POLISH POLAR RESEARCH
vol. 35, no. 3, pp. 497–511, 2014 doi: 10.2478/popore-2014-0023

Warm waves in north-western Spitsbergen

Arkadiusz Marek TOMCZYK and Ewa BEDNORZ

Zakład Klimatologii, Instytut Geografii Fizycznej i Kształtowania Środowiska Przyrodniczego, Uniwersytet im. Adama Mickiewicza, ul. Dzięgielowa 27, 61-680 Poznań, Poland
<atomczyk@amu.edu.pl> <ewabedno@amu.edu.pl>

Abstract: In this study, weather conditions causing warm waves in north-western Spitsbergen, exemplified by Ny-Ålesund station, were analyzed. Between 1981 and 2010, 536 days with the maximum temperature exceeding 8.3°C (the value of 95 percentile) were selected. 37 warm waves, which altogether lasted 268 days, were identified. A typical feature of pressure pattern causing warm waves was the appearance of positive anomalies of both the sea level pressure and the height of isobaric surface 500 hPa in the Euro-Atlantic sector of the Arctic. This indicates a presence of high-pressure systems in this region. Extremely warm days appeared more often with the circulation from the eastern than the western sector. Longer and warmer heat waves occurring in the last decade of the analyzed period may be considered as a sign of climate warming, which has a significant impact on environment, *i.e.* reduction in area and thickness of glaciers, reduction of permafrost and snow cover, changes in biodiversity, *etc*. The increase in the air temperature and more frequent occurrence of heat waves may encourage development of tourism in polar areas, potentially causing further changes in the environment.

Key words: Arctic, Svalbard, air temperature, warming, atmospheric circulation.

Introduction

Atmospheric circulation has a strong impact on the air temperature, especially in high latitudes, where the insolation is lower, and the heat is transferred mainly by atmospheric and oceanic circulation (Alekseev *et al.* 1991, cited in Przybylak 2000; Bednorz and Kolendowicz 2013). The occurrence of thermal extremes and the influence of atmospheric circulation on thermal conditions in the Arctic have been of great interest (Polyakov *et al*. 2003; Zhang *et al*. 2004; Shabbar 2006; Niedźwiedź *et al*. 2012). Research on the air temperature changes in the Arctic region showed an increasing trend (Nordli *et al.* 2003; Turner *et al*. 2006; Przybylak 2007b; Marsz and Styszyńska 2009; Bednorz 2011; Bednorz and Kolendowicz 2013); still, the reasons for the contemporary warming in the Arctic are considered to be very complex and

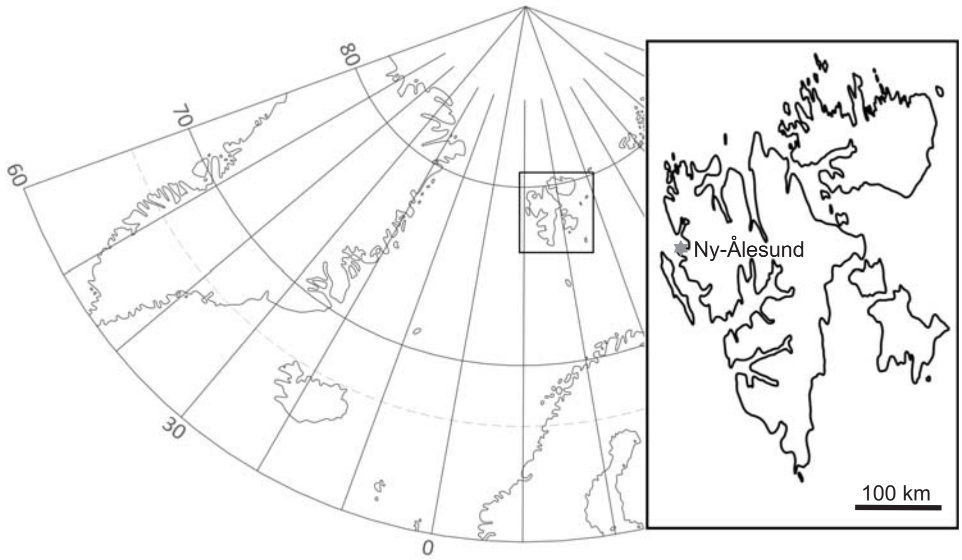

Fig. 1. Area of the study.

