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TEMPORAL AND SPATIAL VARIATION OF SURFACE AIR TEMPERATURE OVER THE PERIOD OF INSTRUMENTAL OBSERVATIONS IN THE ARCTIC

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ABSTRACT

A detailed analysis of the spatial and temporal changes in mean seasonal and annual surface air temperatures over the period of instrumental observations in the Arctic is presented. In addition, the role of atmospheric circulation in controlling the instrumental and decadal-scale changes of air temperature in the Arctic is investigated. Mean monthly temperature and temperature anomalies data from 37 Arctic, 7 sub-Arctic and 30 grid-boxes were used for analysis.

The presented analysis shows that the observed variations in air temperature in the real Arctic (defined on the basis of climatic as opposed to other criteria, e.g. astronomical or botanical) are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect. The highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s and can be attributed to changes in atmospheric circulation. The second phase of contemporary global warming (after 1975) is, at most, weakly marked in the Arctic. For example, the mean rate of warming for the period 1991–1995 was 2–3 times lower in the Arctic than the global average. Temperature levels observed in Greenland in the last 10–20 years are similar to those observed in the 19th century.

Increases of temperature in the Arctic are more significant in the warm half-year than in the cold half-year. This seasonal pattern in temperature change confirms the view that positive feedback mechanisms (e.g. sea-ice–albedo–temperature) as yet play only a small role in enhancing temperature in the Arctic. Hypotheses are presented to explain the lack of warming in the Arctic after 1975.

It is shown that in some parts of the Arctic atmospheric circulation changes, in particular in the cold half-year, can explain up to 10–50% of the temperature variance. For Arctic temperature, the most important factor is a change in the atmospheric circulation over the North Atlantic. The influence of atmospheric circulation change over the Pacific (both in the northern and in the tropical parts) is significantly lower. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: Arctic; temporal and spatial changes; time series analysis; instrumental period; atmospheric circulation

1. INTRODUCTION

Intensification of contemporary global warming in recent decades with the enhancement of the greenhouse effect (Houghton *et al.*, 1990, 1992, 1996) has caused a marked rise of interest in year-to-year and decadal-scale climate variability. The Polar Regions, according to both observations and climate model simulations, are most sensitive and vulnerable to climatic changes. As a result, warming and cooling epochs should be seen most clearly here and should also occur earlier than in other parts of the world (e.g. Polar Group, 1980; Jäger and Kellogg, 1983). The amplification of greenhouse-induced warming in the Polar Regions should result from several positive feedbacks, including the following: ice and snow melt leading to decreases in surface albedo, atmospheric stability trapping temperature anomalies near to the surface, and cloud dynamics magnifying change (Houghton *et al.*, 1990; Chapman and Walsh, 1993). As a result, the Polar Regions should play a very important role in the detection of global changes.

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Moreover, these changes are significantly easier to measure in the Arctic than in other regions because sea-ice, snow cover, glaciers, tundra and permafrost are all very sensitive indicators of global climate changes.

However, the second phase of contemporary warming (after 1975) that is common in most parts of the world appears to be very weakly expressed or even absent in the Arctic, as defined in *Atlas Arktiki* (1985) (see e.g. Hanssen-Bauer *et al*., 1990; Nordli, 1990; Chapman and Walsh, 1993; Kahl *et al*., 1993a,b; Walsh, 1993; Przybylak and Usowicz, 1994; Karl *et al*., 1995; Weber, 1995; Born, 1996; Przybylak, 1996a, 1997a,b; Forland *et al*., 1997; Martin *et al*., 1997; Radionov and Aleksandrov, 1997; Zukert and Zamolodchikov, 1997). Similar situations are also evident over Iceland (Einarsson, 1991) and over Antarctica (Jones, 1995). The existing discrepancy between global and polar air temperature courses is one of the most intriguing issues for climatologists to resolve. It also means that the temperature predictions produced by numerical climate models significantly differ from those actually observed. The magnitude of these differences is very difficult to estimate because temperature projections, e.g. for the Arctic, using different general circulation models (GCMs), show wide variations (see e.g. Cattle, 1992; Walsh and Crane, 1992; Bromwich *et al*., 1994, 1995; Chen *et al*., 1995; Tao *et al*., 1996).

Curry *et al*. (1996) give three reasons for the current deficiencies of climate models concerning the description of the Arctic climate (after Rinke *et al*., 1997a,b): (i) The models show inadequacies in the parameterization of physical processes. Typical Arctic phenomena, e.g. the summertime stratus, ice crystal clouds and 'Arctic haze' have not been taken into account. (ii) The present GCMs are characterized by a coarse horizontal resolution and, therefore, they have not captured different mesoscale phenomena. (iii) Errors in the Arctic large-scale dynamics can arise from problems that are a consequence of the insufficient description of low-latitude processes.

The present paper has two main aims. The first is to present the temporal variations in surface air temperature (hereafter temperature) over the whole period of instrumental observations in the Arctic and its spatial changes in the shorter period 1951–1995, for which the network of stations is sufficient to conduct such investigations. The second is to estimate the role of atmospheric circulation in controlling the interannual and the decadal-scale changes of Arctic air temperatures. Atmospheric circulation is one of the most important factors influencing the Arctic climate, which has undergone significant changes in recent decades (see e.g. Serreze and Barry, 1988; Serreze *et al*., 1993, 1997; Kożuchowski, 1993; Schinke, 1993; Jönsson and Bärring, 1994; Trenberth and Hurrell, 1994; Hurrell, 1995, 1996; Trenberth, 1995; Maslanik *et al*., 1996; Przybylak, 1996a, 1999).

2. LITERATURE REVIEW

The Arctic climate first attracted serious study in the 19th century. At the end of that century (1882/1883) the First International Polar Year was organized. This event is widely considered to mark the beginning of systematic climatic investigations in the Arctic (Dolgin, 1971). Scientists of that epoch assumed correctly that the Arctic played a very important role in shaping global weather patterns. Meteorological investigations conducted following the Polar Year, although initially only during expeditions, confirmed this view. Strong interest in the Arctic climate has persisted throughout the 20th century, resulting in the publication of a considerable number of papers analysing different aspects of Arctic climate. The majority of these papers, however, are local studies presenting highly localized information, providing air temperature measurements but often little else.

Despite the large quantity of literature on Arctic climate, short-term climatic fluctuations in the Arctic have received surprisingly little attention (Aleksandrov *et al*., 1986; Walsh and Chapman, 1990; Przybylak, 1996a). Only a few works analyse this problem for the Arctic as a whole. The most widely cited work is that of Vowinckel and Orvig (1970), which provides very little information. More information is included in Walsh and Chapman (1990), Chapman and Walsh (1993), Kahl *et al*. (1993a,b) and Przybylak (1996a,b, 1997a). The most comprehensive and detailed analysis was published by Przybylak (1996a). The present paper is an updated version of elements of that work. Significantly more papers are devoted to the analysis of the areal average Arctic temperature (the Arctic being defined according to various criteria which are presented in the next section) (Rubinshtein, 1973, 1977; Kelly and Jones, 1981a,b,c,d, 1982; Kelly *et al*., 1982; Jones, 1985, 1995, personal communication; Alekseev and Svyashchennikov, 1991; Dmitriev, 1994).

It is worth mentioning two very interesting works reconstructing the areal average 'Arctic' temperature based on proxy data, i.e. tree ring records (D'Arrigo and Jacoby, 1993) and lake sediment, marine sediment, ice core and tree ring records (Overpeck *et al*., 1997). However, the areas categorized as Arctic in these analyses significantly differ from the Arctic as defined using climatic criteria. In the work by D'Arrigo and Jacoby (1993), almost all proxy temperature records were taken from outside of the Arctic. In the Overpeck *et al*. (1997) case, the same concern may be raised with respect to the tree ring records which are dominant among the used proxy records (62%). Other records (except one) are situated in the real Arctic but mainly in the eastern part of the Canadian Arctic and in (and around) Greenland (see their figure 1). It is worth noting that in recent decades this part of the Arctic has shown an opposite tendency in air temperature variability to the rest of the Arctic (see Chapman and Walsh, 1993 or Przybylak, 1996a, 1997a). Based on these facts, I cannot agree with the use of the term Arctic for these reconstructed palaeoclimatological series.

The majority of the works analysing contemporary climatic fluctuations in the Arctic are restricted to specific sites or areas (e.g. Scherhag, 1931, 1937, 1939; Hesselberg and Birkeland, 1940, 1941, 1943; Vize, 1940; Weickmann, 1942; Groissmayer, 1943; Ahlmann, 1948; Lysgaard, 1949; Stepanova, 1956; Hesselberg and Johannessen, 1958; Petrov, 1959; Bolotinskaya, 1961; Thomas, 1961; Prik, 1968; Steffensen, 1969, 1982; Putnins, 1970; Bradley and Miller, 1972; Bradley, 1973a,b; Markin, 1975; Zakharov, 1976; Bradley and England, 1978; Higuchi, 1980; Maxwell, 1980, 1981; Berry, 1981; Brázdil, 1988; Frydendahl, 1989; Kamiński, 1989; Hanssen-Bauer *et al*., 1990; Nordli, 1990; Przybylak and Usowicz, 1993, 1994; Findlay *et al*., 1995; Forland *et al*., 1997).

Some information relating to short-term climatic fluctuations in the Arctic is also present in studies which describe the climate of greater areas, e.g. of the Northern Hemisphere or the globe as a whole (e.g. Yamamoto, 1980; Jones and Kelly, 1983; Jones *et al*., 1986, 1988; Parker and Folland, 1988; Karoly, 1989; Alekseev and Svyashchennikov, 1991; Kukla *et al*., 1992; Parker *et al*., 1994). This information is, however, very strongly generalized and rarely offers the possibility of estimating spatial variations of Arctic air temperatures.

Summarizing these works, it can be stated that there exists an agreement in estimating temperature tendencies prior to 1950. Practically all (old and new) of the papers which cover this time period concentrate on the analysis of the significant warming which occurred in the Arctic from 1920 to about 1940. The greatest rise of temperature occurred in the Atlantic region. Estimates of the areal average Arctic temperature trend in the second half of the 20th century are inconsistent. Most probably, this is related to different periods being used for computing trends and also to different areas being included as part of the Arctic (see below).

3. STUDY AREA, DATA AND METHODS

There is no agreed southern border to the Arctic. The three most widely used criteria are astronomical, climatological and botanical (see Baird, 1967; Petrov, 1971; Jahn, 1977; Przybylak, 1996a). Astronomically, the Arctic Circle forms the southern limit. In this case, the Arctic encompasses not only the real Arctic but also, on occasion, very large areas which are situated in sub-Arctic or even temperate latitudes. Nevertheless, the majority of investigators adopt a modified astronomical criterion. Researchers most often define the Arctic as that area situated above 60°N (Walsh, 1977, 1978; Yeserkepova *et al*., 1982; Aleksandrov and Subbotin, 1985; Subbotin, 1985; Jones, 1995, personal communication), 65°N (Kelly and Jones, 1981a,b,c,d, 1982; Jones, 1985; Alekseev and Svyashchennikov, 1991) or 70°N (Dmitriev, 1994).

This approach, whilst convenient for computer analyses, is a source of error when the areal average Arctic temperature is computed. In this sense, use of the astronomical criterion is methodologically incorrect. For example, when using this approach data analyses can report different, even opposite, estimates of temperature tendencies for the last 40–45 years. This occurs because of significantly different trends between the northern mid-latitudes on the one hand and the real Arctic on the other, in relation to contemporary global warming (see e.g. figures 1 and 2 in Chapman and Walsh, 1993).

It is surprising that contemporary climatologists very rarely use the climatic criterion to define the limits of the Arctic. The most generally adopted climatic criterion is the 10°C isotherm of the warmest month, which was first proposed by Supan (1884) in his climatic classification and later popularized by Köppen (1900, 1918, 1936). This criterion, whilst preferable to astronomically-derived criteria, is still not perfect in that, for example, it does not take into account the winter temperatures, despite the fact that this is the longest season in the Arctic. Some proposals to reduce this weakness were put forward by Nordenskiöld and more recently by the authors of the *Atlas Arktiki* (1985). This latest proposal is the most satisfactory one known to this author. The southern Arctic border has been delimited using mean multiyear values of almost all-meteorological elements. In addition, the authors of the Atlas have also distinguished seven climatic regions within the Arctic (see Figure 1). These facts have persuaded the adoption of 'their' definition of the Arctic for the analysis presented here, in order to ensure that the areas identified represent the most realistic Arctic climate.

