Recent air-temperature changes in the Arctic

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ABSTRACT. A detailed analysis of the spatial and temporal changes in mean seasonal and annual surface air temperature (SAT) in the Arctic is presented mainly for the period 1951–2005. Mean seasonal and annual homogenized and complete series of SAT from up to 35 Arctic stations were used in the analysis. The focus in this paper is on the 11 years 1995–2005, a period which saw dramatic warming in the Arctic (>1°C for annual values in relation to the 1951–90 mean). An abrupt rise in SAT occurred in the mid-1990s and was most pronounced in autumn and winter (>2°C). The greatest warming in the period 1995–2005 occurred in the Pacific and Canadian regions (>1°C), while the lowest was in the Siberian region (0.82°C). This period has been the warmest since at least the 17th century. In particular, 2005 was an exceptionally warm year (>2°C in relation to the 1951–90 mean) and was warmer than 1938, the warmest year in the 20th century. The seasonal and annual trends of the areally averaged Arctic SAT for the periods 1936–2005, 1951–2005 and 1976–2005 are positive, with the exception of winter and autumn for the first period. The majority of trends calculated for the last two periods are statistically significant. While there are varying opinions about the forces driving the present warming, it seems likely that the marked rise in SAT in the mid-1990s (mainly from 1994 to 1995) was caused by (i) a set of natural factors, (ii) non-linear effects of greenhouse-gas loading, or (iii) the combined effect of these two groups of factors.

INTRODUCTION

It has been known since at least the end of the 19th century that the polar areas play a very important role in the formation of the Earth's climates. It is also known today that they are the most sensitive regions to climatic change, and are thus perfect case studies for the detection of such changes. The most serious obstacle to the study of climatic and other geographical elements of the polar areas (including the Arctic) has always been the severe climatic conditions that prevail in these regions. Because of these extreme conditions, research into particular elements of the climatic system (including the atmosphere) began here much later than it did in lower latitudes.

The instrumental record of Arctic surface air temperature (SAT) is brief and geographically sparse. Only five records (Upernavik: start date 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 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. After the Second Polar Year (1932/33) most of the Russian stations were established, while most of the Canadian stations were set up after World War II. For this reason, reliable estimates of spatial distribution of SAT in the Arctic, as well as its areally averaged values, are only possible for the last 56 years.

Comprehensive literature overviews presenting the results concerning SAT changes in the Arctic during the 20th century have been given in my previous works (Przybylak, 1996, 2000, 2002), and this information is not repeated here. Briefly summarizing these overviews, it should be noted that prior to the 1990s there were significantly fewer papers dealing with the issue of the Arctic SAT changes. In the present century, due to marked warming of the Arctic starting in 1995 and the decision of international scientific bodies to organize the Fourth International Polar Year in 2007–08, scientific interest in the Arctic has become even greater. As a result, quite a large number of different kinds of elaborations investigating the issue of SAT changes and its causes have been published (e.g. Moritz and others, 2002; Rigor and others, 2002; Bobylev and others, 2003; Comiso, 2003; Polyakov and others, 2003; Przybylak, 2003; Bengtsson and others, 2004; Johannessen and others, 2004; Overland and others, 2004a, b; McBean and others, 2005; Styszyńska, 2005; Turner and others, 2006).

The main aim of the present paper is to briefly summarize recent Arctic SAT changes with a particular emphasis on the last 11 years, which have been characterized by a dramatic warming even greater than the warmest decade of the 20th century (the 1930s). Probable reasons for this abrupt increase in Arctic SAT in the mid-1990s (mainly from 1994 to 1995) are also given.

AREA, DATA AND METHODS

For the purposes of this paper, the Arctic and its climatic regions are defined after Treshnikov (1985) (Fig. 1). For a review presenting different criteria used to delimit the Arctic see Przybylak (2002, 2003).

The mean monthly SAT values of 35 Arctic stations were available for analysis (see Fig. 1). The majority of data came from national meteorological institutes (the Danish Meteorological Institute, the Norwegian Meteorological Institute and the Canadian Climate Centre) or other institutions (the Arctic and Antarctic Research Institute at St Petersburg, Russia, and the National Climatic Data Center at Asheville, NC, USA). The Arctic stations generally show a good spatial distribution, with the exception of the central part of the Arctic Ocean and the interior part of Greenland. Their SAT series are complete, and, with the exception of one station (Hall Beach), all of

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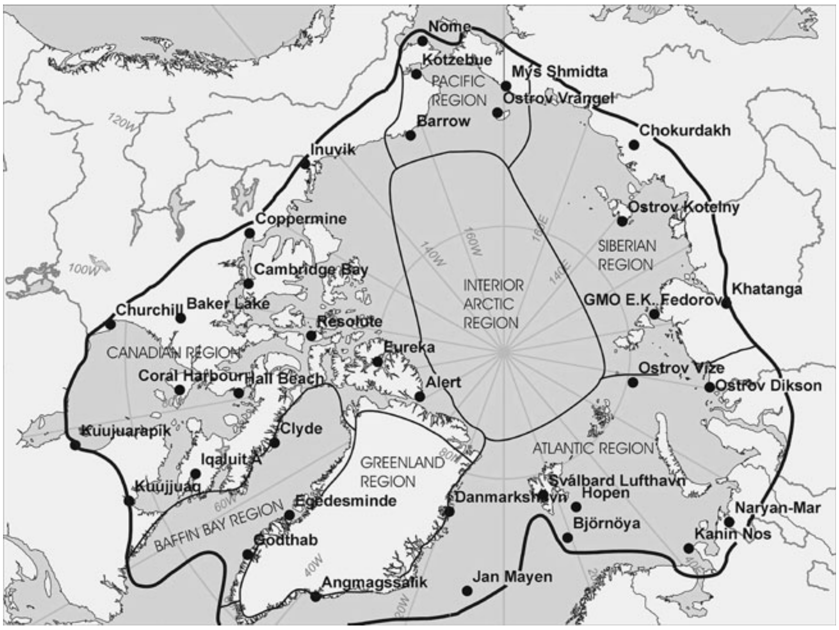

Fig. 1. Location of meteorological stations used. Continuous thick line: border of the Arctic after Treshnikov (1985); solid lines: the borders of the climatic regions; dots: meteorological stations.

them began operating prior to 1951. Data quality and their homogeneity have been checked (see Przybylak, 2002). All the stations used are located near the sea coast and below 100 m a.s.l. For these reasons, and due to the fact that the global gridded dataset (Jones and others, 1999) contains many gaps in the northern high latitudes, the stations' SATs still provide the best source of data that can be used to compute areally averaged Arctic SAT along with other characteristics (for more details, see Przybylak 2000). Vizi and Przybylak (in press) have also noted that the US National Centers for Environmental Prediction/US National Center for Atmospheric Research (NCEP/NCAR) re-analysis data (Kalnay and others, 1996) widely used for studies of climate variability are still the least reliable source of such information for the Canadian Arctic (in comparison with four different datasets) and probably also for the whole of the Arctic.

