www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

POLISH POLAR RESEARCH
vol. 40, no. 4, pp. 339–359, 2019 doi: 10.24425/ppr.2019.130902

Warm winter and cold summer spells in Spitsbergen and their circulation conditions

Arkadiusz M. TOMCZYK[1*], Ewa B. ŁUPIKASZA[2] and Sebastian KENDZIERSKI[1]

[1] *Department of Climatology, Adam Mickiewicz University, B. Krygowskiego 10, 61–680 Poznań, Poland*

[2] *Institute of Earth Sciences, University of Silesia in Katowice, Będzińska 60, 41–200 Sosnowiec, Poland*

* *corresponding author <atomczyk@amu.edu.pl>*

Abstract: The objective of the study was to determine multi-annual changes and variability of occurrence of cold spells in summer and warm spells in winter on Spitsbergen in the period 1976–2016, and circulation conditions of their occurrence. Cold days in summer were defined as days with mean daily air temperature lower than temperature corresponding to the 10th percentile from daily temperature, and warm days in winter as days with mean daily air temperature exceeding the 90th percentile from daily air temperature. The research showed a statistically significant increase in mean air temperature, the rate of which in winter was more than four times higher than in summer. The observed warming translated into a decrease in the number of cold days in summer (-2.5 days/10 years in Svalbard Lufthavn and -1.3 days/10 years in Ny-Ålesund) and an increase in the number of warm days in winter (2.7 days/10 years in Svalbard Lufthavn and 2.4 days/10 years in Ny-Ålesund), and warm and cold spells related to the frequency of such days. The rate of the changes was higher in Svalbard Lufthavn than in Ny-Ålesund. The occurrence of cold days and cold spells was particularly related to the advection of air masses from the north-western sector. The occurrence of warm days and warm spells was related to the advection of air masses from the south-west.

Key words: Arctic, Svalbard, thermal spells, climate change, atmospheric circulation.

Introduction

The rate of modern climate changes is increasing (IPCC 2013). This is suggested by not only the increasing value of the trend of global air temperature (1°C since 1880), but also by the record high air temperature appearing in subsequent years, like in 2015, 2016, 2017 and 2018 (www.climate.nasa.gov).

Such a culmination of warm years occurred for the first time in the history of instrumental measurements (Rahmstorf *et al*. 2017).

In the Arctic, the rate of changes in air temperature is at least twice higher than global trends (Miller *et al*. 2010; AMAP 2011; Walsh *et al*. 2011; Bintanja and van der Linden 2013; IPCC 2013), and shows both spatial (Bhatt *et al*. 2010) and temporal variability; in the annual and multi-annual scale (Gjelten *et al*. 2016). In the multi-annual course of air temperatures on the Svalbard, two warm phases are designated: so-called early 20th century warming in the period 1920–1960, and modern warming which commenced at the turn of the 1980's and 1990's and has been lasting until now (Styszyńska 2011; Gjelten *et al*. 2016; Vikhamar-Schuler *et al*. 2016; Łupikasza and Niedźwiedź 2019). In the annual scale, the course of air temperatures is much more intensive in winter than in summer (Bednorz 2011; Bednorz and Kolendowicz 2013; Tomczyk and Bednorz 2014; Gjelten *et al*. 2016; Isaksen *et al*. 2016; Łupikasza and Niedźwiedź 2019). The mean rate of increase in temperatures in winter exceeds 1.6°C/10 years, and in summer it reaches approximately 0.7°C/10 years (Bednorz 2011; Førland *et al*. 2011; Bednorz and Kolendowicz 2013; Tomczyk and Bednorz 2014; Gjelten *et al*. 2016; Wei *et al*. 2016; Araźny 2019).

Scenarios of changes in the climate of the Spitsbergen assume a further increase in air temperature, particularly in the winter season. According to Osuch and Wawrzyniak (2016), in far future (2071–2100), an increase in air temperature may exceed 11°C in relation to the reference period. The modern climate warming leads to an increase in the frequency of occurrence of warm days and warm spells (Bednorz 2011; Tomczyk and Bednorz 2014; Vikhamar-Schuler *et al*. 2016; Wei *et al*. 2016). The above changes are accompanied by a decrease in the number of frosty days and frost waves (Bednorz 2011; Niedźwiedź *et al*. 2012; Bednorz and Kolendowicz 2013; Łupikasza and Niedźwiedź 2013; Tomczyk 2014; Matthes *et al*. 2016; Sulikowska 2017). The occurrence of cold spells in summer and warm spells in winter, however, has not been determined so far. In the Arctic, warm spells in the winter period are particularly important, because they are often accompanied by snow-on-rain events that are of key importance for Arctic terrestrial ecosystems (Thompson *et al*. 2013; Decamps *et al*. 2017).

The rapid Arctic warming is usually attributed to the combined effect of sea-ice loss (Overland and Wang 2010; Overland *et al*. 2011, 2012; Alekseev *et al*. 2016), increased SST (*e.g*., Serreze *et al*. 2011), reduced sulphate aerosols (Navarro *et al*. 2016), increased water vapour (Park *et al*. 2015), strong low-level stability, cloud conditions (Graversen *et al*. 2014; Pithan and Mauritsen 2014), or strong anthropogenic radiative forcing (Fyfe *et al*. 2013; Wegmann *et al*. 2018). The occurrence of warm or cold days is to some degree governed by atmospheric circulation (Bednorz 2011; Bednorz and Fortuniak 2011, 2012; Niedźwiedź *et al*. 2012; Bednorz and Kolendowicz 2013; Łupikasza and Niedźwiedź 2013; Tomczyk and Bednorz 2014).

Atmospheric circulation in the area of the Svalbard Archipelago is particularly controlled by the Iceland Low and high over Greenland (Przybylak 1992a, 1992b; Hisdal 1998; Sulikowska *et al*. 2018a), determining the direction of advection of cold air masses from the north and relatively warm air masses from the south. Weather on Spitsbergen also depends on the type of the baric system (Bednorz 2011; Niedźwiedź 2001, 2013). In Hornsund, in January, air temperature in the period of advection of air masses from the northern sector in the conditions of anticyclonic circulation can be approximately 3°C lower than in the case of cyclonic circulation (Niedźwiedź 2013). Atmospheric circulation has also had considerable influence on the occurrence of periods of Arctic warming and cooling (Łupikasza and Niedźwiedź 2019).

The progressing climate warming, particularly in the winter period, constitutes a threat for the natural environment. The possible consequences may be a balance disturbance both in the cryosphere and biosphere. Moreover, climate warming favours an increase in tourist traffic contributing to the degradation of the Arctic environment. Considering the importance of occurrence of sequences of exceptionally warm and cold days, characterising the structure of the modern warming and role of atmospheric circulation in shaping thermal conditions, this article determines the character of multi-annual changes and variability of occurrence of cold spells in summer and warm spells in winter on Spitsbergen in the period 1976–2015 (1976/77–2015/16), and circulation conditions of their occurrence.

Data and Methods

The paper was based on average daily air temperatures for the years 1976–2016 for two meteorological stations on Spitsbergen, namely Svalbard Lufthavn (SL) and Ny-Ålesund (NÅ) (Fig. 1). The material was obtained from the commonly available data base of the Norwegian Meteorological Institute (eklima.met.no). The analyses were performed for the summer season, defined as two warmest months in a year (July and August), and for the winter season covering four coldest months (December–March) (Tomczyk and Bednorz 2014).

Cold days in summer were defined as days with mean daily air temperature lower than temperature corresponding to the 10th percentile from daily temperature. Warm days in winter were defined as days with mean daily air temperature exceeding the 90th percentile from daily air temperature. Threshold values corresponding to the 10th and 90th percentiles were calculated for each month separately from the analysed period (1976–2015 and 1976/77–2015/16). A cold spell was defined as a sequence of at least three cold days, and a warm spell as a sequence of at least three warm days.