The instrumental record of Arctic temperature is brief and geographically sparse. Only five records (Upernavik: date of start 1874; Jakobshavn: 1874; Godthåb: 1876; Ivigtut: 1880; and Angmagssalik: 1895) extend back to the second half of the 19th century. As can be seen, all climatic stations operating during the 19th century were located in Greenland. Outside of Greenland, the first station was established in Spitsbergen in 1911 (Green Harbour). In the 1920s, the next seven stations came into operation, mainly in the Atlantic region of the Arctic. Following the Second Polar Year (1932/1933) most Russian stations were established, while most Canadian stations were founded after World War II. For this reason, the spatial distribution in addition to reliable estimates of air temperature characteristics in the Arctic are only possible for the last 40–50 years.

Mean monthly temperatures of 37 Arctic and seven sub-Arctic stations, as well as temperature anomalies (computed as deviations from 1961–1990 mean) of 30 grid-boxes (5° × 5°), were available for analysis. The majority of the station-generated data come from national Meteorological Institutes (Danish Meteorological Institute, Norwegian Meteorological Institute and Canadian Climate Centre) or other institutions (Arctic and Antarctic Research Institute at St. Petersburg and National Climatic Data Center at Asheville). The grid-box data were taken from Jones (1994, updated). Only 30 grid-boxes located in the Arctic have complete and reliable temperature data suitable for use in the analysis. Their spatial distribution in the Arctic is, however, very irregular (see Figure 1). Most of the grid-boxes (two to three of them) in the Arctic are located in the sector 0°W–120°W and are thus in Canadian Arctic and Greenland. Siberia is poorly covered with only one series available. On the other hand, the Arctic stations show good spatial distribution (see Figure 1). Therefore, the temperature data from these stations provides the only data that can be used to compute areal average Arctic temperature as well as other temperature characteristics.

The data quality control for these stations is briefly described in earlier works (Przybylak, 1996a, 1997a). Przybylak (1996a) also provides more detailed information relating to data sources.

Atmospheric circulation changes on a regional scale are usually investigated using so called circulation indices, computed as a pressure difference between two different sites (or zones) characterizing high and low pressure systems. The most often used indices are as follows: the zonal index (ZI), the North Atlantic Oscillation Index (NAOI), the North Pacific Index (NPI) and the Southern Oscillation Index (SOI). All of these indices have been used to investigate the influence of atmospheric circulation on Arctic temperature. The index series were taken from the following sources: ZI from Kożuchowski (1993), NAOI from Hurrell (1995) and Jones *et al.* (1997), NPI from Trenberth and Hurrell (1994) and Trenberth (1995), and SOI from Ropelewski and Jones (1987, updated).

Year-to-year variability in air temperature in the Arctic has been investigated using seasonal (December, January, February etc.) and annual means. Linear trends for different periods have been computed both for area average air temperature (for the whole Arctic and each region) and for each station. The

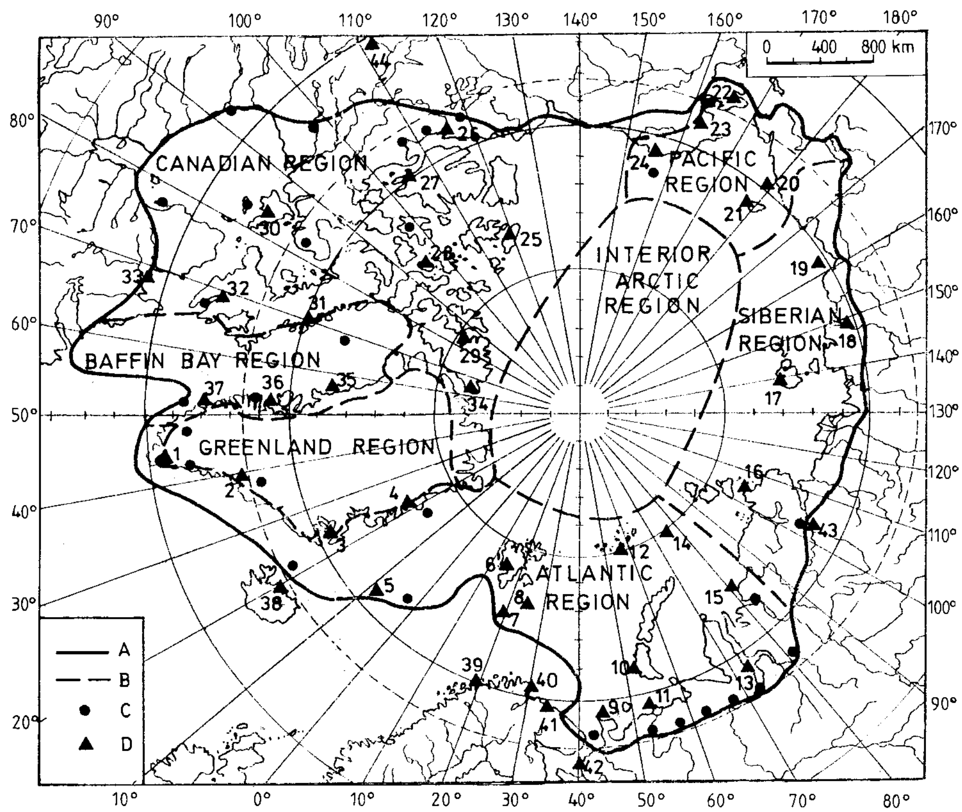

Figure 1. Location of meteorological stations and central parts of the grid-boxes used. Key—A: the border of the Arctic after *Atlas Arktiki* (1985); B: the borders of the climatic regions; C: central part of grid-boxes; and D: meteorological stations

1 Prins Christian Sund (height above sea level, H = 76 m)
2 Angmagssalik (H = 35 m)
3 Kap Tobin (H = 41 m)
4 Danmarkshavn (H = 11 m)
5 Jan Mayen (H = 10 m)
6 Svalbard Lufthavn (H = 28 m)
7 Björnöya (H = 15 m)
8 Hopen (H = 6 m)
9 Kanin Nos (H = 49)
10 Malye Karmakuly (H = 46 m)
11 Naryan-Mar (H = 7 m)
12 Polar GMO E.T. Krenkelya (H = 20 m)
13 Mys Kamenny (H = 7 m)
14 Ostrov Vize (H = 18 m)
15 Ostrov Dikson (H = 20 m)
16 GMO E.K. Fedorova (H = 13 m)
17 Ostrov Kotelny (H = 10 m)
18 Chokurdakh (H = 48 m)
19 Ostrov Chetyrekhstolbovoy (H = 6 m)
20 Mys Szmidta (H = 7 m)
21 Ostrov Vrangel (H = 3 m)
22 Nome (H = 11 m)
23 Kotzebue (H = 5 m)
24 Barrow (H = 4 m)
25 Mould Bay (H = 15 m)
26 Coppermine (H = 24 m)
27 Cambridge Bay (H = 27 m)
28 Resolute A (H = 67 m)
29 Eureka (H = 10 m)
30 Coral Harbour A (H = 64 m)
31 Clyde A (H = 25 m)
32 Iqaluit A (H = 34 m)
33 Kuujjuaq (H = 37 m)
34 Alert (H = 63 m)
35 Upernavik (H = 63 m)
36 Jakobshavn (H = 47 m)
37 Godthåb (H = 20 m)
38 Akureyri (H = 27 m)
39 Tromsö (H = 10 m)
40 Vardo (H = 15 m)
41 Murmansk (H = 46 m)
42 Arkhangelsk (H = 13 m)
43 Khatanga (H = 24 m)
44 Forth Smith A (H = 203 m)

significance of computed trends was checked using the Student's t-test. Recent changes in temperature in the Arctic were investigated using data from the pentad 1991–1995. Pentad anomalies of seasonal and annual air temperatures, using the 1951–1990 mean, were computed for each station, each region and for the whole Arctic. All analysed characteristics of the air temperature (trends and anomalies) in the Arctic are presented in the form of maps. The isolines have been drawn using simple mathematical interpolation.

The relationships between atmospheric circulation and temperature in the Arctic have chiefly been investigated using correlation analysis. For certain indices, mean seasonal and annual temperature differences between sets of years with the highest and lowest values of indices have been computed and presented in maps.

4. RESULTS AND DISCUSSION

4.1. Temperature variations over the period of instrumental observations

It is clear from the previous section that a reliable estimate of areal average Arctic temperature can only be offered since circa 1950. Nonetheless, in the literature many works can be found which also provide an areal average 'Arctic' temperature for earlier years (e.g. Kelly and Jones, 1981a,b,c,d, 1982; Kelly *et al.*, 1982; Jones, 1985; Alekseev and Svyashchennikov, 1991; Dmitriev, 1994). 'Arctic' is used here in inverted commas because, in reality, these series represent the temperature changes in selected northern latitude bands which, as stated above, significantly differ from the Arctic as defined in this paper. Until 1911 the only Arctic stations for which it has been possible to compute these series were located in Greenland. Other data used in these analyses were taken from stations located in the sub-Arctic and even mid-latitudes. Moreover, station coverage of these regions was very low, especially in 19th century, and was biased toward lower latitudes. For example, Jones (1985) states that the 'Arctic' temperature was computed from grid points (5° × 10°) covering only 6%, 10% and 20% of the latitude band 65°N–85°N in the years 1851, 1874 and at the end of 19th century, respectively. This author opposes the definition of such series as 'Arctic' because such definitions lead inevitably to the identification of misleading estimates of Arctic air temperature tendencies. This is very well illustrated in Figure 2, from which it is seen that a warming in the 1930s was most pronounced in the real Arctic (see the top curve which represents in the greatest degree the real Arctic). This warming is reduced when more areas from the sub-Arctic and from the mid-latitudes are included in the Arctic. The second phase of contemporary warming (after 1975) in the real Arctic series is not seen, while in the other series it is distinct. For the whole Northern Hemisphere (bottom curve), the warming in the last decades is even greater than in the 1930s.

Because the role of the Arctic climate system in the global climate is very important, scientists should strive to adopt a common definition of the southern border of the Arctic as soon as possible. It is clear that climatic criteria should be used for this purpose. The proposition presented in *Atlas Arktiki* (1985) appears to be the best to be put forward in recent years. The line of the border (see Figure 1) is highly irregular, which makes it inconvenient for certain computer analyses, but such a definition of the Arctic allows one to find realistic climatic tendencies in areas sharing similar climatic features. Furthermore, knowledge of real climatic tendencies is crucial in the search for the physical processes which govern these changes and in verifying the reliability of present Arctic climate simulations, based on general circulation models.

