they were to follow, three caches with provisions had been left by former expeditions. The plan seemed safe, but unexpected events happened. Captain Amundsen did not succeed in beginning the drift, and the *Maud* reached Nome safely in July, 1920, but the two men who carried our observations lost their lives. With them all the meteorological registrations, together with registrations of the magnetic declination and the tides, were lost, but copies of the meteorological observations made three times daily, at 8 a. m., 2 p. m., and 8 p. m., L. M. T., and of the results of pilot-balloon ascents and kite flights, had fortunately been made and kept on board the vessel.

In September, 1919, when the *Maud* proceeded to the east, the ice conditions were still more unfavorable than in the summer of 1918. Every attempt to penetrate to the north was frustrated, and at the end of the month there was nothing left but to seek a new place for winter quarters on the coast. Thus it happened that the *Maud*, in the winter of 1919–20, was frozen in about 700 miles west of Bering Strait at the island of Ayon. When we stopped there, the island was inhabited by natives of the Siberian tribe known as the Chukchi, who, in a short time, would leave the coast and follow their herds of domesticated reindeer to the inland, where they were accustomed to spend the winter. Captain Amundsen realized that here we had a unique opportunity to study the habits and customs of this little-known tribe, and therefore suggested that I join the natives, accompany them to the interior and return to the ship in the spring. I left the *Maud* in the beginning of October, 1919, and found her in the same place when I returned in May, 1920, after having spent seven and one-half months alone among the Chukchi. Besides having gathered information and made collections of ethnological interest, I had taken meteorological observations usually three times a day, and had secured magnetic observations from five stations in an inaccessible part of the country. On board the *Maud* the registrations of the meteorological elements had been kept up continuously, and the daily observations taken regularly.

In July, 1920, the *Maud* was released from the ice, and Captain Amundsen proceeded to Nome where he had decided to call in order to take on board additional equipment for the drift. After a short stay in Nome, the ex-