9. AIR TEMPERATURE

9.1. Annual air temperature

The multiannual mean annual air temperature in the recording period at Hornsund (1979–2009) was –4.3°C. The lowest recorded mean annual air temperature amounted to –7.3°C (1988), the highest to –1.5°C (2006). The distribution of mean annual temperatures in the period differs (to an insignificant extent) from a normal distribution, showing left hand skewness. The greatest number of individual annual mean temperatures (10 observations) is in the range between –5.99 and –5.00°C, when in an expected normal distribution the maximum of observations (8–9 observations) should rank between –4.99 and –4.00°C and incorporate the multiannual (or “grand”) mean. The two next ranges in which annual mean temperature fell most frequently, were from –3.99 to –3.00°C (7 observations) and from –4.99 to –4.00°C (6 observations; Fig. 9.1). In its distribution of mean annual air temperature, the Hornsund station is a transient type between oceanic, skewed to the left Björnöya, and the more "continental" stations situated further north on Spitsbergen (Ny Ålesund, Svalbard-Lufthavn; Fig. 9.1).

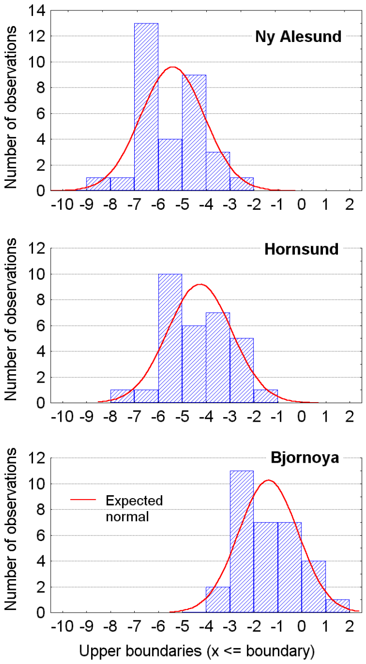

Fig. 9.1. Frequency of annual air temperature in ranges of one degree centigrade [°C] at the Ny Ålesund, Hornsund and Björnöya stations in 1979–2009.

The interannual variability of annual air temperature at Hornsund was not great, the standard deviation (σn) being only 1.34°C. This value is almost exactly the same as the standard deviation of annual temperature at Ny Ålesund (1.33°C) and only somewhat smaller than the standard deviation of annual air temperature at the Svalbard-Lufthavn station (1.67°C) located in the interior of the island.

The course of mean annual air temperatures at Hornsund is shown in Fig. 9.2. The first, most important feature of this course is the distinct increase of annual air temperature over the period of the station record. A statistically significant positive trend of the annual temperature equal +0.096 (±0.021)°C·yr^{-1} ($p < 0.00007$) occurs here. This trend explains 40.7% of the variance of annual mean temperatures during the investigated period.

Such positive sub-trends in the course of air temperatures at the Hornsund station were suspected for a long time (e.g. Wielbińska 1991), but before 1999 these trends were statistically insignificant. The statistically significant trend appeared for the first time in 2000 (+0.073°C·yr^{-1}, $p < 0.04$) and up to 2009 the positive trend in air temperature remained significant at $p < 0.05$ strength in all consecutive years. The coefficients of the trend ranged from +0.071 to +0.098°C·yr^{-1} in different years.

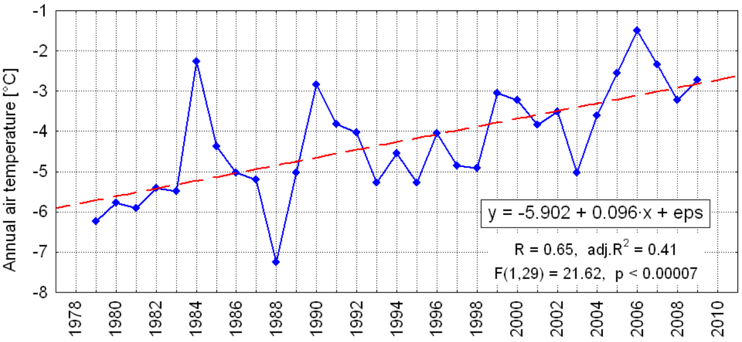

Fig. 9.2. The annual air temperature at Hornsund in 1979–2009.

The second feature of the course of mean annual air temperatures at Hornsund was a sudden, almost linear, increase of annual air temperature in 2004, 2005 and 2006, which led to the fact that the mean temperature in 2006 (–1.5°C) was the highest noted in the history of measurements at the station. Before 2006 the highest recorded annual temperature was –2.3°C (1984). These three years of intensive warming are the reason that the coefficient of the trend is so high.

The course of annual air temperatures at Hornsund shows strong correlations with those at surrounding stations (Fig. 9.3). The correlation coefficients between the annual temperature at Hornsund and annual temperatures at the Svalbard-Lufthavn and Barentsburg stations are 0.99, Ny Ålesund and Hopen – 0.98 ($p < 0.0000$). Correlation with the annual temperature at Björnöya, around 300 km distant, is 0.94, and with the Jan Mayen station (over 1000 km distant), the correlation is 0.84 ($p < 0.0000$). Such a finding shows clearly that the interannual variability of temperature at Hornsund is shaped by sets of climatic processes common to the entire area of the Atlantic Arctic, and that local factors play a lesser role here.

It is also easy to perceive (Fig. 9.3) that Hornsund is warmer than stations situated further north on Spitsbergen and more distant from the direct influences of the Greenland Sea (Svalbard-Lufthavn, Ny Ålesund). Hornsund is however distinctly cooler (~3°C) than Björnöya to the South. It is also seen that in years in which the annual temperature over Spitsbergen is relatively high,

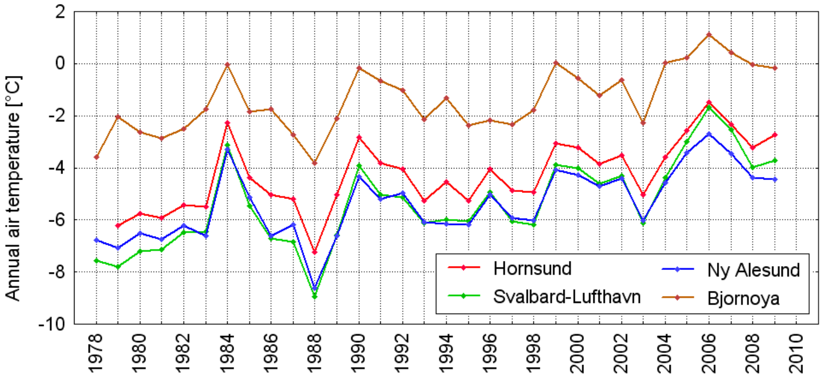

Fig. 9.3. Annual air temperature [°C] at stations: Hornsund, Svalbard-Lufthavn,
Ny Ålesund and Björnöya in 1978–2009.

differences in the temperature between Hornsund and other stations on Spitsbergen decrease. In contrast, in cold years the difference in annual temperature between Hornsund and Ny Ålesund as well as Svalbard-Lufthavn increases – falls of temperature at Hornsund are not as great as at these stations. These distinctions represent relatively stable, minor differences in annual temperature between Hornsund and other stations that, depending on the thermal characteristics of a given year, are manifestations of the activity of local factors. Local differences include, first of all, the opening of Hornsund Fjord to the Greenland Sea and thus exposing the station to air flow from it, as well as the proximity of the West Spitsbergen Current carrying warm water and the effects of sheltering from the North and northeast by the mountain ranges.

9.2. Monthly air temperatures

The annual pattern of multi-annual mean monthly air temperatures at the Hornsund station is characterized by a distinct, extended flattening of minimum values and a sharply demarcated peak with a flat top (Fig. 9.4). Such annual behaviour of the air temperature is generally characteristic for areas of the Atlantic Arctic, in which there are very strong marine influences.

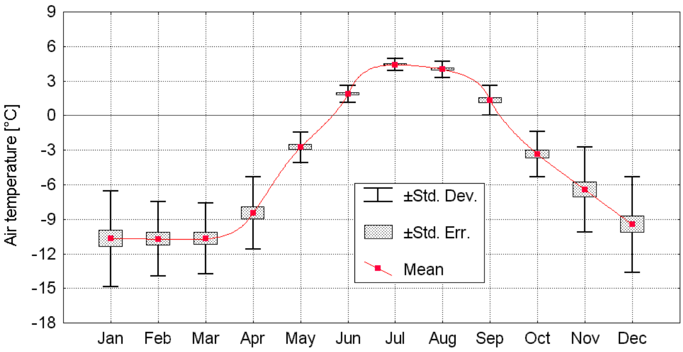

Fig. 9.4. The range of mean monthly air temperatures in 1979-2009.

For many years, minimum monthly temperatures occurred in January and were –10.9°C, whereas the maxima in July reached +4.4°C. The mean multiannual amplitude is thus 15.3 deg. The temperature increased quickly between March and July, to stay at a similar level of around +4°C throughout July and August. The greatest intermonthly increase of temperature occurred on the average between April and May, when the mean increase was 5.7°C. Following the August peak, the decline of temperature continued through to December and was somewhat slower than the spring increase. The fastest decrease of mean monthly air temperature was on the average between September and October, when it was 4.8°C. The winter minimum, encompassing December, January, February and March was characterized by the mean multiannual monthly air temperatures between –9.5 and –10.9°C.

The occurrence of minimum air temperatures always in January and maxima in July is considered to be more characteristic of a continental climate than a marine one, in which, as is commonly considered, there is often a shift of one month in either occurrence. Analysing the pattern of mean monthly values and their statistical characteristics in more detail, (Table 9.1 and Fig. 9.4) it may be noted that between December and March monthly temperatures differed very little. Analysis of the standard error of means and its standard deviation shows that differences between the means of these months are statistically not significant.

Table 9.1. Mean monthly air temperatures (1979–2009) at the Hornsund station and their statistical characteristics

Month	Mean	σn	ΔTa	Min	Max	Max – Min	Lower quartile	Upper quartile
January	–10.9	4.11	–1.4	–17.9	–1.7	16.2	–14.30	–7.40
February	–10.8	3.23	+0.1	–16.6	–5.1	11.5	–13.20	–7.50
March	–10.6	3.09	+0.2	–16.8	–4.9	11.9	–12.50	–7.80
April	–8.5	3.17	+2.1	–14.2	–0.3	13.9	–11.26	–6.30
May	–2.8	1.28	+5.7	–7.3	–0.2	7.1	–3.49	–2.20
June	1.9	0.75	+4.7	–0.1	3.2	3.3	1.40	2.40
July	4.4	0.55	+2.5	3.5	5.5	2.0	4.01	4.78
August	4.1	0.55	–0.3	3.0	5.3	2.3	3.70	4.40
September	1.4	1.24	–2.6	–1.7	4.5	6.2	0.80	2.00
October	-3.4	2.02	–4.8	–7.9	1.9	9.8	–4.20	–2.15
November	–6.4	3.75	–3.0	–14.9	–0.6	14.3	–9.20	–3.40
December	–9.5	4.21	–3.1	–17.5	–1.2	16.3	–12.40	–6.10

Explanations: mean – mean multiannual monthly air temperature, σn – standard deviation from mean monthly temperature, ΔTa – temperature changes from month to month (Ta of preceding month – Ta of current month), Min – the lowest monthly temperature recorded, Max – the highest monthly temperature recorded in a given month.

Particularly small temperature differences occurred between January and February (0.1 deg), when standard errors of mean monthly temperature estimate for January are ±0.74, and for February ±0.58°C. Similarly between February and March difference of mean monthly temperature was 0.2 deg, while standard errors of estimate for each of these means were ±0.58 and ±0.56°C, respectively. There was a somewhat greater difference of mean multiannual monthly temperature between December and January (1.4 deg) and the augmented standard errors increased in concordance, to ±0.73 and ±0.74°C respectively.

Such weakly developed mean air temperature minima in the annual cycle at the Hornsund station result from the very big interannual variability of air temperature during the coldest season of the year, which permits the annual minimum to fall with equal probability in December, January, February, March, and even to occur in April. Over the research period (31 years) the minimum in the annual cycle occurred 7 times in December (1980, 1983, 1985, 1987, 1988, 1991 and 1996), January (1981, 1982, 1993, 1994, 1995, 1997, 2003) and February (1979, 1986, 1989, 1992, 1998, 1999, 2004), 8 times in March (1984, 1990, 2000, 2001, 2002, 2005, 2006 and 2008) and 2 times in April (2007, 2009). Analysing the temporal distribution of the minimum in the annual cycle more accurately one may notice that over the research period an "exchange" of moments of appearance of minimum from December to March occurs (Table 18.16). In the initial part of the 31 year period, the annual minimum occurred more frequently in December. Later on, it occurred more frequently in March. This shift in the timing of the occurrence of the mean minimum temperature in the annual cycle is a result of a strong positive trend in December temperatures (see Chapter 16).

A review of maximum mean monthly air temperatures in the winter at the Hornsund station (December-March; Table 9.1) shows that February and March were the coldest. In neither of these months was the monthly air temperature higher than –5.1 and –4.9°C, respectively. At the same time, the highest monthly air temperature in December was –1.2°C (1984) and in January –1.7°C (2006). Such a distribution of monthly means shows that at Hornsund "the second part" of winter (February-March) is on average cooler than the "first part" (December-January).

More detailed analysis reveals features in the distribution of the winter monthly temperature that are connected with oceanic effects. It is useful to remember here that a characteristic feature of the annual course of monthly air temperatures at the Arctic stations situated in sea ice surroundings is that the minimum occurs in March (Ferdynus 1993).

The flat peak in the monthly temperatures over the annual cycle is created by the monthly means of July (+4.4°C) and August (+4.1°C). The difference between the mean multiannual temperature of these two months is small (0.3 deg) and does not exceed the threshold of statistical significance (the standard errors of estimate of mean temperature of July and August are ±0.10°C). During the whole period of observations at Hornsund, the mean temperature of July and August was higher than 0°C, which definitely differentiates them from other months with multiannual positive means (June, September) in which negative monthly means were recorded in some years. Broadly speaking, this allows us to treat July and August as "the summer".

A similar distribution of temperature occurs at the other Spitsbergen stations: however, in contrast to Hornsund, the differences between the multiannual means of July and August at these stations are significantly greater (Table 9.2). At Barentsburg these differences amounted to 0.8 deg and at Ny Ålesund to 1.0 deg. The greatest differences occurred at Svalbard-Lufthavn (1.1 deg) and Svea (1.2 deg) stations situated in the island's interior.

The interannual variability of monthly air temperature in July and August was very small; standard deviations were only 0.55 deg. Even more distinctly, this small interannual variability in July and August emphasizes the gap between values of the upper and of the lower quartile. Against the background of interannual variability for the other months (Table 9.1 and Fig. 9.4), July and August stand out by their exceptionally stable temperatures.

The minimum recorded monthly mean temperature of "the summer" was +3.0°C in August 1994 and +3.5°C in July 1982. The maximum recorded monthly air temperature of this period was

Table 9.2. The mean monthly and annual air temperature [°C] at the stations on the western coast of Spitsbergen, 1979-2009.

Station	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Ny Ålesund*	–12.5	–13.1	–12.6	–9.9	–3.2	2.1	5.2	4.2	0.2	–5.4	–8.1	–11.1	–5.4
Svalbard-Luft.*	–13.5	–13.9	–13.4	–10.4	–3.1	2.8	6.5	5.4	1.1	–5.1	–8.3	–11.6	–5.3
Barentsburg**	–12.4	–12.6	–12.5	–9.9	–3.5	2.1	5.9	5.1	1.0	–4.8	–7.7	–10.7	–5.0
Svea*	–15.1	–15.2	–14.6	–11.5	–3.8	2.4	6.4	5.2	1.0	–5.4	–9.5	–13.3	–6.1
Hornsund	**–10.9**	**–10.8**	**–10.6**	**–8.5**	**–2.8**	**1.9**	**4.4**	**4.1**	**1.4**	**–3.4**	**–6.4**	**–9.5**	**–4.3**
Björnöya*	–6.3	–6.3	–5.9	–4.2	–0.8	2.4	4.9	5.2	3.3	–0.0	–2.7	–5.5	–1.3

* – data from the Norwegian Meteorological Institute (eKlima), ** – data from RIHMI-WDC[1]

in 2002, when in July it was +5.5°C and in August +5.3°C. A mean monthly temperature of +5.0°C or higher in July was recorded at Hornsund 6 times (in 1985, 1990, 1992, 1998, 2002 and 2009), the same temperature in August occurred 3 times (in 1991, 1998 and 2002). Note that the August temperature in closing part of the series is distinctly higher than in the initial and middle parts. Simultaneously in the closing part of the series there were two years (1998 and 2002), in which the temperature of both July and August reached ≥ +5.0°C, clearly showing "warming of the summer " (Fig. 9.5). The same behaviour is also found at the other stations. However, at Björnöya, Hopen and Svalbard-Lufthavn the increase of mean temperature of July and August is stronger than at Hornsund.

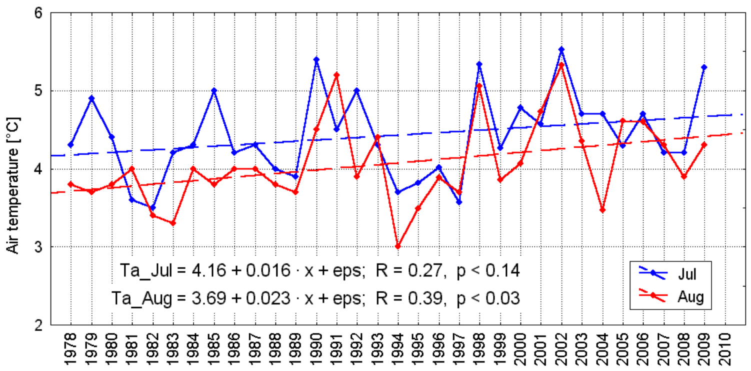

Fig. 9.5. Mean monthly air temperature in July and August at Hornsund in 1978–2009.