they are still discussed (*e. g.* Hanssen-Bauer and Førland 1998; Niedźwiedź 2003; Polyakov *et al*. 2003; Przybylak 2003). Changes in the air circulation are indicated as one of the main factors influencing warming in the Arctic. Changes in the Arctic Oscillation (AO), often considered as a manifestation of global warming (Palmer 1999) and they are important for understanding variability in Arctic atmospheric circulation (Feldstein 2002; Overland and Serreze 2012). However, AO represents only a single geographic center, while air circulation over the Arctic is more complex with multiplied centers of action (Overland *et al.* 2011). Therefore closer and more detailed analysis of observed circulation-temperature relationship is significant for recognizing the global climate changes (Przybylak and Wyszyński 2009).

Warming of the Arctic in the 20th century was a two-phase process. The first warming phase started after the minimum recorded in the 10s of the 20th century, and it reached a maximum in the 30s. That period was called "the Early 20th Century Warming". The minimum of the 20th century was recorded in the 60s, and; subsequently, a temperature increase began, and it is on-going. The last period; namely, 2005–2012, has been recognized as one of the warmest of all (Nordli 2010; Nordli *et al.* 2014). Johannessen *et al*. (2004) indicate that the present warming of the Arctic started at the beginning of the 80s of the 20th century. However, the reasons for the contemporary changes have remained unexplained. Both natural factors, such as heat delivery to the Arctic through the oceanic circulation (Bengtsson *et al*. 2004; Polyakov *et al*. 2004; Marsz and Styszyńska 2009), and anthropogenic factors, among which there is an increase of CO_2 concentration in the atmosphere, are considered to be important (Johannessen *et al.* 2004). Another reason for climate change is solar variation (Fröhlich and Lean 1998; Soon 2005).

However, as Bengston *et al.* (2004) indicated, the influence of solar variations on climate changes should be perceived only as a hypothesis, which can only be rejected or accepted on the basis of further research. What is more, among the reasons for present warming of the Arctic, there is anthropogenic warming in combination with other factors as the warm Atlantic water inflow and circulation changes (Overland and Serreze 2012). There are researchers who claim that the current warming of the Arctic is caused mainly by natural factors; still, the anthropogenic factor cannot be ruled out (Polyakov *et al.* 2003; Soon 2005; Marsz and Styszyńska 2009).

The aim of the study is (i) to analyze the occurrence of warm waves in north-western Spitsbergen and its multiannual variability, and (ii) to determine synoptic situations causing appearance of extremely warm days and warm waves in this region.

Data and methods

Spitsbergen is the largest island of the Svalbard Archipelago and it is a part of Euro-Atlantic sector of the Arctic. The island is surrounded by the Arctic Sea waters from the north, the Barents Sea from the south-east, and the Greenland Sea from the south-west. The Ny-Ålesund station ($\phi = 78°56'$N and $\lambda = 11°57'$E) is located in the north-western part of Spitsbergen, on the north-eastern coast of Brøgger Peninsula (Fig. 1), at the height of 11 m a.s.l.

The study used the mean, maximum, and minimum daily air temperatures in Ny-Ålesund from the period of 1981–2010. The source material was obtained from the Norwegian Meteorological Institute datasets, available at e-klima portal (eklima.met.no).

An extremely warm day was defined as a day with the maximum temperature (T_{max}) exceeding the value of 95 of percentile, which in Ny-Ålesund reached 8.3°C. A sequence of at least 5 extremely warm days was regarded as a warm wave, with a one-day possible break, during which a maximum temperature could not drop below 90 annual percentile (6.9°C). These criteria were based on a probability density function and they were applied according to the definition of extreme weather phenomena determined by the Intergovernmental Panel on Climate Change (IPCC 2007).

The basic climatologic characteristics were computed using source data, *i.e.* average annual air temperature, average temperature for a summer season (June–September) and the number of extremely warm days in every season. Subsequently, the multiannual variability of each characteristic was examined, and linear trends of changes were estimated. For days with T_{max} >8.3°C, circulation types were determined according to the calendar of circulation types for Spitsbergen worked out by Niedźwiedź (2013).