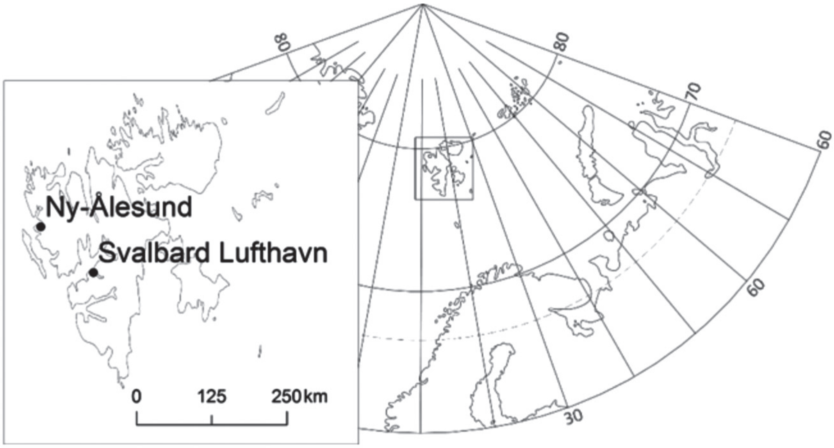

Fig. 1. Location of the weather stations used for this study.

The statistical significance of trends in air temperature and number of cold and warm days was assessed by means of a non-parametric Mann-Kendall test, assuming $\alpha \leq 0.05$ for significant trends. The rate of changes of the analysed characteristics was determined by means of the related Sen's slope method (Mann 1945; Sen 1968; Kendall 1975; Hamed and Rao 1998; Salmi *et al*. 2002). The trend characteristics were calculated with the use of MAKESENS 1.0 application (freeware) provided by the Finnish Meteorological Institute (Salmi *et al*. 2002).

The determination of the effect of circulation on the occurrence of cold and warm days was based on the calendar of circulation types for Spitsbergen (Niedźwiedź 2018), described in detail in studies by Łupikasza and Niedźwiedź (2019). The calendar covers 21 types, including 4 non-advection types, describing the direction of advection of air masses (*e.g.*, N – advection from the north) and type of baric system (a – anticyclonic, c – cyclonic). Non-advection types cover the centre of the high (Ca) and low (Cc), low pressure trough (Bc), and anticyclonic wedge (Ka). Situations complicated in terms of air flow or pressure col are marked as x. Then, the frequency of cold and warm days in particular circulation types was calculated. Moreover, the conditional probability of the occurrence of the analysed days in particular circulation types was calculated.

A detailed analysis of baric conditions during the occurrence of cold and warm spells was performed based on daily data concerning the distribution of sea level pressure, height of isobaric surface of 500 hPa, and air temperature at a level of 850 hPa. The data were obtained from the collection of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay *et al*. 1996) available in the archives of NOAA ESRL PSD (Earth System Research Laboratory Physical Science Division).

The aforementioned data provided the basis for the preparation of maps of mean sea level pressure (SLP), height of isobaric surface of 500 hPa (z500 hPa), and maps of SLP and z500 hPa anomalies, as well as maps of anomalies of air temperature at a level of 850 hPa (T850) for cold and warm spells. The anomalies were calculated as the difference between the mean value on a particular day of sea level pressure, heights of isobaric surfaces, and air temperature, and mean value of the aforementioned elements on a given day in the analysed multi-annual period. The analysis of baric conditions covered only days on which a given spell occurred in both stations.

Moreover, for the purpose of determination of the direction of air masses, 48 h backward trajectories of air particles were designated based on the HYSPLIT model (Stein *et al*. 2015; Rolph 2016). The model is frequently used for the determination of sources of air pollutants (Avila and Alarcon 1999; Salvador *et al*. 2010; Czernecki *et al*. 2017). Movement of air particles was traced at a level of 500 m a.s.l., corresponding with the middle level of the atmospheric mixing layer (Bednorz 2013). The designated trajectories were divided into four groups in accordance with the thermal classification of days constituting cold spells in summer and warm spells in winter.

The thermal classification covered deviations of air temperature on days constituting thermal spells from the aforementioned threshold values of the 90th (warm days) or 10th (cold days) percentile. The resulting deviations were divided into 4 equally probable quartile groups, differentiated by the threshold value of 1, 2 and 3 quartile. It provided the basis for the designation of slightly cold, moderately cold, cold, and very cold days during cold spells, and slightly warm, moderately warm, warm, and very warm days during warm spells.

Results

Mean air temperature in the summer season. — Mean air temperature in the summer was 6.0°C in SL and 4.9°C in NÅ. In both stations, the coldest summer occurred in 1994 (SL: 4.3°C, NÅ: 3.5°C), and in SL also in 1982 (Fig. 2). The highest mean air temperatures occurred non-synchronically, *i.e*. in 1998 in SL (7.5°C), and in 2015 in station NÅ (6.1°C). Generally higher air temperatures in summer in station SL result from more continental climate of the station in comparison to the station in NÅ. In both stations, a statistically significant change in mean summer air temperature was observed in the analysed period, with increases of 0.5°C/10 years in SL and 0.3°C/10 years in NÅ. On the background of the multi-annual period, high temperature particularly occurred in the period from the beginning of the 21st century.

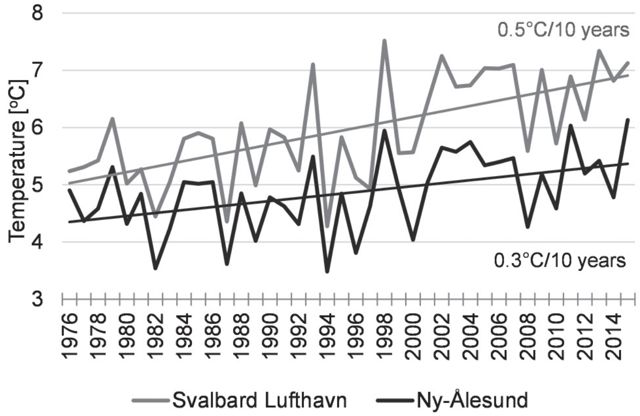

Fig. 2. Mean air temperature in the summer season in Svalbard Lufthavn and Ny-Ålesund in the period 1976–2015.

Cold days and cold spells in the summer season. — In both stations, the occurrence of cold days was characterised by high variability from year to year. The highest number of cold days occurred in 1987 (SL: 27 days, NÅ: 19 days; Fig. 3). High frequency of cold days in SL was also observed in summer in 1994 (17 days), and in NÅ in summer in 1996 (17 days). No cold days occurred during six seasons in SL (1993, 1998, 2005, 2006, 2011 and 2014), and during five seasons in NÅ (1986, 2002, 2004, 2006 and 2015) the majority of which occurred in the 21st century. An increase in air temperature in the summer season manifested in a decrease in the number of cold days which in SL equalled -2.5 days/10 years and -1.3 days/10 years in NÅ. The decreasing trend was only significant in SL.

Cold days usually occurred in the conditions of cyclonic circulation. The ratio of the frequency of occurrence of the analysed days in cyclonic and anticyclonic types in SL was 73.3% to 24.2% and 72.9% to 24% in NÅ (Fig. 4). On cold days, air advection from the north-western sector related to cyclonic systems (NWc, Nc and Wc) was prevalent. The types were also characterised by the highest probability of occurrence of cold days ranging from approximately 20% (Nc and Wc) to more than 30% in SL, and to almost 50% in NÅ, in both cases in type NWc.