Year-to-year variability of Arctic SAT has been investigated using seasonal (December–February, etc.) and annual means. Linear trends for different periods have been computed both for areally averaged SAT (for the whole Arctic and for five distinguished regions) and for each station. The significance of computed trends was checked using the Student's *t* test. More recent changes in Arctic SAT were investigated using data obtained since 1995. Anomalies for the periods 1995–2005 and 2001–05 of seasonal and annual SAT, using the 1951–90 mean, were computed for each station, each region and for the Arctic as a whole.

RESULTS AND DISCUSSION

SAT anomalies

Detailed research into air-temperature tendencies in the Arctic for the periods 1936–90 and 1951–90 (Przybylak, 1996, 2002) as well as 1951–95 (Przybylak, 2000) revealed the predominance of negative trends, though most of them were not statistically significant. Slight increases in SAT have been prevailing in the recently observed 'second phase of contemporary warming' (after 1975). However, they have been up to four times smaller for the areally averaged Arctic SAT than for the analogous series for the Northern Hemisphere (land + ocean). Such a situation occurred, for example, in the period 1976–95. Thus, it may be assumed that up to 1995 the impact of the greenhouse effect was only slightly observable in the Arctic or, as is suggested by Przybylak (2000, 2002), it had decreased significantly through the combined activity of sulphate aerosol and natural factors.

In comparison both to the period 1951–90 and to the period 1951–95, the inclusion of the data from the last 11 years (warmer than the 1951–90 mean by >1.0°C; Table 1) exerted a significant influence on the values of trends of Arctic SAT (Tables 2 and 3; Figs 2 and 3).

The most characteristic feature of the recent changes in areally averaged Arctic SAT is its abrupt rise (about 1°C) in the mid-1990s (first noted by Przybylak, 2002). More importantly, however, this high level of SAT has persisted through the present (see Fig. 2). This implies that the Arctic, with about a 20 year delay, has reacted dramatically to the global warming which started in about the mid-1970s. This is especially true for the Canadian and Baffin Bay regions, which even show a cooling trend from the 1950s until the mid-1990s. This was then followed in these regions by the occurrence of rapid warming (by about 1.5–3.0°C) (Fig. 2). In the remaining part of the Arctic, and particularly in the Siberian and Pacific regions, this warming started significantly earlier. The abrupt rise of Arctic SAT (by >2°C) is markedly greatest in autumn, although the 1980s and the beginning of the 1990s were the coldest period since the 1950s (Fig. 3) and even since the 1930s (not shown). The behaviour of winter SAT is roughly similar to that of autumn, and is characterized by a cooling trend up to the mid-1990s. On the other hand, in spring and summer an increase in the rate of warming (seen from the 1960s) started earlier, i.e. in the mid-1980s (Fig. 3). From this figure it is also evident that the last 11 years are the warmest in all seasons since 1951. They are also warmer than the period 1936–45 (except for winter) when the greatest warming of

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Table 1. Anomalies of mean seasonal and annual SAT (in °C) in the Arctic referred to the mean 1951–90. Bold font indicates the highest temperature anomaly values

Area	Dec.–Feb.		Mar.–May		Jun.–Aug.		Sep.–Nov.		Annual	
	1995–2005	2001–05	1995–2005	2001–05	1995–2005	2001–05	1995–2005	2001–05	1995–2005	2001–05
Atlantic region	0.91	**1.46**	**1.25**	1.07	0.60	1.12	1.07	1.34	0.98	1.34
Siberian region	0.46	–0.04	1.05	1.12	0.51	0.79	**1.14**	**1.55**	0.82	0.93
Pacific region	0.93	2.11	**2.17**	**2.51**	0.74	1.25	1.81	2.07	**1.45**	**1.93**
Canadian region	1.14	1.12	1.24	0.65	0.78	0.58	**1.82**	**1.98**	1.26	1.11
Baffin Bay region	0.99	**1.98**	1.12	1.77	0.63	0.99	**1.15**	1.74	1.02	1.62
Arctic 1	0.93	1.28	1.33	1.17	0.68	0.89	**1.46**	**1.74**	1.12	**1.3**
Arctic 2	0.89	0.92	**1.16**	1.10	0.64	0.91	1.06	**1.33**	0.93	1.07
Arctic 3	0.93	0.98	**0.95**	0.91	0.60	0.85	0.75	**1.14**	0.81	0.97
Arctic 4	0.95	1.06	1.33	1.14	0.76	0.90	**1.38**	**1.66**	**1.13**	1.25
NH (land+ocean)	**0.56**	0.57	0.49	0.57	0.54	0.60	0.51	**0.66**	0.52	0.61

Note: Arctic 1: areally averaged SAT based on data from 34–35 Arctic stations; Arctic 2: areally averaged SAT for 65–90° N latitude band (source: Jones and others, 1999, updated); Arctic 3: areally averaged SAT for 60–90° N latitude band (source: Jones and others, 1999, updated); Arctic 4: areally averaged SAT based on data from 18–19 Arctic stations, having the longest series; NH (land+ocean): areally averaged SAT for Northern Hemisphere (source: Jones and others, 1999, updated).

the Arctic in the 20th century occurred (not shown). As a result, the areally averaged annual Arctic SAT is now also higher than for the whole of the 20th century, and, taking into account the results obtained by Overpeck and others (1997), Przybylak (2000, 2002) and also by Przybylak and Vizi (2005), it is possible to state that the period 1995–2005 is probably one of the warmest since the 17th century. It is also worth noting here the especially high SAT in 2005 (which increased by >2.0°C in comparison with the 1951–90 mean) (Fig. 3). That year was over 0.5°C warmer than 1938, which was the warmest year in the 20th century.

