

# Occurrence of winter air temperature extremes in Central Spitsbergen

Ewa Bednorz

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**Abstract** The occurrence of daily air temperature extremes in winter in Central Spitsbergen in the period 1975–2008 was analysed. The mean winter temperature was found to be increasing by approximately 1.65°C per decade. Negative extremes were becoming less frequent, decreasing at a rate of approximately 5 days per decade, whereas the frequency of positive extremes showed a small (2 days per decade) but insignificant positive trend. Furthermore, circulation patterns responsible for positive and negative temperature extremes were analysed. Composite maps of the sea level pressure (SLP) and 500-hPa geopotential heights (z500 hPa) means and anomalies were constructed for the days with positive and negative extremes. Circulation patterns causing extremely warm winter days are characterised by a cyclonic centre or a low pressure trough over the Fram Strait. Cyclones located west of Spitsbergen with a warm sector over the archipelago bring warm air masses from the southern quadrant. On extremely cold days, the cyclone centres are usually located over the Barents Sea. This SLP pattern implies airflow from the north and northeast that brings cold Arctic air to the North Atlantic. Another factor in the occurrence of the temperature extremes in Central Spitsbergen is the sea-ice cover. Negative temperature extremes usually occur together with a high concentration of sea ice, particularly in the middle and end of winter.

## 1 Introduction

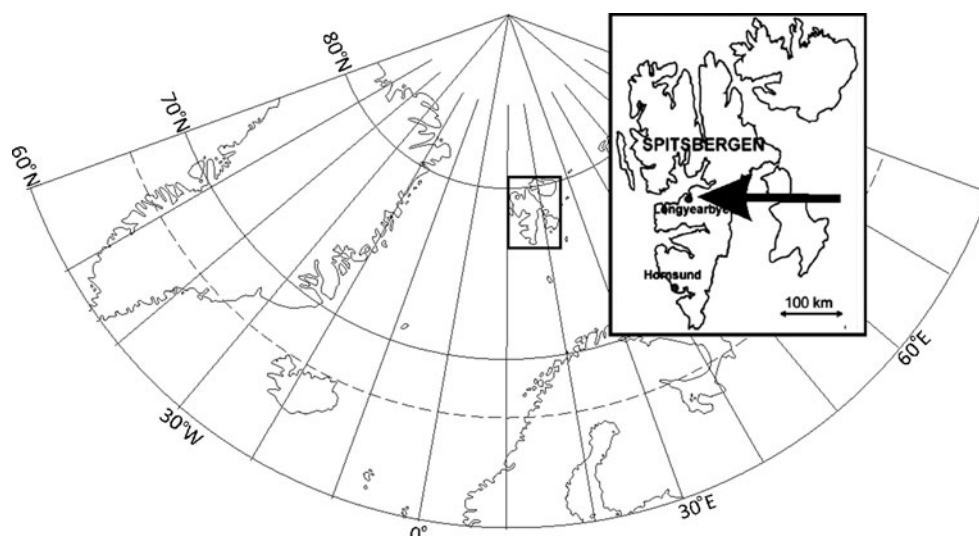
Polar regions are considered to be most vulnerable to climate changes, particularly to the effects of the global warming observed in recent decades. The biotic and abiotic environments of these regions (tundra, permafrost, sea ice, glaciers, snow cover, etc.) are very sensitive indicators of climate fluctuations. Several positive feedback mechanisms (e.g. decrease in surface albedo owing to ice and snow melt) are well known to enhance the air temperature in the Arctic. These mechanisms possibly led to the abrupt temperature rise in the mid-1990s. However, reasons for the contemporary warming of the Arctic are still being discussed and are thought to be very complex. One group of factors is associated with the anthropogenic greenhouse effect and its nonlinear influence on the air temperature. The other group includes natural factors, chiefly changes in the atmospheric circulation (IPCC Fourth Assessment Report 2007; ACIA Scientific Report 2005).

The influence of the circulation on the weather and climate at higher latitudes is much greater than at lower latitudes, particularly in winter, when there is no inflow of solar irradiation. During the polar night, atmospheric circulation accounts for 95% of the advection of warmth to the Arctic, while the other 5% is due to oceanic circulation (Alekseev et al. 1991; cited in Przybylak 2000). In the Norwegian Arctic, intense cyclonic activity and variation in the extension of air masses, originating from the northeast and southwest, cause great variation in the weather and in temperature conditions (Steffensen 1982; Nordli 1990; Førland et al. 1997). Therefore, atmospheric circulation (particularly cyclonic activity) in the Arctic and its influence on weather conditions (particularly on temperature) have been addressed by several studies at different temporal and spatial scales (e.g. Serreze

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E. Bednorz (✉)  
Institute of Physical Geography and Environmental Planning,  
Adam Mickiewicz University,  
ul. Dzięgielowa 27,  
61-680 Poznań, Poland  
e-mail: ewabedno@amu.edu.pl

**Fig. 1** Area covered by the study. Location of Svalbard Lufthavn station indicated with an arrow



and Barry 1988; Wielbińska and Skrzypczak 1988; Serreze et al. 1993; Przybylak 1996, 2000; Hanssen-Bauer and Forland 1998; Niedźwiedz 2003, 2006; Zhang et al. 2004; Rogers et al. 2005; Maciejowski and Michniewski 2007). In view of the importance of circulation in the formation of polar climates, these studies are of great significance (Przybylak 2000). The influence of macroscale circulation patterns, mainly the North Atlantic Oscillation (NAO), on the climate of the Atlantic region of the Arctic has been well documented (Hurrell 1995; Przybylak 2000).