The number of cold spells in consecutive decades of the period 1976–2015 is presented in Fig. 5. Throughout the study period, 27 cold spells occurred in SL and 21 cold spells in NÅ. In total, they lasted (respectively) 123 days and 105 days. In SL, the highest number, *i.e.* 12 cold spells occurred in the decade 1986–1995. They lasted for a total of 55 days (Fig. 5A). Cold spells also occurred with a somewhat higher frequency in the first decade of the multi-

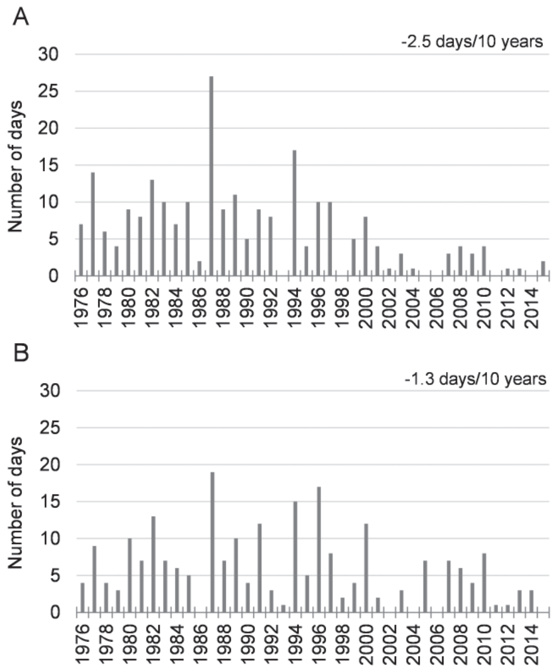

Fig. 3. Number of cold days in the summer season in Svalbard Lufthavn (**A**) and Ny-Ålesund (**B**) in the period 1976–2015.

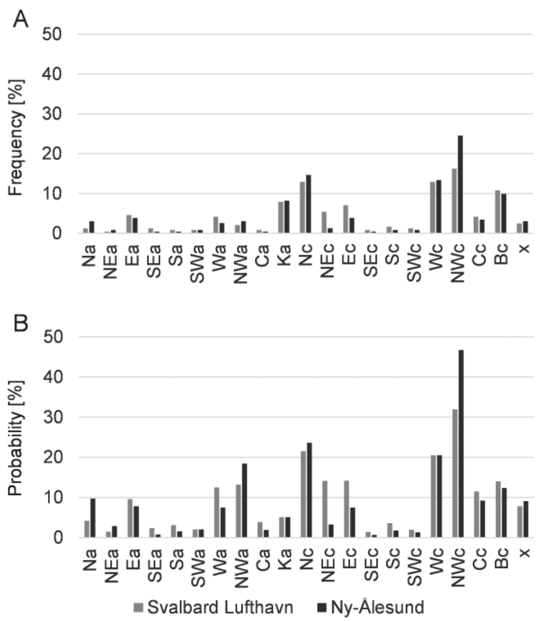

Fig. 4. Frequency of occurrence of cold days in Svalbard Lufthavn and Ny-Ålesund in particular circulation types (**A**), and probability of their occurrence (**B**).

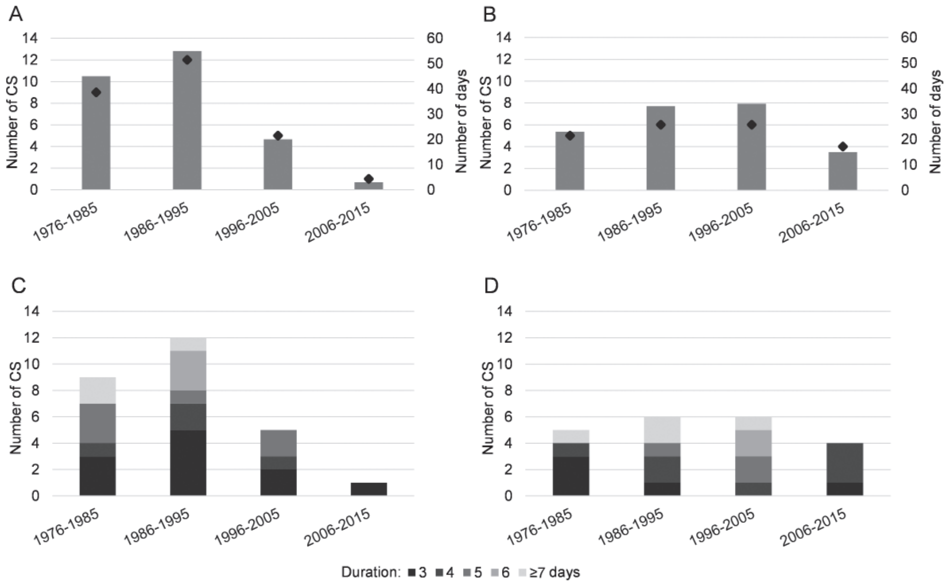

Fig. 5. Number of cold spells (CS) marked by diamonds and their duration marked by bars (**A** – Svalbard Lufthavn, **B** – Ny-Ålesund), and number of cold spells with division by duration (**C** – Svalbard Lufthavn, **D** – Ny-Ålesund).

annual period – nine spells (lasting for a total of 45 days). In NÅ, a maximum of six cold spells occurred. They were observed in the decade 1986–1995, and with the same frequency in the decade 1996–2005, lasting respectively 33 and 34 days. In both stations, cold spells occurred the most seldom in the years 2006–2015, *i.e.* one spell in SL (duration three days) and four spells in NÅ (total duration 15 days).

In SL, 3-day cold spells occurred the most frequently, followed by 5-day spells, and in NÅ 4-day spells followed by 3-day spells (Fig. 5B). Spells of six, seven, and more days occurred the most frequently in the first two decades. In the last, warmest decade, the longest cold spells lasted for four days. The longest cold spells in SL lasted for nine days, and occurred twice, *i.e.* on 23–31.08.1982 and on 15–23.08.1987, and in NÅ they lasted for ten days, and also occurred twice, *i.e.* on 22–31.08.1982 and on 4–13.07.1991.

Mean air temperature during the recorded cold spells was 2.1°C in SL and 1.1°C in NÅ. In the case of both stations, the coldest cold spell occurred in August 1989. Mean air temperature during the spell was 0.2°C (SL) and -0.8°C (NÅ). During the coldest day of the cold spells in summer, the lowest mean daily air temperature was -1.5°C in SL (31.08.1989) and -2.2°C in NÅ (29.08.1994).

Circulation conditions of cold spells. — During the occurrence of cold spells on Spitsbergen, a system of higher than average pressure was located over Greenland. In the centre, air pressure was > 1014 hPa, and over the Franz Josef Land, a low system persisted with pressure in the centre < 1003 hPa (Fig. 6A). Moreover, North Europe was within the range of a high pressure wedge. Over the study area, SLP varied from < 1004 hPa to > 1006 hPa. During the occurrence of cold spells, SLP was lower than average in the multi-annual period. In the centre of the low pressure system, anomalies reached < -9 hPa, and over Spitsbergen they varied from < -8 hPa (north-eastern part) to > -5 hPa (south-western part). During the cold spell, the isobaric surface of 500 hPa persisted lower than on average by a maximum of 150 m in the centre of the low pressure system (Fig. 6B).

The baric situation described above caused advection of cold air masses, particularly from the north-western and northern sector, as also suggested by 48-h backward trajectories of air particles (Fig. 7). During the coldest days, classified as very cold, as well as during cold days, the north-western trajectories were evidently shorter than during slightly and moderately cold days, when during the 48-h preceding the occurrence of cold spells, air masses flew in over Spitsbergen from distant areas such as the Canadian Arctic or North Pole. This suggests a decrease in the intensity of advection during days with stronger cooling. On some days, cold air flew in over Spitsbergen from the south-east, although 48-h earlier it was located over the cold Barents Sea between the Franz Josef Land and Novaya Zemlya. The presence of cold air masses is confirmed by negative T850 anomalies with a maximum over Spitsbergen (< -4°C) (Fig. 6C).