Relating the occurrence of extremely warm days to synoptic conditions, the "environment to circulation" approach was applied. In this method, the circulation classification is executed in accordance with specific environment-based criteria set for a particular environmental phenomenon, *i.e.* temperature extremes in this case (Yarnal 1993; Yarnal *et al.* 2001; Dayan *et al.* 2012). In order to recognize pressure patterns and circulation conditions, which are favorable for positive thermal extremes, the sea level pressure (SLP) and the height of isobaric surface 500 hPa (z500 hPa) daily data were applied. They were derived from the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al*. 1996), available at the Climate Research Unit. In the study, values for area of 60–90°N, 60°W–80°E were used.

Firstly, average SLP and z500 hPa were mapped out for the summer period and; subsequently, composite maps and anomaly maps were constructed for extremely warm days in Ny-Ålesund. Additionally, correlation coefficients between the T_{max} and the SLP/z500 hPa values in each grid point were computed and mapped for days with T_{max} >8.3°C. Furthermore, different circulation types causing appearance of warm waves were distinguished using the Ward's (1963) minimum variance method. For that purpose standardized SLP values were used. The Ward's method is a hierarchical clustering technique, most frequently used for a climatic classification (Kalkstein *et al.* 1987) and for identifying the atmospheric circulation patterns associated with the occurrence of specific weather phenomena (*e.g.* Birkeland and Mock 1996; Esteban *et al.* 2005; Bednorz 2011; Bednorz and Fortuniak 2012; Suwała 2013). In this study, the clustered objects were the extremely warm days. Composite maps and anomaly maps of SLP and z500 hPa were constructed for each circulation type obtained by the clustering.

Results

Occurrence of extremely warm days. — The average annual air temperature in Ny-Ålesund in the analyzed period amounted to -5.1°C and ranged from -8.5°C in 1988, to -2.7°C in 2006 (Fig. 2A). Standard deviation amounted to 1.2°C. A statistically significant increase ($p < 0.05$) of the annual average air temperature was proved for the analyzed period with a rate of 0.8°C per 10 years.

In the annual course of temperature, the highest values appeared during the polar day with the maximum in July (5.3°C). Then, a rapid decrease was observed right after the beginning of the polar night in September. The air temperature reached its annual minimum in February (-12.7°C) (Fig. 2B). The average air temperature in summer (June–September) was 3.0°C and it varied from 1.6°C (1982) to 4.2°C (1990). The absolute maximum of the air temperature was recorded on