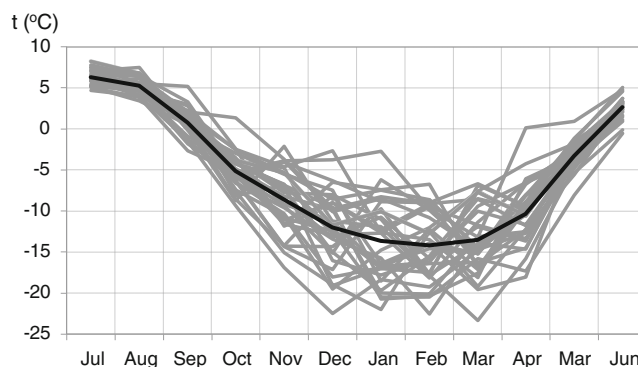
This study analyses the occurrence of winter air temperature extremes on the island of Spitsbergen, located in the Atlantic region of the Arctic. The area under study is considered to be one of the most climatically sensitive in the world. Its sensitivity is related to the variability of the cyclonic activity over the northern Atlantic and the frequent exchange of thermally contrasted air masses originating from the northeast and southwest (Steffensen 1982; Nordli 1990; Førland et al. 1997; Rogers et al. 2005). Therefore, this study places special emphasis on the daily circulation conditions, including the occurrence of winter cyclones, and their impact on the occurrence of air temperature extremes. The study also analyses the influence of mesoscale conditions, namely sea-ice cover on the local fiord, on the air temperature.

## 2 Area, data and methods

The island of Spitsbergen is part of the Svalbard Archipelago, located in the Northern Atlantic. The archipelago is bordered by the Arctic Ocean in the north, the Barents Sea in the southeast, and the Greenland Sea in the southwest. The archipelago is separated from Greenland by the narrow Fram Strait. The surrounding seas are icebound for part of the year. The occurrence of sea ice is strongly controlled by

the warm West Spitsbergen Current and cold East Spitsbergen Current. This study covered the central part of the island, represented by the Svalbard Lufthavn station (78.25°N, 15.46°E, 2 m a.s.l.) situated at the inner end of Adventfjorden, a southern branch of Istfjorden. This fiord is cut deeply into the land from the west side (Nordli 1990; Fig. 1). The Svalbard Lufthavn station recorded the lowest temperature (−46.3°C in March 1988) ever observed at any Norwegian Arctic station. Daily mean temperature data for the Svalbard Lufthavn station for the years 1975–2008 were collected from the Norwegian Meteorological Institute dataset, available at the eKlima web portal. Only the winter (December–March) values from the seasons 1975/1976–2007/2008 were used in further analysis.

Several methods and criteria are used to characterise extreme meteorological phenomena. The maximum and minimum values, measures of dispersion and frequency of occurrence are often used for this purpose. Here, the extreme daily mean temperatures were defined, according to the Intergovernmental Panel on Climate Change (IPCC) rules, as occurring with a frequency lower (higher) than or



**Fig. 2** Annual values of air temperature for every year (in grey) and mean (in black) for the period 1975–2008 at Svalbard Lufthavn station

**Table 1** Mean temperature and its standard deviation (°C) at Svalbard Lufthavn (1975/1976–2007/2008)

	July	August	September	October	November	December	January	February	March	April	March	June
Mean	6.3	5.3	0.8	-5.1	-8.6	-12.0	-13.7	-14.2	-13.5	-10.4	-3.3	2.7
Monthly SD	0.9	1.0	1.6	2.2	3.9	4.5	5.0	4.3	4.1	3.8	1.6	1.2
Daily SD	2.2	2.2	3.3	5.0	6.4	7.8	8.1	8.6	8.4	6.6	4.0	2.5

SD standard deviation

equal to 10% (90%; IPCC Fourth Assessment Report 2007; Ustrnul and Czekierda 2009).

In order to describe the circulation, the sea level pressure (SLP) and 500-hPa geopotential heights (z500 hPa) daily data were selected from the National Centers for Environmental Prediction (NCEP)—National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996). The synoptic area encompasses the region of 60–90° N latitude and 60°W–80°E longitude. Composite maps of the SLP and z500 hPa means as well as anomaly maps were constructed separately for the days that exhibited the positive and negative extremes of the mean daily temperature. Anomalies were computed as differences between composite values and winter means. Furthermore, based on daily patterns of SLP, different circulation types were distinguished separately for the days with positive and negative temperature extremes. Principal component analysis (PCA) was conducted on the standardised daily SLP data to derive the dominant pattern of variability from the raw fields (Yarnal et al. 2001; Esteban et al. 2005). Six principal components were chosen for further analysis by using the criterion that a minimal percentage (85%) of the total variability of the raw data must be represented by the chosen principal components (Jolliffe 1993). Subsequently, the Ward (1963) minimum variance method, the most frequently used hierarchical clustering technique for climatic classification, was applied to cluster the days with temperature extremes (Kalkstein et al. 1987). Composite