Table 2. Seasonal and annual SAT trends (°C decade^{-1}) in the Arctic, 1936–2005

Station/region	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.	Annual
Angmagssalik	0.01	–0.12	–0.13‡	–0.02	–0.06
Jan Mayen	0.03	0.13	0.04	–0.03	0.05
Svalbard Lufthavn	–0.22	0.26*	0.16‡	–0.01	0.06
Björnöya	–0.10	0.25*	0.09	–0.04	0.06
Naryan Mar	–0.17	0.21	0.05	–0.18	0.01
Ostrov Dikson	–0.35	0.00	–0.06	–0.22	–0.15
Khatanga	–0.15	0.16	0.03	–0.07	–0.00
GMO E. K. Fedorova	–0.42*	0.05	–0.03	–0.33*	–0.17*
Ostrov Kotelny	–0.13	0.11	0.01	–0.19	–0.04
Mys Shmidta	0.03	0.29*	0.19†	0.07	0.15*
Ostrov Vrangel	0.16	0.27†	0.06	0.13	0.16†
Barrow	0.23	0.32†	0.16*	–0.02	0.17*
Inuvik	0.51‡	0.23	0.19†	0.14	0.27‡
Coppermine A	0.24	0.03	0.14	0.10	0.13
Cambridge Bay A	0.25*	0.00	0.10	0.19	0.14*
Churchill A	0.20	0.17	0.13	0.06	0.14*
Coral Harbour A	–0.01	–0.09	0.21†	0.24*	0.09
Kuujjuarapik A	0.04	0.09	0.26†	0.16*	0.14
Godthab	–0.20	–0.25†	–0.19‡	0.02	–0.15*
Arctic 1	–0.01	0.11*	0.08*	–0.00	0.04
Arctic 2	0.02	0.12*	0.06*	–0.05	0.03
Arctic 3	0.10	0.16‡	0.07†	–0.02	0.07*
NH (land+ocean)	0.09‡	0.08‡	0.06‡	0.05‡	0.07‡

*†‡ Trends statistically significant at the levels of 0.05, 0.01 and 0.001, respectively.
Note: Arctic 1: areally averaged SAT based on data from 18–19 Arctic stations; Arctic 2: areally averaged SAT for 65–90° N latitude band (source: Jones and others, 1999, updated); Arctic 3: areally averaged SAT for 60–90° N latitude band (source: Jones and others, 1999, updated); NH (land+ocean): areally averaged SAT for Northern Hemisphere (source: Jones and others, 1999, updated).

Table 1 shows how large these SAT anomalies are in comparison to the 1951–90 reference period. In the past 11 years (1995–2005) the Arctic was warmer than the norm by 1.12°C. The greatest warming in the annual course occurred in autumn (by 1.46°C) and spring (by 1.33°C), and the lowest in summer (by 0.68°C). The warming was greatest in the Pacific region (by 1.45°C) and in the Canadian region (by 1.26°C), and lowest in the Siberian region (by 0.82°C). Spatial distribution of annual SAT anomalies averaged for the period 1995–2005 is shown in Figure 4. The greatest warming (>1.5°C) occurred in northern Alaska and in the Beaufort Sea. Anomalies of >1.0°C were noted in the rest of the Arctic, except for most of the Russian Arctic, southern Greenland and the southern part of the Baffin Bay region. Roughly similar patterns of spatial distribution of SAT anomalies were observed in winter and autumn (not shown), but of course in both cases the differentiation of anomalies was about twice as high and oscillated between 2–3°C and 0.5°C. In spring, the greatest warming (by >1.5°C) was noted in the Pacific region, in the central and northern parts of the Canadian Arctic Archipelago and in the region from Spitsbergen to Severnaya Zemlya. Lower warming (<0.5°C) occurred in the isolated areas located in southern Greenland and in the Kola Peninsula and the eastern part of the Siberian Arctic. In summer, the greatest warming (>1.0°C) was observed in the continental part of the Canadian Arctic, and the least (<0.5°C) in the central part of the Arctic Ocean and in the western part of the Russian Arctic (not shown).

The areally averaged annual Arctic SAT for the 5 years 2001–05 was warmer than any of the other 5 year averages since 1951. In comparison with the mean SAT from 1951 to 1990, the described period was warmer by 1.30°C (Table 1). Considerable warming occurred mainly in the Pacific (1.93°C) and Baffin Bay (1.62°C) regions. The lowest warming (by 0.93°C) occurred in the Siberian region.

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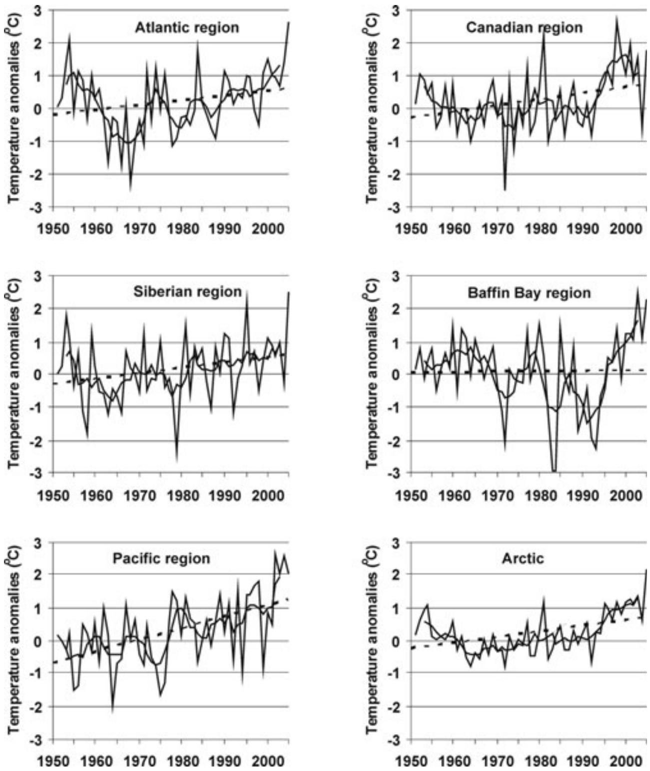

Fig. 2. Year-to-year courses of mean annual anomalies of SAT and their trends in the climatic regions of the Arctic and for the Arctic as a whole over the period 1951–2005 (based on data from 35 stations). Solid lines are year-to-year courses, heavy solid lines are running 5 year mean and dashed lines are linear trends.

