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THE SPATIAL AND TEMPORAL CHARACTERISTICS OF NORTHERN HEMISPHERE SURFACE AIR TEMPERATURE VARIATIONS

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ABSTRACT

The spatial and temporal characteristics of variations in surface air temperature over the Northern Hemisphere landmasses during the present century are determined. The spatial patterns of change accompanying major warming and cooling episodes are mapped. The spatial representativeness of the Northern Hemisphere average is assessed and implications for proxy climate studies are considered. Finally, the seasonal breakdown of trends and correlations between monthly and annual data for the Arctic and Northern Hemisphere is considered.

It is shown that, although generally similar, significant differences in the spatial patterns of change accompanying warming and cooling in the Northern Hemisphere average have occurred. In particular, the early 20th century warming was more coherent spatially (as well as more rapid and stronger) then either the cooling that followed or the recent warming. Various regions tend to vary consistently with the Northern Hemisphere average but the relationships are not as marked or widespread as some investigators have claimed or assumed.

The annual Northern Hemisphere average is shown to be more strongly correlated with late spring and summer temperatures than with winter temperatures (although in the latter season the variability is greatest). Trends in temperature over the Northern Hemisphere have been strongest in April and May, whereas over the Arctic they have been strongest in January. This seasonal distribution may give an indication of the physical mechanisms underlying these climatic variations.

KEY WORDS Climatic change Statistics Surface air temperature Carbon dioxide

INTRODUCTION

The characteristics of variations in the hemispheric fields of surface air temperature are of importance to many branches of the study of climatic change (cf. van Loon and Williams, 1976; Groveman and Landsberg, 1979; Wigley and Jones, 1981; SCOPE, 1983). There has, however, been a marked reliance on simple measures of these variations, for example on indices such as the mean annual temperature of the Northern Hemisphere, which obscure much regional and seasonal detail (van Loon and Williams, 1976; Barnett, 1978; Brinkmann, 1979). It is precisely this detail which is needed to aid understanding of the causes of climatic change and to assess the social significance of past and potential climatic variation. There has also been a tendency for investigators, particularly in the field of climate reconstruction, to make hemispheric generalizations on the basis of records from a limited geographic area without consideration of the hemispheric representativeness of the area under study.

In this article, we document some of the basic spatial and temporal characteristics of variations in the Northern Hemisphere surface air temperature field. The spatial patterns of warming and cooling accompanying long-term trends in the 'mean annual temperature of the Northern Hemisphere' are presented and differences in the character of these trends from month to month are described. 'Trend' is used in this paper to denote fluctuations on time scales of around 20 years or more.

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DATA

The analysis is based on a gridded surface air temperature data set for the Northern Hemisphere. The derivation of this data set has been discussed by Jones *et al.* (1982); only the main details are given here. Monthly mean station data were drawn from *World Weather Records* for the period 1881 to 1960 (Jenne, 1975) with updates from *Monthly Climatic Data for the World* (published by the U.S. National Oceanic and Atmospheric Administration) to 1979. More recent data were abstracted from the CLIMAT network. Additional data, particularly for high latitudes, were obtained from published sources and from national meteorological agencies. These data were checked for reliability and interpolated onto a 5 degree latitude by 10 degree longitude grid using an inverse distance weighted best fit plane. The station data were gridded as departures from the appropriate monthly mean for the period 1946 to 1960 (the period of best data coverage) in order to avoid or reduce the effects of, *inter alia,* station height, aspect and observing times.

The certainty of any scientific analysis can be no better than the reliability of the data on which it is based. We note particular concerns here; the reader is referred to Jones *et al.* (1982) and Kelly *et al.* (1982) for further discussion:

(a) although the station data were checked for gross inhomogeneities in the course of the gridding, errors inevitably remain;
(b) the reliability of the gridding procedure is affected by the station density which varies with time at every gridpoint;
(c) even today only about 60 per cent of the hemisphere can be gridded, and for the 1880s the coverage is restricted to around 20 per cent of the total number of gridpoints.

The final point warrants some amplification. The geographical regions missing throughout the period 1881 to 1980 in the gridded data set are the Pacific, Atlantic and Indian Oceans, the Asian highlands and the central Arctic (Jones *et al.*, 1982, their Figure 3). Data are, therefore, mostly confined to the continental regions of the hemisphere and these may not be representative of conditions over the oceans. In view of the poorer coverage in the late 19th century, we restrict our analysis to the period 1901 to 1980.