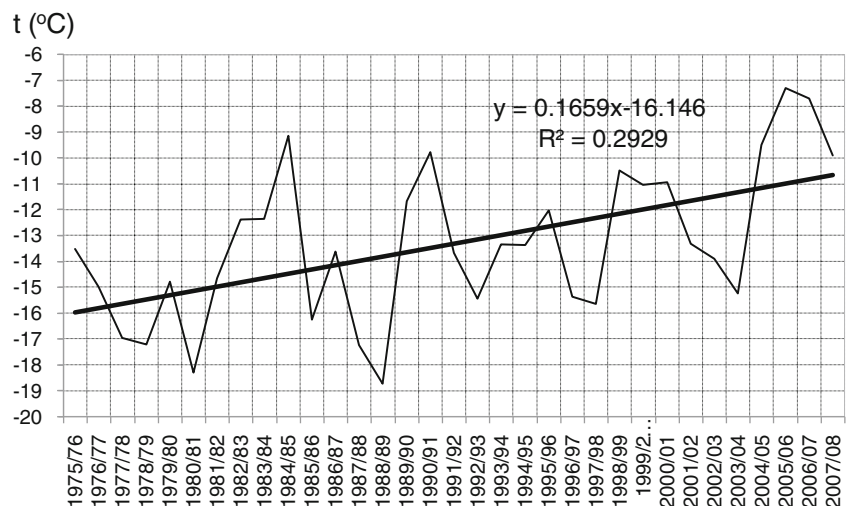
analyses, PCA and clustering techniques have all been used previously to identify the atmospheric circulation patterns associated with the occurrence of specific weather phenomena (e.g. Birkeland and Mock 1996, Esteban et al. 2005).

Additionally, the ice conditions on the Istfjorden fiord on the days of occurrence of extreme daily temperatures were analysed using the Historical Ice Chart Archive issued by the Arctic Climate System Study (ACSYS 2003), available at <http://acsys.npolar.no>.

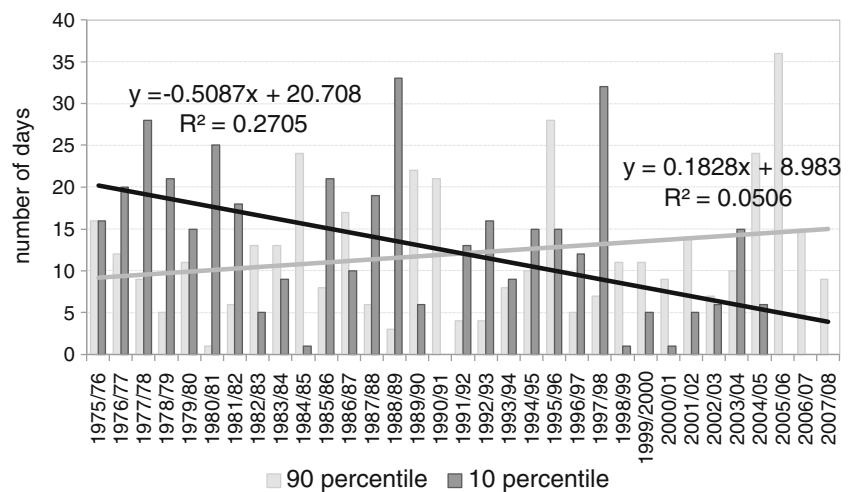
### 3 Results

On an annual scale, the air temperature at the Svalbard Lufthavn station, averaged over 33 years, reaches its maximum value of 6.3°C in July, then gradually decreases to its minimum value of -14.2°C at the end of the polar night (February; Fig. 2, Table 1). The spring increase in the air temperature is usually rapid, particularly in April and May, owing to the start of the polar day. The lowest temperatures (-12.0°C to -14.2°C) occur from December to March. However, the graphs for particular years show great variability in the annual temperature from year to year. The temperature of summer months, with a standard deviation close to 1°C, is much less variable than the temperature of winter months, with a standard deviation ranging from 4°C to 5°C.

**Fig. 3** Multiannual values of winter mean air temperature at Svalbard Lufthavn station with trend line and equation



**Fig. 4** Multiannual values for the number of days with positive (light grey) and negative (dark grey) winter air temperature extremes at Svalbard Lufthavn station with trend lines and equations

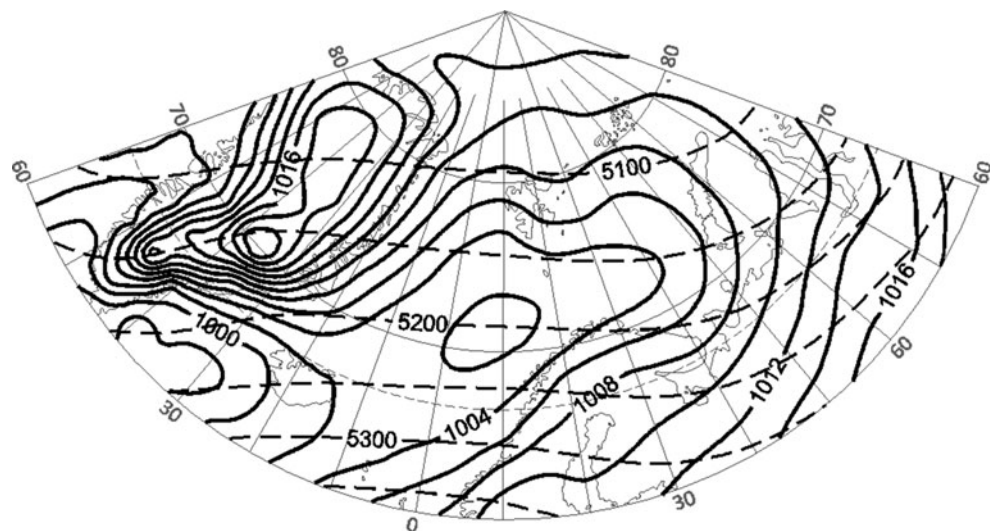


Positive (negative) extremes of daily mean temperatures were determined for the winter season as higher (lower) than or equal to the value of the 90th (10th) percentile, namely  $\geq -2.4^{\circ}\text{C}$  ( $\leq -24.1^{\circ}\text{C}$ ). In total, 392 days with positive temperature extremes and 398 days with negative temperature extremes were selected from the 33 winter seasons for further analysis. On a multiannual scale, both the number of days with extreme temperatures in winter and the mean winter temperatures in Svalbard Lufthavn show great year-to-year variability (Figs. 3 and 4). This variability notwithstanding temperature changes in Central Spitsbergen tends to exhibit a clear trend. The mean winter temperature increased by approximately  $1.65^{\circ}\text{C}$  per decade from the 1975/1976 season to 2007/2008 (the trend is statistically significant at  $p=0.01$ ). At the same time, the number of days with extremely low mean daily temperatures ( $\leq -24.1^{\circ}\text{C}$ ) decreased at a rate of approximately 5 days per decade (the trend is statistically significant at  $p=0.01$ ). The number of days with extremely high mean daily

temperatures increased slowly (2 days per decade), but this trend is not statistically significant (Fig. 4).