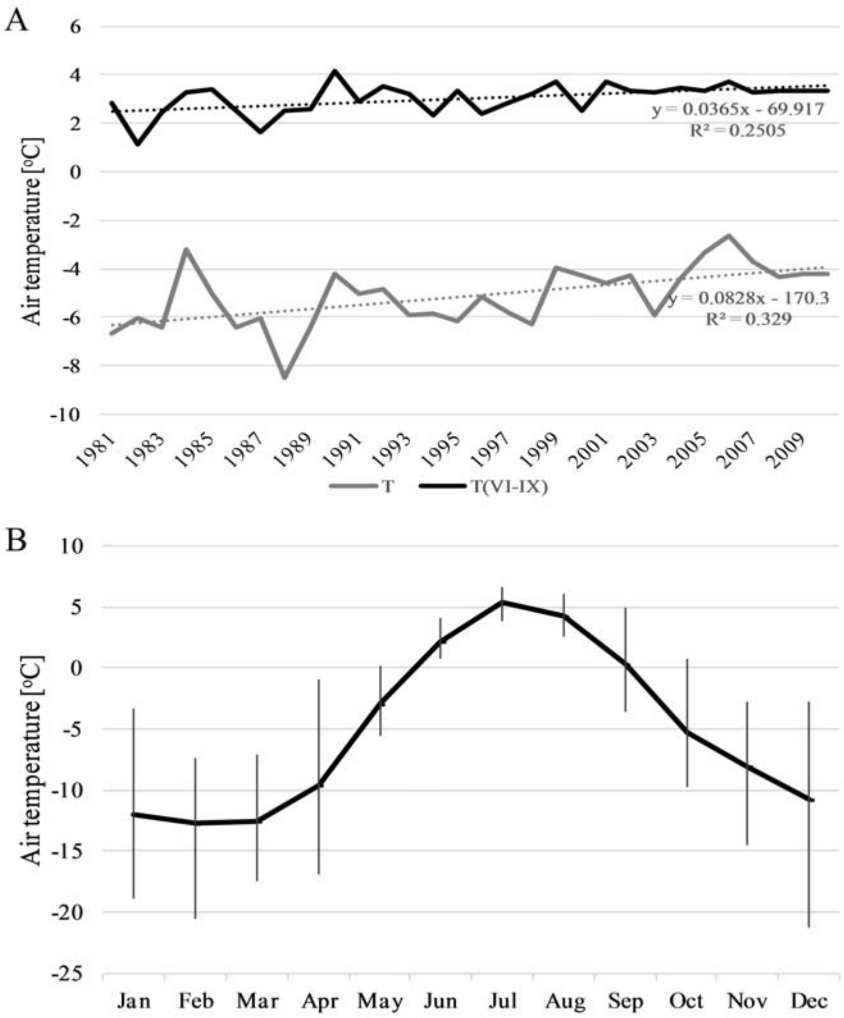

Fig. 2. **A**. Multiannual course of the average annual air temperature (T) and average summer (June–September) air temperature. **B**. Annual course of the air temperature, verticals indicate range of the average monthly air temperature changes.

July 7, 2005 (18.7°C). An multiannual increase in the average air temperature in summer period was statistically significant ($p < 0.05$) and it was 0.4°C per 10 years.

The mean annual number of extremely warm days (maximum temperature >8.3°C) in Ny-Ålesund amounted to 18 days (536 in the analyzed period). However, it ranged from 1 day in 1982 to 31 days in 2007; the standard deviation amounted to 8 days (Fig. 3A). In the analyzed period, there was an increase in the number of extremely warm days by 2.8 days per 10 years, statistically significant at $p = 0.05$. In general, days with T_{max} >8.3°C appeared in the period from June to September; however, they were also recorded in May and October (a single re-