9.3. The annual patterns of diurnal temperature

When analysing the diurnal temperatures in the annual cycle at Hornsund it should be remembered that during a year inflow of solar radiant energy changes diametrically. Between April 24 and August 18 there is a polar day during which the Sun is above the horizon during the whole time. The change of the height of the Sun during the day over this period is marked, but for around 1.5 months (around 3 weeks before and 3 weeks after the annual culmination of the Sun) diurnal

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[1] RIHMI-WDC – Russian Research Institute of Hydrometeorological Information – World Data Centre.

changes of its height are small. As a result, the potential changes of inflow of solar energy to the ground are also small. The real variability of diurnal temperature is determined by the changes of cloudiness and the advection factor. Between October 31 and February 11 there is a polar night, during which the Sun is below the horizon all of the time. The concept of day (24 hours) in the sense of energy ceases to exist – day becomes solely a concept of counting the passage of time and the "diurnal cycle" is an abstract notion. During a polar night advection processes steered by the course of regional and super-regional atmospheric circulation and the associated variability of cloudiness decide the variability of air temperature during the day and from day to day. In days with the same calendar date radically contrasted temperature conditions may be recorded in different years, depending on the actual synoptic situation. In such situations, any averaging of diurnal temperature (leading to construction of "multiannual diurnal means") is devoid of sense because the result of such operations would be analysis of statistical artefacts and not of reality.

From February 12 to April 23 and from August 19 to October 30 sunset and sunrise occur during the day at Hornsund. In the first period the day grows longer very quickly and in the second it shortens similarly. Only in these periods may one speak of a "diurnal cycle" of air temperature *sensu stricto,* although components of the radiation balance change strongly from day to day.

These characteristics of wide energy balance within the short diurnal period, is reflected in values characterizing different features of diurnal temperature over the year. These values are shown in Table 9.3.

Table 9.3. Extreme values of air temperature (Min_a, Max_a), means of diurnal minimum (Min_m) and diurnal maximum (Max_m) in a given month and mean range of variability of diurnal air temperature [°C] in a month (Ad; diurnal amplitude) in 1979–2009.

Feature	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Min_a	–35.9	–33.6	–34.2	–30.7	–19.5	–7.4	–1.0	–4.9	–11.2	–20.8	–28.9	–32.1
Year	1981	1979	1986	1988	1981	1981	1996	1994	1988	1988	1980	1988
Max_a	4.9	4.3	3.2	5.7	7.8	11.3	13.5	12.0	10.7	7.6	4.9	4.4
Year	2006	2005	1996	2006	2006	1983	2005	1987*	2001	1984	2006	1984
Min_m	–13.9	–14.0	–13.8	–11.5	–4.9	0.3	2.7	2.3	–0.4	–5.6	–9.0	–12.3
σn	4.49	3.62	3.23	3.69	1.60	0.85	0.56	0.75	1.37	2.22	4.23	4.49
Max_m	–7.7	–7.7	–7.8	–5.7	–0.6	3.8	6.6	6.0	3.1	–1.3	–3.9	–6.5
σn	3.66	3.01	2.86	2.79	1.18	0.77	0.70	0.76	1.33	1.87	3.46	3.90
Ad	6.2	6.3	6.0	5.8	4.3	3.5	3.9	3.7	3.5	4.3	5.1	5.8

* as well as in 1989, 1996 and 2001

Knowledge of absolute extreme temperatures allows us to state that the range of air temperature changes at Hornsund was from –35.9 to 13.5°C. Mean diurnal temperatures show a somewhat smaller range. The lowest diurnal temperature known until present at Hornsund was –32.5°C (on January 16, 1981), the highest was +10.8°C (on July 22, 1998).

A review of the extreme temperatures (Tables 18.19 and 18.20) shows that in the each of months minimum temperatures lower than 0°C were noted and, similarly, there were occurrences of maximum temperatures higher than 0°C in the each month. This shows the potentially great variability of diurnal air temperature in particular years. If attention is paid to the years in which occurrence of absolute minimum and maximum in particular months were recorded one may perceive that appearance of the minima falls mainly in the seventies and eighties of the 20th century (10 of 12 possible cases). The absolute maxima were recorded chiefly in the first nine years of the 21st century (7 of 12 possible cases). Such a distribution of extremes reflects the non-stationary thermal regime at Hornsund over the research period – the advancing increase of air temperature appears here in an additional variable, reflecting on the diurnal trends in air temperature.

The analysis of frequency of days with mean diurnal temperature (Td) divided into ranges of 5°C shows the unquestionable domination of days with temperatures in the range $0 < Td \leq +5°C$ in all years[2]. In the year there were 118 such days on average ($\sigma n = 14.4$), or 32.3%. The minimum number of such days was 93 (in 1998), the maximum was 147 (in 2006). On the second place in frequency of occurrence are days with temperatures in the range $–5 < Td \leq 0°C$. There were 84 ($\sigma n = 17.1$) of such days in a year on average, or around 22.9% of the time. In this case, however, differing frequencies of such days from year to year are clearly greater than the differences with temperatures in the range 0 ÷ +5° (minimum was 52 days in 1995, maximum – 129 days in 2005). Thus days with mean temperatures in the range –4.9 to +5.0°C form the basic "thermal framework" at Hornsund, occurring more than half of a year on average.

The other characteristic attribute of the course of air temperature at Hornsund is the relatively small range of temperature changes during a day. Mean diurnal amplitudes of temperature are relatively even, considerably smaller in the warmer than in the cooler part of the year.

In 1979–2009, the most frequent range of air temperature changes during a day at Hornsund was 2.0–3.9 deg. There were somewhat more than 145 such days (145.3; $\sigma n = 14.6$ day) on average in the year, i.e. around 40% of the year. The greatest number of days with such small diurnal amplitudes was recorded in 2004 (171), 2006 (166), 2002 and 2005 (each 165) and in 1984 (161). The clearly smaller number of such days with the same amplitudes of the diurnal air temperature occurred at the beginning of observations at Hornsund (121 in 1979, 123 in 1980 and 1986, and 124 in 1989). After 1994 there were no cases when the number of such days in a year was smaller than 130. There were 103 days ($\sigma n = 8.8$) on average during which the range of temperature changes was from 4.0 to 5.9 deg, around 28% of the year. The greatest number of such days was recorded in 1985 (120), the smallest (85) in 2004.

If when considering the frequency of these two ranges of temperature changes during the day, account is also taken of those days in which the diurnal amplitude was smaller than 2 deg (range 0–1.9 deg; 24 days on average over many years ($\sigma n = 10.4$ or around 6% of the year), a picture of rather small variability of the diurnal temperature during a year appears. For 64% of the year air temperature at Hornsund changed less than 6°C during the day.

The small variability of air temperature during the day characteristic of Hornsund does not mean that there are not abrupt increases or decreases with great diurnal temperature amplitude. In the cold season of the year days in which temperature amplitudes exceed 10 deg were common. Most of the great (10.0–17.9 deg) and very great (≥18 deg) diurnal temperature ranges recorded were increases of temperature, temperature drops being significantly smaller. The greatest number of occurrences of great and very great diurnal temperature changes was in February and January.

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[2] Year 2005 is the exception here; frequency of days with diurnal temperatures in the range –5° ÷ 0°C (129 days; 35.2% of the year) insignificantly predominate over frequency of days with temperature in the range from 0 to +5°C (124 days; 33.9% of the year).

In March and April, frequency of its occurrence was somewhat smaller; the length of analysed series is too short that differences in the monthly means can be statistically significant.

The greatest day-to-day, diurnal temperature amplitudes recorded at Hornsund were 22.5 and 21.6 deg (on February 16 and 17, 1980), when during the day air temperature first dropped from –7.7 to –30.2°C (February 16, 1980) and next increased from –27.8 to –6.2°C (February 17, 1980). The second greatest example was 21.8 deg (January 1, 1989), when temperature increased from –22.8 to –1.0°C. Analysis of the distribution of great and very great amplitudes in particular years clearly shows a lessening of the greatest diurnal amplitudes with time. For example, the greatest diurnal temperature amplitudes in 5-years period, 1983–1988, recorded in a given year was 19.54 deg (σ_{n-1} = 2.47), while the same mean for the 5 years period 2002–2006 was only 15.82 (σ_{n-1} = 3.14). Amplitudes of mean diurnal temperature calculated for consecutive years decreased similarly. The decrease of diurnal amplitude in consecutive years is result of continuing increase of minimum temperature. This tendency has been noted for a longer time and covers vast areas of the Arctic, not merely the Atlantic Arctic or Spitsbergen (Przybylak 1996a, 1999, 2000).

Analysing Table 9.3 it is easy to note that diurnal temperatures in the positive range (mean minimum diurnal temperature > 0°C) are practically limited to July and August (Table 18.18). In these two months, variability of diurnal temperature is clearly lower than in other months (see σn in Table 9.3). In turn, in the five successive months, December to April, the mean minimum temperature is lower than –10°C. In these same months the mean daily maximum is lower than –5°C, meaning that the diurnal temperature typical for this period must also be lower than –5°C. The same period is characterized by considerably greater range of air temperature changes during a day than in the other months; the mean diurnal air temperature amplitude was in the range 5.9–6.3 deg.

Fig. 9.6 shows the range of diurnal temperature changes in two years: 1984 (which was one of the warmest in the history of observations at Hornsund and second, after 2006, in relation to annual temperature) and 1988 (the coldest one in history of observations); these give a satisfactory representation of the variability of diurnal temperatures during a year at Hornsund. Two periods may be clearly distinguished – the first is the conventionally termed "warm" season, the second is the "cold" season of the year.

The typical course of the warm season of the year begins on average in the second decade of May and lasts until the second decade of September (4 months on average). The low variability of air temperature from day to day is typical for this period. Diurnal means differ from each other no more than 3°C on average, and daily amplitude between maximum and minimum temperatures is usually smaller than 6°; the most frequent values of amplitude were in the range from 2 to 5°. Only in exceptional cases, usually from 2 to 4 times in this season, does the diurnal amplitude exceed 8 deg. Variability of temperature from day to day connected with variability of atmospheric circulation characteristics is relatively weak, showing a prevailing periodicity of 2–3 days. Occurrences of greater day-to-day variability and increase of diurnal amplitude in this period[3] are due mainly to the variability of sunshine duration. Particularly great insolation, especially in the conditions of reduced (but not zero) wind velocity, yields a sudden increase both of maximum temperature and

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[3] In the described period the diurnal amplitude is statistically significantly ($p < 0.000$) correlated with mean diurnal temperature. The higher this temperature the greater on average amplitude of air temperature in a given day.

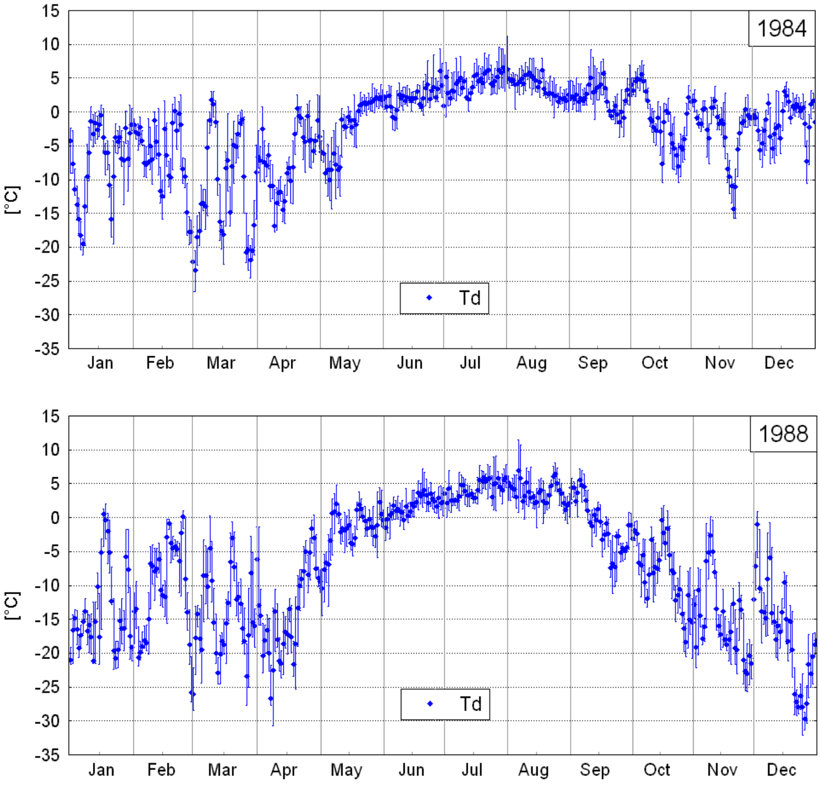

Fig. 9.6. The range of diurnal changes (minimum, mean (Td), maximum) of air temperature [°C] at Hornsund in 1984 and 1988.

of mean diurnal temperature. A reduction of diurnal temperature amplitude is associated with a strong increase of cloudiness, in general with great cloudiness (N ≥ 6) or total (N = 8). In such conditions, greater drops of diurnal air temperature are not usually observed, while increase of temperature occurs frequently. Such a course for diurnal air temperatures typical of the warm season of the year occurs in all analysed consecutive "warm" seasons, allowing us to consider it typical of the Hornsund climate.

The course of diurnal air temperature in the cold season of the year, from the second decade of September to the second decade of May, is characterized by a great, and in some periods even very great interdiurnal variability. A rhythm of changes of 5–14 days (dominated by 8.6 days) is typical. “Interlacing” of days with very big (exceeding 8–10° amplitude) with days of relatively small diurnal amplitudes is characteristic of this rhythm. A systematic drop of air temperature usually occurs for 2 to 4 days; the minimum temperature of a given day is frequently very close to the maximum temperature of the next day (Fig. 9.6). After a period of temperature decrease, for the next few days the temperature remains at a similar low level, diurnal amplitudes of temperature clearly decrease (3 to 6° on average). Next, and similar to this pattern of decrease, an increase of diurnal air temperature begins, lasting from 1–2 to few days. Diurnal amplitudes strongly increase then (8–14°). After reaching some characteristic higher temperature, for the succeeding days diurnal temperatures remain at a similar level and the diurnal amplitude decreases (3–6°). Analysis of values and signs of interdiurnal changes of temperature shows that in the cold period the increase of temperature is faster than its drop. In this period diurnal amplitude of temperature is negatively correlated with diurnal temperature – diurnal amplitude increases together with a decrease of diurnal temperature.

During the cold season of the year situations of massive and simultaneously long lasting advection of warm air happen sometimes, causing a complete "retuning" of the diurnal temperature change regime typical for a given period. An example of such a situation is seen in the pattern of diurnal temperatures in 1993. At the end of the year advection from the South, lasting from half of the first decade of November to half of the first decade of December led, despite the onset of the polar night, to a sudden increase of temperature and occurrence during the month of a diurnal temperature changes regime typical for the warm season of the year (Fig. 9.7). Similarly, in 2009 a strong inflow of air from the South in November caused two periods of increased air temperature with diurnal trends typical of the warm season of the year (1–13 November and 18 November – 1 December). Similarly strong advections of heat and "retuning" of the course of diurnal temperature to the warm season type were never recorded in the second half of the cold period during the entire observation period at Hornsund. We may suppose that changes of the diurnal temperature regime of such types may occur only sporadically in the first half of the cold season of the year. In transitional seasons there are sometimes advections of cold air that, however, are never so long lasting. In the warm season of the year similar advections of cold air capable of changing the thermal regime typical for this period were not recorded at Hornsund.

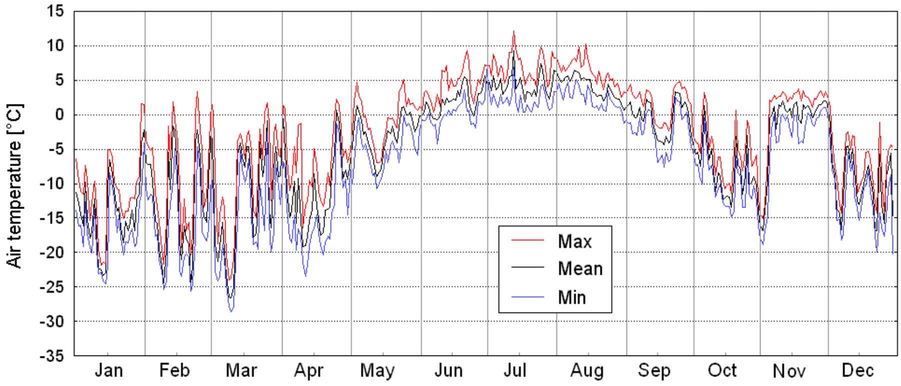

Fig. 9.7. The course of diurnal maximum, mean and minimum air temperature [°C] at Hornsund in 1993.

Such types of patterns in diurnal temperature courses prove that circulation processes regulate their variability. The structure of the synoptic processes regulates not only the direction and intensity of advection but also variability of cloudiness, so influencing variability of temperature. During the cold season of the year the change of mean diurnal general cloudiness for 1 octa brings change concordant with the sign of mean diurnal air temperature for around 1.9°C ($p < 0.000$).

During the cold season, it is characteristic that at the culmination of the warming phases maximum diurnal temperatures relatively frequently exceed 0°. Such situations are observed 2–3 times even during the coldest winters. During "gentle" winters even in the coldest months, in the height of polar night, besides exceeding the maximum diurnal temperature threshold of 0°C, there are cases where diurnal temperatures reach positive values. This feature of the course of diurnal temperature must also be recognized as typical for Hornsund climate.

The differentiation of the course of diurnal temperatures during a year at the Hornsund station is perfectly illustrated in plots of interdiurnal temperature differences (Fig. 9.8; these plots were made for the same years for which the range of diurnal courses was presented, 1984 and 1988). In particular years, depending on the character of the winter period, the boundaries between the diurnal temperature pattern typical for the cold period and typical for the warm period undergo shifts in time, the unquestionable majority of these shifts occurring within 10–20 days. In each year, these boundaries are clear and sharp; a gentle, gradual passage from the first to the second diurnal temperature regime is not observed.