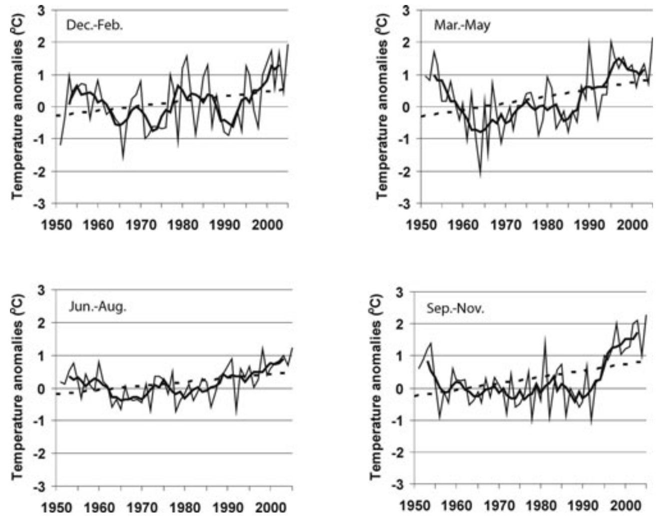

Fig. 3. Year-to-year courses of mean seasonal anomalies of SAT and their trends in the Arctic over the period 1951–2005 (based on data from 35 stations). Solid lines are year-to-year courses, heavy solid lines are running 5 year mean and dashed lines are linear trends.

Here even in the winter a small negative anomaly is noted (–0.04°C). On the other hand, this season displayed the greatest warming of all the analyzed seasons in the Baffin Bay and Atlantic regions. Autumn anomalies in these areas are only a little lower than in winter. However, in turn, in the Canadian and Siberian regions this season warmed more than others. The greatest anomaly in spring was only noted in the Pacific region. The spatial distributions of seasonal and annual anomalies of SAT in the Arctic during this time period (not shown) are generally similar to those described for the period 1995–2005. The anomalies are greatest almost everywhere, except (in general terms) for winter in the Siberian region, spring in the Atlantic and Canadian regions and summer in the Canadian region. Thus, the greatest change of SAT anomalies in the Arctic between the periods 1995–2005 and 2001–05 occurred in the Canadian Arctic where a significant decrease in the rate of warming in the warm half-year was noted (see Table 1).

Comparison of the SAT anomalies for the real Arctic (Arctic 1), for the latitude band 61–90° N (Arctic 3) and for the Northern Hemisphere (NH) presented in Figure 5 shows that in the first region they were the greatest in the 1950s and from 1995 onward. On the other hand, from the beginning of the 1960s to the mid-1990s the SAT anomalies here were mainly lower than in the two other analyzed areas. Visual analysis of the 5 year running mean anomalies for the real Arctic and for the Northern Hemisphere proves the correctness of the earlier statement that the marked warming of the former region occurred later (about 15–20 years) than the warming in the latter one. On the other hand, this behaviour is not evident for the SAT in the latitude band 60–90° N, which shows steady

Table 3. Seasonal and annual SAT trends (°C decade^{-1}) in the Arctic

Area	1951—2005					1976–2005				
	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.	Annual	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.	Annual
Atlantic region	0.09	0.29†	0.10*	0.09	0.15	0.70	0.60*	0.45‡	0.53†	0.59‡
Siberian region	0.12	0.29*	0.04	0.17	0.16*	0.08	0.69*	0.29	0.59	0.48*
Pacific region	0.45†	0.46†	0.25‡	0.26	0.35‡	0.12	1.08†	0.27	0.66	0.52*
Canadian region	0.16	0.12	0.14*	0.30†	0.18*	0.20	0.52	0.48†	0.94†	0.53*
Baffin Bay region	–0.02	–0.10	0.00	0.15	0.02	0.33	0.62	0.51†	0.80†	0.57
Arctic 1	0.16*	0.21†	0.12†	0.20*	0.18‡	0.36	0.65‡	0.42‡	0.74‡	0.54‡
Arctic 2	0.22†	0.29‡	0.14‡	0.14*	0.19‡	0.38*	0.60‡	0.40‡	0.51‡	0.45‡
Arctic 3	0.28‡	0.31‡	0.14‡	0.13†	0.21‡	0.42*	0.53‡	0.41‡	0.42‡	0.43‡
NH (land + ocean)	0.13‡	0.13‡	0.10‡	0.10‡	0.12‡	0.27‡	0.24‡	0.25‡	0.25‡	0.25‡

*†‡ Trends statistically significant at the levels of 0.05, 0.01 and 0.001, respectively.

Note: Arctic 1: areally averaged SAT based on data from 34–35 Arctic stations; Arctic 2: areally averaged SAT for 65–90° N latitude band (source: Jones and others, 1999, updated); Arctic 3: areally averaged SAT for 60–90° N latitude band (source: Jones and others, 1999, updated); NH (land+ocean): areally averaged SAT for Northern Hemisphere (source: Jones and others, 1999, updated).