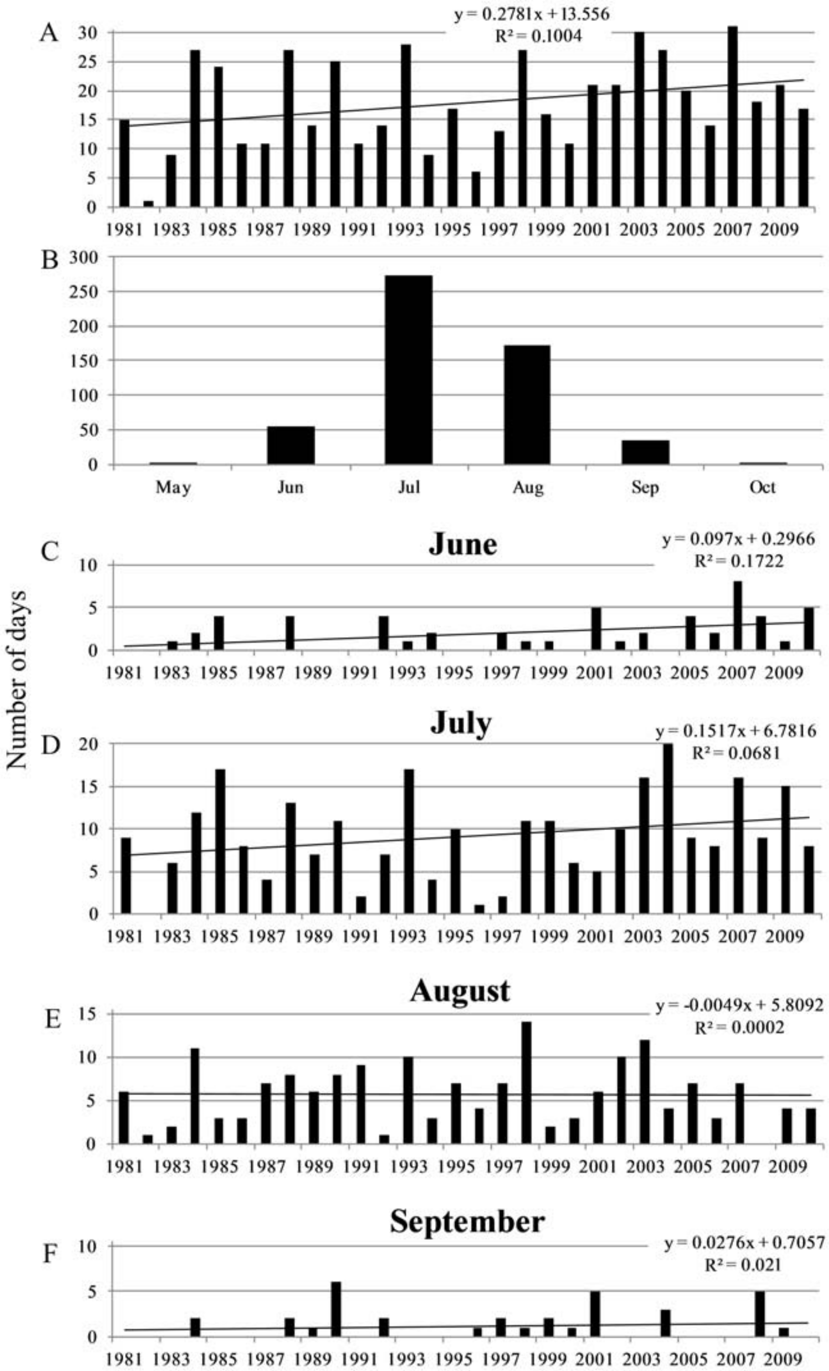

Fig. 3. **A**. Multi-annual course of the annual number of days with T_{max} >8.3°C. **B**. Annual course of the number of days with T_{max} >8.3°C. **C**–**F**. Multi-annual course of the monthly number of days with T_{max} >8.3°C.

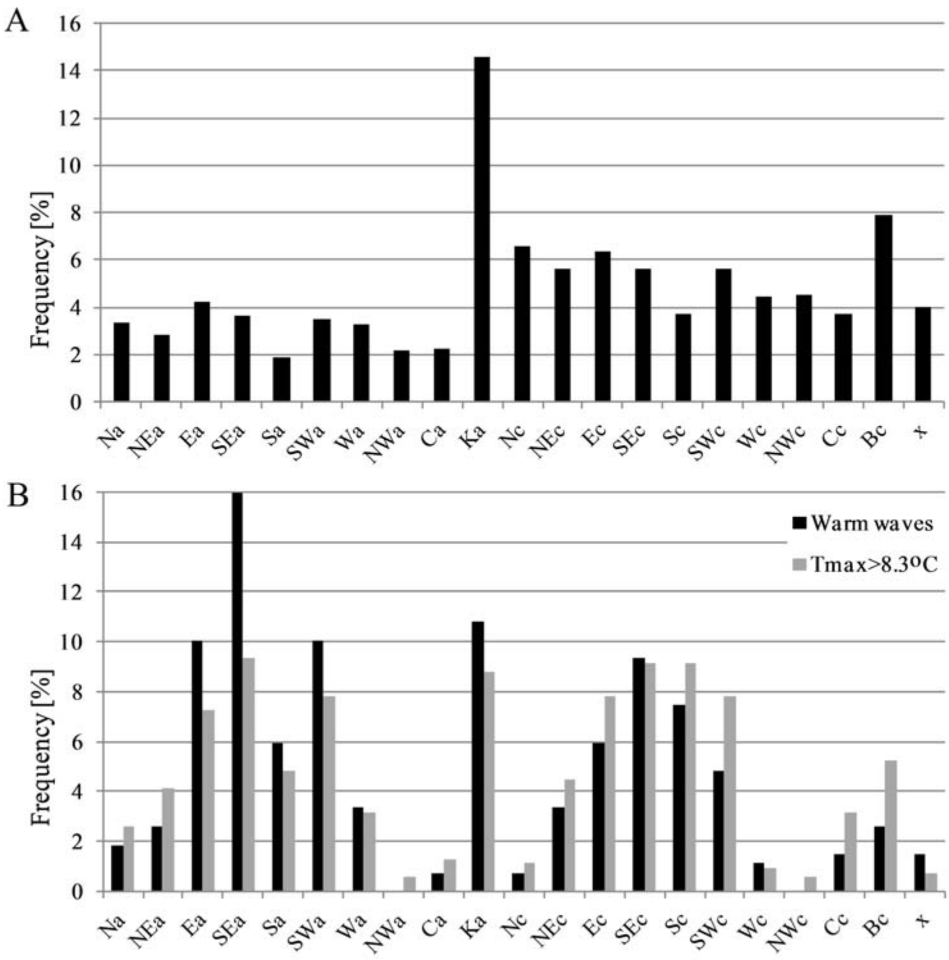

Fig. 4. Frequency of circulation types. **A**. For the summer period (June–September) between 1981 and 2010. **B**. For days with T_{max} >8.3°C and for the days composing warm waves.