4.2. Temperature variations prior to 1950

Six stations have been chosen to illustrate the variation of Arctic air temperatures prior to 1950 (Figure 3). All of them represent the analysed climatic regions and offer long series. Figure 3 shows slightly rising temperatures in Greenland prior to 1920. After this time, the rate of warming significantly increases. This trend was noticed very early in Greenland and the Atlantic Arctic region and was described by various authors (e.g. Knipovich, 1921; Scherhag, 1931, 1937, 1939; Hesselberg and Birkeland, 1940; Vize, 1940;

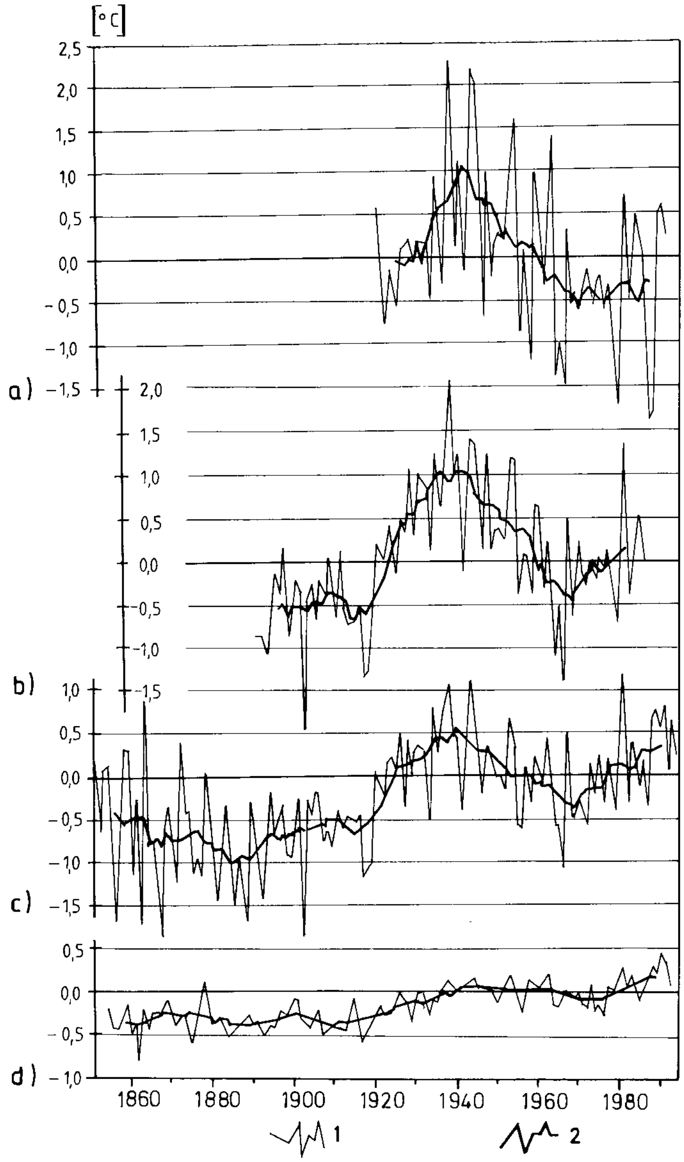

Figure 2. Year-to-year course of the annual (1, solid line) and 5-year running (2, heavy solid line) mean anomalies of air temperature for the zones (after Przybylak, 1996a): (a) 70°N–85°N (after Dmitriev, 1994); (b) 65°N–85°N (after Alekseev and Svyashchennikov, 1991); (c) 60°N–90°N (after Jones, 1995, personal communication); (d) 0°N–90°N (after Jones, 1994)

Weickmann, 1942; Lysgaard, 1949). The maximum temperature occurred in the 1930s and was higher by about 2–5°C than those occurring prior to the 1920s. The most pronounced rise in temperature occurred in the Atlantic region and in the whole Arctic in winter. In this season, the mean temperature rose locally by up to 9°C (Przybylak, 1996a). Since the 1930s, a statistically significant decrease of temperature has been noted.

All stations (except Barrow and Coppermine, representing only a small part of the Arctic) show the greatest warming in the 1930s. The reason most often given for this warming wave is a change in atmospheric circulation (see e.g. Scherhag, 1931; Weickmann, 1942; Petterssen, 1949; Lamb and Johnsson, 1959; Girs, 1971; Lamb, 1977; Lamb and Morth, 1978; Kononova, 1982). A secondary maximum can be seen in the central part of the Atlantic region (Svalbard Lufthavn) in the 1950s and in Greenland in the

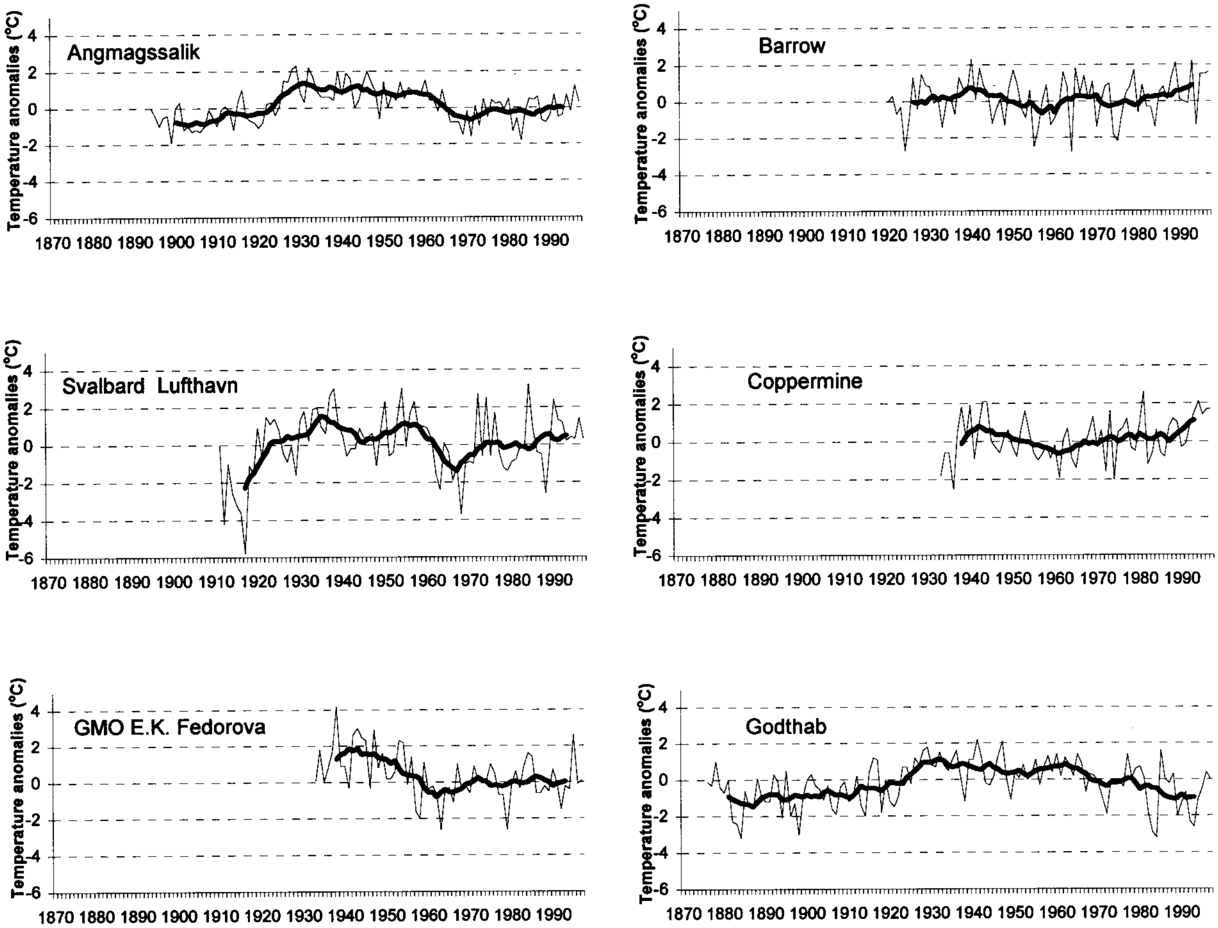

Figure 3. Year-to-year course of the annual (solid line) and 5-year running (heavy solid line) mean anomalies of air temperature in the Arctic stations having the longest observational series

1960s. This is not present in the Siberian region. Spatial coherency in Arctic temperature changes was significantly greater prior to the 1950s than afterwards (see Figure 3). Besides the two factors mentioned previously, this feature has probably also impeded the similar estimates of areal average Arctic temperature trends by various researchers.

4.3. Temperature variations after 1950

In the context of global warming it is very important to estimate both the trends in areal average Arctic temperature and the spatial pattern of temperature trends in the area studied. Figure 4 presents mean seasonal and annual anomalies of Arctic temperature over the period 1950–1995, computed using data from 33 to 35 stations. Based on running averages, the highest temperatures were in the 1950s and the lowest in the 1960s. Since the mid-1970s, the annual temperature shows no clear trend (see also Table I). In Greenland, the temperature levels are even similar to those of the 19th century (see Figure 3). Seasonal temperatures are characterized by downward (winter and autumn) or upward (summer and spring) trends. It is important to note that, thus far, the 1990s have shown a large decrease of air temperature in winter and a smaller decrease in autumn. For the period 1950–1995, the downward trend is noted in winter, autumn and for the year. A small increase of air temperature has occurred in summer and spring. None of these trends, however, is statistically significant (Table I).

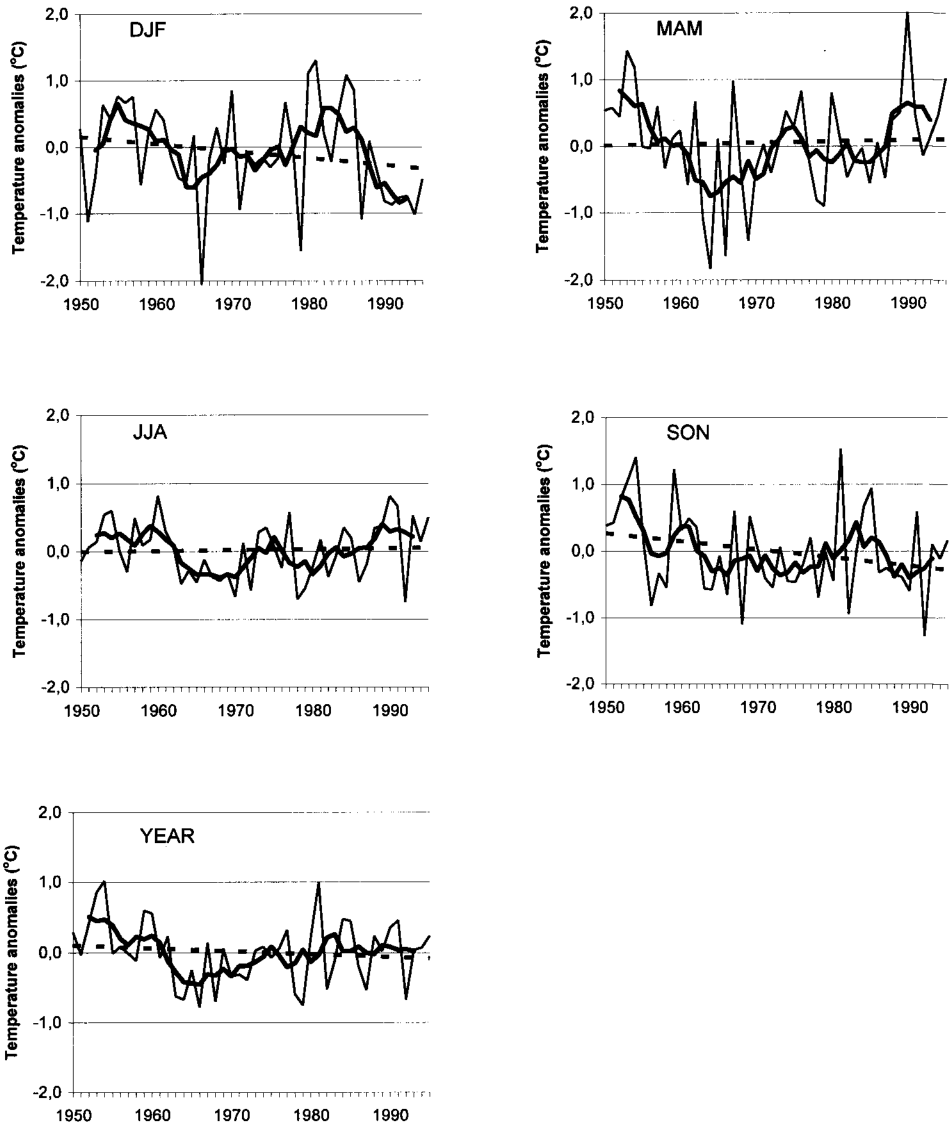

Figure 4. Year-to-year courses of mean seasonal and annual anomalies of air temperature and their trends in the Arctic over the period 1950–1995 (based on data from 33 to 35 stations). Key: solid lines = year-to-year courses, heavy solid lines = running 5-year mean, and dashed lines = linear trends

The areal average seasonal and annual Arctic temperatures have also been computed using data from 30 grid-boxes located in the study area (see Figure 5). This data set, however, represents the Arctic without almost the entire Siberian region. In addition, one should add that the quality of this type of data in its present state is significantly lower than the station data used in this work. In contrast to grid-box data, the temperature series from stations have no gaps. Taking these factors into account, identification of characteristics of Arctic temperature variations should still be based on stations' data.