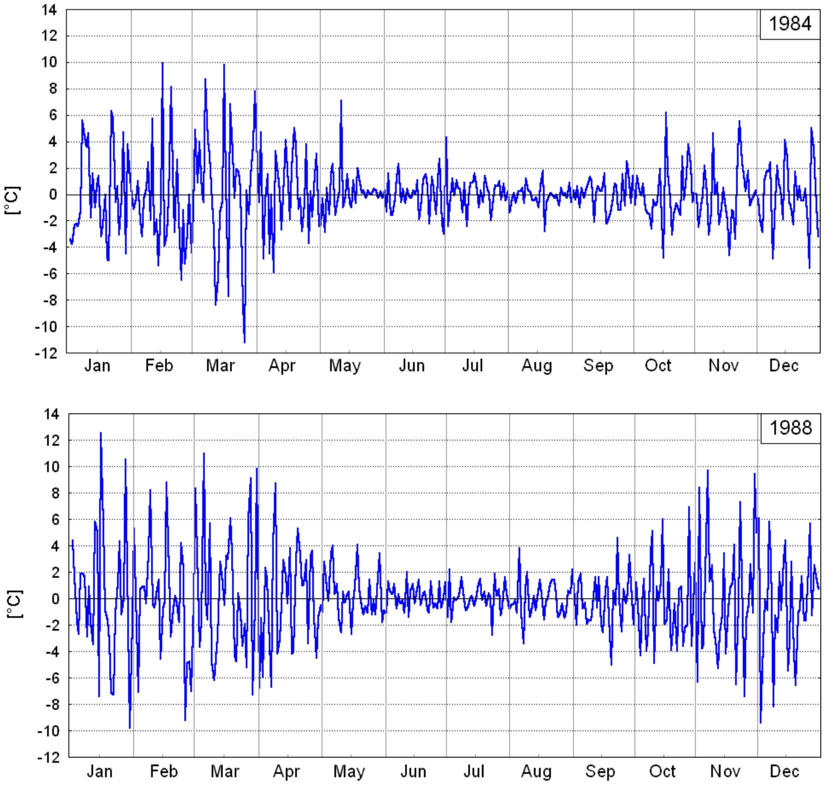

Fig. 9.8. The course of interdiurnal air temperature [°C] differences at Hornsund in 1984 and 1988.

9.4. Thermal seasons

Until now the thermal seasons at Hornsund were distinguished by determining moments of temperature passage, usually averaged, through established threshold limits (Baranowski 1968, Pereyma 1983, Rodzik and Stepko 1985, Kwaśniewska and Pereyma 2004). If we depart from the criterion of threshold values[4], and pay attention to characteristic features of the diurnal temperature regime and the diversity of monthly temperature variability as well as the statistical significance of differences between monthly temperatures we will obtain different criteria for assigning thermal seasons.

As noted, the course of diurnal temperatures divides year into two clear periods – that typical for a "cold period", from the second decade of September to the second decade of May, and that typical for "warm season of the year", from the second decade of May to the second decade of September. Characteristics of differences between these courses were discussed earlier. The duration of these periods is 8 and 4 months. In the averaged course of the diurnal temperature two "flat" periods are seen, in which mean diurnal temperatures do not show greater changes. This is the period between the turn of November and December and the turn of April and May and between the turn of June and July and the turn of August and September. Both these periods differ substantially in mean diurnal temperature. The period July-August fits entirely in the "warm period" type; the period December-April fits wholly in the "cold period" type.

Taking into account that in the pattern of diurnal temperature there are two clearly contrasting periods – from December to April and July-August, divided by transitory periods (May-June and September-November) we may provisionally define four thermal seasons:

- cold (winter) – from December to April,
- increase of temperature (spring) – from May to June,
- warm (summer) – encompassing July and August,
- decrease of temperature (autumn) – from September to November.

The criterion of extreme temperature cannot be used to delimit thermal seasons at Hornsund because in all months of the year the occurrence of both positive and negative temperatures is recorded. A better criterion is the differentiation of mean maximum and mean minimum temperatures in particular months. In the case of mean minimum temperature there is a lack of statistically significant differences between the temperature of December (–12.8°C), January (–14.3°C), February (–14.3°C) and March (–14.0°C). The difference between means of March (–14.0°C) and April (–11.4°C) is significant, but the level of this significance is very low, whereas difference between mean from minimum temperature of April (–11.4°C) and May (–5.1°C) is highly significant. Thus from the point of view of development of mean minimum air temperature, the period from December to April inclusive is relatively homogenous. The quantitative feature of this period is that means for the minimum temperatures are lower than –10°C in the whole period. The significance of differences between means from maximum diurnal temperature between December and April is similar, although in this case differences between mean maximum in March (–7.9°C) and April (–5.5°C) are greater, from the point of view of the level of significance. However, the difference between the mean maximum in April (–5.5°C) and the mean in May (–0.7°C) is so big that there can be no case to assign both these values in one common period. The common feature of the period December-April is development of diurnal maximum means at values lower than –5.0°C.

The period July-August differs very clearly from neighbouring months. These are the only months in the year in which mean minimum temperatures are higher than 0°C in the whole period of observations at Hornsund (2.6 and 2.3°C, respectively). Also in no one July or August was

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[4] In the Arctic, the only rational thermal threshold is temperature 0°C, after crossing which the state of water phase changes.

a mean monthly temperature lower than 0°C recorded at Hornsund, whereas such temperature was recorded 5 times in September and once in June (–0.1°C in 1979). Despite the fact that differences between the mean multiannual temperature means of July and August (0.4 deg) are statistically significant, the differences between mean diurnal maxima (6.6 and 5.9°C) and diurnal minima (2.6 and 2.3°C), are not significant after allowance for the standard error of mean estimate. Therefore, July and August undoubtedly are a coherent, homogenous thermal period.

The other periods (May-June and September-November) are transitional periods, in which differences between monthly means and means from diurnal temperature maximum and minimum are statistically significant, being connected with rapid increases or decreases of temperature. If these months are compared significant differentiation of the means is noted (Fig. 9.9), quite extreme in relation to stable periods of "the summer" and "the winter". In such depictions the spring period is characterized by mean minimum of diurnal temperature in the range from –5.5 to 0°C, and mean maximum from –1 to 4°C (values rounded), at the mean monthly temperature from –3 to 1.8°C, with the permanent passage of diurnal air temperature through 0°C in general in the second part of this period. In the spring the typical diurnal pattern of temperature in the "cold season of the year" converts into the "warm period" type. During the autumn, which is longer than the spring the reverse changes take place. In the beginning, in September, the "warm season of the year" pattern converts into the "cold season of the year" type, while the courses typical for the "warm period" may return again for shorter or longer times. As opposed to August, in which minimum of diurnal temperature drops below 0°C only exceptionally, in September drops below this boundary become the rule. The range of mean diurnal minimum of diurnal temperature decreases from –0.6°C in September to –9.5°C in December. Mean diurnal maximum falls from 3.0°C in September to –4.3°C in November.

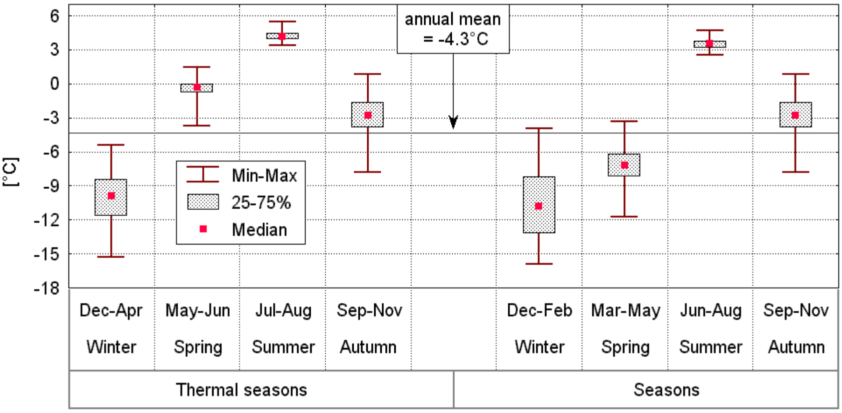

Fig. 9.9. Variability of mean air temperature [°C] in the thermal seasons and seasons of the year at Hornsund in1978–2009.

Such division of the year into thermal seasons is schematic. In reality, the boundaries between seasons distinguished by this way show also interannual variability, are blurred and show shifts of monthly decade in particular years. The generalised characteristics of thermal seasons distinguished are shown in Table 9.4.

Table 9.4. Characteristics of thermal seasons at Hornsund in 1979–2009.

Season	Period	Days	Ts [°C]	σn	Min [°C]	Max [°C]
Spring	1 May – 30 June	61	–0.5	0.95	–3.7 (1979)	1.5 (2006)
Summer	1 July – 31 Aug	62	4.2	0.48	3.4 (1994)	5.4 (2002)
Autumn	1 Sept – 30 Nov	91	–2.8	1.79	–7.8 (1988)	0.8 (2000)
Winter	1 Dec – 30 Apr	151	–10.1	2.18	–14.3 (1981)	–4.8 (2006)

Explanations: Ts – mean multiannual air temperature in the season, σn – standard deviation of Ts, Min – the lowest mean temperature of the season recorded and year in which it was recorded (winter dated as year of January), Max – the highest mean temperature of the season recorded (winter dated as above).

The depicted changes of duration of thermal seasons are frequently identified with seasons of the year, in comparison to other delimitations of seasonality (e.g. Kwaśniewska and Pereyma 2004). Given the different criteria for distinguishing such seasons such comparison has no sense. It is worth paying attention, however, to the characteristics of temperature variability in individual seasons – very big in the season named winter, big in the autumn, relatively small in the spring and minimum (nearly four times smaller than in the winter) variability in the summer. Characteristic also are changes of the years of occurrence of minimum and maximum of temperatures in the individual seasons, confirming the non-stationary thermal conditions during the research period.

In the face of the lack of sharp marked boundaries for the individual seasons of the year, the climatological division presented makes it impossible to trace changes of the beginning and ending of individual seasons. Nothing prohibits analysis of changes of the moments of passage of diurnal temperatures through appropriate thresholds. Thermal seasons distinguished here are somehow natural periods, dividing a year according to the course of air temperature and not only its values.

9.5. Factors shaping interannual variability of the air temperature

The air temperature and atmospheric precipitation are considered the most important climatic elements by most climatologists. The variability and changes of temperature regulate a number of physical and biotic processes, contributing to both the development of cyclic changes in the environment and, as in the case of long-term changes of the air temperature, to transformations and change of the state of the environment. The broadest changes of temperatures are found in the variability of the annual value. Long-term changes of temperature are results of apparently tiny, interannual fluctuations.

Because during the observations at the Hornsund[5] station the air temperature displayed non-stationarity expressed as statistically significant trends in some months and a shifting of the timing of the annual minimum (and as a consequence a significant positive trend in the annual temperature (Chapter 16)), the associations of this temperature behaviour with the large scale and regional atmospheric circulation, the sea ice cover and ocean surface temperature, which in the environment of the Atlantic Arctic may be considered as the main factors determining the climate, will be presented. The aim of analysis of these associations is to attempt to determine which factors and to what extent can explain the observed interannual variability of air temperature, and may be the cause of changes occurring both at Hornsund and wider in this part of the Arctic.

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[5] Similarly like in the other stations of the Atlantic Arctic.

9.5.1. Associations of air temperature at Hornsund with indices describing the large scale atmospheric circulation

Some researchers formulate theses that changes of the air temperature in the Atlantic Arctic are determined by the variability of the large-scale atmospheric circulation. The last increase of the air temperature is often explained as a result of the increase of intensity of the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO), which have been recorded since the 1970s (e.g. Holland 2003, ACIA 2004, Rogers *et al.* 2004). The principal argument indicating atmospheric circulation as the direct or indirect causative factor of increase of the air temperature in the Atlantic Arctic is the conformity of the AO or NAO trends with the trend of temperature or the statistically significant correlations between these quantities that are supposed to occur. Rigor *et al.* (2000) attributed increase of temperature in the Atlantic Arctic observed in 1979–1997 principally to variability of AO, which explained less than 50% of temperature variability there. Thompson and Wallace (2001) saw strong associations between changes of the air temperature in the Arctic and variability of AO (or otherwise NAM – Northern Annular Mode). A different view on this subject is expressed by Polyakov *et al.* (2003), Styszyńska (2005) or Semenov (2008), who stress the weak, non-stable in time, associations between AO and NAO, and air temperature in this part of the Arctic. Marsz (1999) paid attention to very weak, synchronous and asynchronous, associations of the air temperatures of Spitsbergen and Jan Mayen with the NAO index of Hurrell (1995). Overland and Wang (2005) wrote of the "paradox of the Arctic climate" in which, despite the decrease of AO index in the recent years, the increase of air temperature, decrease of sea ice surface, shifting borders of the extent of individual species to the north are still observed. Their conclusion is the assertion that changes of the Arctic climate occur to a greater degree to the influence of the action of inter-system mechanisms than to the external atmospheric circulation.

During observations at the Hornsund station (1979–2009) an obvious warming trend is evident, the AO trend is positive but not statistically significant ($+0.005\cdot yr^{-1}$), the NAO trend is negative ($-0.020\cdot yr^{-1}$) and also statistically not significant. Such behaviour of the AO and NAO trends does not change the opinions of some climatologists and glaciologists who consider that the influence of the large-scale atmospheric circulation on changes of the air temperature in the Arctic is significant.

A study was made to what degree changes of air temperature at Hornsund are connected with the variability of large-scale atmospheric circulation. Series of monthly AO values were used for analysis, being the first vector EOF of the geopotential field 1000 hPa in the zone between 20°N and 90°N (Thompson and Wallace 1998; data: NOAA NWS-CPC, monthly_mean_AO_index). The AO index is assumed by its founders to characterize atmospheric circulation at the hemispheric scale. From the NAO indices monthly values of NAO CRU index were used for analysis (Jones et al. 1997), being the difference of standardized deviations of pressure between Gibraltar and SW Iceland. The NAO index characterizes the macroregional atmospheric circulation in the Atlantic-European sector.

The AO and NAO indices are strongly intercorrelated, especially in winter months; this is one reason why discussions persist to the present time concerning the degree to which the Arctic Oscillation is a reflection of reality, what statistical artefact is and what is a mutual relationship in both oscillations (Deser 1999, Wallace 2000). Both indices characterize changes of the lower field of pressure, the variability of which is steered by the middle tropospheric circulation. For this reason also a possible influence of this circulation in the Atlantic-European sector on the behaviour of air temperature at Hornsund was taken into account. The middle tropospheric circulation is characterized by the number of days in months with the occurrence of particular macrotypes, describing the long wave arrangements at the 500 hPa level according to the Vangengejm-Girs classification (Vangengejm 1952, Girs 1981). The results of analyses are shown in Table 9.5. The correlation coefficients in this table show that in the period investigated there were no statistically significant associations between temperature at Hornsund and the Arctic Oscillation (Fig. 9.10). Significant associations in intercorrelations (with a time shift in the range of ±15 years) between the annual AO index and annual air temperature were also not found. It is hard to find the cause of the observed increase of temperature in the activity of the AO[6].

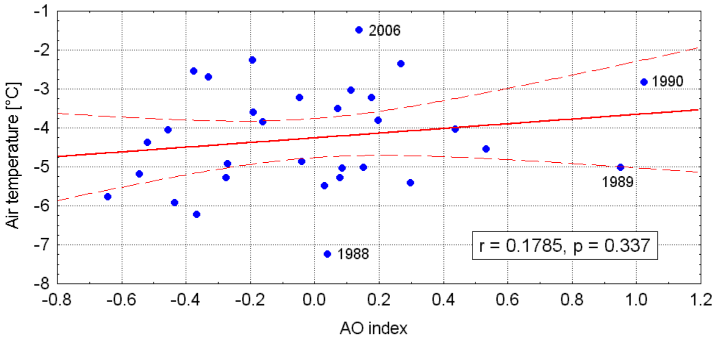

Fig. 9.10. The association of the annual air temperature [°C] at Hornsund with the annual index of the Arctic Oscillation (AO).

Monthly NAO indices show significant positive correlation with air temperature in April, October and November. However, although statistically significant these associations are rather weak. Analysis of regression shows that variability of NAO in these months does not exert measurable influence on the variability of annual temperature at Hornsund, although it explains around 11% of air temperature variability in April, 18% in October and less than 7% in November. Associations between the annual air temperature at Hornsund in the same year (Fig. 9.11), and with annual values of NAO CRU index in preceding years were also not found.

Statistically significant associations of air temperature at Hornsund with indices of the middle tropospheric circulation occur at the end of year, during the autumn and beginning of winter. The W macrotype circulation of Vangengejm-Girs is the type for strong zonal circulation. The appearance of waves with significant length (wave number of 4) and small amplitude is characteristic for this

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[6] It should be noted here that monthly values of AO indices show very strong associations with monthly atmospheric pressure at Hornsund. Correlation coefficients are in the range from –0.89 in March to –0.53 in July; during 10 months in the year correlation coefficients are equal, higher than |0.7|. Variability of the annual AO index explains 63% of the annual pressure variability at Hornsund (r = –0.8). More on reasons for such strong associations of atmospheric pressure at the station with the AO index can be found in Marsz and Styszyńska (2006). Statistically significant associations of atmospheric pressure with air temperature are however not found at Hornsund in any month.

type of circulation in the Atlantic-European circulation sector. The occurrence of zonal circulation should not be accompanied by the increase of air temperature in the Atlantic Arctic. Significant correlations between monthly temperature and the frequency of days with macrotype W are not found in the investigated period of 31 years. The correlation coefficient between the annual W index and annual air temperature at Hornsund is +0.27, statistically not significant (p = 0.149). This means that the zonal circulation in the Atlantic-European circulation sector does not exert measurable influence on the air temperature at Hornsund.