Circulation represents a possible reason for this variability of winter temperatures and for the observed trends. The pattern of mean SLP in winter shows two main centres in the Atlantic sector of the Northern Hemisphere (Fig. 5). One of these features, the Greenland High, exhibits a pressure of 1,020 hPa at its centre. The other feature, the Icelandic Low, exhibits a pressure of 998 hPa at its centre and is located southwest of Iceland. This low spreads to the northeast and forms a secondary centre (1,002 hPa) over the North Atlantic, south of the Svalbard Archipelago. A strong pressure gradient occurs between Greenland and the aforementioned low centres. A smaller pressure gradient is observed towards northeastern Europe, where the SLP increases gradually. In winter, the mean z500 hPa level inclines from the south (5,250 gpm) to the north ( $<5,100$  gpm over the Arctic Sea). The z500 hPa level is often used to study the upper-level airflow as it relates to the surface weather.

**Fig. 5** Mean sea level pressure (solid lines) and geopotential height 500 hPa (dashed lines) over the North Atlantic for winter seasons 1975/1976–2007/2008

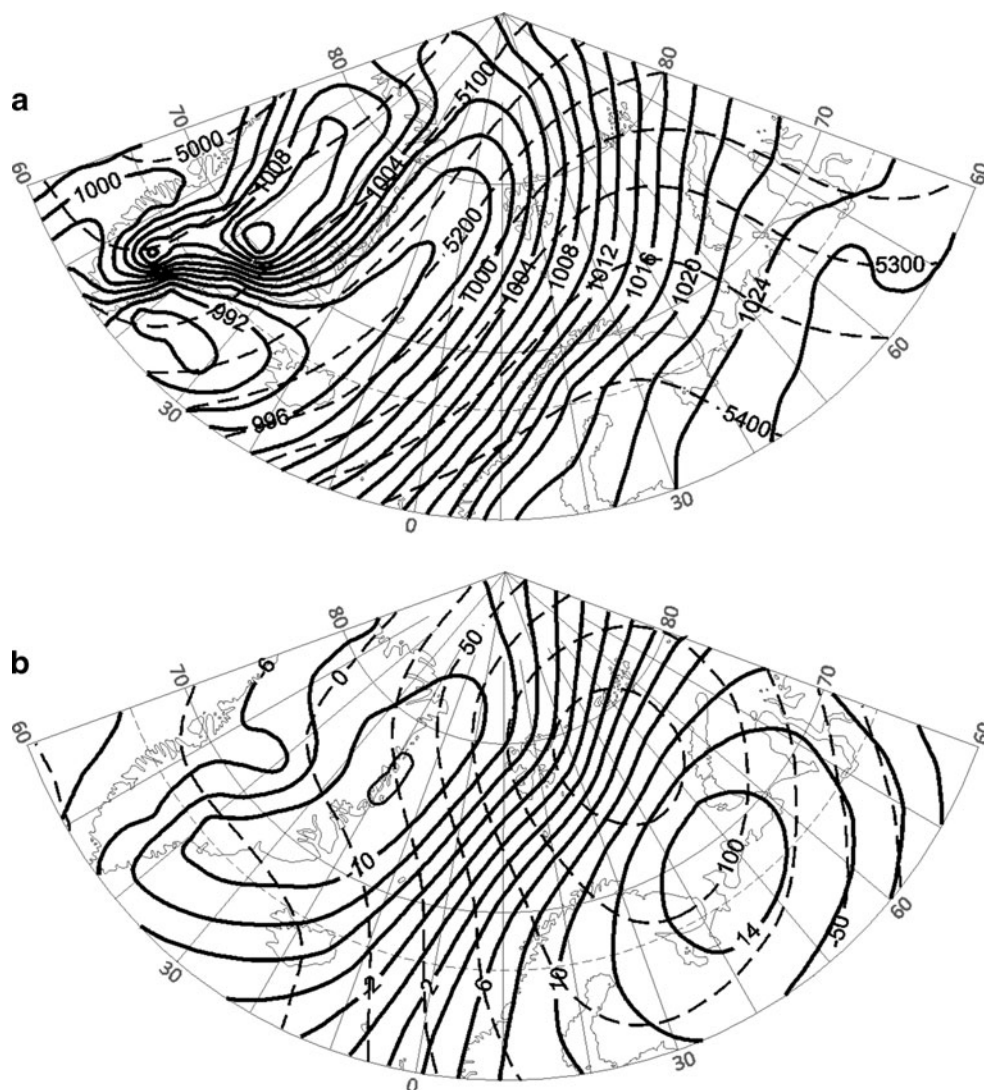


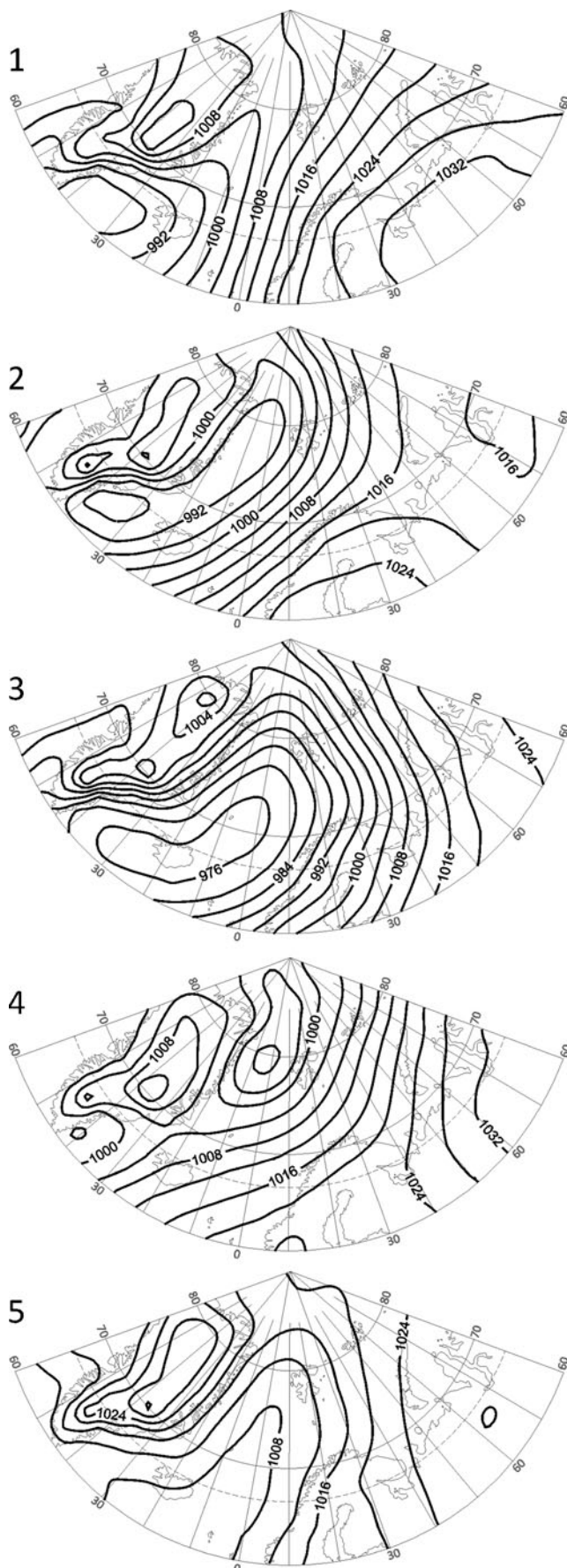
On a contour map of SLP, constructed for the days with positive temperature extremes, the northern Atlantic low is pushed to the west by the high pressure system located over the land and expanding to the northwest (Fig. 6a). This area is characterised by strong (up to 14 hPa) positive SLP anomalies. At the same time, a lower-than-normal SLP occurs in the west of the study area. This anomaly has a value of over  $-10$  hPa along the eastern coast of Greenland and over the Fram Strait. Contours of z500 hPa constructed for the days with positive temperature extremes bend to the north over the eastern part of the study area