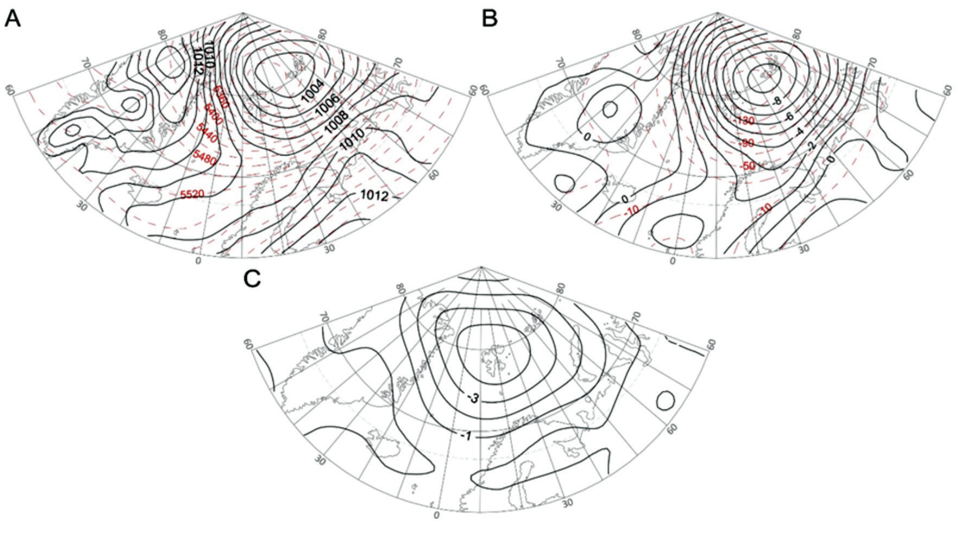

Fig. 6. Mean sea level pressure and height of isobaric surface of 500 hPa (**A**), their anomalies (**B**) and anomalies of air temperature at a level of 850 hPa (**C**) during cold spells.

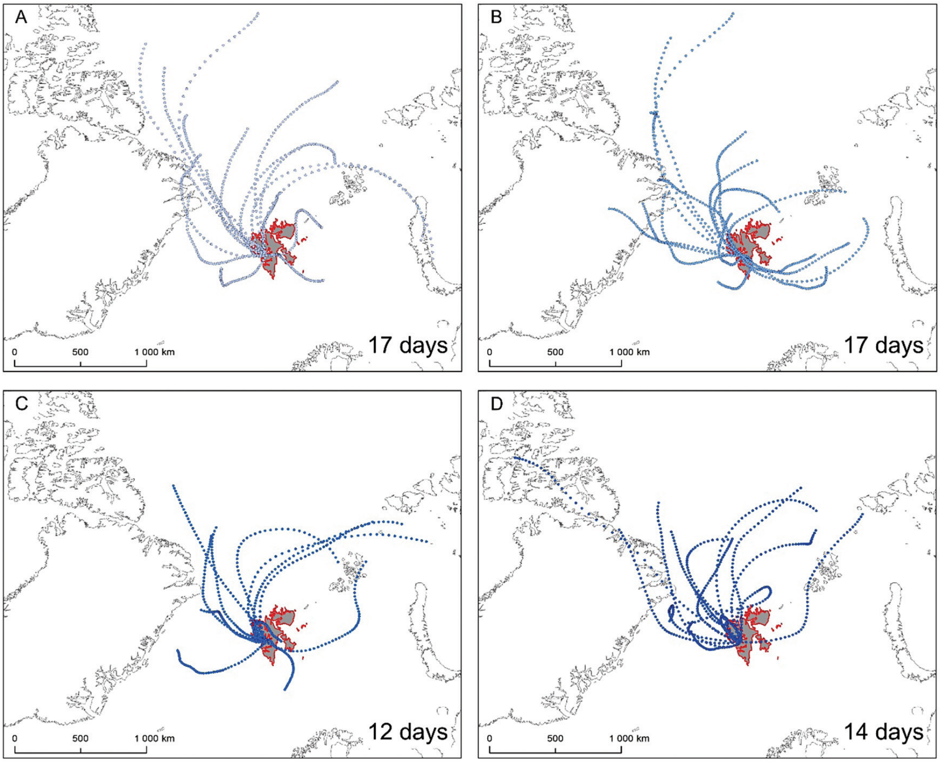

Fig. 7. 48-h backward trajectories of air particles during slightly cold (**A**), moderately cold (**B**), cold (**C**), and very cold days (**D**) with number of cases (bottom right corner).

Mean air temperatures in the winter season. — Mean air temperature in the winter season in SL was -12.4°C and in NÅ -11.7°C. In the case of both stations, winter 1988/89 was the coldest, with mean temperature of -18.7°C in SL and -17.7°C in NÅ (Fig. 8). The warmest winter season occurred in 2011/12. Mean temperature in the period from December to March was -5.2°C in SL and -5.8°C in NÅ. A higher variability of mean air temperature in winter was observed in SL, standard deviation 3.5°C *vs*. 2.9°C in NÅ. In the analysed period, a statistically significant increasing tendency in mean winter air temperature was observed of a rate of 2.1°C/10 years in SL and 1.7°C/10 years in NÅ.

Warm days and warm spells in the winter season. — The year-to-year occurrence of warm days in both stations was characterised by high variability. Like in the case of mean air temperature in winter, a somewhat higher variability was recorded in station SL, for which the value of standard deviation was 8.8 days, for comparison 8.0 days in NÅ. In the case of both stations, the maximum number of warm days (36 days) occurred in winter 2013/14 (Fig. 9).

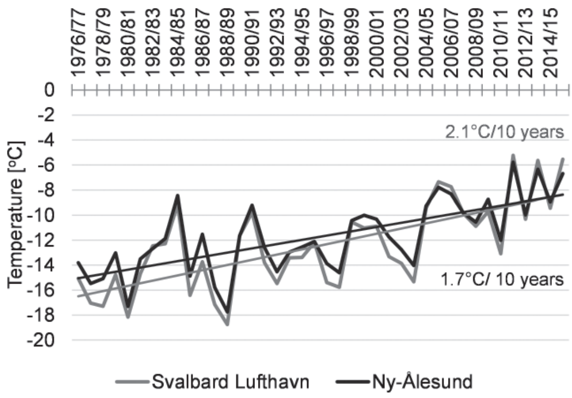

Fig. 8. Mean air temperature in the winter season in Svalbard Lufthavn and Ny-Ålesund in the years 1976/77–2015/16.

The next season in which only inconsiderably less warm days occurred was winter 2005/06 (34 days) in SL, and season 2011/12 in NÅ (29 days). The lowest number of warm days in winter (1 day) in both stations occurred before 1990 (SL 1980/81 and 1988/89, NÅ 1980/81). In the analysed stations, a statistically significant increase in warm days in winter by 2.7 days/10 years was observed in SL, and by 2.4 days/10 years in NÅ.

Warm days in winter, like cold days in summer, usually occurred in the conditions of cyclonic circulation. The ratio of the frequency of occurrence of warm days during cyclonic *vs*. anticyclonic circulation was in SL 79.8% to 20.0%, and in NÅ 78.4% to 21.2% (Fig. 10). This results from the dominant cyclonic circulation in comparison to anticyclonic circulation, and is suggested by the results of the analysis of conditional probability of warm days in circulation types. The highest frequency of warm days in winter concerns types SWc, Sc and SEc. The highest probability of their occurrence, however, concerns types SWa (SL 64.3%, NÅ 67.1%), SWc, Sc, Wa and Sa.

The characteristics of warm spells, *i.e*. their duration, frequency, and changes in course of time were approximately the same in both stations. In the study period, 57 spells occurred in SL and 55 spells in NÅ. They lasted for a total of 243 days and 242 days, respectively. Warm spells occurred the most frequently in the years 2005/06–2015/16 (21 and 24 spells with a total duration of 93 days in SL and 102 days in NÅ; Fig. 11A), and the lowest frequency in the years 1976/77–1985/86 in SL (10 cases lasting 37 days), and in the years 1986/87–1995/96 and 1996/97–2005/06 in NÅ (10 cases each, lasting 45 and 53 days).