A comparison of Figures 4 and 5 indicates that the general patterns of seasonal and annual Arctic temperature variation are roughly similar. The greatest differences occur in winter and autumn. Correlation coefficients computed between these series entirely confirm these conclusions. The highest correlation was found for summer ($r = 0.90$) and spring ($r = 0.82$), and the lowest for winter ($r = 0.55$) and autumn ($r = 0.66$). For the annual values, the correlation coefficient is equal to 0.74. All these correlations are statistically significant at the level of 0.001.

Table I. Seasonal (December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON)) and annual air temperature trends (°C per 10 years) in the Arctic

Station	1951–1995					1976–1995				
	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
Angmagssalik	−0.17	−0.35*	−0.25**	−0.01	−0.21*	−0.04	−0.28	−0.09	0.53	−0.01
Danmarkshavn	0.01	0.05	0.05	−0.13	−0.02	0.29	−0.30	0.30	0.29	0.08
Jan Mayen	−0.05	0.16	0.08	−0.15	0.01	0.94	0.47	0.32	0.60	0.54
Svalbard Lufthavn	−0.12	0.36	0.10	−0.36	−0.01	1.08	1.46	0.43	−0.53	0.51
Björnöya	−0.05	0.34	0.09	−0.27	0.02	1.32	0.98	0.21	−0.36	0.44
Hopen	−0.35	0.38	0.12	−0.40	−0.06	1.04	1.76	0.53	−0.69	0.68
Kanin Nos	0.10	0.32	−0.12	−0.04	0.06	1.67	1.37*	0.44	0.13	0.93*
Naryan Mar[a]	0.64	1.16**	0.17	−0.06	0.45*	1.77	2.12*	1.11	−0.91	1.05
Polar GMOE.T. Krenkelya[a]	0.55	0.63*	0.02	−0.19	0.23	0.54	1.14	0.18	−0.63	0.30
Ostrov Vize	−0.58	0.14	−0.06	−0.44	−0.24	−0.19	1.01	0.02	−0.55	0.16
Ostrov Dikson	0.13	0.39	−0.18	0.04	0.09	0.26	1.72*	−0.03	−0.32	0.46
GMO E. K. Fedorova	−0.02	0.28	−0.04	−0.24	−0.01	0.01	1.34	0.18	−0.29	0.38
Ostrov Kotelny	0.17	0.17	0.01	−0.12	0.07	0.24	0.98	0.31	0.77	0.69
Ostrov Chetyrekhstolbovoy	0.11	0.02	0.01	0.30	0.17	0.65	1.54*	0.14	2.28*	1.47**
Mys Szmidta	0.14	0.11	0.15	0.02	0.10	−0.13	1.33	0.40	0.38	0.50
Nome	0.61	0.43	0.34**	−0.00	0.36*	−0.85	0.68	−0.03	−0.94	−0.30
Kotzebue	0.92**	0.01	0.31*	0.03	0.32*	−0.37	−0.28	−0.13	−1.06	−0.52
Barrow	0.59	0.36	0.22	−0.28	0.22	0.29	1.67**	0.54	−0.95	0.30
Mould Bay	0.31	0.19	0.04	−0.03	0.12	−0.24	1.93	0.49	0.31	0.59
Coppermine	0.62*	0.32	0.34*	−0.12	0.28*	0.18	1.33	1.23*	−0.62	0.45
Cambridge Bay	0.52*	0.26	0.09	0.04	0.20	0.16	0.53	1.26	0.30	0.44
Resolute A	0.04	−0.03	−0.11	0.04	−0.01	−0.96	0.82	0.40	0.63	0.18
Eureka	−0.19	−0.11	−0.06	0.03	−0.08	−1.07	1.57	0.44	2.04**	0.74
Coral Harbour A	−0.22	−0.54*	0.04	0.04	−0.16	−1.53	−0.22	0.53	0.14	−0.32
Clyde A	−0.54	−0.55**	−0.02	−0.14	−0.31*	−3.23**	−1.14	0.90*	0.08	−0.86
Iqaluit A	−0.75	−0.70**	−0.03	0.05	−0.34*	−2.59	−1.29	0.26	0.71	−0.72
Kuujjuaq	−0.75*	−0.46*	−0.07	−0.07	−0.32*	−2.46	−0.60	0.27	0.64	−0.51
Alert	−0.02	0.07	−0.03	0.08	0.02	−0.84	1.42	0.53	1.34*	0.59
Egedesminde	−0.81	−0.62**	−0.18*	−0.06	−0.39**	−3.71*	−2.25**	−0.03	0.32	−1.41*
Godthåb	−0.70*	−0.75***	−0.35***	−0.19	−0.48***	−2.45	−1.28*	−0.32	0.15	−0.97
Atlantic region	−0.19	0.19	−0.06	−0.24	−0.07	0.82	1.14	0.27	−0.20	0.52
Siberian region	0.15	0.15	−0.17	−0.04	0.04	0.41	1.15	−0.30	0.64	0.60
Pacific region	0.55**	0.31	0.36***	−0.02	0.31**	0.02	1.36	0.74*	−0.22	0.43
Canadian region	−0.06	−0.11	0.02	+0.00	−0.03	−1.04	0.62	0.60*	0.59	0.16
Baffin Bay region	−0.66	−0.65***	−0.19*	−0.13	−0.40**	−3.03*	−1.52*	0.22	0.18	−1.04
Arctic 1	−0.10	0.04	0.01	−0.12	−0.04	−0.63	0.46	0.30	−0.10	0.06
Arctic 2	0.01	0.06	0.04	−0.04	0.02	−0.17	0.27	0.46*	−0.09	0.02
NH (land+ocean)	0.08**	0.08***	0.04	0.04	0.06**	0.30**	0.25***	0.24***	0.18*	0.24***

* Trends statistically significant at the level of 0.05.
** Trends statistically significant at the level of 0.01.
*** Trends statistically significant at the level of 0.001.
[a] Data for 1958–1995.
Arctic 1: area average temperature based on data from 33 to 35 Arctic stations (see Figure 1); Arctic 2: area average temperature based on data from 30 grid-boxes (source: Jones, 1994, updated); NH (land+ocean): area average temperature for Northern Hemisphere (source: Jones, 1994, updated).

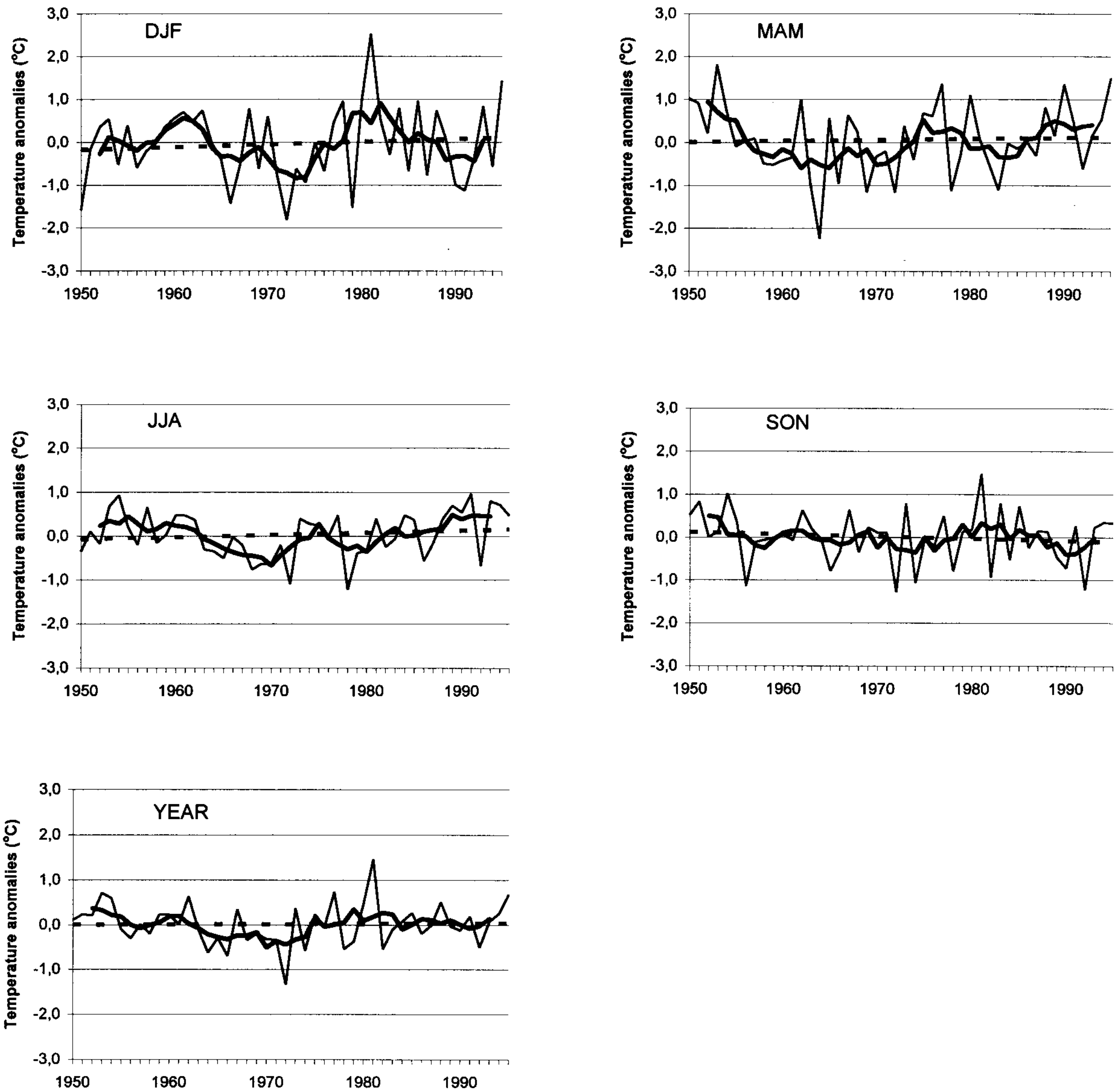

Figure 5. Year-to-year courses of mean seasonal and annual anomalies of air temperature and their trends in the Arctic over the period 1950–1995 (based on data from 30 grid-boxes after Jones, 1994, updated). Key: solid lines = year-to-year courses, heavy solid lines = running 5-year mean, and dashed lines = linear trends

The analysis of Table I and Figure 6 shows that the greatest temperature changes over the analysed period occurred in the Pacific and the Baffin Bay regions. In the Pacific region, statistically significant warming was observed in winter, summer and for the year as a whole. An opposite tendency was observed to have occurred in the Baffin Bay region in all seasons, with statistically significant cooling in spring, summer and for the year (Table I). Weak negative trends in areal annual average temperature also occurred in the Atlantic and Canadian regions. On the other hand, analysis of data for the Siberian region reveals little warming. In the last 20 years, when the mean Northern Hemisphere temperature shows a statistically significant positive trend in all seasons, most Arctic climatic regions (except the Baffin Bay region) reveal small and statistically insignificant increases of average annual temperature (Table I). Seasonal trends are mostly statistically insignificant. Significant warming occurred only in summer in the