and suggest southwesterly airflow in the middle troposphere over the northern Atlantic. A composite anomaly map shows the SLP and z500 hPa differences between the selected weather situations (days with positive temperature extremes) and normal winter climate patterns (Fig. 6b). The interpretation of the contoured composite anomalies is similar to the traditional weather anomaly maps, with clockwise (anticyclonic) flow around the positive centres and counterclock-

wise (cyclonic) flow around the negative centres (Birkeland and Mock 1996). The centre of positive SLP and z500 hPa anomalies occurs over the Barents Sea. Consequently, the circulation during the days with positive temperature extremes is characterised by a strong southerly (in the middle troposphere) and southwesterly (at sea level) flow component, in contrast to the average winter circulation over the North Atlantic.

Obviously, the circulation patterns observed during the selected 392 days could not be identical. Therefore, an attempt was made to classify the circulation types causing the positive temperature extremes in Central Spitsbergen. After clustering based on the SLP data, composite maps of the five most relevant groups were constructed (Fig. 7). The SLP patterns are similar on all the maps; however, they differ according to the location and intensity of the pressure centres. The southeastern mid-latitude anticyclone may be located over central or eastern Europe (types 1 and 2), or close to the winter

**Fig. 6** **a** Mean sea level pressure (solid lines) and geopotential height of 500 hPa (dashed lines). **b** Anomalies of the sea level pressure (solid lines) and geopotential height of 500 hPa (dashed lines) for the days with positive temperature extremes





◀ **Fig. 7** Circulation types identified for the days with positive temperature extremes (SLP in hPa)