SPATIAL PATTERNS OF WARMING AND COOLING

Although it may be axiomatic that the Northern Hemisphere mean temperature record, 'NH', masks much detail concerning the spatial distribution of temperature change, it has been relied on heavily. Jones *et al.* (1982) discuss the limitations and interpretation of this record. In this section, we identify the spatial patterns accompanying long-term warming and cooling in NH.

The annual values of NH are shown in Figure 1. Warming is apparent from the turn of the century to about 1940. Cooling then occurred until the mid-1960s, since which time warming appears to have occurred. Three phases can be defined: strong warming, *circa* 1917 to 1940; cooling, *circa* 1940 to 1965; and warming, *circa* 1965 to 1980. 1981 was the warmest year in the NH record, but has not been included in this analysis.

To identify the spatial patterns of change associated with these generalized warming and cooling trends, we have fitted a linear trend at each gridpoint to temperature data for each of these periods (Figure 2: 1917–1939; Figure 3: 1940–1964; Figure 4: 1965–1980). The trends are expressed in °C/year $\times$ 10^{-1}. The spatial patterns accompanying trends in NH over the period 1891–1979 have been studied by Vinnikov and Kovyneva (1983). We have included the most recent warming despite the fact that it is not well-defined and is short in duration because of concern that it might be the first sign of rapid carbon dioxide-induced warming. The shaded areas in Figures 2–4 indicate that the slope of the trend is significant at the 5 per cent level, although, strictly, this statistical test is invalidated by the preselection of the three periods as ones of maximum change. Nevertheless, the shaded areas provide a guide to the regions where the magnitude of the trend is large compared to the local variability.

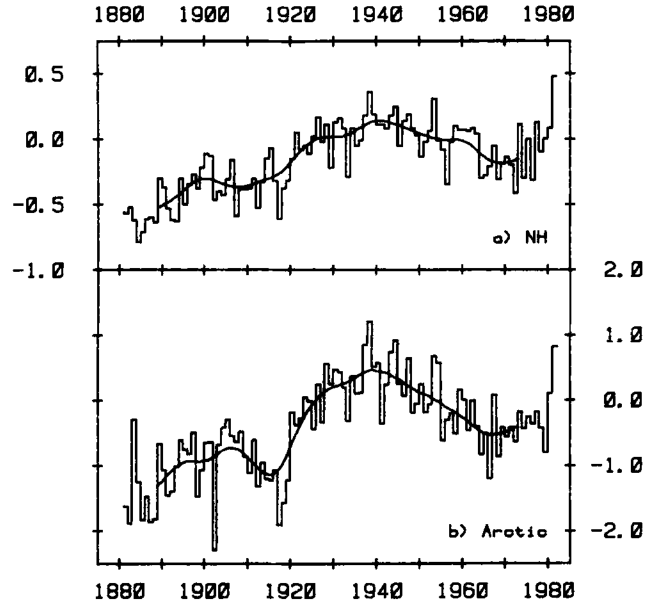

Figure 1. Annual means of surface air temperature for the Northern Hemisphere and for the Arctic (expressed as departures in °C from the 1946–1960 reference period). Data for 1981 are included in this figure but have not been analyzed. The smoothed curves show the data smoothed with a binomial filter designed to suppress variations on time scales of less than 20 years