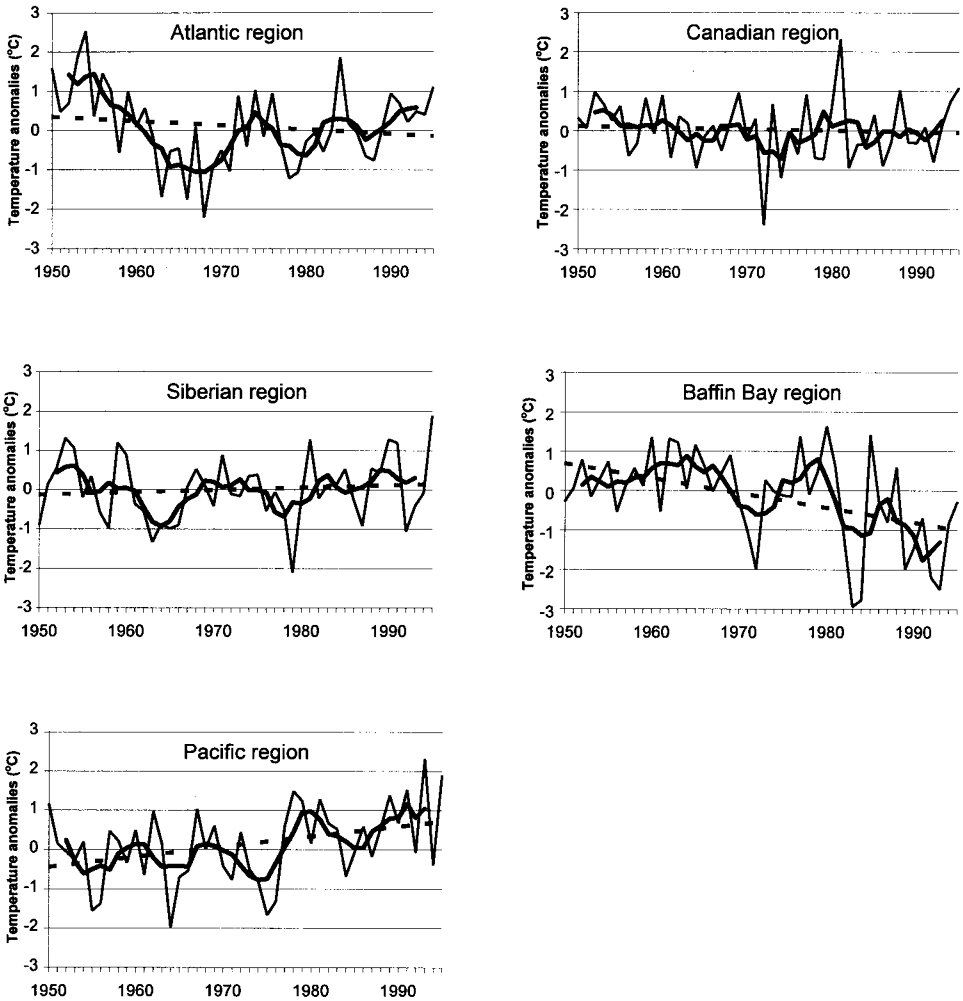

Figure 6. Year-to-year courses of mean annual anomalies of air temperature and their trends in the climatic regions of the Arctic over the period 1950–1995 (based on data from stations). Key: solid lines = year-to-year courses, heavy solid lines = running 5-year mean, and dashed lines = linear trends

Pacific and Canadian regions. On the other hand, great cooling was observed in the Baffin Bay region in both winter and spring.

Spatial patterns of annual and seasonal temperature trends over the period 1951–1995 are presented in Table I and Figures 7 and 8. Negative trends in annual air temperatures are present in a large part of the Atlantic region, in the Baffin Bay region and in the eastern part of the Canadian Arctic. The largest statistically significant cooling occurred in the peripheral eastern parts of the Canadian Arctic, in the Baffin Bay region and in the southern part of Greenland (Table I, Figure 7). On the other hand, the statistically significant warming is observed in the southern part of the Pacific region and in some small areas located in the southwestern part of the Canadian Arctic. Cooling was most common in the cold half-year (especially in autumn) (Figure 8). In autumn, more than half of the Arctic shows a downward trend for temperature. However, statistically significant trends occurred only in the region of Franz Joseph Land. In winter, the area with statistically significant negative trends is greater and includes the region of Franz Joseph Land, the eastern part of Canadian Arctic, the Baffin Bay region and the southwestern part of Greenland. On the other hand, the Pacific region and the southwestern part of the Canadian Arctic show large statistically significant warming in winter (Table I, Figure 8).

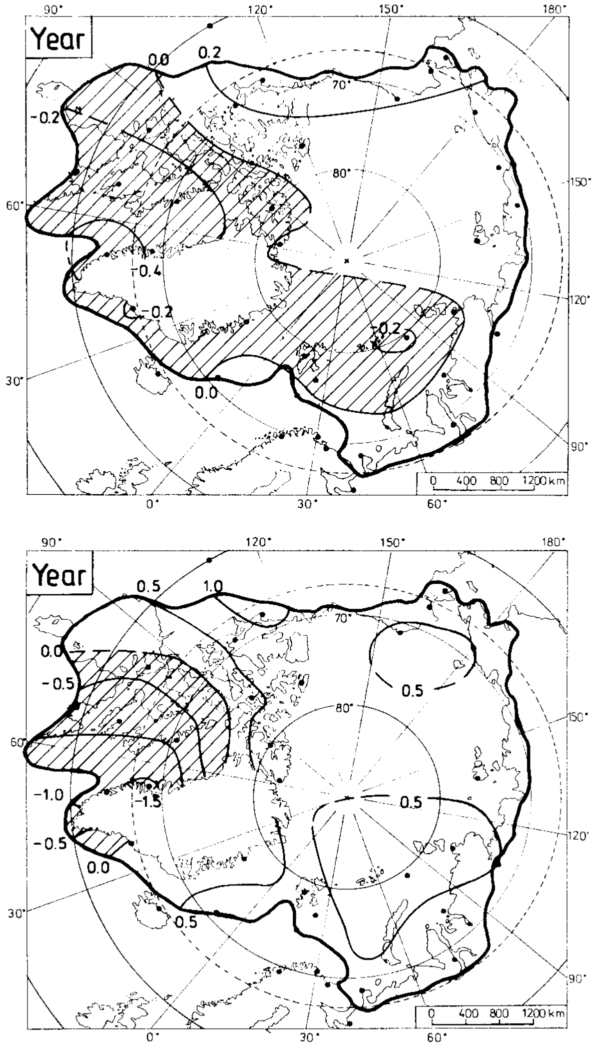

Figure 7. Spatial distribution of the mean annual air temperature trends (°C per decade, upper map) over the period 1951–1995 and the anomalies of mean annual 5-year (1991–1995) air temperatures, with the 1951–1990 mean (°C, lower map). Key: dashed contours over the Arctic Ocean indicate that the data are extrapolated from the coastal stations

In the analysed period, warming was most pronounced and widespread in spring and summer. The greatest increase in temperature occurred, similarly as for winter, in the Pacific region and in the southwestern part of Canadian Arctic. Areal average summer temperature for these regions shows a statistically significant increase in the last 20 years (see Table I). In spring, although cooling was limited to the eastern part of Canadian Arctic, the Baffin Bay region and the southern part of Greenland, its magnitude was significantly higher than the magnitude of warming in the areas mentioned above (Table I, Figure 8). Most stations show insignificant changes in seasonal and annual temperatures in recent decades.

The mean 5-year (1991–1995) annual temperature was lower than normal (1951–1990 mean) only in the eastern part of the Canadian Arctic, the Baffin Bay region and in the southern part of Greenland (Table II, Figure 7). It was very cold on the western coast of Greenland, where mean anomalies were equal to -1.6°C and -1.4°C in Egedesminde and Godthåb, respectively. The other, significantly greater part of the Arctic had air temperatures above-normal. Anomalies lying in the interval 0.5–1.0°C were most common. The pentad 1991–1995 was the warmest of all the analysed pentads only for the nine

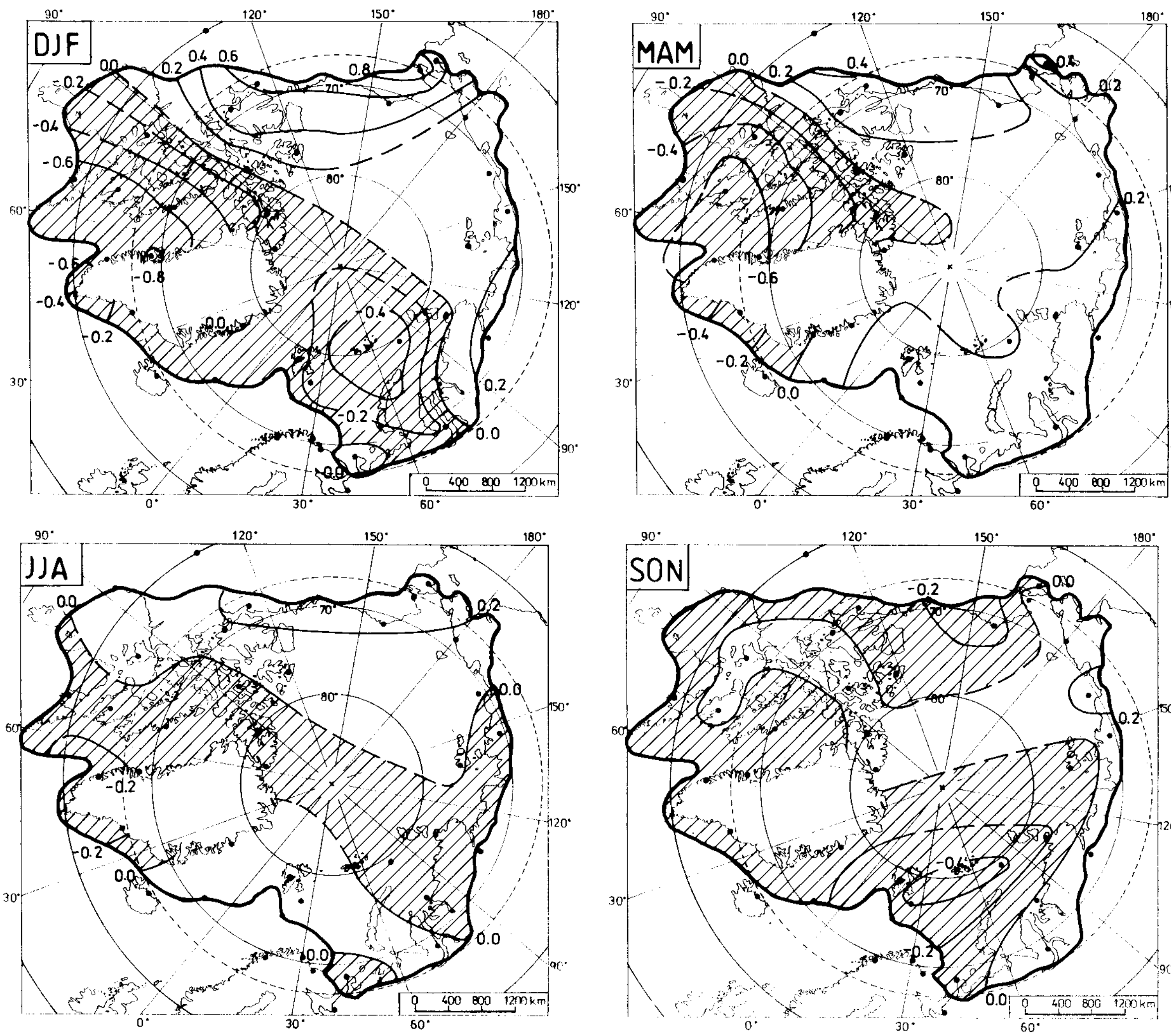

Figure 8. Spatial distribution of the mean seasonal air temperature trends (°C per decade) in the Arctic over the period 1951–1995. Key as in Figure 7

stations located in the northern and western parts of the Canadian Arctic, as well as in some parts of the Russian Arctic (Table II). It is worth noting that the Baffin Bay region was the coolest in this period since 1951. Areal average temperature for most analysed regions and for the Arctic as a whole was the highest in the pentad 1951–1955. The last pentad had the highest mean temperature only in the Pacific region. In the Arctic, the areal average annual temperature in this pentad was higher than normal for the period 1961–1990 by only 0.1°C. Analogical values for the Northern Hemisphere, the Southern Hemisphere and the whole globe were equal to 0.3°C, 0.2°C and 0.26°C, respectively (based on updated data from Jones, 1994 and Parker *et al.*, 1994). Similar results were obtained using the 1951–1990 reference period (Table I). However, according to climatic models, the doubling of CO_2 in the atmosphere should have caused 2–3 times greater warming in the Polar Regions than the global average (Houghton *et al.*, 1990, 1992, 1996).