cords, respectively in 2006 and 2000) (Fig. 3B). Their highest number was recorded in July and August; respectively, 274 and 172 days. The increase in the number of days of the discussed category was recorded in June, July and September, and it was statistically significant only for June (1 day per 10 years) (Fig. 3C–F). In August, a decline in the number of days with T_{max} >8.3°C was detected. It was not statistically significant.

Circulation conditions favorable for the occurrence of the extremely warm days. — According to Niedźwiedź's (2013) classification, the Ka circulation type (anticyclonic wedge or ridge of high pressure) appeared most often (14.6%) in summer and the Bc type (trough of low pressure with different directions of air flow and with frontal systems in the axis of trough separating different air masses) was the

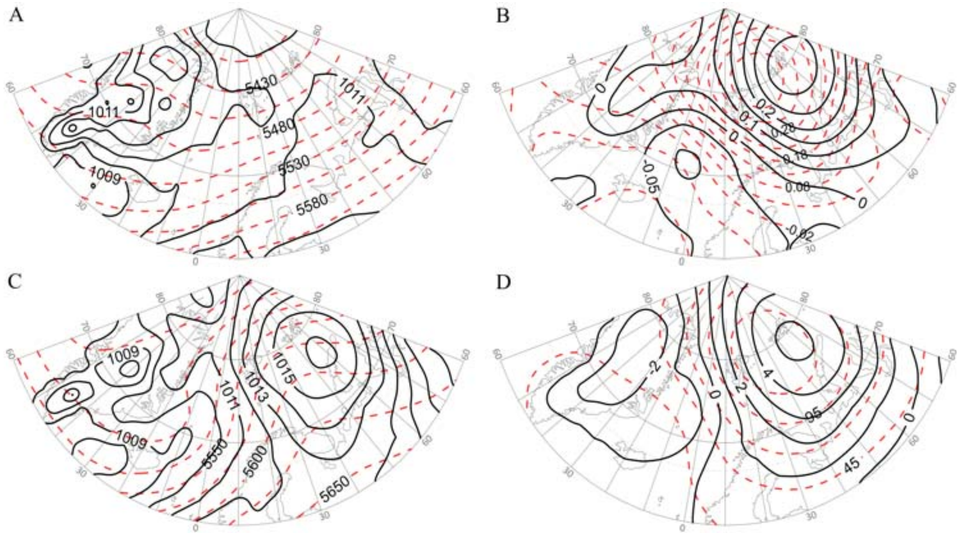

Fig. 5. **A**. Mean summer sea level pressure (SLP) and z500 hPa in the period of 1981–2010. **B**. Correlation coefficient between the T_{max} and SLP/z500 hPa values in each grid point computed for the extremely warm days. **C**–**D**. Composite map/anomaly map of SLP and z500 hPa for the days with T_{max} >8.3°C.

second most frequent one (7.9%) over the Spitsbergen region (Fig. 4A). The Sa type (the first letter means the direction, the second one stands for cyclonic or anticyclonic circulation type, here: southern anticyclonic) appeared most rarely with frequency of 1.9%. The cyclonic circulation prevailed (54.2%) over the anticyclonic (41.9%) during the analyzed period. Days with T_{max} >8.3°C appeared twice more often with the circulation from the eastern sector (NEa, Ea, SEa, NEc, Ec, SEc) than from the west (NWa, Wa, SWa, NWc, Wc, SWc) (Fig. 4B). Extremely warm days appeared most often with SEa (9.3%), SEc (9.1%), and Sc circulation types (9.1%), and the most rarely with NWa (0.6%), NWc (0.6%), and Wc types (0.9%). Days of the analyzed category were reported with similar frequency with cyclonic and anticyclonic situations (respectively 49.4% and 49.8%).