Table 9.5. Correlation coefficients (r) and the statistical significance (p) between indices of atmospheric circulation and monthly air temperature at Hornsund in 1979–2009; AO – monthly index of the Arctic Oscillation, NAO CRU – monthly index of NAO (Gibraltar – SW Iceland), W(V-G), E(V-G), C(V-G) – number of days in the month with occurrence of macrotypes W, E and C of the middle tropospheric circulation of Vangengejm-Girs

Month		AO n = 31	NAO (CRU) n = 31	W (V-G) n = 31	E (V-G) n = 31	C (V-G) n = 31
January	r	0.189	0.134	–0.046	0.068	–0.036
	p	0.308	0.472	0.805	0.718	0.846
February	r	0.018	0.010	–0.217	**0.375**	–0.259
	p	0.923	0.958	0.241	0.038	0.160
March	r	0.161	0.108	–0.181	0.213	–0.112
	p	0.387	0.563	0.331	0.251	0.547
April	r	0.073	**0.379**	0.018	0.256	**–0.368**
	p	0.698	0.035	0.923	0.165	0.042
May	r	0.197	0.068	0.119	–0.264	0.244
	p	0.289	0.715	0.524	0.151	0.186
June	r	0.091	–0.121	0.161	–0.009	–0.164
	p	0.628	0.516	0.388	0.963	0.378
July	r	–0.315	–0.063	0.120	–0.011	–0.125
	p	0.085	0.735	0.520	0.952	0.502
August	r	–0.067	0.166	0.219	–0.015	–0.191
	p	0.721	0.371	0.236	0.937	0.303
September	r	–0.244	–0.258	–0.345	**0.395**	–0.024
	p	0.186	0.161	0.058	0.028	0.900
October	r	0.001	**0.460**	0.136	0.152	**–0.399**
	p	0.998	0.009	0.466	0.416	0.026
November	r	0.032	**0.363**	–0.342	**0.666**	**–0.588**
	p	0.863	0.045	0.060	0.000	0.001
December	r	–0.029	0.115	–0.298	**0.416**	–0.183
	p	0.878	0.537	0.104	0.020	0.325

The E macrotype has strong meridional circulation, with clearly reduced wavelength (wave number 5) and big amplitude. Occurrence of an upper bay with the axis approximately along the meridian 0° and an upper wedge (the top of which reaches Spitsbergen) with the axis approximately along 45°E is characteristic of this type. Such location of the boundary between the upper bay and the upper wedge directs low-pressure systems from the Northern and Norwegian Seas to the region of Spitsbergen. Significant positive correlation coefficients between frequency of days with occurrence of E macrotype and air temperature at Hornsund occur in February (~0.38), September

(~ 0.39), November (~0.67) and December (~0.42). The very strong association in November – (the frequency of days of E macrotype explains 45% of temperature variability in this month) catches the attention. The strength of association in December is somewhat smaller – changes of frequency of E macrotype explain around 17% of temperature variability. The arrangement of signs of correlation coefficients between monthly frequency of days with occurrence of E macrotype and monthly air temperature at Hornsund seems to indicate the character of influence of meridional middle tropospheric circulation on air temperature at Hornsund. Between September and April the correlation coefficients were positive, regardless of their values and between May and August were negative. This suggests that the occurrence of strong meridional atmospheric circulation in the cold season of the year may induce a weak increase of temperature in the Hornsund region. The variability of frequency of days with E macrotype does not explain changes of the annual air temperature at Hornsund, despite the stronger correlations in November and December and the weaker in April and September.

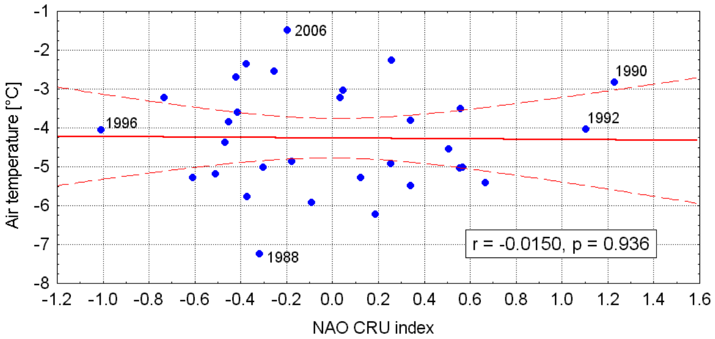

Fig. 9.11. Association of annual air temperature [°C] at Hornsund with the annual NAO CRU index.

Interesting but also not readily comprehensible is the finding that variability of frequency of the E macrotype in the winter (DJFM) is negatively associated with the air temperatures which will occur at Hornsund in the following calendar year ($r = -0.42$, $p < 0.019$) and with temperature of the warmest months of that year, July ($r = -0.48$) and August ($r = -0.47$). If these correlations are not matter of chance (?), this means that after a winter with increased frequency of E macrotype, in July and August of the following year the temperature at Hornsund will be lower than average, and thus the mean annual temperature of that year should also be lower. Emphasizing the associations occurring with such time delays shows that the influence of the winter atmospheric circulation connected with increase of frequency of the E macrotype must be next transferred through some inertial link acting in the regional climatic system. What is this link? More detailed analysis uncovers significant relationships between the frequency of E macrotype in the winter (DJFM) and sea ice area on the Greenland Sea in the period January-May in the following year (r equal 0.43, 0.54, 0.52, 0.55 and 0.43, respectively) and from September and December of the following year. Positive correlation coefficients show that after increase of frequency of E macrotype, at the end of the next winter the sea ice area increases, so a delay in the melting of ice cover occurs. This in turn influences air temperature in the summer, contributing to its decrease. The agreement of signs of changes is clear here but still nobody knows what and how the atmospheric circulation occurring in the winter of one year influences the area of sea ice cover on the Greenland Sea at the end of winter of the following year. There should be some associations with heat transport together with sea water or development of anomalies in the ocean surface temperature here. The problem is additionally complicated by the fact that significant associations between frequency of E macrotype during the winter and the area of sea ice cover on the Barents and Kara Seas in the following year are not found. Settling of these issues needs further research and at present some further leading hypotheses seem not to be justified.

The C macrotype of Vangengejm-Girs is also a type of strong meridional circulation; it differs from the E type by arrangement of upper bays and wedges. In this macrotype the upper wedge of large amplitude is located over the eastern part of the North Atlantic and Western Europe, reaching with its northern extremities on the NE coast of Greenland; the upper bay, reaching the Caspian Sea, is located over Eastern Europe and the NW part of the West Siberian Lowland. Spitsbergen is located in the border region of the eastern part of the upper wedge and at the base of the western part of the upper bay, in the top part of the upper wedge. With such an array of upper wedges and bays, cyclonic systems from the Atlantic should be directed along the northern peripheries of anticyclonic systems with the centre over the Scandinavian Peninsula, the Baltic Sea or Central Europe, thus passing south of Spitsbergen. With such low pressure system trajectories Spitsbergen should be in the zone of inflow of air from the NW and N. Statistically significant correlations in April, October and November (-0.37, –0.40 and –0.59, respectively) meet the condition of air temperature decrease with increase of frequency of the C macrotype. In the remaining months associations are weak, not statistically significant and, additionally, with changing signs. Neither the values of October and November nor also the annual frequencies of C macrotype exert significant influence on the annual air temperature at Hornsund, even with time lags.

In conclusion one should stress that associations between air temperature at Hornsund and indices characterizing large-scale atmospheric circulation of hemispherical and macroregional scale in the research period[7] 1979–2009 are so weak that they do not justify formulating hypotheses on significant influences of the AO or the I NAO on the variability of air temperature in this region[8]. Somewhat stronger associations, although restricted to the autumn – the beginning of winter, are evident between monthly temperature and indices characterizing the middle tropospheric circulation according to classification of Vangengejm-Girs. These associations do not however extend to more general features of the behaviour of air temperature at Hornsund, as the latter is described by annual temperature. There are not arguments to attribute the warming observed in the region of South Spitsbergen to the direct action of the large-scale atmospheric circulation, both low and middle tropospheric, discussed here.

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[7] Also in 1951–2006, with reference to the temperature at the Bjornöya and Svalbard-Lufthavn stations.

[8] Maslanik et al. (2007), with reference to Overland and Wang (2005), showed that there is not a "paradox" in the changes of climate in the Arctic. There are no associations between changes of temperature and changes of ice area in the Arctic and the variability of the Arctic Oscillation (AO). The main role in the warming is played by three interacting patterns of local (regional) atmospheric circulation, which leading to the “sweeping” of sea ice from the Arctic, activate the process of warming.

9.5.2. Influence of atmospheric circulation on the air temperature at Hornsund

While macroscale atmospheric circulation does not exert significant influence on the variability of air temperature at Hornsund except for few months, the regional circulation (see Chapter 4) is of great importance in that regard. Results were based on 11357 days of measurements made in 1979–2009 (with only one break, between 1–26 July 1981). The influence of individual types of circulation on temperature was considered over the annual course. It was the strongest in the winter (Fig. 9.12), when deviations of mean diurnal temperature from multiannual mean during the extreme circulation types were in the range from -8 to +8 deg. Such big anomalies occurred also in March (Fig. 9.13, Table 9.6).

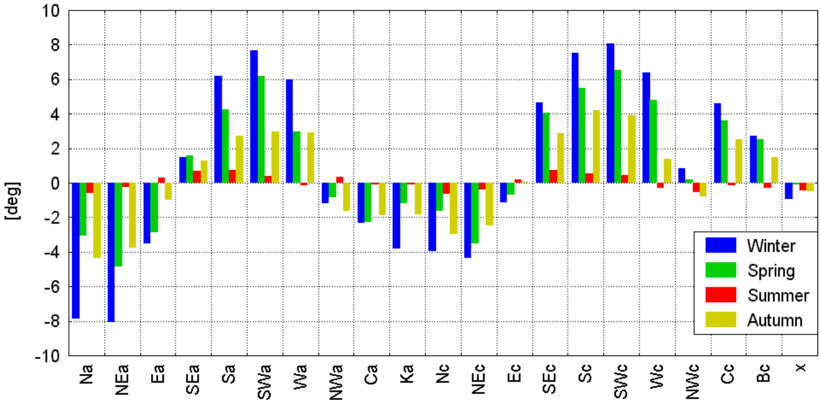

Fig. 9.12. Deviations of diurnal means of air temperature for individual types of atmospheric circulation, from multiannual means in seasons of the year, 1979–2009.

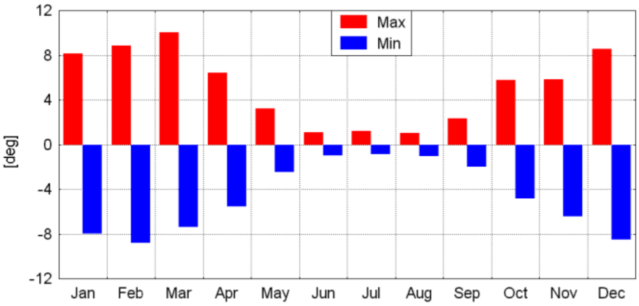

Fig. 9.13. The range of deviations of mean diurnal air temperature from multiannual mean caused by influence of types of atmospheric circulation, 1979–2009. Explanations: Max – the biggest positive deviation, Min – the biggest negative deviation.

The strongest winter warming (anomaly around +8 deg) was caused by two types of circulation: SWa and SWc. Equally big positive deviations (from +6 to +7.5 deg) occurred also during situations Sc, Sa, Wc and Wa (Fig. 9.12). The biggest negative anomalies (around –8 deg) occurred only with the anticyclonal situations, Na and NEa. Smaller coolings (around –4 deg) were associated with the Ka high-pressure system situation without advection, and also by low-pressure systems with advection of air from the NE (NEc). The biggest range of changes of mean diurnal air temperature, amounting over to 17 deg was observed in February, March and December. In February, mean diurnal temperature changed from –19.6°C at an NEa situation to –2.0°C with the circulation type SWc, and in March from –18.0°C at the centre of a high-pressure system to –0.6°C in high-pressure systems with advection of air from the SW (Table 9.6). In January, the lowest mean diurnal air temperature, –18.9°C, occurred in situation NEa (mean for January amounted –10.9°C).

Table 9.6. Mean diurnal air temperature [°C] at Hornsund at the individual types of circulation (Tc)

Tc	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Na	–18.6	–17.7	–15.9	–13.2	–4.2	**0.9**	4.4	3.7	–0.3	**–8.1**	**–12.7**	**–18.0**
NEa	**–18.9**	**–19.6**	–17.2	**–14.1**	**–5.4**	1.6	4.8	**3.1**	–0.5	–6.7	–11.7	–17.2
Ea	–14.4	–15.3	–14.3	–11.3	–5.1	2.5	**5.6**	3.6	1.5	–3.9	–8.2	–11.8
Sea	–8.5	–10.4	–8.8	–6.8	–1.7	1.7	5.4	5.0	2.4	–1.5	–5.1	–7.5
Sa	–5.2	–4.1	–4.3	–3.4	–0.2	**3.0**	4.7	5.0	3.3	–0.6	–1.2	–3.1
SWa	–4.3	–3.5	**–0.6**	–2.2	0.3	2.4	4.4	4.9	3.2	–0.8	–0.7	**–0.9**
Wa	–6.6	–2.3	–3.5	–3.6	–1.2	1.8	4.4	3.7	2.2	**2.5**	–2.2	–4.5
NWa	-	–10.0	-	–11.9	–2.9	2.5	4.8	3.4	0.8	–6.0	–8.3	–12.8
Ca	–13.5	–15.9	**–18.0**	–10.5	–3.5	1.6	4.6	4.0	–0.1	–5.6	–8.9	–8.0
Ka	–15.0	–14.6	–14.2	–10.1	–2.9	1.8	4.4	3.9	0.5	–5.1	–9.5	–13.0
Nc	–16.0	–14.1	–13.9	–10.3	–3.1	1.2	4.0	3.2	**–0.6**	–6.3	–10.3	–12.9
NEc	–15.3	–15.0	–14.8	–12.5	–4.5	1.7	4.1	3.5	0.6	–5.4	–10.7	–14.0
Ec	–12.8	–11.7	–11.5	–9.3	–3.0	2.2	4.8	4.1	1.3	–2.3	–7.3	–10.0
Sec	–6.0	–7.0	–6.2	–3.9	–0.7	2.1	5.1	**5.1**	2.9	0.3	–2.8	–4.3
Sc	–3.3	–3.7	–4.5	**–2.2**	–0.3	2.7	4.5	4.9	**3.7**	1.1	**–0.5**	–1.7
SWc	**–2.8**	**–2.0**	–2.4	–2.3	**0.4**	2.7	4.5	4.8	3.7	1.1	–0.9	–2.6
Wc	–3.9	–5.6	–2.8	–3.6	–0.2	2.3	3.7	3.8	1.4	–2.0	–1.7	–2.7
NWc	–11.4	–9.7	–11.7	–7.2	–3.1	1.6	4.1	**3.1**	–0.4	–3.7	–6.1	–7.7
Cc	–6.1	–6.4	–5.9	–4.1	–1.6	2.0	**3.6**	4.2	2.1	–0.7	–2.5	–4.9
Bc	–8.6	–7.6	–7.3	–6.0	–1.3	1.6	4.0	3.8	2.3	–2.0	–4.0	–6.9
X	–12.8	–10.1	–11.6	–8.1	–2.5	1.3	4.0	3.7	0.6	–4.0	–6.2	–10.8
Average	**–10.9**	**–10.8**	**–10.6**	**–8.6**	**–2.9**	**1.9**	**4.4**	**4.1**	**1.4**	**–3.3**	**–6.3**	**–9.5**
Max	–2.8	–2.0	–0.6	–2.2	0.4	3.0	5.6	5.1	3.7	2.5	–0.5	–0.9
Min	–18.9	–19.6	–18.0	–14.1	–5.4	0.9	3.6	3.1	–0.6	–8.1	–12.7	–18.0
Range	16.1	17.7	17.4	12.0	5.7	2.1	2.1	2.1	4.3	10.6	12.3	17.1

The smallest range of variability of mean diurnal air temperature under the influence of atmospheric circulation was 2.1 deg in the summer months. In July mean diurnal temperature with individual types of circulation changed from 3.6°C at the centre of low pressure systems (Cc) to 5.6°C for situation Ea (the mean for July amounted to 4.4°C). In eastern anticyclonic situations, the additional warming results also from the foehn effect which occurs with this direction of air advection on the western coast of Spitsbergen. The detailed annual course of deviations of mean diurnal air temperature from monthly standard means for selected circulation types is shown in Fig. 9.14.

As with mean diurnal temperatures, different types of circulation impact on maximum air temperatures (Table 9.7, Fig. 9.15). The highest maximum temperatures appeared mainly with situations SWa and SWc, the lowest with types Na and NEa. The biggest range of changes was

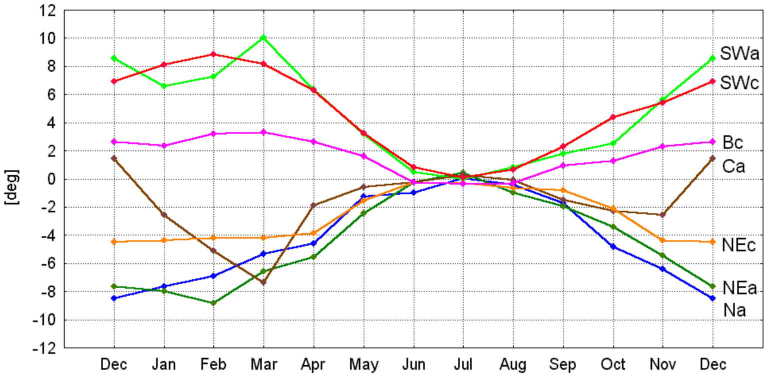

Fig. 9.14. Monthly means of deviations of mean diurnal air temperature from multiannual mean for selected types of circulation in 1979–2009.

between November and April, the smallest in the summer. The maximum temperatures were somewhat different in the centres of high-pressure systems. The lowest negative deviations of maximum temperature from standard means in these situations were recorded in March (–6.3 deg) and in February (–6.0 deg). In the summer these characteristics do not differ from average values, while a secondary decrease of the anomaly to –2.6 deg appears again in October.