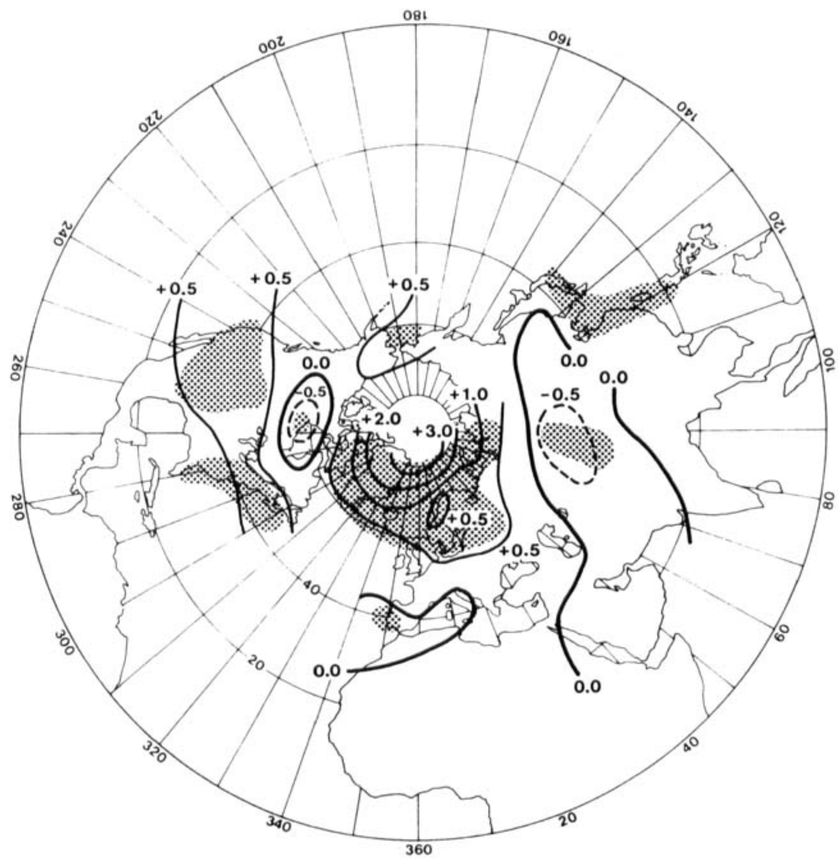

Figure 2. Linear trend of gridpoint temperatures over the period 1917–1939 (°C/y×10^{-1}). Shaded areas are significant at the 5 per cent level

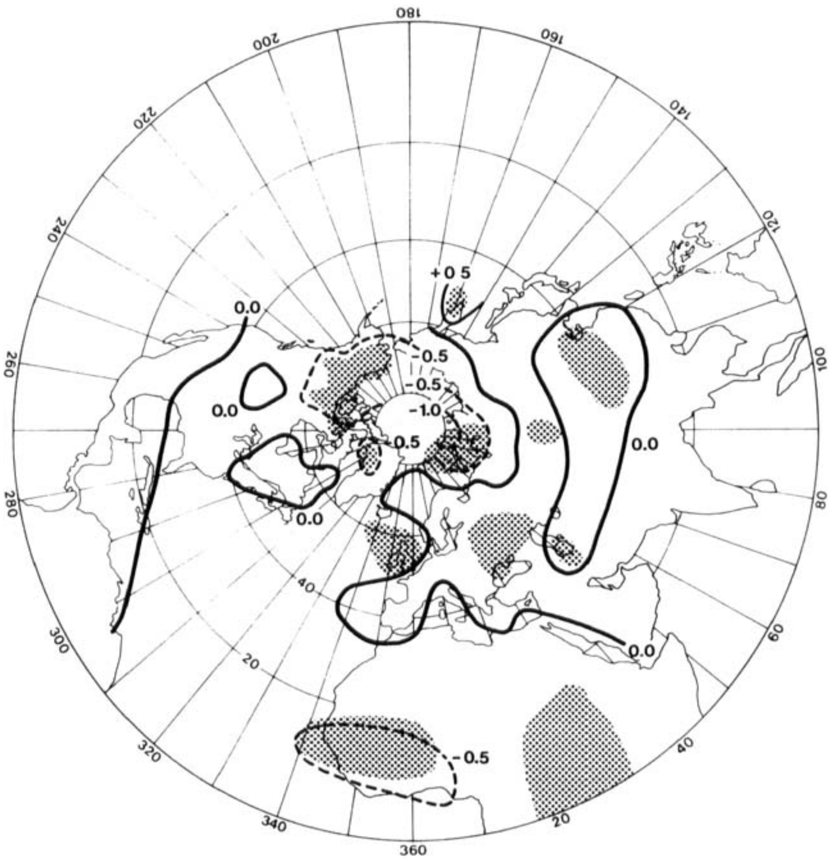

Figure 3. Linear trend of gridpoint temperatures over the period 1940–1964 (°C/y×10^{-1}). Shaded areas are significant at the 5 per cent level

Throughout this paper, temporal autocorrelation has been allowed for, when appropriate, in calculating significance levels (Quenouille, 1952; Mitchell *et al.*, 1966) but spatial autocorrelation has not been considered.