The pressure field in summer over the Euro-Atlantic sector of the Arctic was characterized by appearance of the high pressure center above north Greenland (>1012 hPa) and low pressure center south-west to Iceland (<1009 hPa) (Fig. 5A). Negative gradient of the z500 hPa from the south-east (>5600 g.p.m) to the north-west (<5405 g.p.m) was observed.

Mean SLP during the days with T_{max} >8.3°C reached the maximum value over the Barents Sea and the Novaya Zemlya (>1016 hPa) (Fig. 5C). A center of low pressure was located over the north Atlantic south-west to Iceland (<1008 hPa). Negative gradient of the z500 hPa was observed towards the north-west and the z500 hPa exceeded the height of 5650 g.p.m over Russia, and it dropped below 5500 g.p.m over north-western Greenland. A center of positive SLP anomalies;

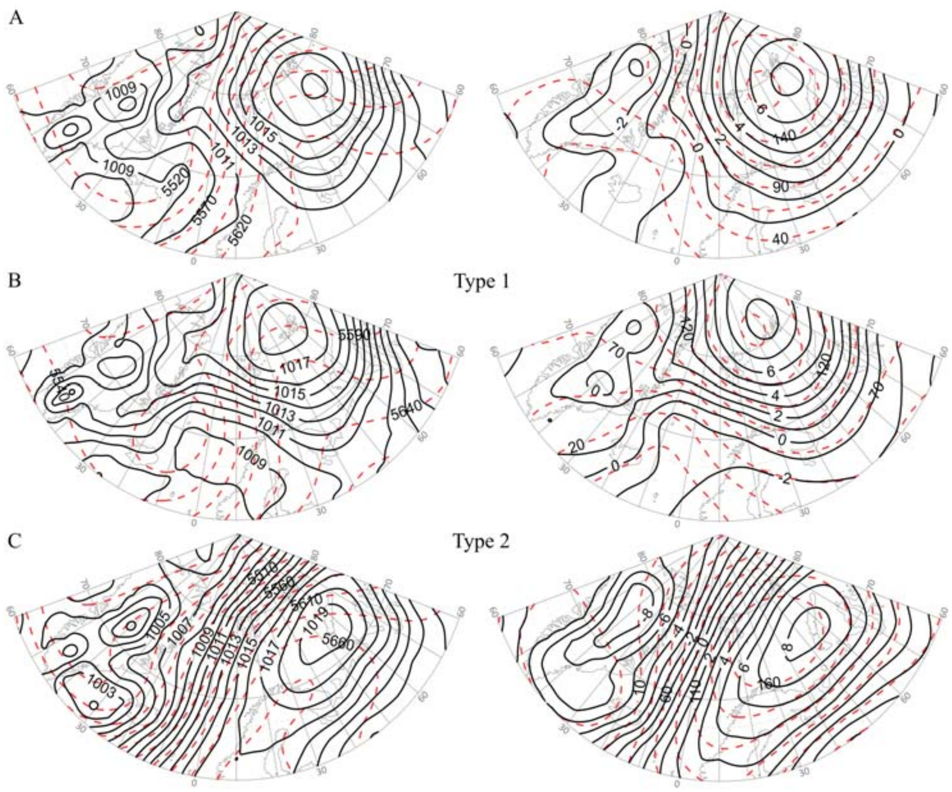

Fig. 6. Mean composite sea level pressure and z500 hPa (left column) and anomaly maps (right column). **A**. For all warm waves in Ny-Ålesund. **B**. For warm waves in type 1. **C**. For warm waves in type 2.

exceeding 5 hPa, was located over the Barents Sea. Weak negative anomalies spread over the western part of the studied area with a center over Greenland (<-2 hPa). The Spitsbergen Island was encompassed by positive anomalies of SLP (about 2 hPa). The correlation coefficient between T_{max} and SLP values in each grid point computed for the extremely warm days ranged from -0.07 over the North Atlantic to 0.32 over the Franz Josef Land (Fig. 5B), which meant that an increase in the T_{max} was simultaneous with intensifying of the anticyclone over the Barents Sea. Such pressure pattern caused an inflow of warm air masses from the southern sector.