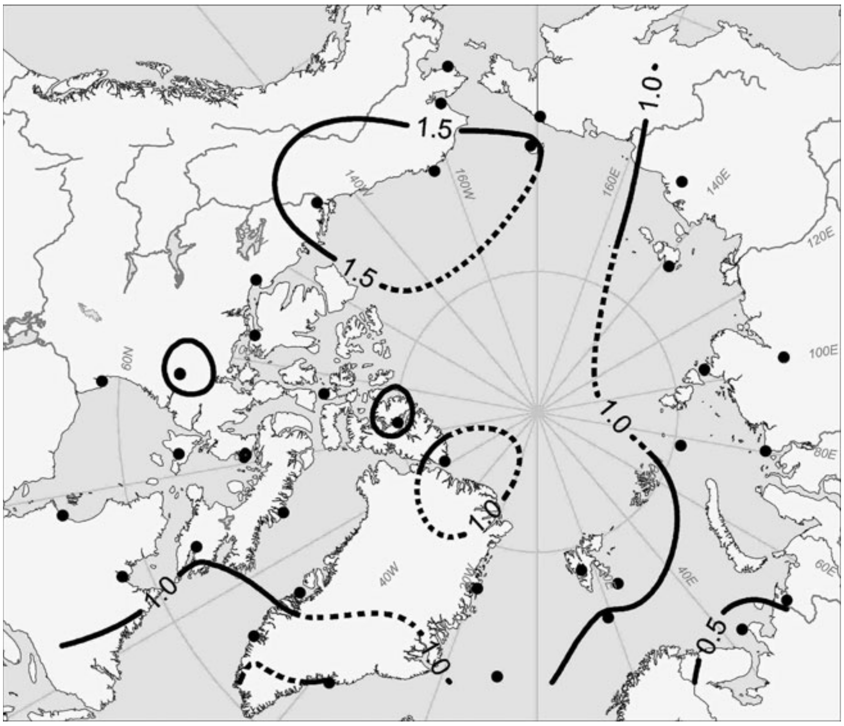

Fig. 4. The spatial distribution of the anomalies of mean annual 11 year (1995–2005) SAT, with the 1951–90 mean (°C) in the Arctic. Dashed contours over Greenland and the central part of the Arctic Ocean indicate that the data are extrapolated from the coastal stations.

warming since the mid-1960s. The rate of warming here is also significantly greater than for the Northern Hemisphere. Thus, the delimitation of the southern boundary of the Arctic is very important for the estimation of areally averaged Arctic SAT tendencies. For more details see Przybylak (2000, 2002, 2003). Therefore, in my opinion, the greatest weakness of the popular Arctic Climate Impact Assessment (ACIA) report (Huntington and others, 2005) is connected with the way in which it delimits the southern boundary of the Arctic. The report states in the introduction (p. 2): 'there was a deliberate decision not to define the Arctic for the assessment as a whole. Each chapter of this report describes the area that is relevant to its particular subject, implicitly or explicitly determining its own southern boundary'.

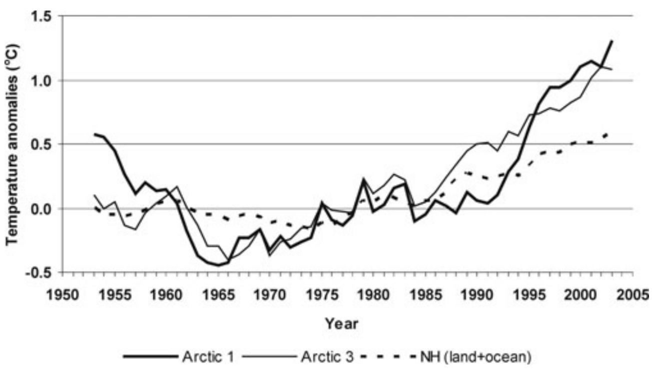

Fig. 5. Running 5 year mean annual anomalies of SAT in the Arctic (Arctic 1 and Arctic 3) and the Northern Hemisphere (NH) over the period 1951–2005. Arctic 1: areally averaged SAT based on data from 35 Arctic stations (see Fig. 1); Arctic 3: areally averaged SAT for 60–90° N latitude band (after Jones and others, 1999, updated); NH: combined land+ocean areally averaged SAT for Northern Hemisphere (after Jones and others, 1999, updated).

SAT TRENDS

1936–2005

During the period 1936–2005, statistically significant trends in areally averaged Arctic SAT (Arctic 1) are noted for spring (0.11°C decade^{-1}) and summer (0.08°C decade^{-1}). In the other two seasons, SAT trends were slightly negative and not statistically significant (Table 2). A similar situation is also seen in the latitude bands 65–90° N (Arctic 2) and 60–90° N (Arctic 3) except for winter, when positive trends occur. These small SAT trends in the period analyzed are influenced by the very warm conditions that prevail during the early part of the study period. On the other hand, the Northern Hemisphere shows statistically significant positive SAT trends in all seasons and for the year as a whole. It is worth noting that the trends here are significantly higher than in the real Arctic in the cool half-year, while they are only a little lower in the warm half-year. As a result, the trend of the areally averaged annual NH SAT is almost twice as large as it is for the Arctic.

The majority of stations used to calculate areally averaged seasonal and annual Arctic SAT show positive trends. Such trends clearly dominate in spring and summer, being statistically significant in the Pacific region and in Spitsbergen (Table 2). Negative SAT trends in these seasons generally occur only in Greenland (where they are even statistically significant) and probably also in the Baffin Bay region. In autumn and winter mixed trends occur. Only three stations show statistically significant trends in every season analyzed (one negative and two positive). Annual values of SAT trends are mainly positive, being statistically significant in the Tschukotka Peninsula, Alaska and the northwestern part of the Canadian Arctic. Negative and, in the case of some stations, statistically significant SAT trends are noted for stations located in the Siberian region and in Greenland (Table 2).

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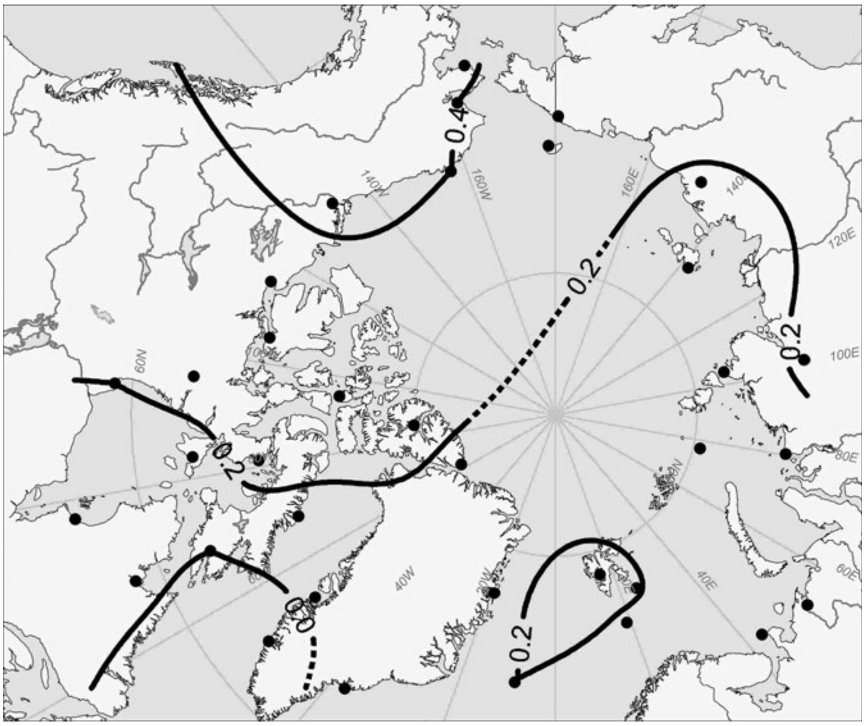

Fig. 6. The spatial distribution of the mean annual trends in SAT (°C decade^{-1}) in the Arctic over the period 1951–2005. Dashed contours over Greenland and the central part of the Arctic Ocean indicate that the data are extrapolated from the coastal stations.