The pattern associated with the first, and major, NH warming phase, 1917–1939, shows maximum warming over Greenland, the Barents Sea, northwestern Siberia and northern Europe, the United States, and the Far East (Figure 2). Even during this period of pronounced warming, certain regions go against the overall trend. Cooling is evident over central Canada and central Asia. This pattern strongly suggests changes in the number of mid-latitude cyclones entering the Arctic and variations in the strength of the continental anticyclones.

The pattern associated with the 1940–1964 NH cooling shows major cooling over the Kara Sea, northern parts of the USSR, Alaska and north-western Canada, north-western Greenland and the western Sahel (Figure 3). Warming is evident over the Ukraine and Kamchatka. The cooling in NH during this period was not as marked as the earlier warming, and the spatial patterns of change are not as coherent (see also, Kelly *et al.*, 1982).

The recent warming, 1965–1980, has been strongest over the Greenland Sea, the Barents Sea and northern Scandinavia, most of the USSR, Alaska, north-western Canada, the south-western United States and north Africa (Figure 4). Cooling has occurred over the Canadian Arctic islands and northwest Greenland, and, to a lesser extent, over the Mediterranean region. Although the recent warming has been weak, and few regions in Figure 4 are significant, most of the hemisphere has undergone warming. The spatial pattern is as coherent as that of the previous cooling and the magnitude of the trends are similar (the relative lack of significance is due to the short duration of the warming to date).

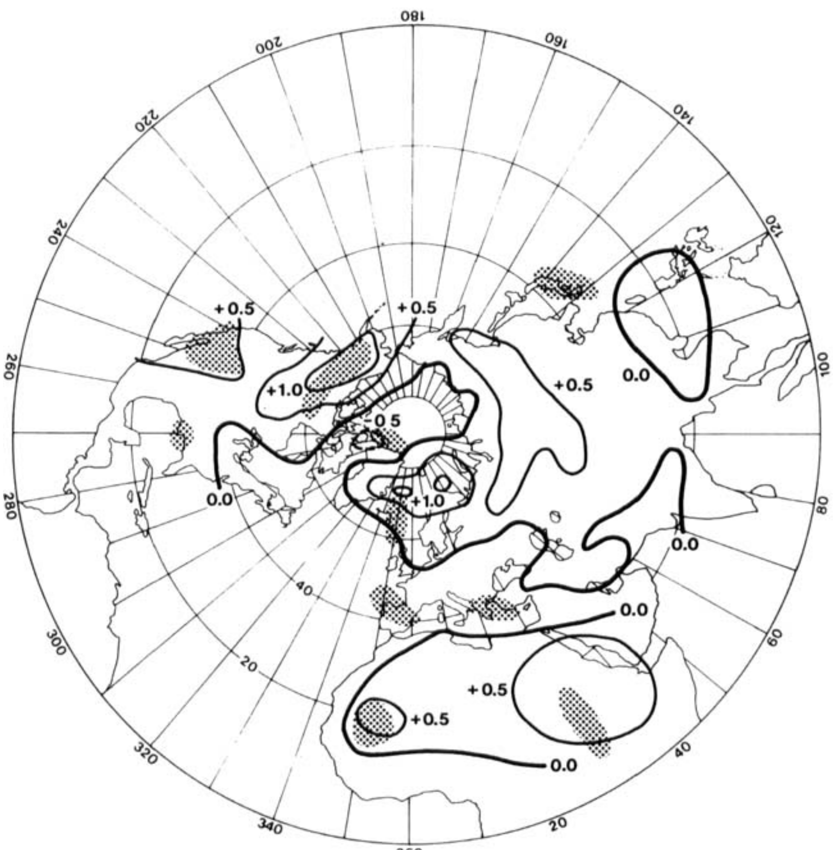

Figure 4. Linear trend of gridpoint temperatures over the period 1965–1980 (°C/y×10^{-1}). Shaded areas are significant at the 5 per cent level

Comparing the pattern of change during the two warming periods, it is noticeable that western Greenland, although strongly affected by warming during the earlier period, cooled during the second hemispheric warming. This reflects continuation of the cooling that had occurred in that region since 1940. The warming over Alaska and north-western Canada has been particularly strong during the most recent period. The cooling in the continental interiors evident during the first warming is not present in the second warming period. Two regions warm significantly in both periods: the Greenland, Barents and Kara Seas and northern Scandinavia and, *albeit* less so, the south-western United States.