Spatial distributions of the mean seasonal 5-year anomalies of air temperature in the Arctic (Figure 9) are significantly different when compared with the previously described spatial distribution of annual anomalies (Figure 7), except in spring. However, in all seasons (except winter) positive anomalies dominate, similarly as for the annual values. These were largest and most common in spring and in

Table II. Anomalies of annual mean 5-year air temperatures (in °C) in the Arctic referred to the mean 1951–1990

Station	1951–1955	1956–1960	1961–1965	1966–1970	1971–1975	1976–1980	1981–1985	1986–1990	1991–1995
Angmagssalik	0.6	**1.0**	0.3	−0.8	−0.5	0.3	−0.7	−0.2	0.1
Danmarkshavn	0.2	**0.5**	0.0	−0.7	−0.3	0.1	0.0	0.2	0.1
Jan Mayen	0.5	**1.1**	0.0	−1.5	−0.2	0.1	0.0	0.0	0.9
Svalbard Lufthavn	0.7	**1.3**	−0.8	−1.7	0.6	−0.4	0.6	−0.3	0.7
Björnöya	0.5	**1.1**	−0.9	−1.2	0.6	−0.3	0.3	0.0	0.6
Hopen	0.9	**1.4**	−1.0	−1.6	0.7	−0.4	0.3	−0.3	0.7
Kanin Nos	0.5	−0.1	0.2	−0.7	**0.7**	−0.7	−0.1	0.3	**0.7**
Naryan Mar[a]	–	–	−0.1	−0.7	0.3	−0.4	0.5	0.6	**1.4**
Polar GMO E. T. Krenkelya[a]	–	–	−0.9	−0.6	0.8	−0.2	**1.0**	−0.4	0.6
Ostrov Vize	**1.8**	0.5	−1.0	−0.7	0.2	−0.4	0.7	−1.0	0.0
Ostrov Dikson	**1.1**	−0.5	−0.3	−0.8	−0.2	−0.4	**1.1**	0.0	0.7
GMO E. K. Fedorova	**0.5**	**0.5**	−0.1	0.0	0.1	−0.1	0.4	0.0	0.3
Ostrov Kotelny	0.5	0.3	−1.0	0.0	0.4	−0.7	0.5	0.0	**0.7**
Ostrov Chetyrekhstolbovoy	0.3	**0.7**	−0.7	0.1	−0.1	−0.7	−0.1	0.5	0.5
Mys Szmidta	−0.1	0.3	−0.5	0.3	−0.1	−0.3	0.1	0.3	**0.5**
Nome	−0.4	−0.2	−0.7	−0.1	−1.2	1.0	**1.1**	0.6	0.6
Kotzebue	−0.6	−0.2	−0.7	0.1	−1.2	**1.2**	0.8	0.5	0.4
Barrow	−0.5	−0.6	0.2	0.3	−0.5	0.3	−0.1	**0.9**	0.4
Mould Bay	0.3	0.2	−0.3	−0.2	−0.3	−0.1	0.2	0.4	**0.8**
Coppermine	0.2	−0.6	−0.7	0.2	−0.2	0.4	0.2	0.4	**1.1**
Cambridge Bay	0.3	−0.3	−0.8	0.2	−0.1	−0.1	**0.6**	0.3	**0.6**
Resolute A	**0.5**	0.1	0.0	−0.1	−0.6	0.0	0.2	−0.2	0.4
Eureka	0.7	0.5	0.4	0.0	−1.0	−0.5	0.0	−0.2	**0.9**
Coral Harbour A	**0.6**	0.3	−0.6	0.4	−0.4	0.0	0.3	−0.6	−0.4
Clyde A	0.4	0.1	0.1	**0.7**	−0.4	0.3	−0.1	−1.2	−0.9
Iqaluit A	**0.7**	0.3	0.0	0.5	−0.8	0.2	0.0	−1.0	−0.9
Kuujjuaq	**1.0**	0.4	−0.4	0.3	−0.7	−0.1	0.2	−0.7	−0.8
Alert	0.3	0.3	0.2	−0.2	−0.5	−0.5	0.2	0.2	**0.6**
Egedesminde	0.1	0.2	1.0	0.1	−0.9	**1.1**	−1.0	−0.6	−1.6
Godthåb	0.4	0.7	**0.8**	0.1	−0.6	0.5	−1.2	−0.6	−1.4
Atlantic region	**1.2**	0.6	−0.5	−1.1	0.0	−0.4	0.3	−0.1	0.6
Siberian region	**0.6**	0.2	−0.8	0.1	0.3	−0.7	0.4	0.2	0.3
Pacific region	−0.3	−0.1	−0.5	0.1	−0.7	0.4	0.3	0.6	**1.1**
Canadian region	**0.5**	0.1	−0.2	0.1	−0.5	−0.1	0.2	−0.2	0.3
Baffin Bay region	0.3	0.3	**0.7**	0.3	−0.6	**0.7**	−0.9	−0.8	−1.3
Arctic 1	**0.5**	0.2	−0.3	−0.3	−0.1	−0.2	0.3	0.0	0.0
Arctic 2	**0.3**	0.0	−0.1	−0.2	−0.3	0.1	**0.3**	0.0	0.2
NH (land+ocean)	0.0	0.0	0.0	0.0	−0.1	0.0	0.1	**0.3**	**0.3**

[a] Data for 1958–1995.
Bold numbers denote the highest mean 5-year anomalies of air temperature in the studied period.
Arctic 1: area average temperature based on data from 33 to 35 Arctic stations (see Figure 1); Arctic 2: area average temperature based on data from 30 grid-boxes (source: Jones, 1994, updated); NH (land+ocean): area average temperature for Northern Hemisphere (source: Jones, 1994, updated).

summer (Figure 9). This seasonal pattern in air temperature changes (both anomalies and trends have been described earlier) is not consistent with climate model outputs (see e.g. Manabe *et al.*, 1992 or Barthelet *et al.*, 1998), which suggests that an enhanced greenhouse effect will result in the greatest warming occurring in winter and autumn. Warming in the analysed pentad was especially high in the western part of the Canadian Arctic and Alaska. On the other hand, negative anomalies were most common in the eastern part of the Canadian Arctic, the Baffin Bay region and in the southern and western parts of Greenland (Figure 9).

Based on presented results for near-surface air temperature, one can state that in the Arctic the second phase of contemporary global warming (after 1975) did not occur. Similar results have also been obtained by Born (1996) when analysing air temperature changes in the Polar Regions in the lower 5-km of the atmosphere. Previously, Kahl *et al.* (1993a,b) investigated air temperature in the whole Arctic troposphere and found no evidence for greenhouse warming.

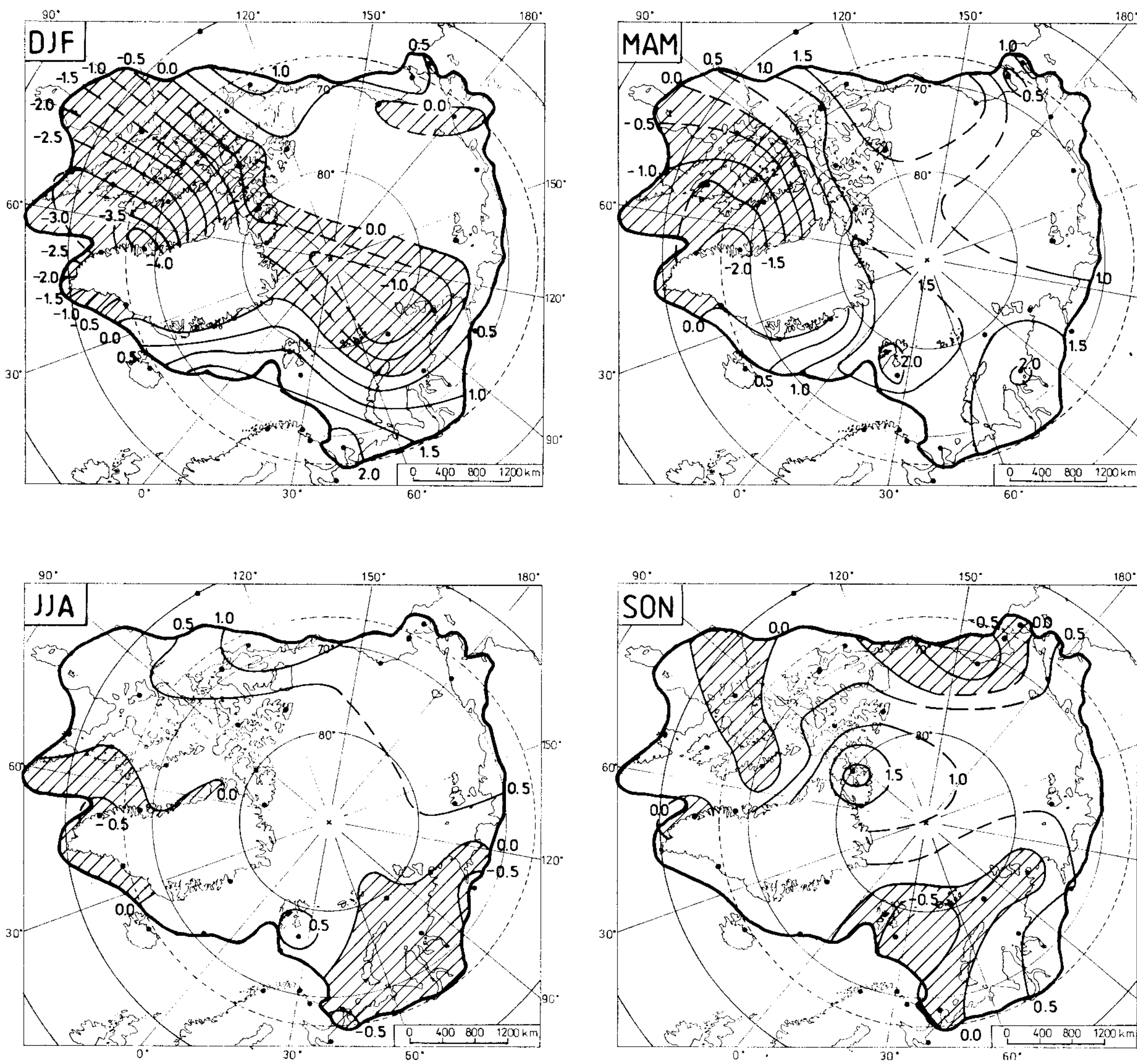

Figure 9. Spatial distribution of the anomalies of mean seasonal 5-year (1991–1995) air temperatures, with the 1951–1990 mean (°C) in the Arctic. Key as in Figure 7

These results raise the following question: what are the causes of the lack of warming in the Arctic after 1975. According to Przybylak (1996a), this situation may have resulted from:

(i) A delay in the reaction of the Arctic climatic system, which has considerable inertia because of large water masses, and sea and land ice. One may compare the Arctic with a large refrigerator. To warm such a refrigerator, a significantly greater amount of energy must be supplied than would be necessary to warm to the same degree a lower latitude region. This means that the warming in the Polar Regions connected with the increasing radiation forcing will occur later (not earlier as is commonly assumed) than in lower latitudes. This conclusion is consistent with results presented by Aleksandrov and Lubarski (1988). Analysing observational evidence, they found that in the phase of global warming the increase of air temperature in the Arctic was occurring later than in lower latitudes. On the other hand, in the phase of global cooling, the opposite relation exists. It may be said that this conflicts with the warming in 1920–1940, which occurred earlier in the Arctic than in other parts of the world. This is correct, but the main reason for the latter warming was a change in atmospheric circulation. In such a case, the reaction of climate to a change of forcing is immediate. The considerable inertia of an Arctic climate system should also significantly delay the start of positive feedback mechanisms (such as sea-ice–albedo–temperature feedback) which are responsible for a significant portion of Arctic greenhouse warming.

(ii) An influence of natural factors (mainly a change in atmospheric circulation) which, while leading to a cooling of the Arctic, considerably reduces or completely removes the warming caused by the greenhouse effect. Przybylak (1996a) shows that significant increases in the frequency of occurrence of zonal macrotype of circulation (W) and decreases of the eastern macrotype of circulation (E), according to Vangengeim–Girs typology (see Girs, 1948, 1971, 1981; Vangengeim, 1952; Barry and Perry, 1973), has occurred since the mid-1970s. The first macrotype gives negative and the second positive temperature anomalies in the Arctic. This means that the described circulation changes lead to the cooling of the Arctic. Other natural factors, e.g. the statistically significant decrease of solar irradiance in the Arctic reported by Stanhill (1995) and the downward trend of solar activity observed since 1957 when the secular maximum occurred, should also cause Arctic cooling. Voskresenskii *et al*. (1991) found decreasing Arctic temperatures in the periods of lower solar activity.