1951–2005

The trends of areally averaged SAT for the whole Arctic during this period are positive and statistically significant for all seasons and for the year as a whole. The greatest trends for the real Arctic (Arctic 1) may be noted for spring (0.21°C decade^{-1}) and for autumn (0.20°C decade^{-1}), and the lowest for summer (0.12°C decade^{-1}) (Table 3). In the case of the two other Arctic regions (Arctic 2 and Arctic 3), trends for winter are greater than for autumn. Also the Northern Hemisphere has the largest trends in spring and winter. In the period analyzed, the real Arctic warmed 1.5 times more than the Northern Hemisphere.

At a regional level, statistically significant trends of areally averaged mean annual SAT are noted for the Pacific (0.35°C decade^{-1}), Canadian (0.18°C decade^{-1}) and Siberian (0.16°C decade^{-1}) regions. Slight warming was noted in the Baffin Bay region (0.02°C decade^{-1}), where trends for winter and spring were even negative (Table 3). The majority of regions display statistically significant positive trends in spring and summer, while in autumn and winter statistically positive trends only occurred in one region.

The spatial distribution of mean annual SAT trends in the Arctic is presented in Figure 6. It is evident that the greatest positive trends (>0.4°C) occurred in Alaska, while the lowest trends were noted in the southern part of the Baffin Bay region (negative) and in the western part of the Russian Arctic and the neighbouring Arctic Ocean. In winter and summer, the spatial patterns of trends (not shown) are similar to the described pattern for the annual values. However, the differences between the highest and lowest trend values are greater in winter (>0.8 to <–0.2°C decade^{-1}) than in summer (>0.2 to <0.0°C decade^{-1}). In spring, significant warming (comparable to that in Alaska) was also observed throughout the Russian Arctic (about 0.4°C decade^{-1}). In turn, in autumn, the greatest SAT trends (not shown) occurred in the central and northern parts of the Canadian Arctic and in the central part of the Siberian region (>0.4°C decade^{-1}), while the lowest were in the Atlantic region and the southern part of the Baffin Bay region (<0.1°C decade^{-1}).

1976–2005

During this period a significant increase in the Arctic SAT is noted, especially in the last 11 years. As a result, trends of areally averaged SAT are greater than in the two previously described periods. Similar to the period 1951–2005, statistically significant trends occurred for all seasons, though with the exception of winter in the real Arctic (Table 3). Again, the greatest trends are noted for spring (0.65°C decade^{-1}) and autumn (0.74°C decade^{-1}). Positive trends in the areally averaged annual SAT occurred in all regions. They are also statistically significant, except in the Baffin Bay region. The greatest increase in the annual SAT was observed in the Atlantic region (0.59°C decade^{-1}) and in the Baffin Bay region (0.57°C decade^{-1}), and the lowest was in the Siberian region (0.48°C decade^{-1}). Only in winter were statistically significant SAT trends not noted in any region.

Reasons for the most recent rapid warming of the Arctic

The issue of the physical causes of the greatest SAT anomalies in the last century in the Arctic (warming in the 1930s and 1940s, cooling in the 1960s and 1970s, and present warming) has been investigated by many researchers. As far as the fluctuations of SAT in the 20th century until about the 1970s are concerned, generally there is a consensus indicating that the observed changes are due to natural variations. Both empirical and modeling studies confirm this (e.g. Moritz and others, 2002; Przybylak, 2002; Polyakov and others, 2003; Bengtsson and others, 2004; Johannessen and others, 2004; Overland and Wang, 2005;

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Styszyńska, 2005; Turner and others, 2006). On the other hand, it is difficult to say whether these natural fluctuations are manifestations of the internal variability of the Arctic Climate System or whether they are externally forced (e.g. by changes in solar irradiance or volcanic activity). Some researchers are convinced that the greatest role is played by internal variability of the climate system (e.g. Delworth and Knutson, 2000; Bengtsson and others, 2004; Johannessen and others, 2004; Overland and others, 2004b; Overland and Wang, 2005), while others have concluded that external factors are more important (e.g. Crowley, 2000; Soon, 2005). The latter author found, for example, that variations in total solar irradiance can explain a larger amount of the observed multi-decadal variability (>75% of the 10 year running means of the annual Arctic SAT) than increases in atmospheric CO_2 (only 8–22%). It seems, however, that the most plausible explanation for this warming is the low-frequency, multi-decadal oscillation related to the North Atlantic Ocean circulation (Schlesinger and Rammankutty, 1994; Delworth and Mann, 2000; Polyakov and Johnson, 2000; Styszyńska, 2005). For a more detailed discussion of this problem see, for example, Moritz and others (2002), Bengtsson and others (2004), Johannessen and others (2004) or Overland and others (2004a, b).

The driving mechanism behind the present global warming (since 1975), including also the Arctic warming, is a significantly more complicated issue and therefore it has provoked a variety of explanations. Some researchers suggest that the present warming of the Arctic is caused mainly by anthropogenic greenhouse gases (e.g. Overpeck and others, 1997; Johannessen and others, 2004). Others, in turn, have argued that the warming is mainly driven by natural factors (Polyakov and Johnson, 2000; Moritz and others, 2002; Przybylak, 2002; Polyakov and others, 2003; Overland and Wang, 2005; Styszyńska, 2005). Most researchers suggest that the key factors are the atmospheric and ocean circulations, which in recent years have been transporting significantly more warmth from the lower latitudes to the Arctic (see, e.g., Zhang and others, 2004). Internal variability within the Arctic Climate System is also very often given as an explanation (e.g. Overland and Wang, 2005). The question is, however, whether these factors should still be treated as purely natural. It seems to me that they probably should not, but it is very plausible that the natural factors are still more powerful than the anthropogenic ones.