Table 9.7. Mean maximum air temperature [°C] at individual types of circulation (Tc)

Tc	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Na	–15.2	–12.9	–11.9	–9.6	–1.3	**3.1**	6.6	5.9	1.5	**–5.3**	**–9.4**	**–14.8**
NEa	**–16.1**	**–16.8**	**–14.1**	**–11.1**	**–3.1**	3.9	7.1	**4.8**	**0.9**	–4.4	–9.2	–14.2
Ea	–11.9	–12.5	–11.7	–8.7	**–3.1**	4.4	**8.0**	5.4	3.2	–2.4	–5.8	–8.5
SEa	–6.4	–8.1	–6.6	–4.6	–0.3	3.6	7.6	**7.1**	3.8	–0.1	–3.3	–5.5
Sa	–2.4	–1.8	–2.5	–1.0	2.0	**5.6**	7.4	7.0	**5.5**	1.0	0.8	–1.2
SWa	–1.4	–0.7	**0.8**	**0.3**	2.0	3.9	6.3	6.9	5.1	1.9	1.4	**1.5**
Wa	–3.9	–0.9	–1.3	–0.1	1.0	3.6	6.9	5.8	4.2	**4.3**	–0.1	–2.4
NWa	-	–6.8	-	–9.3	–0.4	4.8	7.2	5.5	2.4	–4.1	–5.8	–9.4
Ca	–10.0	–13.8	–14.0	–7.1	–1.4	3.6	7.0	6.3	2.1	–3.9	–6.1	–5.0
Ka	–11.9	–11.1	–10.5	–6.8	–0.4	3.7	6.5	6.0	2.3	–3.1	–7.0	–10.4
Nc	–11.7	–9.3	–10.2	–6.7	0.1	3.3	6.2	5.3	1.3	–3.5	–7.1	–9.3
NEc	–11.5	–11.6	–11.4	–9.0	–2.2	3.6	6.1	5.4	2.3	–3.2	–8.1	–11.0
Ec	–10.1	–9.1	–8.7	–6.7	–1.1	4.0	7.1	5.7	2.8	–0.6	–5.1	–7.4
SEc	–3.7	–4.8	–4.2	–1.8	0.9	3.7	7.6	**7.1**	4.5	1.7	–1.0	–2.4
Sc	–1.0	–1.3	–2.5	0.1	1.3	4.4	6.8	7.0	**5.5**	2.8	1.4	0.7
SWc	**0.1**	**0.6**	0.4	0.1	**2.1**	4.4	6.5	6.3	5.4	3.2	**1.7**	0.2
Wc	–0.5	–1.9	–0.1	–0.7	1.6	4.0	5.5	5.6	3.3	0.4	0.8	0.3
NWc	–7.3	–5.6	–6.7	–3.3	–0.7	3.4	6.2	5.1	2.0	–0.7	–1.9	–3.5
Cc	–3.1	–2.9	–2.4	–1.5	0.9	3.7	**5.4**	6.1	4.1	1.5	0.1	–2.0
Bc	–5.7	–4.8	–4.4	–3.0	0.7	3.3	6.0	5.6	3.9	0.1	–1.4	–3.9
x	–9.4	–7.0	–8.1	–5.4	–0.3	3.3	6.0	5.8	2.3	–1.6	–3.5	–7.2
Average	**–7.9**	**–7.8**	**–7.7**	**–5.7**	**–0.6**	**3.7**	**6.6**	**6.0**	**3.2**	**–1.3**	**–3.9**	**–6.7**
Max	0.1	0.6	0.8	0.3	2.1	5.6	8.0	7.1	5.5	4.3	1.7	1.5
Min	–16.1	–16.8	–14.1	–11.1	–3.1	3.1	5.4	4.8	0.9	–5.3	–9.4	–14.8
Range	16.2	17.4	15.0	11.3	5.2	2.5	2.6	2.3	4.6	9.5	11.1	16.3

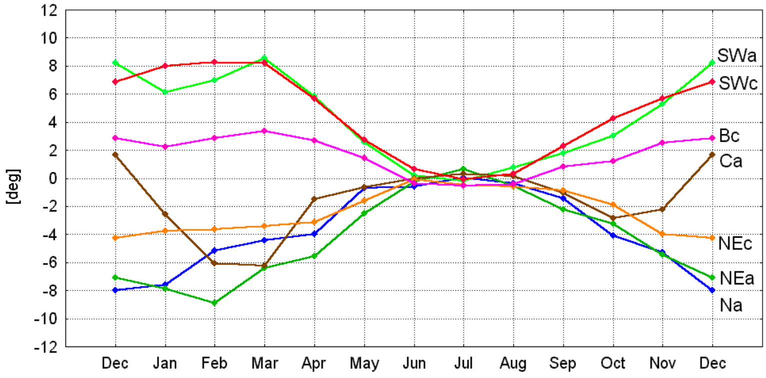

Fig. 9.15. Mean monthly values of deviations of mean maximum air temperature from the multiannual mean for selected types of circulation, 1979–2009.

In February the lowest mean maximum air temperature of –16.8°C (at this month average was –7.8°C) occurred in the NEa situation while in the SWc situation positive values were observed (0.6°C). Therefore, the range of changes of mean maximum temperature under the influence of atmospheric circulation reached the highest value, 17.4 deg, in February. In the summer this differentiation was in the range of only 2.3–2.6 deg. In July, mean maximum temperatures with circulation types changed from 5.4°C at the centre of low-pressure systems (Cc) to 8.0°C in the Ea situation.

The mean minimum air temperature changed the strongest under the influence of atmospheric circulation between December and March, in the range from 15.4 to 19.3 deg (Table 9.8, Fig. 9.16). The lowest mean minimum temperature (– 22.3°C) was in January at situation Na and in February at situation NEa. In the Wa situation the value of the discussed characteristics in February increased to –4.6°C, and in the cyclonal type SWc reached –6.3°C (mean standard of February was –14.0°C). The greatest range of mean minimum temperature changes was recorded in March, from –21.7°C in the centre of a high pressure system (Ca) to –2.4°C in the anticyclonal type SWa

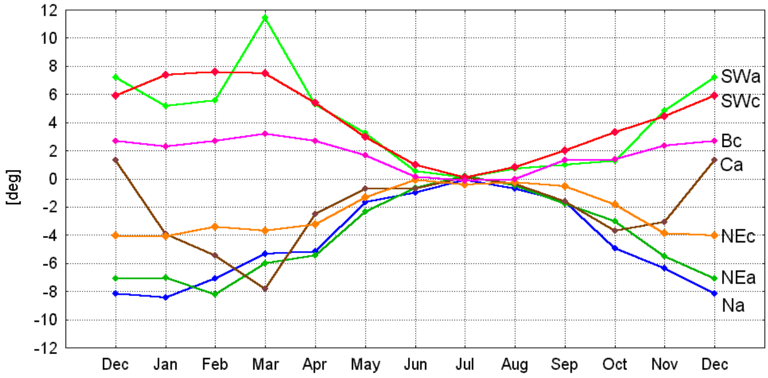

Fig. 9.16. Mean monthly values of deviations of mean minimum air temperature from the multiannual mean for selected types of circulation in 1979–2009.

Table 9.8. Mean minimum air temperature [°C] in individual types of circulation (Tc).

Tc	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Na	**–22.3**	–21.1	–19.0	–16.7	–6.5	**–0.7**	2.4	1.8	–2.0	**–10.5**	**–15.7**	**–20.7**
NEa	–21.5	**–22.3**	–20.1	**–16.9**	**–7.3**	–0.1	2.7	1.6	–2.0	–8.5	–14.4	–19.5
Ea	–16.8	–17.8	–17.0	–13.7	–7.0	1.0	**3.4**	2.0	–0.1	–5.5	–10.3	–14.5
SEa	–11.2	–13.1	–11.6	–10.1	–3.7	0.2	3.2	3.0	0.5	–3.8	–7.6	–9.6
Sa	–8.8	–8.9	–6.7	–7.0	–2.7	1.1	2.8	3.1	1.1	–3.1	–3.7	–6.2
SWa	–8.6	–8.3	**–2.4**	–6.2	**–1.7**	0.8	2.7	3.1	0.8	–4.1	–4.2	**–5.3**
Wa	–9.4	**–4.6**	–6.8	–9.0	–3.6	0.3	2.8	2.2	0.1	**0.4**	–5.2	–7.0
NWa	-	–15.7	-	–15.2	–5.5	0.4	2.3	**1.4**	–0.7	–8.5	–11.6	–15.9
Ca	–18.1	–19.3	**–21.7**	–14.0	–5.8	–0.4	2.6	2.0	–2.0	–9.1	–12.1	–11.1
Ka	–18.5	–18.3	–17.8	–13.9	–5.3	0.3	2.7	2.1	–1.4	–7.8	–12.3	–16.3
Nc	–19.5	–17.2	–16.8	–13.4	–5.3	–0.3	2.3	1.4	**–2.5**	–8.5	–12.9	–15.5
NEc	–18.2	–17.7	–17.8	–15.3	–6.2	0.2	2.3	2.0	–0.9	–7.3	–13.0	–16.6
Ec	–15.4	–14.3	–14.2	–11.8	–5.0	0.5	2.9	2.4	–0.3	–4.0	–9.5	–12.5
SEc	–8.9	–9.6	–9.3	–6.4	–2.9	0.4	2.9	**3.2**	1.0	–2.0	–5.1	–7.0
Sc	–7.4	–7.3	–7.7	**–5.3**	–2.3	1.1	2.7	2.9	**1.6**	–1.6	**–3.4**	–5.4
SWc	**–7.2**	–6.3	–6.5	–5.8	–1.9	**1.3**	2.7	3.1	**1.6**	–2.0	–4.4	–6.6
Wc	–8.1	–10.2	–5.8	–6.4	–1.8	1.0	2.3	2.3	–0.2	–4.5	–4.0	–6.4
NWc	–14.6	–13.0	–15.5	–10.4	–5.1	–0.2	2.4	1.4	–1.9	–5.8	–8.6	–9.9
Cc	–9.6	–10.6	–9.7	–6.7	–3.7	0.4	**1.9**	2.7	0.4	–2.9	–5.3	–7.6
Bc	–11.9	–10.9	–10.5	–9.0	–3.3	0.4	2.5	2.3	1.0	–4.1	–6.6	–9.8
x	–15.9	–13.6	–16.0	–11.0	–4.3	–0.3	2.3	2.0	–1.2	–6.8	–9.2	–15.0
Average	**–14.1**	**–14.0**	**–13.7**	**–11.6**	**–5.0**	**0.3**	**2.6**	**2.3**	**–0.4**	**–5.5**	**–8.9**	**–12.4**
Max	–7.2	–4.6	–2.4	–5.3	–1.7	1.3	3.4	3.2	1.6	0.4	–3.4	–5.3
Min	–22.3	–22.3	–21.7	–16.9	–7.3	–0.7	1.9	1.4	–2.5	–10.5	–15.7	–20.7
Range	15.1	17.8	19.3	11.6	5.6	2.0	1.5	1.8	4.1	11.0	12.2	15.4

(mean minimum temperature of March was –13.7°C). During the summer the range of changes of mean minimum temperature was from 1.5 deg in July to 2.0 deg in June. At the mean minimum air temperature amounting 2.6°C, mean minimum temperature changed from 1.9°C in situation Cc to 3.4°C in the Ea type of circulation.

The impact of circulation types on the diurnal amplitude of air temperature was least clearly evidenced (Table 9.9, Fig. 9.17). The amplitude of changes under the influence of atmospheric circulation ranges from 1.1 deg in August to 5.6 deg in March. During the summer somewhat higher diurnal amplitudes occurred in anticyclonal situations than in cyclonal. The situation is frequently the opposite during the winter because bigger diurnal fluctuations are caused by changes in the direction of air mass inflow in the low-pressure situations.

If we proceed to the more generalized characteristics of regional atmospheric circulation described by indices W (zonal circulation), S (meridional circulation), and C (cyclonicity; Chapter 4.3–4.5), and from mean diurnal temperature and its anomalies to monthly means, we may also obtain a more general view of the role of circulation factors in developing the variability of air temperature.

From the distribution of correlation coefficients shown in Table 9.10 it is seen that the strongest influence on the air temperature is the meridional circulation, unceasing for 9 months (from August to April). The meridional circulation exerts an especially strong influence during the polar night from November to January. During this period the variability of the meridional circulation

Table 9.9. Mean values of diurnal amplitude of air temperature [°C] for individual types of circulation (Tc).

Tc	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Na	7.1	8.3	7.2	7.1	5.2	3.8	4.1	4.1	3.5	5.3	6.2	5.9
NEa	5.4	5.5	5.9	5.8	4.2	4.0	4.4	**3.2**	**2.9**	4.0	5.1	5.4
Ea	4.9	5.3	5.3	5.0	3.9	3.5	4.6	3.4	3.3	**3.1**	4.5	6.0
SEa	**4.8**	5.0	5.0	5.5	3.4	3.4	4.4	4.1	3.4	3.7	4.3	**4.1**
Sa	6.3	7.1	4.2	6.0	4.6	**4.5**	4.6	3.9	**4.5**	4.1	4.4	5.0
SWa	7.2	7.6	**3.2**	6.5	3.7	3.1	3.6	3.8	4.2	**6.1**	5.5	6.8
Wa	5.5	**3.7**	5.5	**8.9**	4.6	3.3	4.0	3.6	4.1	3.8	5.1	4.7
NWa	-	**8.9**	-	5.9	5.1	4.4	**4.9**	4.1	3.1	4.5	5.8	6.6
Ca	8.1	5.6	7.7	6.9	4.5	4.0	4.3	**4.3**	4.0	5.1	6.0	6.1
Ka	6.6	7.1	7.4	7.0	4.9	3.4	3.9	3.9	3.6	4.7	5.3	5.9
Nc	7.8	7.9	6.6	6.7	**5.4**	3.6	3.9	3.9	3.7	5.0	5.8	6.2
NEc	6.7	6.0	6.4	6.3	4.0	3.4	3.8	3.4	3.2	4.1	4.9	5.6
Ec	5.4	5.2	5.6	5.1	4.0	3.5	4.2	3.3	3.1	3.5	4.4	5.1
SEc	5.2	4.8	5.1	**4.5**	3.8	3.3	4.7	4.0	3.6	3.7	**4.1**	4.7
Sc	6.4	6.0	5.2	5.4	3.6	3.3	4.1	4.1	3.8	4.4	4.8	6.1
SWc	7.3	6.9	6.9	5.9	4.0	3.1	3.7	**3.2**	3.8	5.2	6.2	6.8
Wc	7.6	8.2	5.7	5.7	**3.3**	3.0	**3.3**	3.3	3.5	4.9	4.8	6.6
NWc	7.4	7.4	8.8	7.0	4.3	3.6	3.8	3.7	4.0	5.1	**6.7**	6.4
Cc	6.5	7.7	7.3	5.3	4.5	3.3	3.5	3.4	3.7	4.4	5.4	5.7
Bc	6.2	6.2	6.2	6.0	4.0	**2.9**	3.5	3.3	**2.9**	4.2	5.2	6.0
x	6.5	6.6	7.9	5.6	4.0	3.5	3.7	3.7	3.5	5.1	5.7	**7.8**
Average	**6.2**	**6.2**	**6.0**	**5.9**	**4.4**	**3.4**	**4.0**	**3.7**	**3.5**	**4.3**	**5.1**	**5.7**
Max	8.1	8.9	8.8	8.9	5.4	4.5	4.9	4.3	4.5	6.1	6.7	7.8
Min	4.8	3.7	3.2	4.5	3.3	2.9	3.3	3.2	2.9	3.1	4.1	4.1
Range	3.3	5.2	5.6	4.4	2.1	1.6	1.6	1.1	1.5	2.9	2.6	3.7

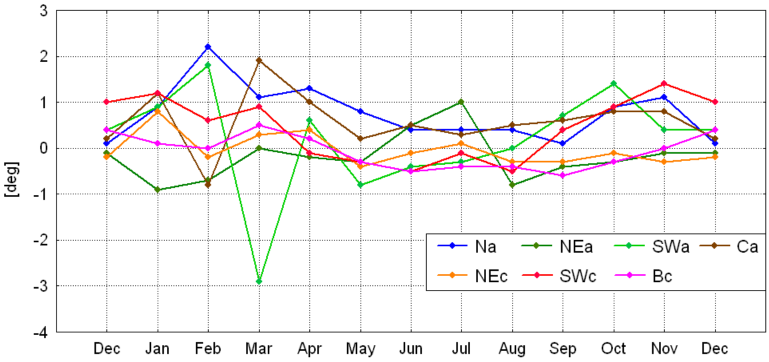

Fig. 9.17. Mean monthly values of deviations of mean amplitude of diurnal air temperature from multiannual mean for selected types of circulation in 1979–2009.

explained from 73% of temperature variability in December to 55% in January. In February, when the polar night ends, the strength of association between meridional circulation and air temperature weakens, but remains significant, and in March and April increases again. Lack of association of air temperature with the meridional circulation is evident only during the highest angles of the Sun during the polar day, in May, June and July. During this period, in the face of the inflow of large amounts of solar energy, the role of advectional factors in determining air temperature variability is weakened. During periods when these associations are statistically significant, inflow of air from the southern sector (positive value of index S) correlates with an increase of temperature, and the advection of air from the north (negative value of index S) with a decrease. Variability of annual index S explains around 30% of the variability of annual air temperature.

Table 9.10. Correlation coefficients between the Niedźwiedź (Tc) W, S and C indices, monthly and annual temperature at Hornsund in 1979–2009 Significant correlation coefficients ($p < 0.05$) are shown in bold.