In all three periods, the magnitudes of the trends are greatest in the Arctic and interior of the two main continents, North America and Asia. This is not surprising as those are the areas of greatest variability on all time scales. Indeed, this fact makes certain of the trends calculated in these areas insignificant despite their magnitude.

It is notable that the pattern of cooling (1940–1964) is not opposite to the pattern of the earlier warming (1917–1939) and that the two patterns of warming are different. However, the recent warming (1965–1980) is in many respects almost opposite to the pattern of earlier cooling (1940–1964). This implies that the recent warming is returning surface temperatures to levels similar to those experienced in the 1940s. Furthermore, because the two warming periods are somewhat different in their spatial nature, it may be that they are the results of different causal mechanisms. The short duration of the recent warming and its relative weakness do, however, make strict comparison impossible at this time.

SPATIAL REPRESENTATIVENESS OF NH

We have noted that the spatial patterns of change accompanying major warming and cooling in NH are not identical. It does appear, however, that variations in certain regions have a consistent relationship

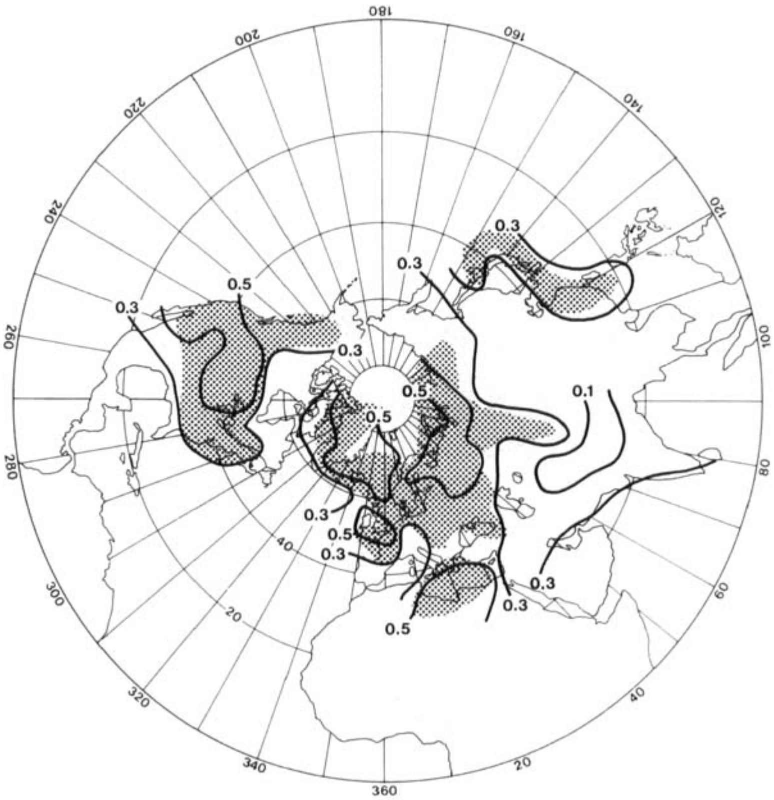

Figure 5. Correlations between the annual Northern Hemisphere temperature average and gridpoint temperature data, 1901–1940. Shaded areas are significant at the 5 per cent level

with variations in NH. In order to corroborate this conclusion, we have correlated time series of annual gridpoint values with NH for the two periods 1901–1940 and 1941–1980. We have used two periods to test the reproducibility of the correlations. The results are shown in Figures 5 and 6. Significantly correlated areas are shaded. Brinkmann (1979) has studied long-term relationships between the Northern Hemisphere temperature average and station data in a similar way.

The correlations are highest in the earlier period (Figure 5), particularly in the Arctic and over the North American continent. In the later period (Figure 6), the highest correlations are over Canada and the Arctic correlations are considerably reduced, especially in the North Atlantic sector. This suggests that the spatial coherency of the early period was greater, as was noted in the maps of the linear trend discussed earlier. It should be noted that even in the areas of highest correlation the percentage variance accounted for is only 10 to 30 per cent. Even this figure may be inflated by strong autocorrelation in both the gridpoint and average series.