The shortest, *i.e*. 3-day spells occurred the most frequently (Fig. 11B). An evident increase was observed in the case of the number of spells lasting for seven or more days. In both stations, the longest warm spell lasted for 13 days,

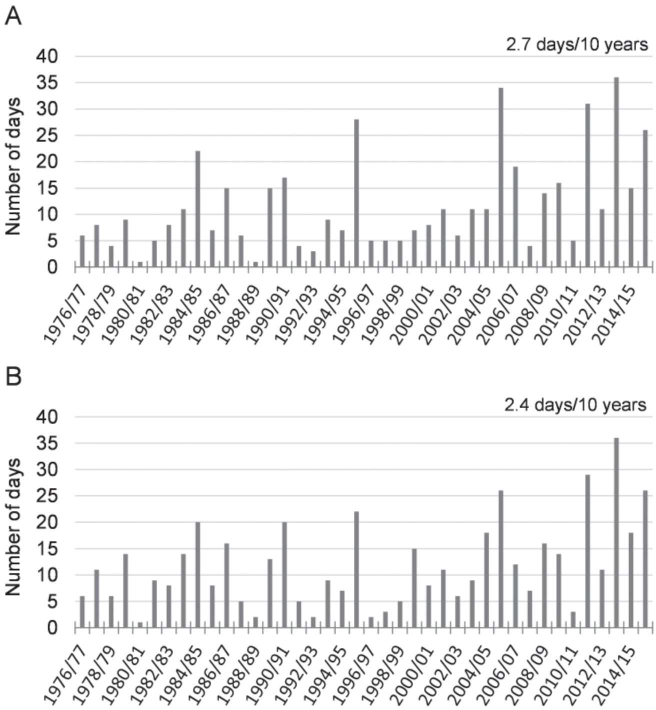

Fig. 9. Number of warm days in the winter season in Svalbard Lufthavn (**A**) and Ny-Ålesund (**B**) in the years 1976/77–2015/16.

and occurred in February 2014, whereas in SL it commenced three days later (from 5 to 17 February) than in NÅ (from 3 to 15 February).

Mean air temperature during warm spells was 0.8°C in SL and 0.2°C in NÅ. In both stations, the most intensive warm spell, *i.e*. that with the highest air temperature (4.0°C in SL and 7.4°C in NÅ), occurred in December 2002. The highest mean daily air temperature during a winter warm spell was 5.9°C (7.12.2002) in SL and 5.1°C (5.12.2002) in NÅ, and was higher by 18.3°C (SL) and 16.8°C (NÅ) than the seasonal mean in the period 1976–2016.

Circulation conditions of warm spells. — The occurrence of warm spells in winter on Spitsbergen was related to the persistence of an extensive trough of low pressure related to the Iceland Low (< 988 hPa) over the Greenland Sea (Fig. 12a). Over the north Eurasia, a high pressure wedge simultaneously persisted. Over Spitsbergen, SLP varied from 1004 hPa to 1010 hPa. During the occurrence of warm spells, high variability of SLP anomalies was recorded in the Arctic, ranging from < -6 hPa to > 18 hPa, and a 0 hPa isoanomaly ran through central Spitsbergen. During warm spells, the isohypse of isobaric surface of 500 hPa were bent northwards, pointing to a greater height of its

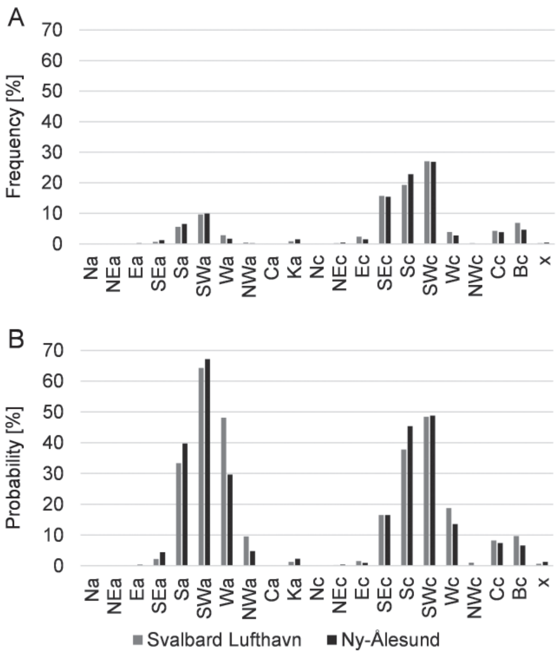

Fig. 10. Frequency of occurrence of warm days in Svalbard Lufthavn and Ny-Ålesund in particular circulation types (**A**), and probability of their occurrence (**B**).

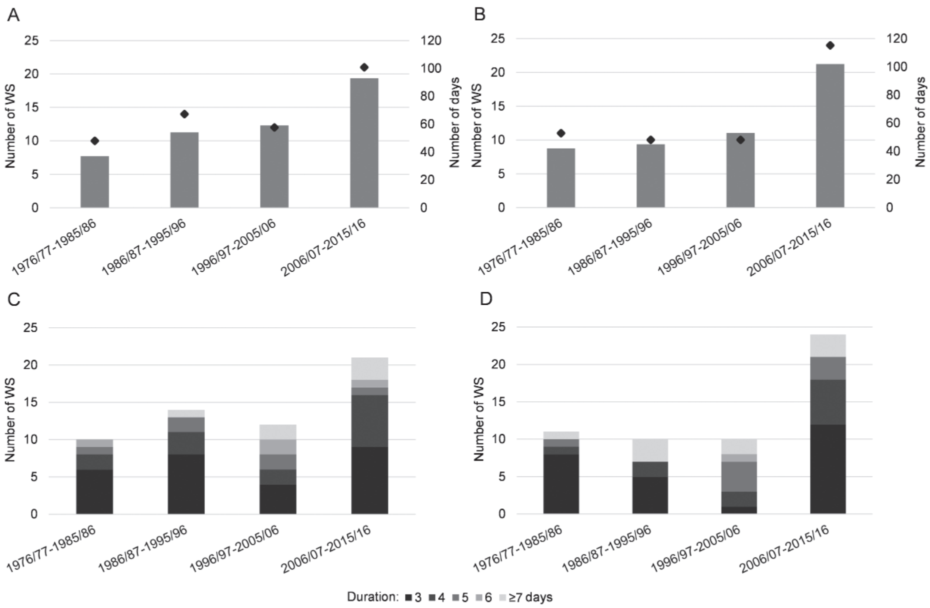

Fig. 11. Number of warm spells (WS) marked by diamonds and their duration marked by bars (**A** – Svalbard Lufthavn, **B** – Ny-Ålesund), and number of cold spells with division by duration (**C** – Svalbard Lufthavn, **D** – Ny-Ålesund).

persistence over Spitsbergen (Fig. 12B). Anomalies of the heights of the surface in the centre of the system were more than 240 m.

The described baric situation caused advection of warm air masses from the south-western sector, as also confirmed by the designated 48-h backward trajectories of air particles (Fig. 13). During days classified as very warm, air particles flew in from the south-east and south from the vicinity of 50°N. During slightly and moderately warm days, air masses flew in from a considerably broader southern sector, *i.e.* from the east to south-west, as well as the western sector from over approximately 60°N. The course of trajectories shows that the intensity of an increase in air temperature during warm days, *i.e.* warm spells in winter, depends not only on the direction, but also duration of advection. In addition to the positive z500 hPa anomalies, the presence of warm air masses is also suggested by positive T850 anomalies of > 9°C with a centre over north Spitsbergen (Fig. 12C). Moreover, the course of isoanomalies also points to the predominant air advection from the south-west.

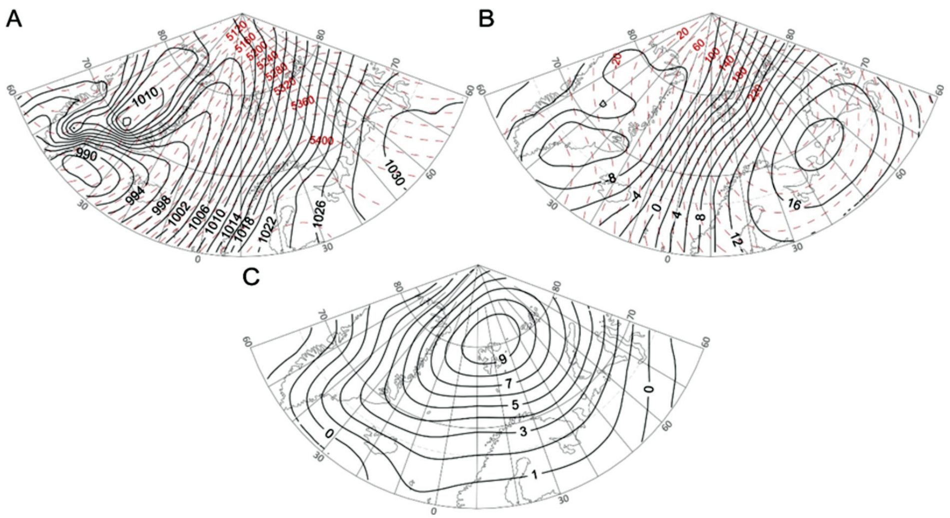

Fig. 12. Mean sea level pressure and height of isobaric surface of 500 hPa (**A**), their anomalies (**B**), and anomalies of air temperature at a level of 850 hPa (**C**) during warm spells.