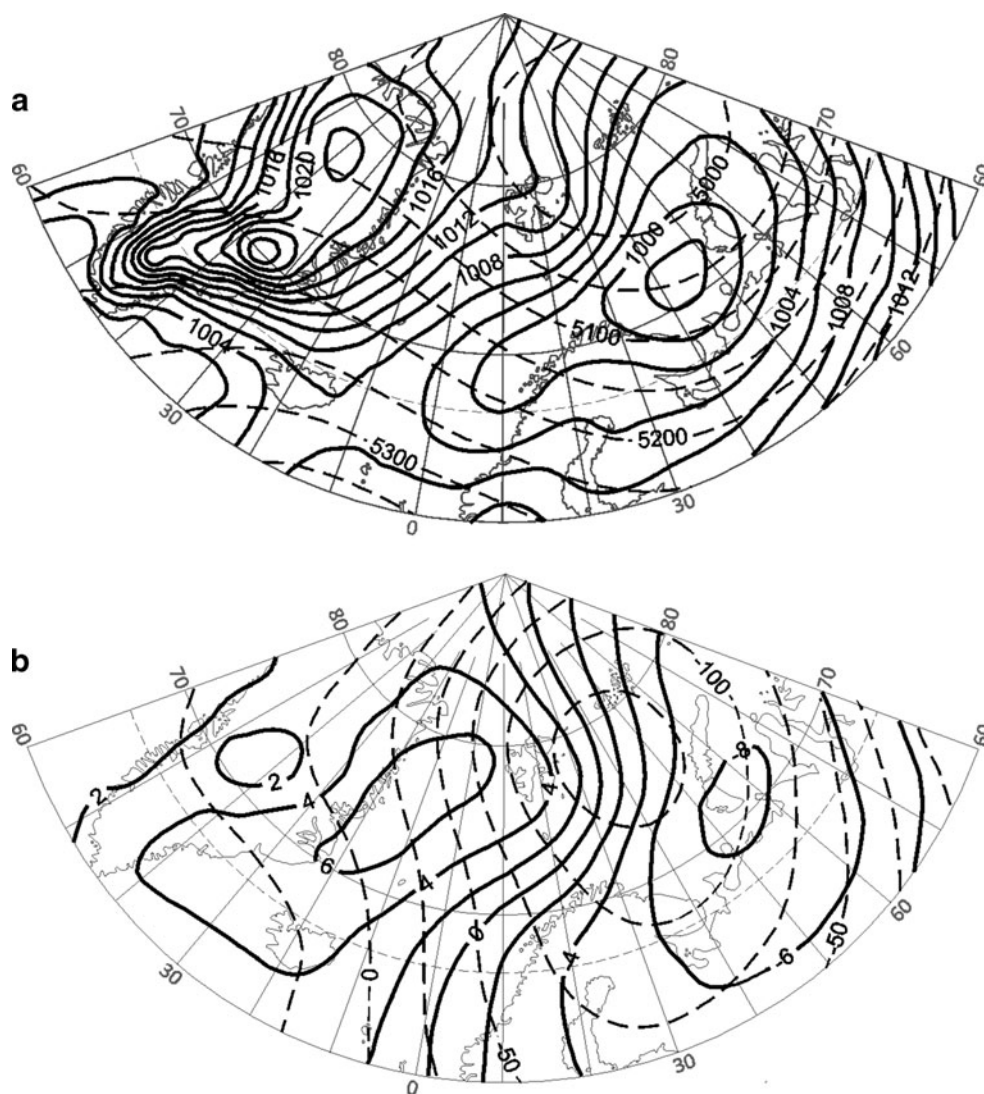
Siberian High, a strong feature at the time (the other types). Western cyclones may form a narrow trough of low pressure spreading along the eastern coast of Greenland (types 1, 3, 5), or they may form a secondary low-pressure centre directly over the Fram Strait (types 2 and 4). The majority of the types presented, with the exception of the least common type 5, are characterised by a high-pressure gradient that causes a very intense airflow from the southern quadrant over the North Atlantic.

Quite different synoptic situations underlie the negative temperature extremes. On the contour map of SLP constructed for the 398 chosen days with negative temperature extremes, the northern Atlantic low moves to the east, and its centre is located over the Barents Sea, a region of negative SLP anomalies ( $-8$  hPa; Fig. 8). Positive SLP anomalies occur over most of the North Atlantic (including the Svalbard Archipelago), over the western part of the Arctic Sea and over Greenland. The centre of positive SLP anomalies is located over the eastern coast of Greenland. Therefore, the Greenland High is slightly stronger than usual, whereas the cyclonic activity over the Fram Strait is much weaker. Such a pressure pattern at sea level indicates a northern and northeastern flow bringing cold Arctic air to the North Atlantic. Contours of z500 hPa constructed for the days with negative temperature extremes bend to the south over the eastern part of the study area. Negative anomalies of z500 hPa spread over most of the study area with a centre ( $<-125$  gpm) located east of the Svalbard Archipelago. The z500 hPa pattern suggests the presence of northerly and northwesterly airflow in the middle troposphere over the island of Spitsbergen.

Again, clustering techniques were applied to distinguish the different circulation types causing extremely low temperatures in Central Spitsbergen. The contour maps of SLP constructed for the five most relevant groups do not differ significantly (Fig. 9). The main feature of the pressure fields in most types of circulation is a cyclone located over the Barents Sea. On the contour map for type 5, the least common type, the low-pressure centre occurs far towards the northeast. The North Atlantic cyclone is sometimes connected by a trough to the Icelandic Low (types 2, 4, 5). An extension of the low-pressure system and the position of its centre affect the direction of airflow over Central Spitsbergen. This direction varies from northward to eastward and brings cold air of Arctic origin in all cases.