Gavin and Kukla (personal communication, 17 Aug. 1982) have suggested that the greater spatial coherency of the earlier period may be due, at least in part, to the reduced station density during that period. This could have affected the spatial variability of the gridded data.

The regions significantly correlated with the Northern Hemisphere average in *both* periods are: north-western Siberia and the Kara Sea, western Greenland, the northern United States and southern Canada, and the central Mediterranean.

Various authors have noted similarities between the long time scale trends in NH and indirect or proxy climate data for certain regions: for example, Iceland (Bergthorsson, 1969), central England (Lamb, 1966), the south-western United States (LaMarche, 1974), and Greenland (Dansgaard *et al.*, 1971). (The references are to the original source of the proxy data where hemispheric representativeness was

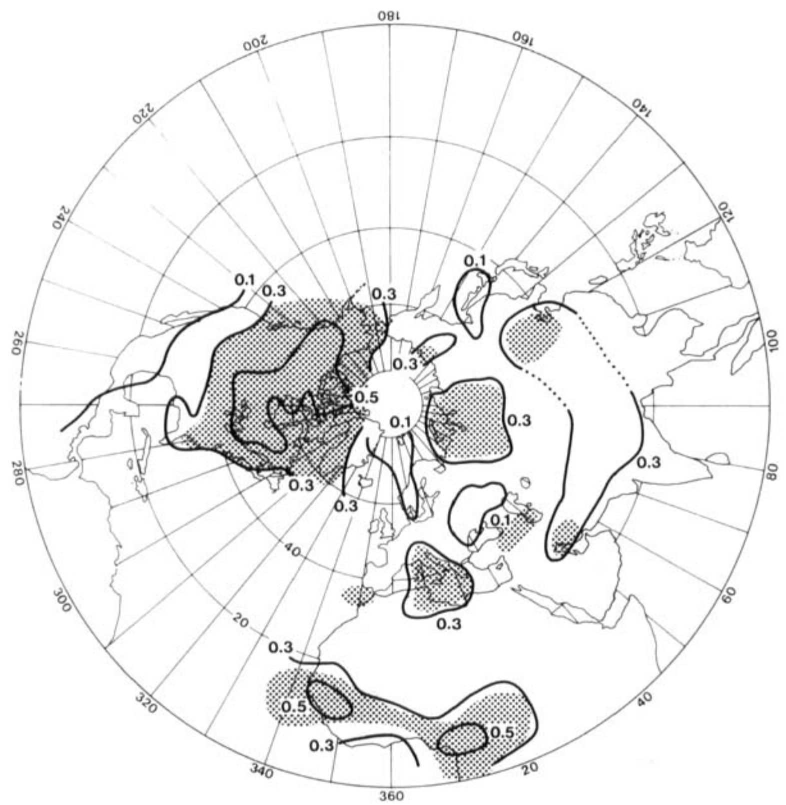

Figure 6. Correlations between the annual Northern Hemisphere temperature average and gridpoint temperature data, 1941–1980. Shaded areas are significant at the 5 per cent level

not necessarily claimed.) Some investigators have gone on to use these records as indicators for the hemisphere as a whole, either on the basis of similarities between recent trends in NH and the proxy climate records or on the basis of similarities between the trends in proxy records from different locations.

We note that this study has shown that none of the areas cited above has been consistently significantly correlated with NH during the present century and that even in the areas which are significantly correlated with NH the magnitude of the correlation (or percentage variance explained) is not high. It may well be that these results, representative of variations on time scales of 2 to around 50 years, are not immediately transferable to the longer time scales of the proxy climate data. Nevertheless, the lack of evidence of any consistent relationship on shorter time scales suggests that caution is desirable in interpreting apparent correlations between longer time scale variations in these and other spatially distant proxy climate records.