(iii) Influence of a rising concentration of anthropogenic sulphate aerosols. Santer *et al*. (1995) found that the anti-greenhouse effect made by sulphate aerosols since pre-industrial times is greater in most of the Arctic than the greenhouse effect connected with the rise of CO_2 during the same period.

(iv) The combined effect of these factors.

4.4. An influence of atmospheric circulation on temperature

It is not possible to investigate the reasons for recent temperature variations without discussing the atmospheric circulation changes. It is widely known that the importance of circulation in the formation of climate is much greater here than at lower latitudes (see Alekseev *et al*., 1991, their table 1). Alekseev *et al*. (1991) also found that advection of warmth from lower latitudes by atmospheric and oceanic circulation provides more than half the energy annually available in the Arctic climate system. This makes such advection more important than solar irradiance flux. The share of advection is especially large in the cold season, when there is only negligible inflow of solar irradiation. During the polar night it is equal to 100%. According to the latest results, atmospheric circulation provides as much as 95% of warmth advection to the Arctic, while oceanic circulation provides only 5% (Alekseev *et al*., 1991). Vangengeim (1952, 1961) showed that changes of synoptic processes in the Arctic are about 1.5 times greater than in moderate latitudes. As a consequence, it is possible to conclude that the Arctic is significantly more sensitive and vulnerable to atmospheric circulation changes than any other area. It follows from this that all works examining Arctic atmospheric circulation variations are of great significance (e.g. Dydina, 1982; Jones, 1987; Serreze and Barry, 1988; Vinogradov *et al*., 1991; Niedźwiedź, 1992–1993, 1993; Serreze *et al*., 1993, 1997; Przybylak, 1996a,b), as are those studying the influence of atmospheric circulation variations on air temperature (e.g. Dydina, 1958, 1964, 1982; Yevseev, 1967; Bardin, 1969; Bardin and

Makarov, 1970; Bradley, 1974; Barry *et al*., 1975; Bradley and England, 1979; Niedźwiedź, 1987, 1992–1993, 1993; Walsh and Chapman, 1990; Milkovich, 1991; Przybylak, 1992, 1996a; Wójcik *et al*., 1992; Maslanik *et al*., 1996; Stone, 1997).

Przybylak (1996a) determined the relations between atmospheric circulation and temperature in the Arctic using daily data. He found that changes observed after 1975 in atmospheric circulation led to the Arctic cooling in the period 1976–1990 (as was mentioned earlier).

The present paper focuses on linkages between regional changes in atmospheric circulation observed outside of the Arctic (in North Atlantic, North and tropical Pacific) and Arctic temperature. In order to do this, the best known indices characterizing atmospheric circulation (ZI, NAOI, NPI and SOI) and the monthly mean temperature from Arctic stations have been used.

From Table III it can be seen that the intensification of zonal circulation in mid-latitudes, which has been noted since 1975 (see Kożuchowski, 1993; Jönsson and Bärring, 1994), accounts for Arctic cooling in all seasons except spring. Cooling is significant mainly in the cold half-year, but only in autumn is it present in all climatic regions. The greatest influence of atmospheric changes represented by ZI on temperature is noted in the Baffin Bay and Canadian regions, where statistically significant negative correlations in winter and autumn were found. On the other hand, the observed intensification of zonal circulation leads to the Northern Hemisphere warming in all seasons except summer. Statistically significant correlations were computed for winter and annual values (Table III).

Roughly similar relations were found between the NAOI and the Arctic temperature (Figures 10–12). In this case, however, the correlation coefficients were computed between the NAOI and the temperature series for all analysed stations (Figures 10 and 11). In addition, temperature differences between the blocks of the years with positive (1989–1995) and negative (1963–1969) modes of the NAOI were computed. These composites were selected by Dickson *et al*. (1997) using winter months and seasons that exceed 1σ from the mean values of the NAOI.

The strongest statistically significant relations exist with mean annual temperatures in the Baffin Bay and the Canadian Arctic (negative correlations) and in the southern part of Atlantic (positive correlation) regions (Figure 10). Changes of the NAOI here explain about 10–25% of the air temperature variance. As is widely known, the relationships between changes in atmospheric circulation in the North Atlantic and temperature, not only in the Arctic, are strongest in the winter months (Hurrell, 1995, 1996; Jones *et al*., 1997). Correlation coefficients computed for particular seasons confirm this finding (see Figure 11). In winter, as for annual values, negative correlations occur in the Baffin Bay and Canadian regions. However, they are significantly greater and, for example, in the central part of Baffin Bay region explain as much as 40–50% of winter temperature variance. Statistically significant positive correlations are present mainly in the eastern parts of the Atlantic region and in the western part of the Siberian region (Figure 11).

Table III. Correlation coefficients between area average seasonal (December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON)) and annual temperature for regions, the Arctic, the Northern Hemisphere and ZI over the period 1951–1990 (after Przybylak, 1996a)

Area	DJF	MAM	JJA	SON	Annual
Atlantic region	0.11	0.13	0.08	−0.01	0.10
Siberian region	−0.07	0.25	−0.32	−0.13	0.15
Pacific region	0.07	0.18	−0.16	−0.06	0.21
Canadian region	−0.40*	−0.11	−0.08	−0.40*	−0.28
Baffin Bay region	−0.48**	−0.18	−0.25	−0.55***	−0.46**
Arctic 1	−0.31	0.09	−0.14	−0.33*	−0.05
NH (land + ocean)	0.43**	0.31	−0.06	0.20	0.39*

* Correlation coefficients statistically significant at the level of 0.05.
** Correlation coefficients statistically significant at the level of 0.01.
*** Correlation coefficients statistically significant at the level of 0.001.
Other explanations as in Table I.

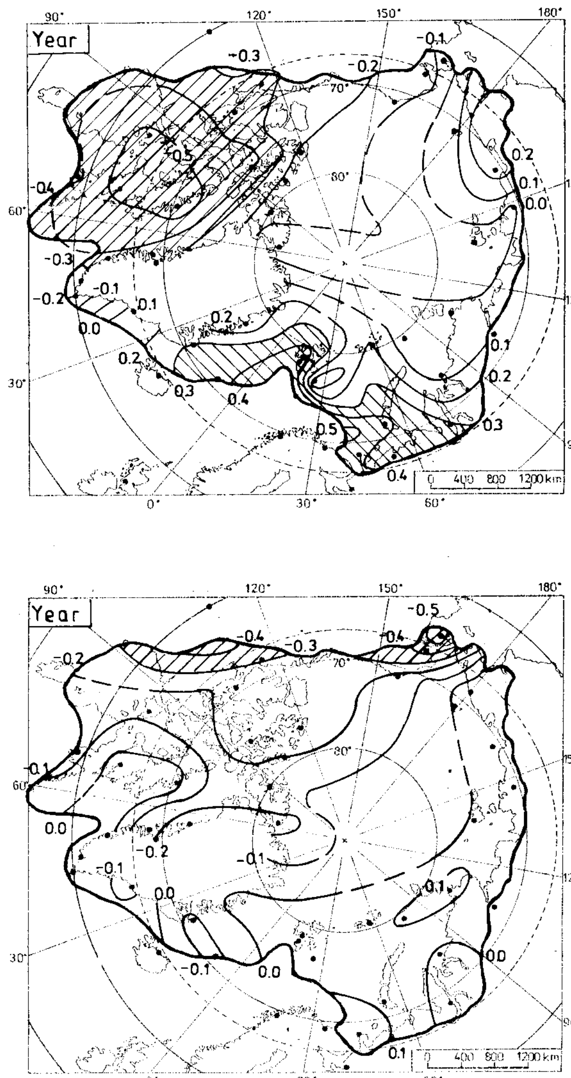

Figure 10. Spatial distribution of the coefficients of correlation between mean annual temperatures in the Arctic and NAOI (upper map) and NPI (lower map) over the period 1951–1995. Statistically significant correlations are hatched. Other key as in Figure 7

Changes in winter temperatures between 7 years with positive modes and 7 years with negative modes of the NAOI are in very high agreement with those presented above (compare Figure 12 with Figure 11). Strong cooling connected with the highest positive values of the NAOI occurred in the Baffin Bay region (4–7°C) and in the eastern part of the Canadian Arctic (1–5°C). On the other hand, warming was observed in the southern and eastern parts of the Atlantic region reaching 1–4°C. These results are in agreement with those presented by Hurrell, 1995, figure 3; Hurrell, 1996, figure 3). In light of the results presented by Serreze *et al.* (1997, their figure 6) concerning the positive minus negative NAO difference field of cyclone events in the cold season, the causes of warming in the Barents and Kara Sea regions are difficult to explain. Serreze *et al.* found a decrease in cyclone events. Recent results published by Dickson *et al.* (1997) may help to resolve this issue. These authors found that the 'increasingly anomalous southerly airflow that accompanies such a change over Nordic seas is held responsible for a progressive warming in the two streams of Atlantic water that enter the Arctic Ocean across the Barents Sea shelf and along the Arctic Slope west of Spitsbergen'. The temperatures of these two Atlantic-inflow streams were

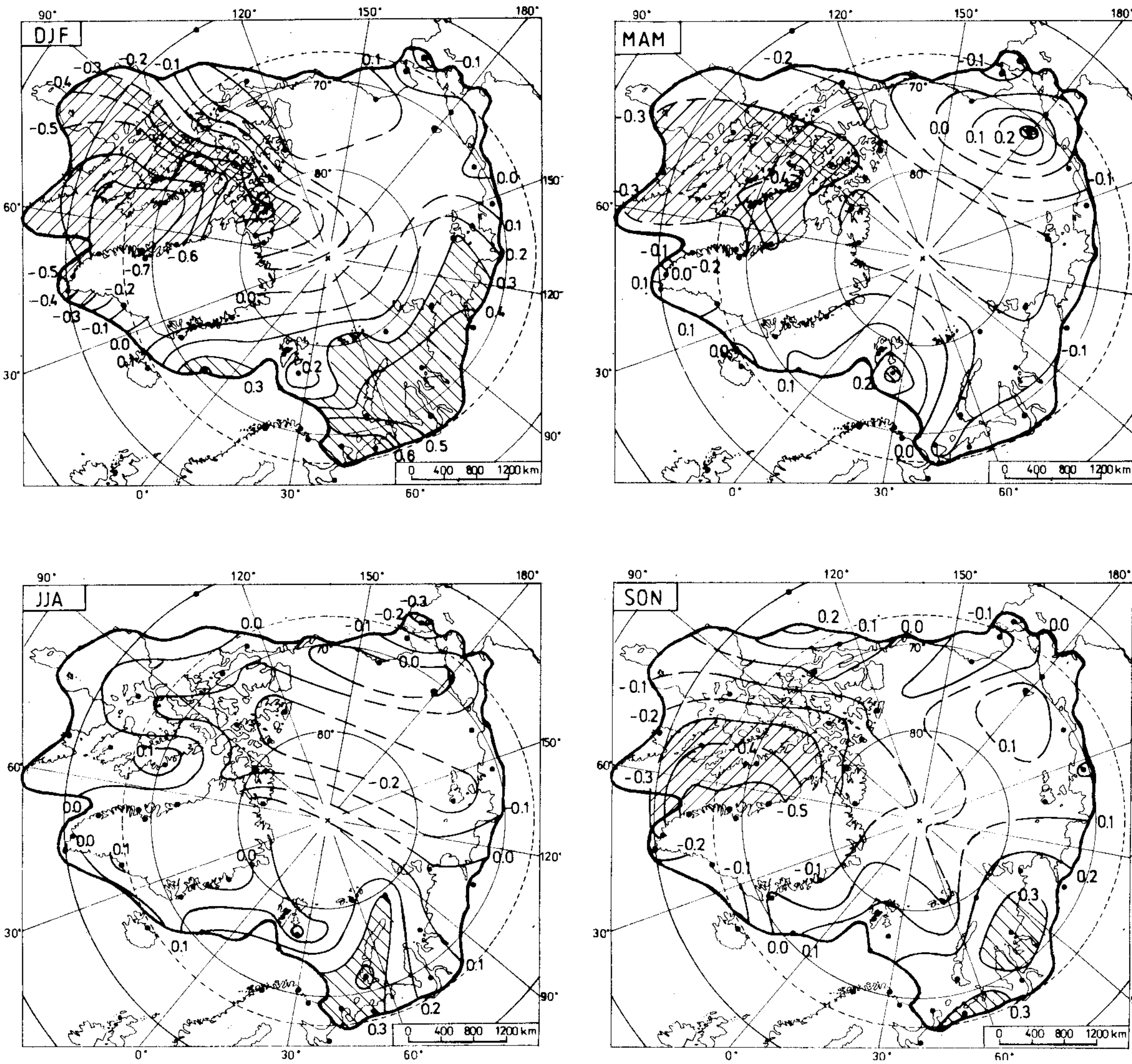

Figure 11. Spatial distribution of the coefficients of correlation between mean seasonal temperatures in the Arctic and NAOI over the period 1951–1995. Statistically significant correlations are hatched. Other key as in Figure 7

between 1°C and 2°C higher than normal in the late 1980s and early 1990s. Alekseev (1997) also presents similar results.