Tc	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
W	0.35	0.05	**0.40**	0.07	0.11	**0.38**	–0.27	–0.27	0.33	–0.16	0.33	**0.44**	0.26
S	**0.74**	**0.44**	**0.62**	**0.76**	0.23	0.08	–0.10	**0.41**	**0.69**	**0.64**	**0.80**	**0.85**	0.34
C	0.36	0.29	0.32	0.33	0.13	0.04	**–0.50**	–0.15	–0.07	0.29	0.23	0.23	**0.40**

A change of the value of annual index S by one unit causes change of annual air temperature for ~0.02°C. For example, in 1984, when the annual index S was +66[9], at the mean multiannual value of this index of –37, the increase of annual air temperature compared to the multiannual mean should amount to around 2 deg. The annual temperature in 1984 indeed was 2.0 deg higher than the multiannual mean (–2.3°C in 1984; –4.3°C multiannual mean). The interrelation between the mean temperature of December and monthly values of the circulation index S is presented in Fig. 9.18. From the regression equation, an increase of 10 index units is accompanied by increase of mean monthly temperature of 3.6 deg. At the lowest value of the index, –23 in December 2003, the mean temperature was –15.3°C. However, in December 1988 air temperatures decreased to as much as –17.5°C, despite an index S value reaching only –15. In contrast, the highest December mean temperature of –1.2°C (1984) was associated with the highest December index value of +18. From the Fig. 9.18 regression equation, we may expect a positive mean temperature in December at Hornsund when the monthly index S exceeds +22.

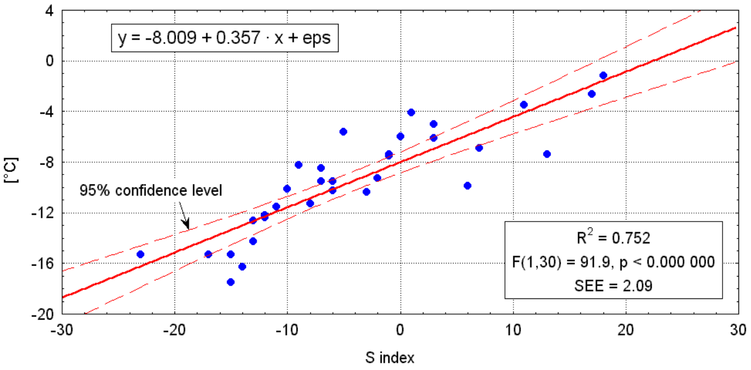

Fig. 9.18. Dependence of mean monthly temperature in December (y) on monthly S index value (x). R^2 – coefficient of determination.

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[9] It was the highest annual value of circulation index S in 1951–2009.

The variability of zonal circulation indices (W) and cyclonicity indices (C) exert weaker influences on the behaviour of air temperature. In the case of the C index one may notice that negative values of correlation coefficients occurred in July, August and September and positive values in the remaining months, with a maximum in February. It may be supposed that increased frequency of cyclonic situations (which create positive index values), is accompanied by the increase of cloudiness (Chapter 7). Increase of sky cover by clouds in winter months restricts outgoing radiation, contributing to the increase of air temperature. In the period between July and September increase of cloudiness restricts inflow of direct radiation to the surface, contributing to decrease of temperature. As opposed to strong influence of the S index on air temperature, the associations between the W and C indices and the temperatures are weaker and change the character of their impacts over time.

9.5.3. The influence of sea ice cover on the air temperature at Hornsund

The insular location of Svalbard ensures that the climate of the archipelago experiences a strong marine influence. One of the controllers of dimensions and character of this influence is the sea ice cover (SIC), its spatial and temporal variability. It introduces additional variability into the course of air temperature. Features and changes of SIC on waters surrounding Spitsbergen were described in Chapter 3.3; here attention will be concentrated on associations between sea ice area and air temperature at Hornsund.

Research into synchronous associations between SIC and air temperature is always encumbered with risk because the two quantities are not independent. Air temperature depends on SIC only to the extent that the ice cuts off flow of heat from the oceans to the atmosphere. In turn, except for special cases[10], characteristics of the ice (degree of compaction, thickness, area …) are in part controlled by air temperature. In such circumstances it is hard to make predictions what is the cause and what is the result of changes, both of air temperature and SIC (e.g. Rigor *et al.* 2002). For that reason, equal attention will be devoted to presentation of the results of research on asynchronous associations in which SIC, assumed to be the independent variable, stays ahead of the dependent variable, air temperature, in time. Result of analyses shown below are based on research on associations between monthly series of sea ice extent (SIE) values, beginning in November 1978 and ending in December 2007 (set sfc.nasateam.month.extent.1978-2007.n)[11]. This enables synchronous and asynchronous analysis (sea ice 1979–2007, air temperature 1979–2007 and 1980–2008) of a series of 28 pairs. With such a number of intercorrelated series, the limit for the correlation coefficient (r) reaching a significance $p < 0.05$ (level of confidence = 95%) is $|0.375|$, for $p < 0.001$ is $|0.593|$. SIC influences air temperature through cutting off the flow of heat from the ocean surface to the atmosphere. This aspect of sea ice activity exerts particular influence on the variability of temperatures during a polar night, when streams of heat from the

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[10] For example in the situation where allochtonous ice cover occurs (i.e. formed on another body of water and transported by drift), in conditions which did not occurred on this area on which ice is present.

[11] Cavalieri, D., C. Parkinson, P. Gloersen, and H. J. Zwally, 1996, updated 2008. Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I passive microwave data. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media (ftp://sidads.colorado.edu/pub/DATASETS/seaice/polar-stereo/trends-climatologies/ice-extent/nasateam/).

ocean to the atmosphere are, beside advection of warmer air masses, the principal "local" source of heat.

Miętus and Filipiak (2005) using data from the ICOADS set estimated mean monthly dimensions of fluxes of actual heat and latent heat of evaporation (1991–2000) from waters around Spitsbergen to the atmosphere. According to these researchers in January in waters enveloping the island from the south and west the actual heat flux reached an intensity of around 100–110 W/m^2, and was similar (90–100 W/m^2) for most of this body of water in December and February. Fluxes of latent heat from open water adjacent to the western coast of Spitsbergen reached somewhat over 110 W/m^2 at the mouth of Bellsund in January, between 110 and 100 W/m^2 from there to the entrance to Isfjorden, and around 100 W/m^2 further to the north, to the edge of the ice (Miętus and Filipiak 2005). The flux of latent heat over the warm core of the West Spitsbergen Current slightly exceeded 120 W/m^2 in January. Generalizing values for the waters off the west coast of Spitsbergen, the aggregate flux of heat from the ocean to the atmosphere was around 200 W/m^2. Unquestionably, the bulk of the latent heat of evaporation from the ocean surface is transformed into the actual heat (latent heat of condensation) by formation of convection clouds over the eastern part of the Greenland Sea and over Spitsbergen. Semenov (2008) estimated similar values for fluxes of heat from the surface of the Barents Sea during the winter (~200 W). According to Smedsrud *et al.* (2010) loss of heat from the surface of the Barents Sea in the middle of winter raises air temperature in the region from –12°C to –8°C.

Interannual variability of SIE on bodies of water eastward and westward from Spitsbergen shows clear associations with the variability of air temperature at Hornsund. Associations between mean annual temperature at the station and mean annual SIE on the Greenland Sea, Barents and Kara Seas are of similar strength – correlation coefficients are around –0.6 ($p < 0.002$), indicating that variability of mean annual SIE explains around 36% of the variability of annual temperature at the station (and contrary).

The distribution of the correlation coefficients between air temperature at Hornsund and SIE on the Greenland Sea and on the bodies of water east and southeast of Spitsbergen (the Kara and Barents Seas) shows however that the impact of ice cover differs (Table 9.11).

Table 9.11. Correlation coefficients between monthly air temperature at Hornsund and SIE on the Greenland Sea and Barents and Kara Seas. Correlation coefficients statistically significant showed in bold, intercorrelated series from 1979–2007 (28 years)

Sea	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Greenland	**–0.59**	**–0.69**	–0.20	**–0.58**	–0.32	–0.32	**–0.40**	**–0.39**	–0.31	**–0.52**	**–0.59**	**–0.73**
Kara & Barents	**–0.72**	**–0.71**	–0.25	**–0.56**	**–0.68**	**–0.59**	–0.11	–0.06	–0.25	**–0.43**	**–0.55**	**–0.73**

The ice cover on the Greenland Sea displays significant associations with Hornsund air temperature in the autumn-winter period from October to April (with a "break" in March), while the strongest associations appear in December ($r = –0.73$). Such associations are conditioned by the influence of the water temperature of the West Spitsbergen Current on the growth of ice cover. The increase of heat resources in this current causes delayed formation of ice at the beginning of the winter and during it. As a result heat fluxes from the sea surface to the atmosphere remain strong, not permitting deep drops of air temperature.

A peculiar feature is the occurrence of statistically significant associations between SIE on the Greenland Sea and the air temperature at Hornsund in July and August. In some years, ice from bodies of water east of Spitsbergen[12] is transported to the SW and is carried with the Sörkapp Current in to the Greenland Sea. This occurs usually in July, therefore SIE increases on the Greenland Sea in that month during these years. This ice is next carried along the western coast of Spitsbergen, frequently filling Hornsund, Bellsund, and at times reaching Isfjord. The occurrence of the belt of sea ice along the coast and in Hornsund Fjord causes a distinct decrease of air temperature in the coastal areas.

A statistically significant impact of the Kara and Barents Sea SIE on air temperature at Hornsund begins in October, like SIE on the Greenland Sea, and lasts until June, with a break in March[13] (Table 9.11). SIE on these seas decides the degree of transformation of air masses flowing over it. In the face of prevailing inflow of air over Spitsbergen from eastern directions (see Chapter 4), a decrease of air temperature at Hornsund results from increased SIE on these seas. In July, August and September, when SIE is smallest on the Barents and Kara Seas, the statistically significant associations with air temperature at Hornsund decline (r equal –0.11, –0.06 and –0.25, respectively). The gradual rebuilding of ice cover in the autumn and the beginning of winter contributes to an increase of strength of the associations, becoming very strong (r > |0.7|) in December, January and February.

Analysis of variance permits us to estimate the degree of explanation of changes of monthly air temperature at Hornsund due to the variability of SIE on the Greenland Sea and on the Barents and Kara Seas. Results of this analysis are shown in Table 9.12.

Table 9.12. Degree of explanation of variance of monthly air temperature (adj. $R^2 \cdot 100\%$) by variability of SIE on the Greenland Sea and the Kara and Barents Seas.

Sea	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Greenland	**34.8**	**47.6**	0.0	**33.6**	0.0	0.0	**16.0**	**15.2**	0.0	**27.0**	**34.8**	**53.3**
Kara & Barents	**51.8**	**50.4**	0.0	**31.4**	**46.2**	**34.8**	0.0	0.0	0.0	**18.5**	**30.2**	**53.3**

Notes: statistically significant values of degree of explanation are given in bold, not significant values are omitted (0.0), data from 1979–2007 (28 years).

One may notice that variability of SIE on the Greenland Sea between October and December better explains variability of temperature at Hornsund than variability of SIE on the Kara and Barents Seas during these months. Changes of SIE on the Barents and Kara Seas explain changes of air temperature at Hornsund well in January-February and between April and June. In the months when SIE reaches its minimum, its changes do not explain changes of air temperature at Hornsund, similarly for the month of maximum development of SIE. Statistically significant impacts of SIE on

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[12] From the region between Nordaustlandet (North-Eastern Land) and Franz Joseph Land.

[13] SIE in March on the Barents, Kara and Greenland Seas, as in the whole Arctic, reaches the greatest dimensions. As a result, despite rapid increases of solar energy, the air temperature reaches minimum values frequently in March and correlations between SIE on particular seas and air temperature at single stations become not significant. The great area of ice in the Arctic acts in March as a “super-regional" factor, totally suppressing effects of local changes.

seas surrounding Spitsbergen[14] on the air temperature are evident only between October and February and in April.

Variability of mean annual air temperature at Hornsund is explained to comparable extents by variability of mean annual SIE on the Greenland Sea, and on the Kara and Barents Seas. The overall impact of mean annual SIE on these bodies of water explains around 49% of the variation of annual temperature, that is about 12% more than for each of these bodies of water separately.

Analysis of these monthly values of SIE to explain to greatest extent of the variability of mean annual air temperature at Hornsund (Ta) determined that these are SIE of the Kara and Barents Seas in December (marking SIE_KB_{Dec}; thousands km^2) and on the Greenland Sea in February (SIE_G_{Feb}; thousands km^2). In a multiple regression equation:

$$Ta = 6.576(\pm 1.103) - 0.005(\pm 0.001)\cdot SIE\_KB_{Dec} - 0.003(\pm 0.001)\cdot SIE\_G_{Feb}\,. \qquad [1]$$

Cumulatively these explain 79% of variability of annual air temperature at Hornsund ($R = 0.90$, $F(2,25) = 51.0$, $p \ll 0.001$). SIE_KB_{Dec} explains 73.8%, and SIE_G_{Feb} 6.5% of variation of annual temperature at Hornsund. Other potential variables, for which estimates of the regression coefficients were statistically significant and which could be entered into a multiple regression equation as successive independent variables, explain around 1% (or less than 1%) of air temperature variation. Such a selection of variables to a considerable extent results from the fact that SIE on the Greenland Sea is in particular months correlated more weakly or strongly with SIE on the Barents and Kara Seas.

Quite curious is the asynchronous association between SIE and future air temperature at Hornsund. Definitely stronger associations with the temperatures that will occur at Hornsund show earlier SIE effects on the Kara and Barents Seas than on the Greenland Sea. The temporal distribution of these associations also develops differently. Correlations between individual series of monthly SIE and future monthly air temperatures at Hornsund are shown in Tables 9.13 and 9.14.

There are some regularities in these asynchronous correlations between SIE and delayed air temperature at Hornsund. SIE in some past periods displays correlation with the air temperature of specific months (e.g. on the Greenland Sea, SIE from March to June correlates significantly with air temperature in December the same year, SIE from March, April and May with air temperature in December of the following year; on the Barents and Kara Seas SIE in June, July, August and September significantly correlates with air temperature in December of the same year, whereas SIE from January, February and March as well as November and December correlates with air temperature at Hornsund in December of the following year (Tables 9.13 and 9.14).

Analysis of distribution of associations seems to show that these correlations display duality. Some of the relationships are effects of the intermonthly inertia of SIE and development of associations of an autocorrelation type. To such should be assigned all those cases in which SIE correlates with the air temperature of the following month. In such cases one may speak of simple relations having a physical nature. Others are signals informing us of the occurrence of some

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[14] Statistically significant in the sense of supporting a multiple regression equation, in which estimation of regression coefficients in front of both independent variables, that is SIE on the Kara and Barents Seas and on the Greenland Sea from the same month is statistically significant.

Table 9.13. Asynchronous correlations between SIE on the Greenland Sea in a given month and delayed (time-lagged) air temperature at Hornsund.

SIE	Months in which significant relations occur between air temperature and SIE
Jan	**Feb** (–0.59), **Apr** (–0.43), **Jun** (–0.48), **Dec** (–0.42), **Feb**$_{k+1}$ (–0.42), **Dec**$_{k+1}$ (–0.42)
Feb	**Apr** (–0.45), **May** (–0.41), **Jun** (–0.57), **Sep** (–0.43)
March	**Apr** (–0,43), **Jun** (–0.50), **Sep** (–0.41), **Nov** (–0.47), **Dec** (–0.50), **Feb**$_{k+1}$ (–0.42), **Dec**$_{k+1}$ (–0.40)
April	**Jun** (–0.39), **Sep** (–0.40), **Dec** (–0.54), **Feb**$_{k+1}$ (–0.62), **Dec**$_{k+1}$ (–0.52)
May	**Jun** (–0.42), **Dec** (–0.55), **Feb**$_{k+1}$ (–0.59), **Dec**$_{k+1}$ (–0.45)
June	**Dec** (–0.39)
July	**Jun**$_{k+1}$ (–0.39)
Aug	-
Sep	**Oct** (–0.38)
Oct	**Jul**$_{k+1}$ (–0.42)
Nov	**Dec** (–0.48)
Dec	**Feb**$_{k+1}$ (–0.41), **Jul**$_{k+1}$ (–0.39)

Notes: only statistically significant correlations were taken into account; k+1 after the name of month means given month in the next year.

Table 9.14. Asynchronous correlations between SIE on the Barents and Kara Seas in a given month and time-lagged air temperature at Hornsund.

SIE	Months in which significant relations occur between air temperature and SIE
Jan	**Feb** (–0.58), **May** (–0.46), **Jun** (–0.49), **Aug** (–0.41), **Dec** (–0.47), **Jun**$_{k+1}$ (–0.50), **Nov** $_{k+1}$ (–0.51), **Dec**$_{k+1}$ (–0.50)
Feb	**May** (–0.56), **Jun** (–0.48), **Aug** (–0.39), **Dec** (–0.48), **Jan**$_{k+1}$ (–0.39), **Feb**$_{k+1}$ (–0.42), **Nov**$_{k+1}$ (–0.40), **Dec**$_{k+1}$ (–0.47)
March	**Apr** (–0.40), **May** (–0.61), **Jun** (–0.58), **Nov**$_{k+1}$ (–0.39), **Dec**$_{k+1}$ (–0.41)
April	**May** (–0.57), **Jun** (–0.59), **Jan**$_{k+1}$ (–0.40), **Feb**$_{k+1}$ (–0.44), **Aug**$_{k+1}$ (–0.39)
May	**Jun** (–0.62), **Feb**$_{k+1}$ (–0.45), **Aug**$_{k+1}$ (–0.38)
June	**Dec** (–0.43), **Aug**$_{k+1}$ (–0.52), **Nov**$_{k+1}$ (–0.41), **Dec**$_{k+1}$ (–0.38)
July	**Dec** (–0.61), **Jan**$_{k+1}$ (–0.43), **Feb**$_{k+1}$ (–0.41), **Jun**$_{k+1}$ (–0.42), **Aug**$_{k+1}$ (–0.49), **Nov**$_{k+1}$ (–0.38)
Aug	**Dec** (–0.60), **Jun**$_{k+1}$ (–0.45), **Aug**$_{k+1}$ (–0.41)
Sep	**Dec** (–0.59), **Jun**$_{k+1}$ (–0.45)
Oct	**Aug**$_{k+1}$ (–0.41)
Nov	**Dec** (–0.44), **Jan**$_{k+1}$ (–0.48), **Dec**$_{k+1}$ (–0.42)
Dec	**Jan**$_{k+1}$ (–0.62), **Feb**$_{k+1}$ (–0.49), **05N** (–0.42), **Jun**$_{k+1}$ (–0.47), **Dec**$_{k+1}$ (–0.47)

Notes: only statistically significant correlations were taken into account; k+1 after the name of month means given month in the next year.

inertial associations between SIE in a given period and development of certain features of the climatic system, which cause "transfers" in the temporal impact of SIE on the air temperature. One may suppose that the reason for occurrence of such delayed associations are slow changes in the function of heat resources in waters of seas surrounding Spitsbergen, regulating both SIE and air temperature.