SEASONAL REPRESENTATIVENESS OF NH

We have so far only considered annually-averaged data. This averaging masks changes in the magnitude and timing of variations that occur in different months. How representative is the annual NH temperature average of individual months? We first consider the net temperature change between the two periods 1901–1940 and 1941–1980 that largely resulted from the strong warming of the early 20th century and then look in detail at the pattern of correlations between the annual data and the monthly data upon which the annual data are based. We consider both the Northern Hemisphere average and an Arctic (65–85°N) average (Kelly *et al.*, 1982); we have seen in earlier sections that the Arctic varies relatively coherently with the Northern Hemisphere average. In the following discussion, the Northern

Table I. Temperature differences, 1941–1980 average minus 1901–1940 averages

	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Northern Hemisphere													
ΔT, °C	0·12	0·17	0·14	0·10	0·23	0·19	0·12	0·03	0·06	0·06	0·14	0·03	0·14
σ (1901–1980)	0·22	0·48	0·49	0·36	0·32	0·27	0·25	0·22	0·22	0·25	0·35	0·37	0·48
$\Delta T/\sigma$, %	55	35	29	28	72	70	48	14	27	24	40	8	29
Arctic													
ΔT, °C	0·22	1·12	0·02	0·31	0·15	0·22	−0·12	−0·17	−0·09	−0·01	0·38	0·30	0·56
σ (1901–1980)	0·63	1·83	1·52	1·37	1·05	0·73	0·61	0·50	0·45	0·50	0·96	1·26	1·57
$\Delta T/\sigma$, %	35	61	1	23	14	30	−20	−34	−20	−2	40	24	36

Hemisphere average is abbreviated as 'NH' and the Arctic as 'A'. A suffix 'a' indicates annual data; 'm' indicates monthly data.

In Table I, the net warming between the periods 1901–1940 and 1941–1980 is shown. In NH_m, the warming was greatest in absolute magnitude in April (0·23°C), May (0·19°C) and January (0·17°C). The corresponding rise in NH_a was 0·12°C. The warming was least in November (0·03°C), July (0·03°C), August (0·06°C) and September (0·06°C). The standard deviation of NH_m is greatest in the winter months. Relative to the appropriate monthly standard deviations, the warming in April and May dominates. In A_m, the seasonal distribution is quite different. The warming between the two periods was greatest in January (1·12°C) and December (0·56°C). The warming in A_a was 0·22°C. Little change occurred in February (0·01°C) and cooling occurred during the months June to September. Even relative to the standard deviation, the January warming dominates the other months.

In Table II, we show correlations between NH_a, NH_m, A_a and A_m. Note that autocorrelation in certain months may have resulted in an artificial inflation of the correlation coefficients. Significance testing is not appropriate for these coefficients as all data are a subset of the same database. In the following discussion, bracketed values give the variance explained by a particular correlation (approximated in the case of more than one correlation).

The correlation between NH_m and NH_a is highest in the months of April to August (60 per cent) and lowest in February, March and November (30 per cent). Although the variability is greatest in winter (implying that winter months might be expected to contribute most to NH_a), the month-to-month correlation during late spring and summer is relatively high (Table II) and so these months, varying together, contribute heavily to NH_a. The year-to-year serial correlation is lowest in January, February, March and November. The month-to-month correlation is lowest for December to January.

The correlation between NH_m and A_a is low in January and February (10 per cent) and consistent throughout the remainder of the year (36 per cent). The correlation between NH_m and A_m (for the same month) is highest in May, June, September and October (56 per cent). It is lowest in February (16

Table II. Correlation coefficients (×100) between monthly and annual Northern Hemisphere and Arctic temperatures for the period 1901–1980 (NH = Northern Hemisphere, A = Arctic, a = annual, m = monthly. r_1 = lag one correlation coefficient)

	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
NH_a with NH_m	—	65	53	48	76	80	77	76	75	70	69	55	57
A_a with NH_m	77	34	29	39	57	59	55	60	56	58	64	55	54
NH_m with A_m	77	48	41	47	55	74	73	64	63	76	80	60	63
r_1(NH)	56	7	10	5	44	30	34	58	46	47	39	17	24
NH_m with NH_{m+1}	—	52	29	48	75	82	71	79	82	66	44	52	17
A_m with NH_a	77	60	33	27	45	60	59	47	40	52	56	53	48
A_m with A_a	—	66	55	60	65	62	60	51	40	60	68	73	64
r_1(A)	62	39	9	−3	26	24	34	27	15	35	25	17	31
A_m with A_{m+1}	—	18	36	47	47	54	55	55	45	57	44	58	36

per cent). The correlation between A_m and NH_a is highest in January, May, June and October (35 per cent) and lowest in February and March (0 per cent). The correlation between A_m and A_a is low in August but is relatively high throughout the rest of the year (36 per cent). The month-to-month correlations are also high throughout the year with the exception of January to February. This exception may be due to the strength of the long-term warming in January and its absence in February (see Table I). The year-to-year correlation in the monthly Arctic data is low in February, March, August and November.