To check for possible Pacific influences on Arctic temperature, the NPI was used. As with the NAOI, correlation analysis was conducted for annual values (Figure 10) and for all seasons (not shown). The NP signal-strength dominates that of the NAO only in some fragments of the Pacific region and in the southwestern part of the Canadian region (Figure 10). Only here are the correlation coefficients statistically significant. A roughly similar situation also occurs in all seasons. Changes in atmospheric circulation in the North Pacific have the greatest influence on Arctic temperature in winter and the lowest in summer (as with the NAOI).

To investigate the role of El Niño–Southern Oscillation (ENSO) on Arctic temperature, the difference of temperature between ten individual El Niño events and ten La Niña events for each Arctic station was computed. The list of El Niño and La Niña events after 1950, as defined by sea surface temperatures (SSTs) in the Niño 3.4 region and exceeding the ± 0.4°C threshold, is presented in Trenberth (1997, table

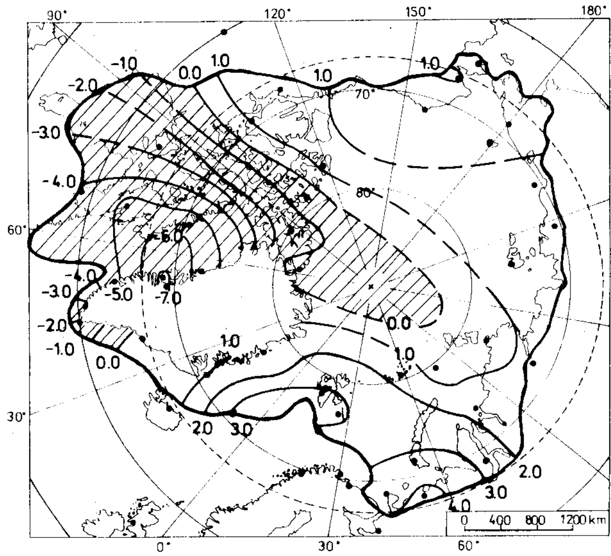

Figure 12. Differences of air temperature (in °C) between the most extreme 7-year run of NAO + winters (December–February 1989–1995) and NAO − winters (December–February 1963–1969). The NAO + and NAO − winters were taken after Dickson *et al.* (1997). Negative differences are hatched. Other key as in Figure 7

2). From this list were chosen 10 years for which the duration of El Niño and La Niña events was at least 6 months. The following years were selected: 1957, 1965, 1969, 1972, 1982, 1987, 1991, 1992, 1993 and 1994 (El Niño); 1950, 1955, 1956, 1964, 1971, 1974, 1975, 1985, 1988 and 1989 (La Niña).

The results of computations are presented in Figures 13 and 14. As expected, the influence of ENSO on Arctic temperature is significantly lower than that associated with circulation changes in the North Atlantic (NAOI)—compare Figures 12 and 13. During the El Niño phenomena, decreases of winter temperature may be observed in the Kara Sea region (by about 2°C), in the Baffin Bay region and in the eastern part of Canadian Arctic (0.5–1.5°C). On the other hand, significant warming is present only in Alaska. In other seasons, the general patterns of temperature differences are similar to that for winter but these differences are significantly less. It is clear that the influence of ENSO on Arctic temperature is indirect and occurs mainly through changes in atmospheric circulation in the North Pacific and North Atlantic. Hurrell (1996) found a statistically significant correlation ($r = 0.51$) between the NPI and the SOI but no correlation between the NAOI and SOI based on data for the period 1935–1994. This author has repeated Hurrell's calculations and have found significantly lower correlations between NPI and SOI ($r = 0.19$). Similar results ($r = 0.23$ and $r = 0.11$) have been obtained for other periods: 1899–1995 and 1951–1995, respectively. In the 1899–1995 period, the correlation coefficient is statistically significant at the level of 0.05. However, after 1975 significant and more consistent changes for all of these indices are observed (see figure 2 in Hurrell, 1996). Computations of correlation coefficients between the analysed indices for the periods 1956–1975 and 1976–1995 confirm this conclusion. For example, correlation coefficients between SOI and NAOI for the winter (December–March) are equal to $r = 0.00$ and $r = -0.23$, respectively. It follows that in the last two decades the ENSO could cause to a greater degree the changes in atmospheric circulation also noted in the North Atlantic.

These results confirm the significant role of atmospheric circulation changes, particularly in the North Atlantic, on Arctic temperature, especially in the cold half-year. It has also been shown that in some parts of the Arctic, atmospheric circulation changes can explain up to 10–50% of the observed temperature variance.

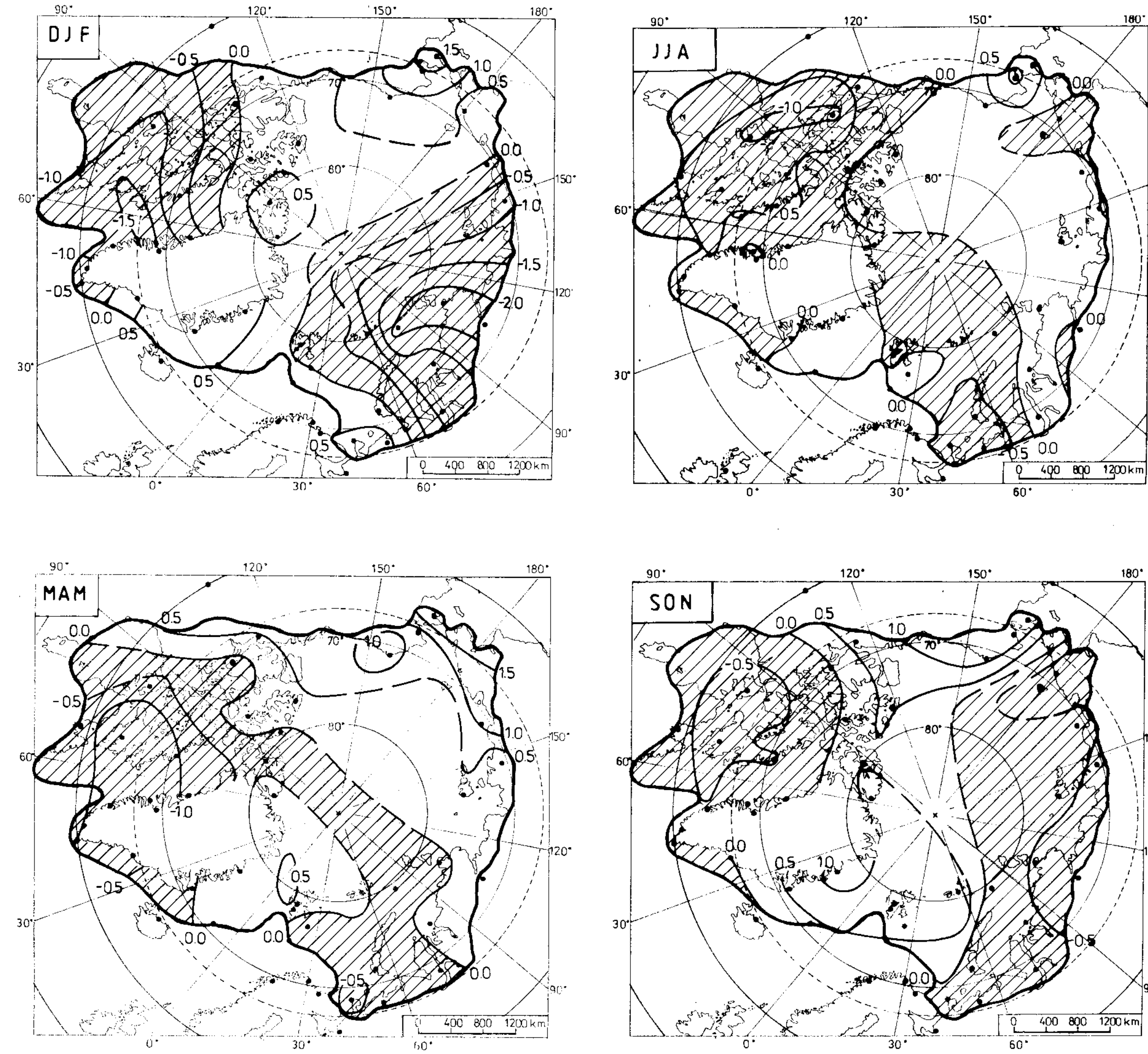

Figure 13. Differences of mean seasonal air temperature (in °C) between 10 years with the strongest El Nino and 10 years with the strongest La Nina phenomena. Negative differences are hatched. Other key as in Figure 7

5. CONCLUSIONS AND FINAL REMARKS

The analysis presented here shows that observed variations in air temperature in the real Arctic (defined on the basis of climatic criteria) are not consistent in many aspects with the projected climatic changes computed by climatic models for the enhanced greenhouse effect. The main differences are as follows:

(i) The second phase of contemporary global warming in the Arctic is either very weakly marked or even not seen at all. For example, the mean rate of warming in the last 5-year period in the Arctic was 2–3 times lower than for the globe as a whole. In the Arctic, the highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s. Moreover, it has been shown that even in the 1950s the temperature was higher than in the last 10 years. It is also worth noting that the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century,

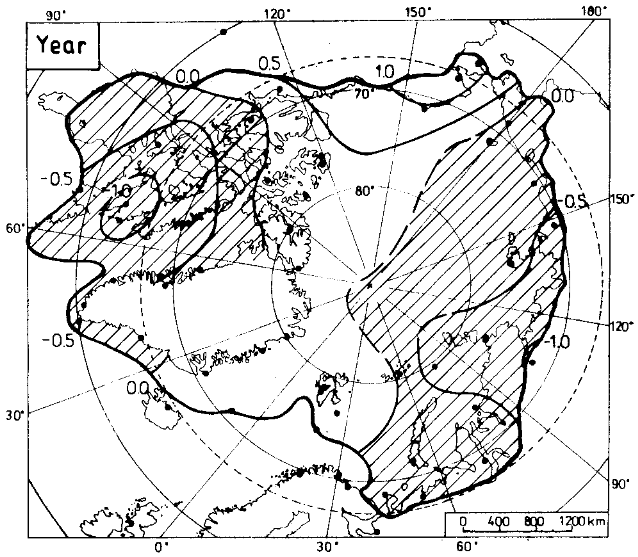

Figure 14. Differences of mean annual air temperature (in °C) between 10 years with the strongest El Nino and 10 years with the strongest La Nina phenomena. Negative differences are hatched

(ii) An increase of temperature in the Arctic is more significant in the warm half-year than in the cold half-year. This seasonal pattern in temperature changes confirms to some degree this author's hypothesis that positive feedback mechanisms (e.g. sea-ice–albedo–temperature) as yet play only a minor role in enhancing Arctic temperature.

The significance of atmospheric circulation changes (probably connected with natural climatic forcings) for Arctic temperature has been documented. It has been demonstrated that in some parts of the Arctic atmospheric circulation changes, particularly in the cold half-year, can explain up to 10–50% of the observed temperature variance. For Arctic temperature, the most important are changes in North Atlantic atmospheric circulation. The influence of the Pacific atmospheric circulation changes (both northern and tropical) are significantly lower.

There is now urgent need to agree on the course of the southern border of the Arctic for the purposes of climatological study. It has been shown here that the present flexibility of definition is one of the main reasons for the inconsistencies in estimates of areal average Arctic temperature trends reported by different authors for the second half of the 20th century.

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