This short review shows that although much has been done to explain the physical mechanism of multi-decadal fluctuations of the Arctic SAT, further research is still needed. For example, the question still remains as to which factors (natural or anthropogenic) have greatest influence on the current observed changes occurring in the Arctic Climate System. Another still unresolved problem is that of the abrupt change of Arctic SAT in the mid-1990s (mainly from 1994 to 1995). No work has yet been devoted to this issue, which is probably connected with the fact that this large rise in SAT is mostly present in the time series constructed for the real Arctic, and is not clearly seen in other so-called Arctic series (see, e.g., Polyakov and others, 2003). However, surface skin temperature estimates based on satellite data for the latitude band 60–90° N clearly confirm the existence of this abrupt change in SAT (see fig. 3 in Wang and Key, 2005). A rise in skin temperature is markedly seen in the winter, autumn and, in particular, spring (>2°C). As a result, the annual mean value from 1994 to 1995 rose by about 1.5°C. Similar to the SAT series for the real Arctic, skin temperature has also remained at this high level at least up to 1999.

Analyses of the published meteorological data suggest that the reasons for the abrupt temperature change from 1994 to 1995 are very complex. However, it is possible to distinguish at least four likely groups of reasons:

the occurrence of a very low average surface broadband albedo (37%, the lowest in the whole study period 1982–99; see fig. 3 in Wang and Key, 2005), which was probably mainly caused by the area of sea ice in the Northern Hemisphere in 1995 being at its lowest since the start of satellite measurements in 1979 (see, e.g., fig. 3 in Overland and Wang, 2005). As a result of that albedo, Wang and Key (2005) found very high values for seasonal (except summer) and annual net all-wave radiation fluxes in the mid-1990s (see their fig. 10). The reliability of such explanations was recently proved by Chapin and others (2005) who investigated the field data for Arctic Alaska and concluded that 'terrestrial changes in summer albedo contribute substantially to recent high-latitude warming trends'. All of these processes are part of sea-ice–albedo–temperature positive feedback (for more details see Moritz and others, 2002, p. 1499). The significant strengthening of this feedback which was observed from 1994 to 1995 could be caused both by natural and anthropogenic factors (some of which are given below).

the very large decrease in sea-level atmospheric pressure, which in the 1990s was at its lowest since the 1880s (see fig. 2 in Polyakov and others, 2003). As a result of that change, the cyclone activity index had the greatest positive anomalies in this decade in comparison with the previous 42 year period (see fig. 5 in Zhang and others, 2004). This means that transport of humid and warm masses from the lower latitudes to the Arctic was the highest at this time (see also Serreze and others, 1993). Much of this decrease in sea-level pressure can be linked to the Arctic Oscillation (Moritz and others, 2002). In turn, some climatic models support the hypothesis that the recent trend in the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) is a consequence of anthropogenic radiative forcing that somehow excites these generally free modes of atmospheric circulation variability. However, there is only a rather small probability that the observed change in AO/NAO behaviour from a positive to a neutral phase in the mid-1990s was responsible for the great rise in temperature from 1994 to 1995. Correlation maps between AO/NAO and temperature in the Arctic presented by Przybylak (2000) and Polyakov and others (2003) evidently show that such a change in AO/NAO behaviour should rather lead to a cooling of the Arctic. On the other hand, Polyakov and others (2003, p. 2067) found that 'peaks in temperature associated with the LFO (low-frequency oscillation) follow pressure minima after 5–15 yr'. If we assume the existence of that delay to be 5–6 years in the last decades of the 20th century then it is possible to explain the temperature peak in 1995 by the significant decrease in air pressure observed at the turn of the 1980s and 1990s.

the rapid rise of sea surface temperature in the mid-1990s (by 1–2°C) for example in the West Spitsbergen Current (Dickson and others, 2000; Kruszewski, 2004), being the result of the intensification of the inflow of Atlantic water to the Arctic reported by many researchers (e.g. Alekseev, 1997; Zhang and others, 1998; Dickson and others, 2000; Styszyńska, 2005).

the combined effect of these changes.

CONCLUSIONS

1. In the Arctic in the mid-1990s an abrupt rise in SAT was noted (by about 1°C in comparison with the 1951–90 mean); this then stabilized and has remained at this level up to now. The greatest warming occurred in autumn and spring, and the lowest in summer and winter. In the period 1995–2005, the warming was greatest in the Pacific (by 1.45°C) and Canadian (by 1.26°C) regions, and lowest in the Siberian region (by 0.82°C).

2. The temperatures in spring, summer and autumn from 1995 onwards are significantly greater than in the 1930s, which was the warmest period in the 20th century in the Arctic. On the other hand, the SAT in winter had slightly smaller values. Based on an analysis of historical data (e.g. Overpeck and others, 1997; Przybylak and Vizi, 2005) it can also be concluded that the period 1995–2005 was the warmest since at least the 17th century. The year 2005 was also exceptionally warm (>2°C above the 1951–90 mean), and was even warmer than 1938, the warmest year in the 20th century.

3. The greatest disparity may be noted with regard to winter SAT which, according to the prognoses based on climatic models, should have been subject to the greatest warming.

4. Changes in the Arctic SAT in the 20th century until about the 1970s are, according to the investigations done by a majority of researchers, mainly the result of the influence of natural factors, while mixed opinions exist regarding the forces driving the present warming. On the other hand, it seems likely that the marked rise in SAT in the mid-1990s was caused by (i) a set of natural factors, (ii) the non-linear effects of greenhouse-gas loading or (iii) the combined effect of these two groups of factors.

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REFERENCES

Alekseev, G.V. 1997. Arctic climate dynamics in the global environment. *In Proceedings of the ACSYS Conference on Polar Processes and Global Climate, 3–6 November 1997, Rosario, Orcas Islands, Washington.* Oslo, International Arctic Climate System Study Project Office, 11–14.

Bengtsson, L., V.A. Semenov and O.M. Johannessen. 2004. The early twentieth-century warming in the Arctic – a possible mechanism. *J. Climate,* **17**(20), 4045–4057.

Bobylev, L.P., K.Ya. Kondratyev and O.M. Johannessen, *eds.* 2003. *Arctic environment variability in the context of global change.* Chichester, Springer-Praxis.

Chapin, F.S., III *and 20 others*. 2005. Role of land-surface changes in Arctic summer warming. *Science,* **310**(5748), 657–660.