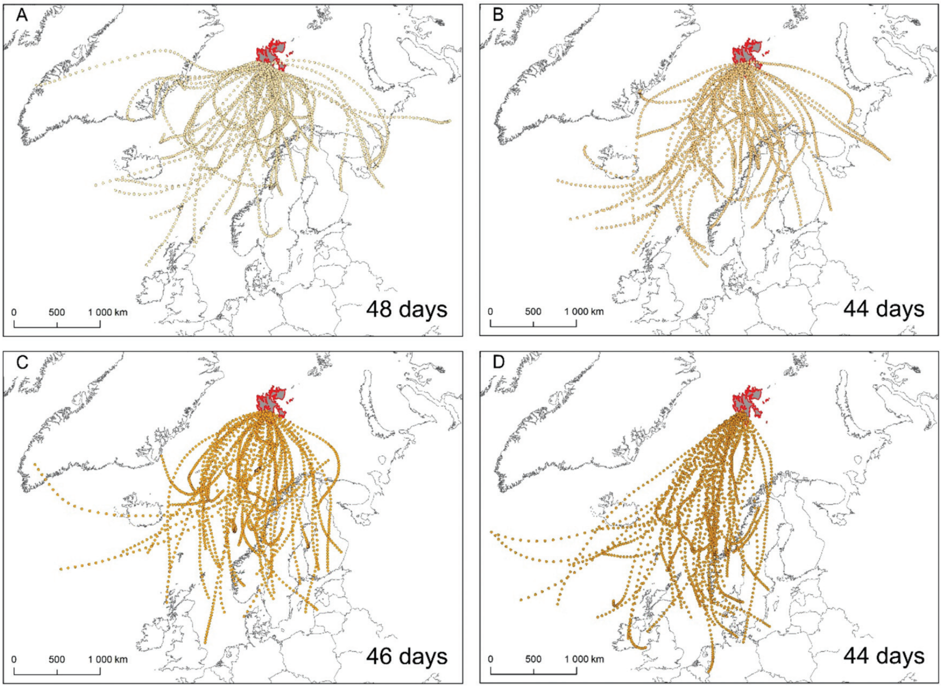

Fig. 13. 48-h backward trajectories of air particles during slightly warm (**A**), moderately warm (**B**), warm (**C**), and very warm days (**D**) with number of cases (bottom right corner).

Summary and discussion

The study showed a statistically significant increase in mean air temperature, with a rate in winter more than four times higher than in summer. In summer, warming in SL was 0.2°C higher than in NÅ. The situation was similar in winter, whereas the trend was 0.4°C higher in SL than in NÅ. The obtained results are in accordance with earlier studies conducted in the central (Bednorz 2011; Bednorz and Kolendowicz 2013) and north-western part of Spitsbergen (Tomczyk and Bednorz 2014; Wei *et al*. 2016), pointing to the strongest warming in the winter season. This suggests that the seasonal and spatial variability of the rate of warming in the Arctic observed in earlier studies (Gjelten *et al*. 2016; Isaksen *et al*. 2016; Osuch and Wawrzyniak 2017) remains a feature of modern climate changes in Spitsbergen. Moreover, studies show that the recent years have been the warmest in 100-year period of instrumental observations (Nordli *et al*. 2014; Gjelten *et al*. 2016; Łupikasza and Niedźwiedź 2019; Hanssen--Bauer *et al*. 2019).

The observed warming translated into a decrease in the number of cold days in summer and an increase in the number of warm days in winter, as well as warm and cold spells related to the frequency of such days. The rate of the changes was higher in SL. On the background of the entire multi-annual period, the last decade (2006–2015) stood out with the lowest frequency of cold spells and their duration, and the highest frequency and duration of warm spells. In both stations, the majority of summer seasons without cold days occurred after 2000. The changes in the duration and intensity of warm and cold spells discussed in this article provide additional characteristics concerning the structure of warming manifesting in an increase in the frequency of days with extremely high temperature (Bednorz and Kolendowicz 2013; Tomczyk and Bednorz 2014; Gjelten *et al*. 2016; Wei *et al*. 2016), as well as a decrease in the number of days with extremely low temperature (Bednorz 2011; Niedźwiedź *et al*. 2012; Łupikasza and Niedźwiedź 2013; Gjelten *et al*. 2016). A similar direction of changes in thermal conditions was also observed in Alaska, where increasingly more frequent occurrence of extremely warm days and abnormally warm months was observed, as well as more seldom occurrence of extremely cold days and abnormally cold months (Wendler and Shulski 2009; Sulikowska 2017; Sulikowska *et al*. 2018b).

Significant decrease in the frequency of summer cold spells and the opposite trends in the frequency of winter warm spells have a profound environmental consequences that will keep strengthening, providing trends are continued. The most evident manifestation of summer warming is a reduction in sea ice extent and snow cover that changes albedo thus a radiative balance of the Arctic areas (Boisvert *et al*. 2016; Cullather *et al*. 2016; Graham *et al*. 2017; Petty *et al*. 2018). Uncovered areas, due to snow cover and ice melting, are more exposed to atmospheric conditions, which influences geomorphological processes. Other consequences include an increase in plant growth and a greening of the Arctic regions being a response of tundra shrub species to warming (Jia *et al*. 2003; Bhatt *et*. *al*. 2010, 2013; Lara *et al*. 2018). Moreover, extending the growing season for algae and other organisms, potentially leads to increased primary production and taxonomic shifts as new habitats become available (Birks *et al*. 2004; Smol *et al*. 2005; Griffiths *et al*. 2017). Winter warm spells are often accompanied by winter rainfall (Hansen *et al*. 2014). Liquid precipitation in a cold part of a year (rain-on-snow events) may lead to ground ice built-up on tundra, causing icing that reduces availability of food for herbivores (Ims *et al*. 2008; Gilg *et al*. 2009; Hansen *et al*. 2013; Stien *et al*. 2012) and affects inhabitant, by closing roads, airports and reducing mobility (Hansen *et al*. 2014).

Studies performed to date show a correlation of negative thermal extremes both in summer and winter with advection of air masses from the northern sector (Bednorz 2011; Niedźwiedź *et al*. 2012; Łupikasza and Niedźwiedź 2013). The occurrence of cold days and cold spells in summer was particularly related to the advection of air masses from the north-western sector, caused by a low pressure system with a centre above the Franz Josef Land. On the analysed days, SLP over a considerable area of the Arctic was lower than average for the summer season. Over this area in summer, a weak gradient pressure field with high pressure usually persisted above Greenland and the lowland southwest of Iceland (Tomczyk and Bednorz 2014). The relation of the intensity of cold spells and the duration of the advection was determined. Slower air flow favours stronger decreases in air temperature, because in such situations air flows to Spitsbergen from over not very distant ice-covered (sometimes even in summer) northern parts of the Greenland Sea. During intensive advection, air flows from over the Canadian Arctic Archipelago, which defrosts in some seasons. Therefore, air persisting over this area is warmer than average, and it is not subject to strong cooling during intensive flow towards Spitsbergen over the ice-covered water surface. Cold spells also occurred in the conditions of advection of air masses from the south-east, although days in such circulation were warmer than in the case of advection from the north-east. Moreover, air flowing in from over Spitsbergen from the SE earlier persisted over the cold Barents Sea between the Franz Josef Land and Novaya Zemlya.