We have also calculated these statistics for the two periods 1901–1940 and 1941–1980. While the general conclusions apply in both periods, the strength of the correlations is somewhat greater during the earlier period, again reflecting the strong warming during that period.

Underlying there statistics, there must be physical mechanisms conditioning the seasonal distribution of covariability. We note that the distribution of monthly correlations between A_m and NH_m (high in May, June, September and October and low in January to March), resembles the seasonal pattern of variability in high-latitude (north of 70°N) sea-ice conditions. The former are times of rapid ice clearance and formation; the latter is the time of southernmost advance of the ice and maximum cover in the Northern Hemisphere. The low variability in the Arctic during summer is related to the presence of melt-water and sea ice constraining temperatures to remain close to the freezing point.

The strength of the January warming in the Arctic during the periods 1901–1940 and 1941–1980 is probably related to the more frequent breakdown of wintertime surface inversions and the varying number of middle-latitude depressions entering the Arctic (Kelly *et al.*, 1982). The greatest input of energy to the Arctic due to cyclonic activity occurs in the Atlantic sector in January and February (Orvig, 1970). Seasonal general circulation models predict that the greatest sensitivity to increased atmospheric carbon dioxide will be in mid-winter in high latitudes (Cess, 1982).

The fact that over the hemisphere as a whole the warming was strongest in April and May is of particular interest and suggests a link with the duration of snow and ice cover over middle to high latitudes. This time of year is notable for the rapid transition from winter to summer conditions in high latitudes when marked changes in the energy balance occur as the snow and ice cover disappears. It is also the time of the year when seasonal energy balance models predict that the effects of increased atmospheric carbon dioxide should be greatest (Cess, 1982). Kukla and Gavin (1981a, 1981b) have observed a similar link between seasonal temperature variations and the snow and ice margin.

It would be unwise to speculate further. Parallel analysis of other climate and climate-linked data sets is needed to throw light on the physical mechanisms underlying these statistics.

CONCLUSIONS

We have shown here and elsewhere (Jones and Kelly, 1981, 1982, Kelly *et al.*, 1982) that the use of annual large-scale averages for the Northern Hemisphere masks much detail concerning the spatial patterns and the seasonal timing of changes in surface air temperature. As van Loon and Williams (1976), Barnett (1978) and others have pointed out, this detail is needed to throw light on the underlying physical mechanisms. Spatial and temporal detail is also needed to assess the societal impact of climatic change and the representativeness of proxy climatic reconstructions based on data for a limited geographical region or time of year.

The reliance on the annual Northern Hemisphere average in many studies of recent climatic change is unfortunate, reflecting more, we believe, its convenience than its value as a physical parameter. As Lamb (1972) has pointed out, the science of climatology has developed rapidly in recent decades due to, *inter alia,* increased awareness of the significance of climatic change. While this has resulted in the elevation of climatology from the 'statistical (and, it was thought, dullest) branch of meteorology' (Lamb, 1972, p. xxv) to a physical science in its own right, the analysis and considered interpretation of descriptive statistics remain important areas of concern and have, perhaps, been unjustifiably neglected in recent years. We have noted instances where commonly held beliefs concerning the character of variations in Northern Hemisphere temperatures have not been confirmed or, indeed, have been contradicted by our analyses.

Theoretical and modelling studies of climate and climatic change must be underpinned by simple statistical exercises such as described above if climatologists are not to lose sight of the real world. For example, the apparent contradiction between the predictions of general circulation and energy balance models concerning the likely seasonal distribution of temperature change caused by atmospheric carbon dioxide increases is reflected in reality by the different seasonal distribution of past long-term temperature trends for the Arctic and for the hemisphere as a whole.

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