It is worth noting here that in all cases signs of correlation coefficients are the same and negative, which means that in the each case of an SIE increase the future air temperature will be lower. This relation may be used as a qualitative predictor of temperature changes. Using these relationships for quantitative forecasts (regression with one variable or multiple regression) seems risky because of the computational problems.

Regression analysis to determine which parameters of the ice cover in a given year to the greatest degree determine annual air temperature at Hornsund in the following year, shows SIE on the Barents and Kara Seas in December and SIE on the Greenland Sea in April as two the most important independent variables. Variation of both variables explains 40% of temperature variability in the next year at Hornsund, of which variability of December SIE on the Barents and Kara Seas explains 35% of variation. This may be interpreted to show that SIE on the Barents and Kara Seas in December indicates thermal state of these bodies of water. When heat resources in these seas are higher than average, the SIE in December is also smaller than average. This results in limitation of ice cover growth on these bodies of water in the following year and thus limitation of falls of air temperature and, in consequence, increase of mean annual air temperature at Hornsund (Fig. 9.19). The local atmospheric circulation has some influence on such development of temperature in the following year at Hornsund, for which domination of winds from the eastern sector, carrying air from over the northern parts of the Barents Sea to Hornsund is characteristic.

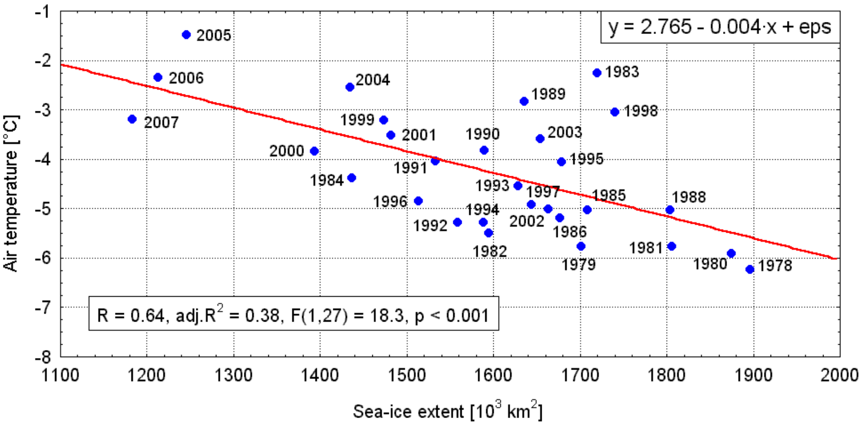

Fig. 9.19. Association of SIE in December on the Barents and Kara Seas (thousands km^2) and annual air temperature at the Hornsund station in the following year. Numbers concern x-axis (e.g. point marked 2007 denotes sea-ice extent in December 2007 (x), what corresponds to annual temperature of year 2007 at Hornsund).

Considering the asynchronous associations of sea ice with air temperature at Hornsund one should pay attention to the fact that there are significantly stronger asynchronous associations between SIE in a given month and SIE in following months than the associations with air temperature. On the Greenland Sea such associations are especially strong in the variability of SIE in November and December. The growth of ice in November indicates its likely extension also in the period from December to the end of following year. The growth of SIE in December indicates growth of SIE from January to August in the next year, with a strong and significant increase of SIE in the spring and summer months. In contrast, decrease of SIE on the Greenland Sea in November indicates decrease of SIE on this sea in all months of the following year.

9.5.4. The influence of sea surface temperature (SST) changes on the air temperature at Hornsund

Changes of temperature of waters surrounding Spitsbergen and influences of SST changes on air temperature were presented in Chapter 3.3. The quantitative (statistical) associations between SST changes and changes of air temperature at the Hornsund station will be discussed here.

Considering the associations of SST with air temperature it should be borne in mind that the two differ in important characteristics. Changes of SST on waters surrounding Spitsbergen are large-scale, encompassing enormous areas in relation to that of Spitsbergen. The variability of air temperature is characterized by large amplitude and rapid temporary changes. Its rhythm is defined by annual radiation balance and by processes at the synoptic scale. Given that the product of the density and specific heat of water is three orders of magnitude greater than that of air and the significant thickness of the water layer participating in heat exchange with the atmosphere, SST changes are characterized by their huge inertia in comparison to air temperature changes. As a result of synoptic activity air temperature in the Spitsbergen region may change by dozen degrees over a few hours, while at the same time the sea surface does not show measurable temperature changes as a rule, despite discharging huge amounts of heat to the atmosphere. The annual rhythm of SST changes is relatively smooth because heat transport by currents is weak. Where it occurs the main causes of SST variability are changing heat resources together with flow of water mass and heat losses by radiation and exchange with the atmosphere. The annual variability of energy inflow to the sea surface plays a minor role, except for the period of the "full summer". For that reason SST changes are well correlated with mean air temperatures averaged over longer periods (seasonal, annual) but considerably weaker with short period means (monthly).

Analysis of associations between annual temperature at the Hornsund station (Ta) and monthly SST on waters surrounding Spitsbergen, done by step-wise regression[15] yielded the following result:

$$Ta = -17.63\ (\pm 2.52) + 3.67(\pm 0.85)\cdot W[76,10]_{May} + 1.57(\pm 0.60)\cdot W[76,26]_{Dec}, \qquad [\,2\,]$$

where:

$W[76, 10]_{May}$ – SST in grid 76°N, 10°E in May,
$W[76, 26]_{Dec}$ – SST in grid 76°N, 26°E in December.

This relation is highly significant statistically ($R = 0.85$, adj. $R^2 = 0.69$, $F(2,28) = 35.0$, $p < 0.00001$) and permits estimation of the mean annual air temperature at Hornsund with a standard error of estimate (SEE) of only ±0.7°C. The plot of relationships estimated with Equation [2] and observed values of annual temperature at Hornsund are shown in Fig. 9.20. Cumulatively SST variability in

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[15] For the step-wise regression monthly values of SST in grids 76°N, 10°E; 76°N, 12°E; 76°N, 14°E (the Greenland Sea; section through West Spitsbergen Current (WSC) and waters of the eastern borders of WSC), 76°N, 26°E (NW part of the Barents Sea) between January and December were taken as independent variables. Analysis determines the equation of multiple regression, ordering the successive, not intercorrelated, independent variables by the R^2 explained by them. In first place is the independent variable that explains the largest percentage of variation of dependent variable, in second place, the independent variable explaining next largest value of R^2. Applying the scree test (see: http://www.statsoft.com/textbook/statistics-glossary/s/button/s/) one may extract the variables (factors) which to the greatest degree determine the variability of dependent variable. Here, because of the set of 31 cases, analysis was restricted to equations with two or three independent variables (15 and 10 cases for one independent variable).

these two months explains around 69% of annual air temperature variability observed at Hornsund so far, in which variability of SST in May on the Greenland Sea, on axis of West Spitsbergen Current (grid 76°N, 10°E) explains 64.4%, and variability of SST in December on the Barents Sea (grid 76°N, 26°E) explains 7.2% of annual air temperature variability.

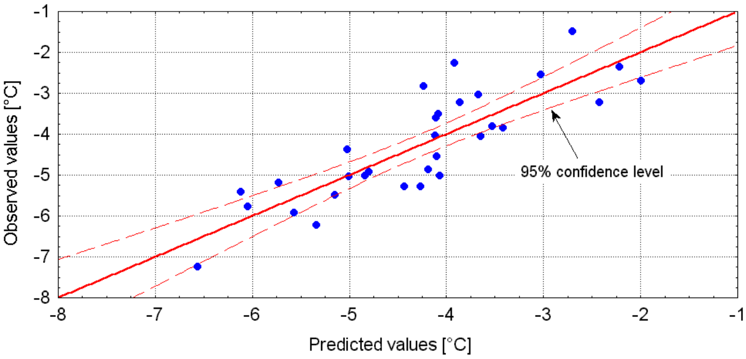

Fig. 9.20. Annual air temperature at Hornsund as a function of SST changes in grids 76°N, 10°E in May and 76°N, 26°E in December. Values estimated with Equation [2].

A complete explanation of the physical sense of Equation [2] would require presentation of associations between monthly SST values on each body of water. Here explanations will be brief. SST in May on the Greenland Sea is very strongly correlated with SST of January, February, March and April. If in those months heat resources in the waters, and therefore also SST, were higher than average so SST in May was also higher than average. Thus high SST in May in this grid is an indicator of high water temperature during the winter, and indirectly – of reduction of ice cover on the Greenland Sea and strong flux of heat from the ocean to the atmosphere during the winter. Similar, in the light of signal analysis, is the importance of water temperature on the Barents Sea. SST in December indicates the heat resources in waters of this part of the Barents Sea from the end of summer warming period. If these are small, SST in grid 76°N, 26°E adopts negative values (see Chapter 3.3.). Sea ice cover forms early there, air flowing from the East to Hornsund Fjord is also colder, which causes decrease of annual air temperature at the station. Therefore, Equation [2] reveals that thermal state of the Greenland Sea during the winter (January-May) exerts the strongest influence on annual air temperature. The thermal state of the NW part of the Barents Sea during the autumn and at the beginning of winter exerts the weaker influence.

The temperature of surface waters surrounding Spitsbergen also carries information what will be likely air temperatures at Hornsund in the next year ($Ta_{(k+1)}$). Stepwise multiple regressions with the same set of independent variables used for analysis in Equation [2], allowing for estimation of annual temperature in the next year is:

$$Ta_{(k+1)} = -17.98(\pm 3.07) + 4.98(\pm 1.07)\cdot W[76,26]_{Sept} - 5.19(\pm 1.40)\cdot W[76,14]_{Nov} + \\ + 4.33(\pm 1.30)\cdot W[76,12]_{Dec}, \qquad [3]$$

where:

$W[76, 26]_{Sept}$ – SST in the grid 76°N, 26°E (the Barents Sea) from September, W [76, 14]$_{Nov}$ – SST in the grid 76°N, 14°E (the Greenland Sea) from November,

W [76, 12]$_{Dec}$ – SST in the grid 76°N, 12°E (the Greenland Sea) from December.

This equation is also highly statistically significant ($R = 0.84$, adj. $R^2 = 0.67$, $F(3,27) = 21.8$, $p < 0.00001$, SEE = 0.77; see Fig. 9.21).

Annual air temperature in the following year is explained here by three variables originating either from the period of end of the summer warming of the ocean surface (1 variable; September), or from the end of the autumn, beginning of the winter (2 variables; November, December). All three variables inform on the heat resources in the waters that are accumulated before the arriving winter. The principal features of Ta_{k+1} at Hornsund are explained by the thermal state of the Barents Sea, in the multiple regression equation variation in variable W [76,26]$_{Sept}$ explains 55.3% of temperature variation at Hornsund, and the next two variables from the Greenland Sea explain 3 and 12% of variation respectively. Similar equations may be also used for seasonal air temperature on Spitsbergen. Statistically significant monthly temperature estimates are obtained only for some months, in addition explaining only a small percentage of the temperature variation.

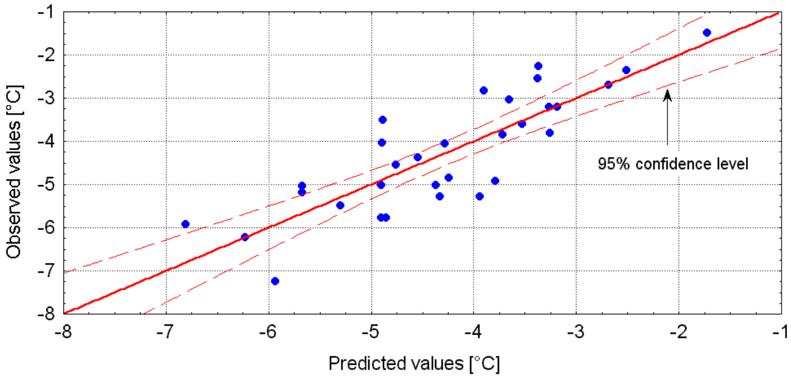

Fig. 9.21. Air temperature of the following year at Hornsund as a function of SST changes in grids: 76°N, 26°E in September, 76°N, 14°E in November and 76°N,12°E in December. Values estimated with Equation [3] in relation to observed values.

It follows from the analyses that more than half of the variability of annual air temperature of a given and the following year is explained by variability of SST of seas surrounding Spitsbergen in the given year. This means that the role of SST changes of these seas in development of the long term, annual and interannual variability of air temperature at Hornsund is fundamental.

It was mentioned earlier (see Chapter 3.3), that variability of heat resources, and thus SST, in waters of the Greenland Sea and Barents Sea is determined by transport of heat with transport of Atlantic water by the North Atlantic, Norwegian and West Spitsbergen Currents. SST on waters of the Greenland Sea adjacent to the western coast of Spitsbergen shows very strong, intensely expanded in time, correlations with $LF_{1\text{-}4\ index}$ and DG_{3L} index from preceding year (see Chapter 3.3).

Air temperature at Hornsund is strongly associated with SST and so in turn is strongly associated with the $LF_{1\text{-}4}$ index. Thus strong correlations of SST on the Greenland Sea with the $LF_{1\text{-}4\ index}$ allow estimation of annual and seasonal air temperatures at Hornsund directly from values of $LF_{1\text{-}4}$ from the preceding year (k-1). The relation between $LF_{1\text{-}4\,(k\text{-}1)}$ value and annual air temperature at Hornsund (Ta_{k}) is:

$$Ta_{(k)} = -20.42(\pm 3.18) + 2.56(\pm 0.50)\cdot LF_{1\text{-}4\,(k\text{-}1)}\,, \qquad [4]$$

and its statistical characteristics are as follows: $R = 0.69$, adj. $R^2 = 0.45$, $F(1{,}29) = 25.9$, $p < 0.00002$, $SEE = 0.99$. Equation [4] has prognostic power because the value of $LF_{1\text{-}4\ \text{index}}$ may be obtained (calculated) in May and from this value temperature for the next year is calculated (Fig. 9.22).

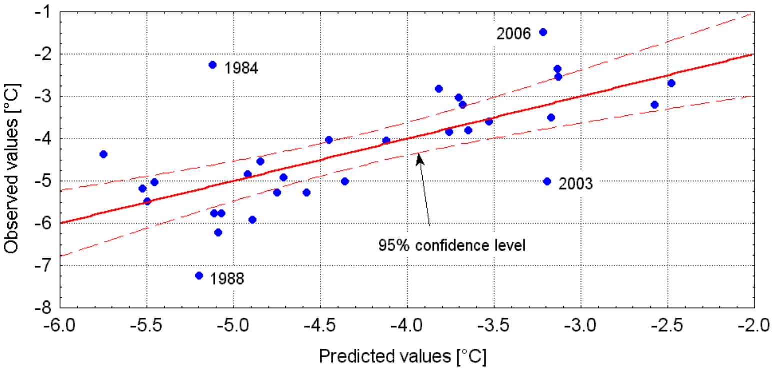

Fig. 9.22. Air temperature of the succeeding year at Hornsund as a function of the $LF_{1\text{-}4}$ index. Values estimated with equation [4] in relation to observed values. Outlying values are marked (as specific years).

Fig. 9.22 shows that this equation exhibits good linearity but one independent variable is too small to obtain more precise explanation of variability of air temperature in the next year at Hornsund. Distribution of the outlying values (1984, 2006, 1988 and 2003) shows that for explanation of variability of annual air temperature at Hornsund at least one additional variable is needed, the periodical influence of which, not being connected with variability of $LF_{1\text{-}4}$, is the cause of strong deviations of annual temperature from the regression line. However the $LF_{1\text{-}4\ \text{value}}$ from the Lofoten region around 1000–1200 km distant from the station explains around 46% of variability of temperature of the following year at Hornsund. This equation is of important prognostic significance and allows determination of the general features of air temperature at Hornsund (warming, cooling) a substantial time in advance.

Like the $LF1_{\text{-}4}$ index the annual temperature of the following year at Hornsund may be estimated from the DG_{3L}index characterizing heat resources of the tropical water flowing northwards (Chapter 3.3). In this case the temporal shift is even bigger – the DG_{3L} index averaging of SST changes in the region of Gulf Stream Delta (grid 38°N, 56°W) from the three preceding years most strongly correlates with air temperature at Hornsund in the succeeding year. The lag of air temperature reaction on Spitsbergen in relation to DG_{3L} changes is from one year to four years. The regression equation treating annual air temperature on Spitsbergen as a function of the DG3L index is:

$$Ta_{(k)} = 4.79(\pm 0.22) + 0.90(\pm 0.19)\cdot DG_{3L\,(k\text{-}1)}\,, \qquad [5]$$

$R = 0.65$, adj. $R^2 = 0.41$, $F(1,29) = 21.4$, $p < 0.00007$, $SEE = 1.03$. Equation [5] explains a somewhat smaller percentage of variation of annual temperature at Hornsund than equation [4], which is understandable given the considerably greater distance between Hornsund and region of origin of the DG_{3L} signal, than the region of origin of LF_{1-4}.