The occurrence of warm days and warm spells in winter, similarly as positive thermal extremes (Bednorz and Fortuniak 2011, 2012; Bednorz and Kolendowicz 2013; Tomczyk and Bednorz 2014), was particularly related to the advection of air masses from the south-west, as well as from the west and east, although in the case of such circulation the inflowing air was colder than in the case of advection from the south-west. The described direction of advection was generated by a vast low pressure system. On the analysed days, the SLP differed from the average SLP in the winter season, involving a strong horizontal pressure gradient in the Atlantic Arctic sector between the strong high above Greenland and the vast Icelandic lowland (Tomczyk 2014). The duration of air advection also affected the intensity of warming during warm spells, whereas the relation was the opposite to that for cold spells, *i.e.* stronger air flow intensified warming during warm days and warm spells, because in such situations air reaching Spitsbergen came from lower latitudes than during weak air advection.

The causes of changes in thermal conditions, and particularly an evident increase in positive extremes in winter, can be associated with a change of circulation conditions. As evidenced by Niedźwiedź (2006), from the second half of the 20th century, an evident increase occurred in the value of the western and southern circulation index, as well as an increase in the activity of lows in all the seasons of the year, and particularly in winter.

Acknowledgements. — The authors would like to thank the two anonymous reviewers for their constructive comments and suggestions that helped to improve the quality of this paper.

References

ALEKSEEV G., GLOK N. and SMIRNOV A. 2016. On assessment of the relationship between changes of sea ice extent and climate in the Arctic. *International Journal of Climatology* 36: 3407–3412.

AMAP 2011. *Executive summary: snow, water, ice and permafrost in the Arctic (SWIPA)*. Arctic Monitoring and Assessment Programme (AMAP), Oslo: 538 pp.

ARAŹNY A. 2019. Temporal and spatial variability of thermal and humidity stimuli in the Hornsund area (Svalbard). *Polish Polar Research* 40: 29–53.

AVILA A. and ALARCON M. 1999. Relationship between precipitation chemistry and meteorological situations at a rural site in NE Spain. *Atmospheric Environment* 33: 1663–1677.

BEDNORZ E. 2011. Occurrence of winter air temperature extremes in Central Spitsbergen. *Theoretical and Applied Climatology* 106: 547–556.

BEDNORZ E. 2013. Synoptic conditions of heavy snowfalls in Europe. *Geografiska Annaler: Series A, Physical Geography* 95: 67–78.

BEDNORZ E. and FORTUNIAK K. 2011. The occurrence of coreless winters in central Spitsbergen and their synoptic conditions. *Polar Research* 30: 12218.

BEDNORZ E. and FORTUNIAK K. 2012. Coreless winters in the European sector of the Arctic and their synoptic conditions. *Polish Polar Research* 33: 19–34.

BEDNORZ E. and KOLENDOWICZ L. 2013. Summer mean daily air temperature extremes in Central Spitsbergen. *Theoretical and Applied Climatology* 113: 471–479.

BHATT U.S., WALKER D.A., RAYNOLDS M.K. *et al*. 2010. Circumpolar Arctic tundra vegetation change is linked to sea ice decline. *Earth Interactions* 14: 1–20.

BHATT U.S., WALKER D.A., RAYNOLDS M.K. *et al*. 2013. Recent declines in warming and vegetation greening trends over pan-Arctic tundra. *Remote Sensing* 5: 4229–4254.

BINTANJA R. and VAN DER LINDEN E.C. 2013. The changing seasonal climate in the Arctic. *Nature Scientific Reports* 3: 1556.

BIRKS H.J.B., JONES V.J. and ROSE N.L. 2004. Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments: An introduction. *Journal of Paleolimnology* 31: 403–410.

BOISVERT L.N., PETTY A.A. and STROEVE J.C. 2016. The impact of the extreme winter 2015/16 Arctic cyclone on the Barents-Kara seas. *Monthly Weather Review* 144: 4279–4287.

CULLATHER R.I., LIM Y.K., BOISVERT L.N. *et al*. 2016. Analysis of the warmest Arctic winter, 2015–2016. *Geophysical Research Letters* 43: 10808–10816.

CZERNECKI B., PÓŁROLNICZAK M., KOLENDOWICZ L. *et al*. 2017. Influence of the atmospheric conditions on PM10 concentrations in Poznań, Poland. *Journal of Atmospheric Chemistry* 74: 115–139.

DESCAMPS S., ARS J., FUGLEI E. *et al*. 2017. Climate change impacts on wildlife in a High Arctic archipelago – Svalbard, Norway. *Global Change Biology* 23: 490–502.

FØRLAND E.J., BENESTAD R., HANSSEN-BAUER I. *et al*. 2011. Temperature and precipitation development at Svalbard 1900–2100. *Advances in Meteorology* 14: 893790.

FYFE J.C., VON SALZEN K., GILLETT N.P. *et al*. 2013. One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports* 3: 2645.

GILG O., SITTLER B. and HANSKI I. 2009. Climate change and cyclic predator-prey population dynamics in the high Arctic. *Global Change Biology* 15: 2634–2652.

GJELTEN H.M., NORDLI Ø., ISAKSEN K. *et al*. 2016. Air temperature variations and gradients along the coast and fjords of western Spitsbergen. *Polar Research* 35: 29878.

GRAHAM R.M., COHEN L., PETTY A.A. *et al*. 2017. Increasing frequency and duration of Arctic winter warming events. *Geophysical Research Letters* 44: 6974–6983.

Graversen R.G., Langen P.L. and Mauritsen T. 2014. Polar amplification in CCSM4: Contributions from the lapse rate and surface albedo feedbacks. *Journal of Climate* 27: 4433–4450.

Griffiths K., Michelutti N., Sugar M. *et al*. 2017. Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds. *PLoS One* 12: e0172989.

Hamed K.H. and Rao A.R. 1998. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* 204: 182–196.

Hansen B.B., Grøtan V., Aanes R. *et al*. 2013. Climate events synchronize the dynamics of a resident vertebrate community in the high Arctic. *Science* 339: 313–315.

Hansen B.B., Isaksen K., Benestad R.E. *et al*. 2014. Warmer and wetter winters: Characteristics and implications of an extreme weather event in the High Arctic. *Environmental Research Letters* 9: 114021.

Hanssen-Bauer I., Førland E.J., Hisdal H. *et al*. 2019. Climate in Svalbard 2100 – a knowledge base for climate adaptation. *Norwegian Environment Agency*, *NCCS Report* 1: 2387–3027.

Hisdal V. 1998. *Svalbard nature and history*. Norsk Polarinstitut, Oslo: 127 pp.

Ims R.A., Henden J-A. and Killengreen S.T. 2008. Collapsing population cycles. *Trends in Ecology & Evolution* 23: 79–86.

IPCC. 2013. *Climate change 2013: the physical science basis*. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, New York.

Isaksen K., Nordli Ø., Førland E.J. *et al*. 2016. Recent warming on Spitsbergen—Influence of atmospheric circulation and sea ice cover. *Journal of Geophysical Research: Atmosphere* 121: 11913–11931.

Jia G.J., Epstein H.E. and Walker D.A. 2003. Greening of arctic Alaska, 1981–2001. *Geophysical Research Letters* 30: 2067.

Kalnay E., Kanamistu M., Kistler R. *et al*. 1996. The NMC/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77: 437–471.

Kendall M. 1975. *Multivariate Analysis*. Charles Griffin & Company, London: 210 pp.

Lara M.J., Nitze I., Grosse G. *et al*. 2018. Reduced arctic tundra productivity linked with landform and climate change interactions. *Scientific Reports* 8: 2345.

Łupikasza E. and Niedźwiedź T. 2013. Frequency of ice days at selected meteorological stations in Svalbard. *Bulletin of Geography – Physical Geography Series* 6/2013: 80–97.