Comiso, J.C. 2003. Warming trends in the Arctic from clear-sky satellite observations. *J. Climate,* **16**(21), 3498–3510.

Crowley, T.J. 2000. Causes of climate change over the past 1000 years. *Science,* **289**(5477), 270–277.

Delworth, T.L. and T.R. Knutson. 2000. Simulation of early 20th century global warming. *Science,* **287**(5461), 2246–2250.

Delworth, T.L. and M.E. Mann. 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dyn.,* **16**(9), 661–676.

Dickson, R.R. *and 8 others*. 2000. The Arctic Ocean response to the North Atlantic Oscillation. *J. Climate,* **13**(15), 2671–2696.

Huntington, H., G. Weller, E. Bush, T.V. Callaghan, V.M. Kattsov and M. Nuttall. 2005. Introduction to the Arctic climate impact assessment. *In Arctic climate impact assessment: scientific report.* Cambridge, etc., Cambridge University Press, 1–20.

Johannessen, O.M. *and 11 others*. 2004. Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus,* **56A**(5), 328–341.

Jones, P.D., M. New, D.E. Parker, S. Martin and I.G. Rigor. 1999. Surface air temperature and its changes over the past 150 years. *Rev. Geophys.,* **37**(2), 173–199.

Kalnay, E. *and 21 others*. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.,* **77**(3), 437–471.

Kruszewski, G. 2004. Zmienność temperatury powierzchni morza w rejonie Spitsbergenu (1982–2002) [Sea surface temperature variability in the region of Spitsbergen (1982–2000) as a signal of current climatic changes]. *Probl. Klimatol. Polarnej,* **14**, 79–86.

McBean, G. *and 9 others*. 2005. Arctic climate – past and present. *In Arctic climate impact assessment: scientific report.* Cambridge, etc., Cambridge University Press, 22–60.

Moritz, R.E., C.M. Bitz and E.J. Steig. 2002. Dynamics of recent climate change in the Arctic. *Science,* **297**(5586), 1497–1502.

Overland, J.E. and M. Wang. 2005. The Arctic climate paradox: the recent decrease of the Arctic Oscillation. *Geophys. Res. Lett.,* **32**(6), L06701. (10.1029/2004GL021752.)

Overland, J.E., M.C. Spillane and N.N. Soreide. 2004a. Integrated analysis of physical and biological pan-Arctic change. *Climatic Change,* **63**(3), 291–322.

Overland, J.E., M.C. Spillane, D.B. Percival, M. Wang and H.O. Mofjeld. 2004b. Seasonal and regional variation of pan-Arctic surface air temperature over the instrumental record. *J. Climate,* **17**(17), 3263–3282.

Overpeck, J. *and 17 others*. 1997. Arctic environmental change of the last four centuries. *Science,* **278**(5341), 1251–1256.

Polyakov, I.V. and M.A. Johnson. 2000. Arctic decadal and interdecadal variability. *Geophys. Res. Lett.,* **27**(24), 4097–4100.

Polyakov, I.V. *and 7 others*. 2003. Variability and trends of air temperature and pressure in the maritime Arctic, 1875–2000. *J. Climate,* **16**(12), 2067–2077.

Przybylak, R. 1996. *Zmienność temperatury powietrza i opadów atmosferycznych w okresie obserwacji instrumentalnych w Arktyce* [Variability of air temperature and precipitation over the period of instrumental observation in the Arctic]. Rozprawy, Uniwersytet Mikolaja Kopernika.

Przybylak, R. 2000. Temporal and spatial variation of surface air temperature over the period of instrumental observations in the Arctic. *Int. J. Climatol.,* **20**(6), 587–614.

Przybylak, R. 2002. *Variability of air temperature and atmospheric precipitation in the Arctic.* Dordrecht, etc., Kluwer Academic Publishers.

Przybylak, R. 2003. *The climate of the Arctic.* Dordrecht, etc., Kluwer Academic Publishers.

Przybylak, R. and Z. Vizi. 2005. Air temperature changes in the Canadian Arctic from the early instrumental period to modern times. *Int. J. Climatol.,* **25**(11), 1507–1522.

Rigor, I.G., J.M. Wallace and R.L. Colony. 2002. Response of sea ice to the Arctic Oscillation. *J. Climate,* **15**(18), 2648–2663.

Schlesinger, M.E. and N. Ramankutty. 1994. An oscillation in the global climate system of period 65–70 years. *Nature,* **367**(6465), 723–726.

Serreze, M.C., J.E. Box, R.G. Barry and J.E. Walsh. 1993. Characteristics of Arctic synoptic activity, 1952–1989. *Meteorol. Atmos. Phys.,* **51**(3), 147–164.

Soon, W.-H. 2005. Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years. *Geophys. Res. Lett.,* **32**(16), L16712. (10.1029/2005GL023429.)

Styszyńska, A. 2005. *Przyczyny i mechanizmy współczesnego (1982–2002) ocieplenia atlantyckiej Arktyki* [Causes and mechanisms of present (1982–2002) warming of the Atlantic part of the Arctic]. Gdynia, Akademia Morska.

Treshnikov, A.F., *ed.* 1985. *Atlas Arktiki.* Moscow, Glavnoye Upravlenye Geodeziy i Kartografiy.

Turner, J., J.E. Overland and J.E. Walsh. 2006. An Arctic and Antarctic perspective on recent climate change. *Int. J. Climatol.,* **27**(3), 277–293.

Vizi, Z. and R. Przybylak. In press. Spatial distribution of the air temperature in the American Arctic for different databases and methods. *In Proceedings of the Conference on Spatial Interpolation in Climatology and Meteorology, 24–29 October 2004, Budapest, Hungary.* 46.

Wang, X. and J.R. Key. 2005. Arctic surface, cloud, and radiation properties based on the AVHRR Polar Pathfinder Dataset. Part II: recent trends. *J. Climate,* **18**(14), 2575–2593.

Zhang, J., D.A. Rothrock and M. Steele. 1998. Warming of the Arctic Ocean by strengthened Atlantic inflow: model results. *Geophys. Res. Lett.,* **25**(10), 1745–1748.

Zhang, X., J.E. Walsh, J. Zhang, U.S. Bhatt and M. Ikeda. 2004. Climatology and interannual variability of Arctic cyclone activity: 1948–2002. *J. Climate,* **17**(12), 2300–2317.