Circulation is not the only factor serving to develop winter thermal conditions in polar climates. Mesoscale conditions such as the sea-ice cover for the stations located

**Fig. 8** **a** Mean sea level pressure (solid lines) and geopotential height of 500 hPa (dashed lines). **b** Anomalies of the sea level pressure (solid lines) and geopotential height of 500 hPa (dashed lines) for the days with negative temperature extremes



close to the shore (like Svalbard Lufthavn) are also important. The sea-ice conditions on the Istfjorden and on the inner end of Adventfjorden in the days of occurrence of extreme daily temperatures were analysed, and the frequencies of particular states of the sea-ice concentration are given in Table 2. Negative extremes of the daily mean temperature in Svalbard Lufthavn are most often connected with high sea-ice concentration on the fiord. The frequency of days with Fast Ice or Very Close Drift Ice, designations that mean 10/10 or 9/10 to 10/10 ice concentration, respectively (according to attributes currently used by the Norwegian Meteorological Institute), varies from approximately 45% in the beginning of winter (December) to over 78% at the end of the season (March). The lowest temperatures appear on rare occasions when fiord waters are ice free or have low concentrations of sea ice rated 0/10 to 3/10 (16% of all cases in winter). The weakest influence of the sea-ice concentration on the occurrence of extremely low temperatures is observed in December, whereas in

March, the air temperature seems to be strongly related to the state of the Istfjorden waters. The analysis performed for the types of circulation distinguished earlier, namely those causing the negative temperature extremes in Svalbard Lufthavn, proved that the type 2 pattern with its eastern direction of circulation is the least relevant to the ice concentration on the fiord.

During the days having positive extremes of temperature, the ice concentration on the fiord was in most cases much lower. In approximately 60% of the instances analysed, the sea-ice conditions were rated as Open Water or Very Open Drift Ice, corresponding to 0/10 or 1/10 to 3/10 sea-ice concentrations, respectively. In December, such conditions appear in approximately 80% of instances of the positive temperature extremes, whereas in March, low-ice conditions appear only on approximately 32% of extremely warm days. In December, extremely high temperatures never occur when the fiord is covered with Fast Ice (10/10 ice concentration), whereas in March, such extremely high

**Fig. 9** Circulation types identified for the days with negative temperature extremes (SLP in hPa)

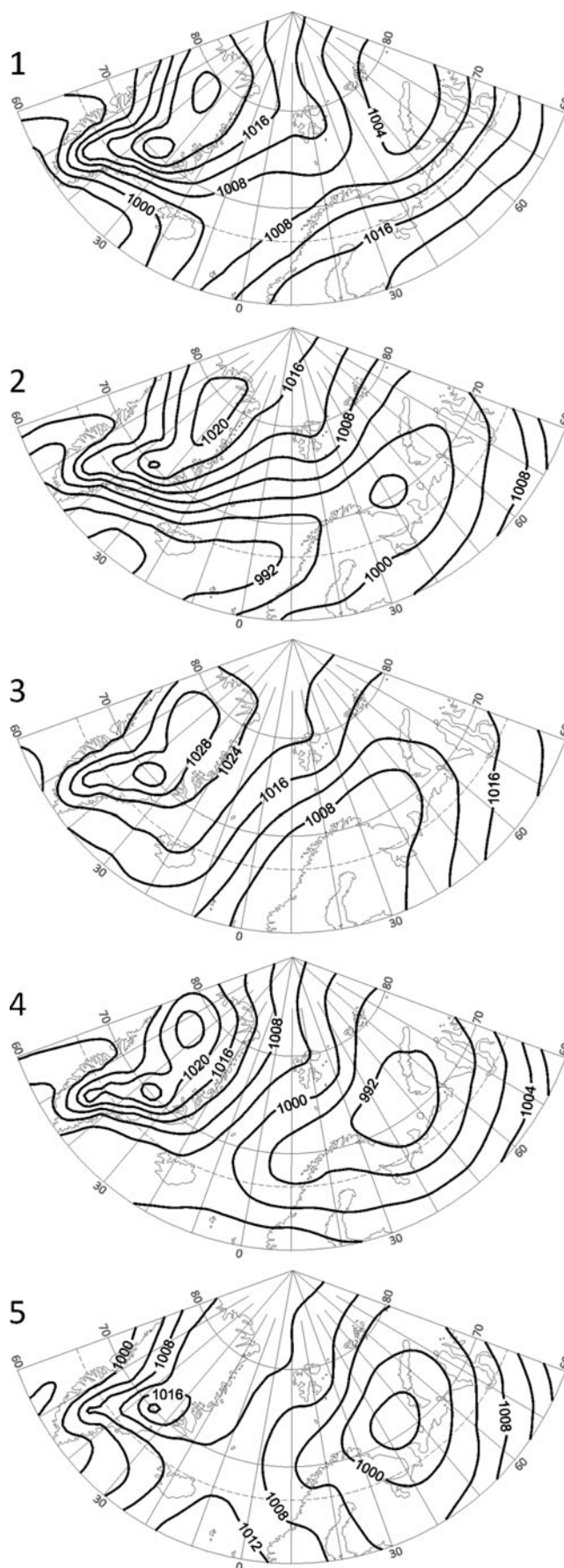
temperatures occur quite often—in approximately 24% of all cases. The analysis performed earlier to identify types of circulation that favour extremely high winter temperatures at the Svalbard Lufthavn station proved that the types causing southern airflow in the Central Spitsbergen, i.e. types 1 and 5, are the most relevant to the sea-ice concentration on the fiord waters. For type 5, 25% of all instances appeared when the fiord waters were ice free, whereas in 22% of all cases, the fiord was covered with Fast Ice.

#### 4 Discussion and conclusions

Extreme meteorological phenomena are an important object of climatological studies, particularly in the age of dynamic climate changes (IPCC Fourth Assessment Report 2007). The frequency of negative extreme daily temperatures in the Central Spitsbergen appears to have decreased since 1975, whereas the frequency of positive extremes shows a small but insignificant positive trend. These trends occurred simultaneously with the increase in daily maximum and minimum temperatures in the second half of the twentieth century demonstrated for the Fenno-Scandia and Nordic Seas regions (Tuomenvirta et al. 2000).