Łupikasza E. and Niedźwiedź T. 2019. The influence of mesoscale atmospheric circulation on Spitsbergen air temperature in periods of Arctic warming and cooling. *Journal of Geophysical Research: Atmospheres* 124: JD029443.

Mann H.B. 1945. Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society* 13: 245–259.

Matthes H., Rinke A. and Dethloff K. 2016. Recent changes in Arctic temperature extremes: warm and cold spells during winter and summer. *Environmental Research Letters* 10: 029501.

Miller G.H., Brigham-Grette J., Alley R.B. *et al*. 2010. Temperature and precipitation history of the arctic. *Quaternary Science Reviews* 29: 1679–1715.

Navarro J.C., Varma V., Riipinen I. *et al*. 2016. Amplification of Arctic warming by past air pollution reductions in Europe. *Nature Geoscience* 9: 277–281.

Niedźwiedź T. 2001. Variability of atmospheric circulation above Spitsbergen in the second half of 20th Century. *Problemy Klimatologii Polarnej* 11: 7–26 (in Polish).

Niedźwiedź T. 2006. The main forms of atmospheric circulation above Spitsbergen (December 1950 – September 2006). *Problemy Klimatologii Polarnej* 16: 91–105 (in Polish).

NIEDŹWIEDŹ T. 2013. Influence of atmospheric circulation on the air temperature at Hornsund. *In*: A.A. Marsz, A. Styszyńska (eds) *Climate and climate change at Hornsund, Svalbard*. Gdynia Maritime University, Gdynia: 165–172.

NIEDŹWIEDŹ T. 2018. *Calendar of circulation types for Spitsbergen*. Database of University of Silesia in Katowice, Department of Climatology, http://www.kk.wnoz.us.edu.pl/nauka/kalendarz-typow-cyrkulacji/.

NIEDŹWIEDŹ T., ŁUPIKASZA E. and MAŁARZEWSKI Ł. 2012. The influence of the atmospheric circulation on the occurrence of ice days in Hornsund (Spitsbergen). *Problemy Klimatologii Polarnej* 22: 17–26 (in Polish).

NORDLI Ø., PRZYBYLAK R., OGILVIE A.E. *et al*. 2014. Long-term temperature trends and variability on Spitsbergen: the extended Svalbard Airport temperature series, 1898–2012. *Polar Research* 33: 21349.

OSUCH M. and WAWRZYNIAK T. 2016. Climate projections in the Hornsund area, Southern Spitsbergen. *Polish Polar Research* 37: 379–402.

OSUCH M. and WAWRZYNIAK T. 2017. Inter- and intra-annual changes in air temperature and precipitation in western Spitsbergen. *International Journal of Climatology* 37: 3082–309.

OVERLAND J.E. and WANG M. 2010. Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus Series A: Dynamic Meteorology and Oceanography* 62A: 1–9.

OVERLAND J.E., FRANCIS J.A., HANNA E. *et al*. 2012. The recent shift in early summer Arctic atmospheric circulation. *Geophysical Research Letters* 39: L19804.

OVERLAND J.E., WOOD K. and WANG M. 2011. Warm Arctic-cold continents: Climate impacts of the newly open Arctic Sea. *Polar Research* 30: 15787.

PARK D.-S.R., LEE S. and FELDSTEIN S.B. 2015. Attribution of the recent winter sea ice decline over the Atlantic sector of the arctic ocean. *Journal of Climate* 28: 4027–4033.

PETTY A.A., STROEVE J.C., HOLLAND P.R. *et al*. 2018. The Arctic sea ice cover of 2016: A year of record-low highs and higher-than-expected lows. *The Cryosphere* 12: 433–452.

PRZYBYLAK R. 1992a. The thermic and humidity relations against a background of the circulations conditions in Hornsund (Spitsbergen) in the period 1978–1983. *Dokumentacja Geograficzna* 2: 1–105.

PRZYBYLAK R. 1992b. Spatial differentiation of air temperature and humidity on western coast of Spitsbergen in 1979–1983. *Polish Polar Research* 13: 113–129.

RAHMSTORF S., FOSTER G. and CAHILL N. 2017. Global temperature evolution: recent trends and some pitfalls. *Enviromental Research Letters* 12: 054001.

PITHAN F. and MAURITSEN T. 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience* 7: 181–184.

ROLPH G.D. 2016. *Real-Time Environmental Applications and Display System (READY)*. Silver Spring, MD: NOAA Air Resources Laboratory: http://ready.arl.noaa.gov.

SALMI T., MAIITTII A., ANTTILA P. *et al*. 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates – the Excel template application MAKESENS. *Finnish Meteorological Institute, Public On Air Quality* 31: 1–35.

SALVADOR P., ARTINANO B., PIO C. *et al*. 2010. Evaluation of aerosol sources at European high altitude background sites with trajectory statistical methods. *Atmospheric Environment* 44: 23162329.

SEN P.K. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* 63: 1379–1389.

SERREZE M.C., BARRETT A.P. and CASSANO J.J. 2011. Circulation and surface controls on the lower tropospheric air temperature field of the Arctic. *Journal of Geophysical Research* 116: D07104.

SMOL J.P., WOLFE A.P., BIRKS H.J.B. *et al*. 2005. Climate-driven regime shifts in the biological communities of Arctic lakes. *Proceedings of the National Academy of Sciences of the USA* 102: 4397–4402.

STIEN A.F., IMS R.A., ALBON S.D. *et al*. 2012. Congruent responses to weather variability in high arctic herbivores. *Biology Letters* 8: 1002–1005.

STEIN A.F., DRAXLER R.R., ROLPH G.D. *et al*. 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* 96: 2059–2077.

STYSZYŃSKA A. 2011. Influence of changes in sea surface temperature in the Barents, Norwegian and Greenland seas on the annual air temperature trend at Spitsbergen. *Problemy Klimatologii Polarnej* 21: 115–131 (in Polish).

SULIKOWSKA A. 2017. Monthly air temperature anomalies in Alaska (1951–2015). *Prace Geograficzne* 148: 33–54 (in Polish).

SULIKOWSKA A., WALAWENDER J.P. and WALAWENDER E. 2018a. Temperature extremes in Alaska: temporal variability and circulation background. *Theoretical and Applied Climatology* 136: 955–970.

SULIKOWSKA A., WYPYCH A., MITKA K. *et al*. 2018b. Summer weather conditions in 2005 and 2016 on the western and eastern coasts of south Spitsbergen. *Polish Polar Research* 39: 127–144.

TOMCZYK A.M. 2014. Frost waves in north-western Spitsbergen. *In*: Migała K., Owczarek P., Kasprzak M., Strzelecki M.C. (eds) *New perspectives in polar research*. University in Wrocław: 247–256.

TOMCZYK A.M. and BEDNORZ E. 2014. Warm waves in north–western Spitsbergen. *Polish Polar Research* 35: 497–511.

THOMPSON R.M., BEARDALL J., BERINGER J. *et al*. 2013. Means and extremes: building variability into community-level climate change experiments. *Ecology Letters* 16: 799–806.

VIKHAMAR-SCHULER D., ISAKSEN K., HAUGEN J.E. *et al*. 2016. Changes in winter warming events in the Nordic Arctic Region. *Journal of Climate* 29: 6223–6244.

WALSH J.E., OVERLAND J.E., GROISMAN P.Y. *et al*. 2011. Arctic climate. Recent variations. *In*: *AMAP Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate change and the cryosphere*. Oslo: 1–13.

WEI T., DING M., WU B. *et al*. 2016. Variations in temperature-related extreme events (1975–2014) in Ny-Ålesund, Svalbard. *Atmospheric Science Letters* 17: 102–108.

WEGMANN M., ORSOLINI Y. and ZOLINA O. 2018. Warm Arctic-cold Siberia: Comparing the recent and the early 20th-century Arctic warmings. *Environmental Research Letters* 13: 025009.

WENDLER G. and SHULSKI M. 2009. A century of climate change for Fairbanks, Alaska. *Arctic* 62: 295–300.

Received 3 July 2019
Accepted 9 October 2019