Both variables DG_{3L}, and LF_{1-4} allow estimation of seasonal air temperature at Hornsund. In the case of estimation of air temperature in the "classical" seasons (DJF, MAM, JJA, SON) statistically significant associations are obtained for the summer, autumn and winter but not significant for the spring. In the case of estimation of air temperature for thermal seasons discussed in Chapter 9.4, statistically significant associations are obtained for all seasons. All of these associations are asynchronous, independent variables guiding the dependent variable for a given year, and hence approximate temperatures at Hornsund may be known a few months or even more in advance.

9.5.5. Comprehensive effects of changes of sea ice extent, sea surface temperature and atmospheric circulation on the air temperature at Hornsund

Air temperature variability at the Hornsund station depends on the activity of a number of factors simultaneously. Some of these factors which display big interannual variations and exert regulating influence on air temperature are in turn steered by other factors. An example of such a factor may be cloudiness, which strongly but indirectly regulates variability of air temperature[16], simultaneously being clearly conditioned by local atmospheric circulation (Chapter 7.1). This causes appearance of ambiguities in the hierarchy of importance of factors shaping variability of air temperature, and additionally introduces problems with calculations of analysis of variance and regression (redundancy). Activity of particular factors regulating interannual variability of temperature at Hornsund, in the face of simultaneous multidirectional activity of a few factors, is additionally changeable in time. A single factor in one year may explain the variability of air temperature very well, but in another year weakly or not at all. The atmospheric circulation and heat transport by the system of marine currents in the Atlantic water (index LF_{1-4}) may be an example. Variability of the index LF_{1-4} generally explains interannual variability of air temperature well; however temperatures in 1984 and 2003 were definitely outliers, not confirming any constancy in the strength of the relationship (Fig. 9.23). The same outlying cases are well explained by features of regional atmospheric circulation, specifically the Niedźwiedź annual S index of circulation (Fig. 9.24). At the same time, the case of 1988 does not correlate with the trend of values of the S index but instead with the trend of values of LF_{1-4} (taking into account its long-term behaviour; see the previous chapter). Complementary activity of individual climate forming factors therefore requires adequately applied analysis, allowing for establishing the correct hierarchy of the role of each of them, in cooperation with others.

Appropriate analyses were made to explain which factors control interannual variability of air temperature at Hornsund and what the hierarchy is. Searching for factors acting synchronously (which to the strongest degree explain interannual variability of air temperature at Hornsund), values characterizing variability of local atmospheric circulation as described by the annual indices of

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[16] Also other climatic elements at Hornsund, e.g. sunshine duration and precipitation; see appropriate chapters of this book.

local atmospheric circulation S, W and C of Niedźwiedź (1992, 2006), annual values of SST in three grids on the Greenland Sea (76°N, 10°E; 76°N, 12°E; 76°N, 14°E), annual values of SST in the grid on NW part of the Barents Sea (76°N, 26°E) and SIE on the Greenland, Kara and Barents Seas were chosen for analysis. In view of the obvious strong association between SIE and air temperature (Chapter 9.5.2), and also the fact that mean annual ice cover averages data from two different ice seasons (peak season and end of one season as well as beginning of the next season), mean annual SIE was not used in analysis. Instead, mean values for periods between January and June and between September and December for both bodies of water were calculated from monthly means.

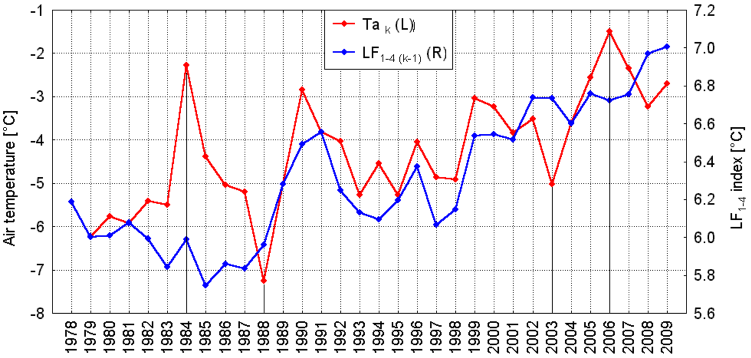

Fig. 9.23. Courses of annual air temperature at Hornsund (Ta $_k$) and the winter SST in the region of Lofoten (LF_{1-4} index). Air temperature at Hornsund (series from 1979–2009), series LF_{1-4} from 1978–2008, shift of one year, temperature in the next year in relation to date of LF_{1-4}.

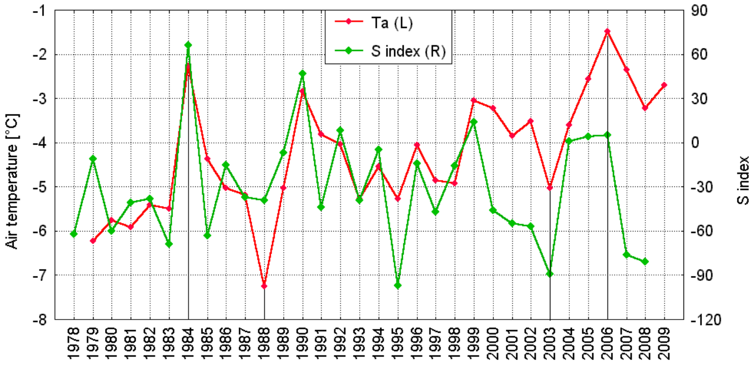

Fig. 9.24. Courses of annual air temperature at Hornsund (Ta) and the Niedźwiedź annual S index in 1978–2009.

As the method for finding dominant factors, step forward regression (see footnote 15 in this chapter) was used. Annual air temperature at Hornsund was the dependent variable and the independent variables were the aforementioned quantities (11 in total, being 3 – local atmospheric circulation, 4 – SST, 4 – variability of SIE). A series of 28 years were analysed, using results from the SIE data series, 1979-2007. Such short series do not allow stable equations with more than three independent variables. The aim of this analysis was to determine these factors, which play fundamental role in the development of annual air temperature variability.

Analysis showed that annual air temperature at Hornsund (Ta), at the set of independent variables adopted for analysis might be described as:

$$Ta = 4.821(\pm 1.017) - 0.006(\pm 0.001)\cdot SIE\_G_{\text{Jan-June}} + 0.014(\pm 0.003)\cdot S_{\text{annual}} - 0.004(\pm 0.001)\cdot SIE\_B_{\text{Sept-Dec}}, \qquad [6]$$

where:

$SIE\_G_{\text{Jan-June}}$ – mean SIE between January and June on the Greenland Sea (thousands km^2),

S_{annual} – annual index of circulation S (meridional) of Niedźwiedź (dimensionless),

$SIE\_B_{\text{Sept-Dec}}$ – mean SIE between September and December on the Kara and Barents Seas (thousands km^2).

This relation is highly statistically significant ($R = 0.90$, adj.$R^2 = 0.78$, $F(3,24) = 33.6$, $p < 0.00001$, $SEE = 0.63$), estimation of all regression coefficients and the free term is highly statistically significant. The plot of scattering (Fig. 9.25) shows good linearity and the lack of clearly outlying points. This allows us to state that the aforementioned variables characterize the most important factors determining variability of annual air temperature at Hornsund in an adequate way.

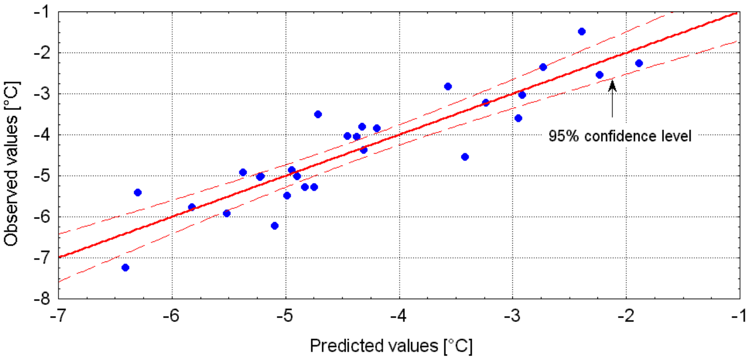

Fig. 9.25. Annual air temperature at Hornsund as function of the mean SIE on the Greenland Sea at peak of development (January to June), annual S index of circulation of Niedźwiedź and SIE on the Barents and Kara Seas during its formation (September to December). Values estimated with Equation [6] in relation to observed values.

All variables in the equation are synchronous, originating from the same years. Three mentioned variables explain in total around 78% of the variability of annual air temperature in 1979–2007. In sequence explanation is: $SIE\_G_{\text{Jan-June}}$ – 51.7%, S_{annual} – 13.4%, $SIE\_B_{\text{Sept-Dec}}$ – 15.7% of variation of annual temperature at Hornsund.

As can be seen, in the first place is mean SIE in January-June on the Greenland Sea, in the second – the circulation factor, specifically annual measure of intensity of meridional circulation, and in the third place – mean SIE on the Barents and Kara Seas in September-December. Together with decrease of SIE on the Greenland Sea in the first half of the year, decrease of mean SIE after the period of summer warming of the surface of the Barents and Kara Seas and increase of intensity of circulation from the southern sector during the year (decrease of negative values, transition to positive values of the index S of Niedźwiedź) air temperature at Hornsund will increase. Other forms of atmospheric circulation (local zonal circulation, cyclonicity and anticyclonicity) play a minor role here. An effect of SST, which finds no reflection in Equation [6] is "camouflaged" by variability of SIE which is a function of variability of SST, especially on the Greenland Sea.

Mean SIE on the Greenland Sea between January and June, which explains over 50% of variation of annual temperature at Hornsund in 1979-2007, is dependent on values of DG_{3L} and $LF_{1\text{-}4}$ one year earlier (correlation coefficients are –0.69 and –0.68, respectively), through correlation with annual SST in the warm core of WSC (grid 76°N, 10°E; $r = 0.71$). Mean SIE on the Barents and Kara Seas between September and December (correlation coefficients –0.54 and –042, respectively) is dependent, although weaker, on the variables DG_{3L} and $LF_{1\text{-}4}$. This means that the cause of changes of the variables which decide on variability of annual air temperature at Hornsund (and more generally in this part of the Atlantic Arctic) are changes of heat resources transported to the Arctic by oceanic circulation.

Estimation of the effects of the combined influence of heat resources carried in with the Atlantic water by oceanic circulation to the Arctic together with local atmospheric circulation on the annual temperature at Hornsund (Ta) in the year k gave following results:

$$Ta_{(k)} = -20.794(\pm 2.684) + 2.687(\pm 0.425)\cdot LF_{1\text{-}4\,(k-1)} + 0.014(\pm 0.004)\cdot S_{year\,(k)}, \qquad [7]$$

and:

$$Ta_{(k)} = 4.887(\pm 0.320) + 0.854(\pm 0.166)\cdot DG_{3L\,(k-1)} + 0.012(\pm 0.004)\cdot S_{year\,(k)} + \\ + 0.006(\pm 0.002)\cdot C_{year\,(k)} \qquad [8]$$

where:

- $LF_{1\text{-}4\,(k-1)}$ – index of heat resources carried in to the Arctic with the Norwegian Current, from the previous year (k-1), in °C,
- $DG_{3L\,(k-1)}$ – index of heat resources directed to the north in the Gulf Stream Delta, from the previous year (k-1), (dimensionless),
- $S_{year\,(k)}$ – annual index of circulation S (meridional) of Niedźwiedź from the year k, (dimensionless),
- $C_{year\,(k)}$ – annual index of cyclonicity C (cyclonal – anticyclonal circulation) of Niedźwiedź from the year (k), dimensionless.

Both equations are similar and highly statistically significant ($p < 0.00001$). Equation [7] explains 61% of the variation of annual air temperature at Hornsund whereas equation [8] explains 58%. In equation [7] $LF_{1\text{-}4\,(k-1)}$ explains ~45% of variability, meridional circulation ($S_{year\,(k)}$) ~17%. In equation [8] the annual index of cyclonicity ($C_{year\,(k)}$) appears as the additional variable, statistically significant, beside the index of meridional circulation. In this equation $DG_{3L\,(k-1)}$ explains ~40%, $S_{year\,(k)}$ ~15%, and $C_{year\,(k)}$ ~7% of variation of annual temperature at Hornsund. The scatter plot of annual temperature at Hornsund, calculated with equation [7] in relation to observations is shown in Fig. 9.26. The course of annual temperature at Hornsund and calculated annual temperature is presented in Fig. 9.27.

Analysis of components of resulting signal, annual temperature at Hornsund, shows that its long-term variability is steered by changes of heat resources in the waters. Operation of heat resources in waters is indirect; they affect variability of ice cover and flux of heat from the ocean to the atmosphere. This long-term signal is modulated by a strong short-term signal contributed by atmospheric circulation. The meridional circulation contributes the strongest short-term signal, steering inflows of air with radically contrasted thermal features. Analysis of regression shows that meridional circulation during the autumn and winter has special importance in the development of variability of annual temperature. The importance of variability of index C of Niedźwiedź (cyclonicity) is not clear; most probably changes of the circulation from cyclonal to anticyclonal (and the contrary) steer changes of cloudiness, which next influence temperature.

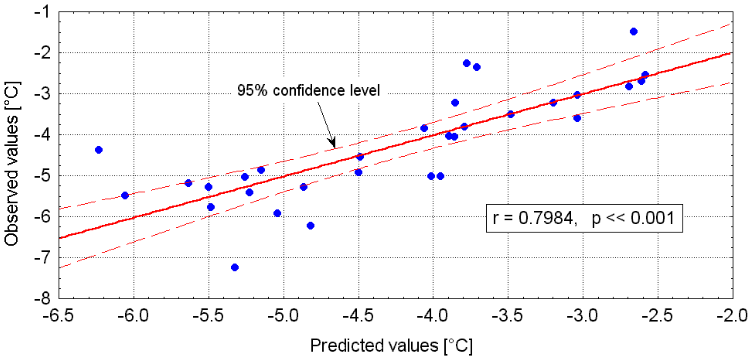

Fig. 9.26. Annual air temperature at Hornsund calculated with equation [7] in relation to observed temperature.

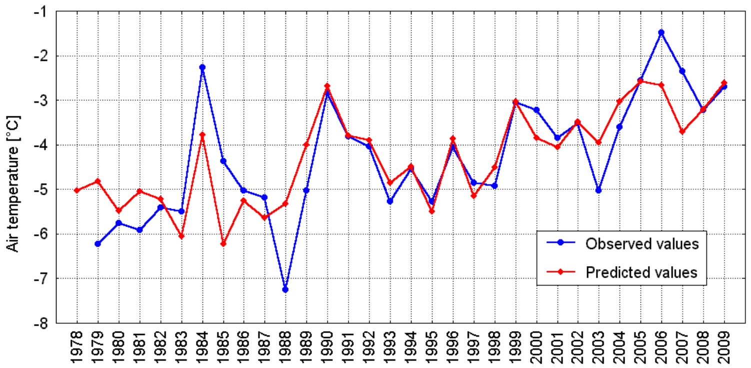

Fig. 9.27. Annual temperature at Hornsund. The course observed and calculated with equation [7].

Extended analysis, where Hurrell's index NAO, annual index NAO CRU, annual index AO, annual and winter (December - March) number of days with occurrence of macro types of middle tropospheric circulation W, E and C of Vangengejm-Girs were added to the set of abovementioned independent variables, gave for the first six places (the first six independent significant variables) results which were identical to analyses in which these variables were not taken into account. This confirms again that large-scale atmospheric circulation characterized by these indices, contrary to common opinion, does not register at a measurable level in the development of air temperature in the Atlantic Arctic.

Taking into account that SST on seas surrounding Spitsbergen, the area of sea ice and atmospheric circulation in the region of Spitsbergen in a given year may act as an inert element in the climatic system (sea ice – directly, circulation – cause results in the environment which will be disclosed with appropriate delay), similar analyses were made with sets of dependent variables in which variables describing transport of heat by the oceanic circulation were not considered. The results obtained may be regarded as interesting. An equation with three independent variables of high significance (R = 0.78) was obtained. In first place - SST in the West Spitsbergen Current (grid 76°N, 10°E) in August, the month with the highest SST in the annual cycle, explains ~42% of variation of air temperature in the next year. The higher the SST on the West Spitsbergen Current the higher will be air temperature in the next year. In more distant places there are indices of cyclonicity (C) in the winter (~10% of variability explained) and the autumn (~8.5%). Signs in front of vectors with cyclonicity are positive, which means that the higher index of cyclonicity (and so increase of activity of the low-pressure systems in the Atlantic Arctic during the winter and autumn) the higher will be air temperature in the next year. Action of these two last variables is most probably multifaceted:

- the more the low-pressure systems, the more frequent advection of heat over Spitsbergen and the surrounding seas. This leads to decrease of differences of temperature between sea surface and the air during the autumn and winter, which in turn reduces losses of heat from the sea surface,
- the greater the activity of low pressure systems, the greater the cloudiness, reducing radiation losses during the autumn and winter.

These two processes decrease losses of heat from the sea surface in a given year, "leaving" it an increased amount to spend in the next year, which will result in the effects on development of SST and sea ice cover already discussed, and because of them also air temperature in the next year.

Analyses of influence of variability of SST, SIE and local atmospheric circulation on development of variability of air temperature at Hornsund show that despite apparent simplicity, the climatic system of this part of the Atlantic Arctic is quite complicated. A number of the complications result from existence of inert links (structures) in the system, transferring states previously existing in time and being the cause of occurrence of strong autocorrelations in the series of annual temperature. Treating annual temperature changes in the region of Spitsbergen as a simple result of the radiation balance, without taking into account transfer of heat by the oceanic and atmospheric circulation from temperate and subtropical latitudes seems to be oversimplification.