Results concerning the significant increase in the temperature of winter months in Central Spitsbergen obtained in this study confirm the contemporary pattern of warming in the Arctic. This pattern has been widely described in the climatological literature (e.g. Brázdil 1988; Førland et al. 1997; Moritz et al. 2002; Comiso 2003; Polyakov et al. 2003; Przybylak 2000, 2002, 2003, 2007; Johannesen et al. 2004; Styszyńska 2005; Turner et al. 2006). The amount of winter warming during the past three decades (approximately 5°C) is still smaller than the amount of warming that occurred at the beginning of the twentieth century in Spitsbergen (nearly 7°C; Rogers 1985; Rogers et al. 2005).

The reasons for the contemporary warming of the Arctic continue to be discussed. These reasons are considered to be very complex, although changes in air circulation have been identified as one of the main factors influencing climate changes at high latitudes (e.g. Hanssen-Bauer and Førland 1998; Niedźwiedź 2003, 2006; Polyakov et al. 2003; Przybylak 2003). Clearly, synoptic activity that forces the air circulation has major impact on the occurrence of winter temperature extremes in Central Spitsbergen. The driving factor is the location and intensity of the winter North Atlantic cyclones. Rogers et al. (2005) indicated three different ‘centres of action’ exhibiting





**Table 2** Frequencies (percent) of ice concentration states on the Istfjorden fiord on the days of negative and positive extremes of the daily temperature at Svalbard Lufthavn (1975/1976–2007/2008)

Ice concentration states		Negative temperature extremes				Positive temperature extremes					
		December	January	February	March	Winter	December	January	February	March	Winter
0/10	Open Water	17.8	6.7	3.8	3.8	6.2	59.4	27.2	15.2	14.0	28.9
1/10–3/10	Very Open Drift Ice	17.8	18.3	6.9	1.9	9.8	19.5	15.2	40.9	18.3	23.5
4/10–6/10	Open Drift Ice	15.6	12.5	3.8	5.7	8.0	13.5	34.8	12.1	17.2	19.4
7/10–8/10	Close Drift Ice	4.4	9.6	13.0	10.4	10.4	7.5	8.7	7.6	26.9	12.7
9/10–10/10 or 10/10	Very Close Drift Ice or Fast Ice	44.4	52.9	72.5	78.3	65.5	0.0	14.1	24.2	23.7	15.5

intensive cyclogenesis in winter: (1) the Fram Strait, a pathway of cyclonic activity trending towards the high Arctic; (2) the Barents Sea—also identified by Serreze and Barry (1988) and Serreze et al. (1993); and (3) a centre located southwest of Iceland and commonly known as the Icelandic Low. In the first centre, cyclogenesis takes place along the northern coast of Greenland. The cyclones traverse just west of Spitsbergen, producing a warm sector over the archipelago. Such a pressure pattern is related to mild winters in Spitsbergen; in addition, a relatively low amount of ice export is observed for the region. For each circulation type identified in this study for extremely warm winter days, the cyclonic centre or a low pressure trough extends over the Fram Strait. These considerations suggest two different (but nonexclusive) hypotheses: the extremely high temperature may be caused by the circulation pattern, or the higher-than-usual temperatures and lower ice export through the Fram Strait may cause more intensive cyclogenesis. Both hypotheses may be true, but according to the findings of this study, the location of the vast and deep low pressure system described above is forced by a strong anticyclone expanding from the south or southeast. This result suggests that circulation is a driving factor.

Far fewer cyclones occur over the Fram Strait during cold winters. The preferred location appears to be over the Barents Sea, as identified by Rogers et al. (2005), Serreze and Barry (1988), Serreze et al. (1993). The cyclone centre may be moved to the northeast and may form north of Novaya Zemlya. A trough may sometimes connect it with the Icelandic Low. The pattern of the SLP anomalies for the days with negative temperature extremes is the exact opposite of the pattern for days with positive temperature extremes, with the centre of the negative values over the Barents Sea and of the positive values along the eastern coast of Greenland. Such layout of SLP and z500 hPa indicates airflow from the north and northeast bringing cold Arctic air to the North Atlantic.

The Svalbard Lufthavn meteorological station is situated close to the fiord Istfjorden. Accordingly, the sea-ice concentration on the fiord waters seems to be another important influence on the occurrence of the temperature extremes. The warm West Spitsbergen Current creates the northernmost area of open water along the western coast of Spitsbergen. Even in winter, this area is frequently ice free (Førland et al. 1997).

This study showed that in the beginning of winter (December), the occurrence of negative extremes of the air temperature is less strongly related to sea-ice concentration on the fiord than it is later on. In the beginning of winter, the air circulation seems to be the driving factor causing the extremely low temperatures. In turn, these low temperatures contribute to freezing of the fiord waters. Thereafter, the ice-covered fiord cools the air and lowers the temperature at the Svalbard Lufthavn station. On the other hand, the occurrence of positive extremes of the air temperature is least strongly related to sea-ice concentration on the fiord at the end of winter (March). Indeed, the extremely warm days may coincide with high sea-ice concentration. This observation suggests that air circulation is the driving factor causing the extremely high temperatures and that it contributes to the thawing of the sea ice.

The results obtained in this study demonstrate that the winter air temperature in the Atlantic region of the Arctic is strongly controlled by the air circulation, particularly by cyclonic activity. However, these findings do not contradict the influence of anthropogenic factors on the climate of high latitudes. Anthropogenic factors may affect air circulation, as several authors have noted (Morton 1998; Hanssen-Bauer and Førland 1998). Indeed, a general global warming trend may influence the winter temperature of Spitsbergen even without any changes in circulation conditions (e.g. by advection of air masses with higher temperatures caused by global warming).

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