Occurrence and synoptic conditions of warm waves. — Only about half of a number of extremely warm days composed periods of warm waves. In the period of 1981–2010, 37 warm waves with a total duration of 268 days were recorded in Ny-Ålesund. The 5-day waves were most frequent (32% of all cases). The longest warm wave lasting 18 days was recorded in 2004 (16 July to 2 August). The average length was 7 days, but in the first decade of analyzed period

(1981–1990) warm waves were shorter than in the next two decades (1991–2000 and 2001–2010) (Table 1). Most warm waves (61%) appeared in the warmest month (July) but they were recorded also in August and September.

Table 1

Occurrence of warm waves in Ny-Ålesund in 1981–2010

Period	Number	Duration	Average length
1981–1990	14	89	6
1991–2000	8	66	8
2001–2010	15	113	8
1981–2010	37	268	7

According to Niedźwiedź's (2013) classification of weather types, warm waves appeared more often with the anticyclonic circulation (61.6%), than with cyclonic one; mostly with SEa (16%) and Ka type (11%) (Fig. 4B). A similar frequency was noted during Ea and SWa types.

Mean SLP for the warm wave days reached the maximum value north-west to the Novaya Zemlya (>1018 hPa), and the lowest south to Iceland (<1008 hPa) (Fig. 6A). Positive anomalies of SLP/z500 hPa spread over the eastern part of the studied area (>7 hPa/>165 g.p.m in a center).

Using the Ward's (1963) hierarchical grouping method, the two types of synoptic situations favorable for appearance of warm waves in Ny-Ålesund were distinguished. In the first type 25 warm waves, with total duration of 176 days, were recorded. The longest warm wave belonging to the type 1 appeared in 1993 and lasted 15 days. The average daily maximum temperature of warm waves in the type 1 amounted to 10.1°C. The highest average maximum air temperature was recorded in 1999 during the warm period of 14–23 July (12°C). The pressure pattern in the type 1 showed the anticyclone spreading in the northeastern part of the studied area, encompassing the Svalbard Archipelago. Anomalies of SLP exceeded 8 hPa in the center of the anticyclone which is located northeast to Spitsbergen Island and anomalies of z500 hPa exceeded 170 g.p.m in the same area (Fig. 6B). Such pressure pattern caused an advection of warm air masses from the south-east.

Twelve warm waves were included into type 2 and they lasted altogether 92 days. In this type, warm periods lasting more than 10 days were recorded three times, including the longest warm wave in the analyzed period (18 days). An average daily maximum air temperature in days; which constitute type 2, amounted to 10.0°C. The highest average daily maximum and minimum temperature was recorded during the warm wave in 2005 (4–10 June) and it was; respectively, 11.5°C and 6. 4°C. Warm waves classified as type 2 were caused by the anticyclone spreading over the Novaya Zemlya, the Barents Sea and north Scandinavia (>1019 hPa in a center) (Fig. 6C). This is the area of positive SLP anomalies (>8 hPa in a center), which embrace also the Svalbard Archipelago (3 hPa). The low pressure area with negative SLP anomalies encompasses Greenland and northwest Atlantic. At the same time, positive anomalies of z500 hPa were observed over the majority of the Euro-Atlantic Arctic forming a center over the Barents Sea (>150 g.p.m). A large pressure gradient, between the pressure centers, indicated an intense inflow of warm air masses from the southwest.

Discussion

A significant increase in the air temperature during the recent three decades in central Spitsbergen was proved also in previous studies for both summer (0.5°C/10 years; Bednorz and Kolendowicz 2013) and winter season (1.65°C/10 years; Bednorz 2011). The strongest warming in the Atlantic Arctic was recorded in autumn (September–Novembre) and in winter (Decembre–February). The summer warming is slower but consistent (Marsz and Styszyńska 2011). On the basis of the long-term temperature data record (1898–2012) for Svalbard Airport, the most recent 30-years period was proved to be warmer than any available previous one (Nordli *et al*. 2014). According to Przybylak (2007a), a significant warming in the Arctic begun with about 20-year delay in respect to global warming, which started in the middle of the 70's of the 20th century. During the last two decades in the Svalbard region, the increase in the mean annual air temperature was 1.0–1.2°C/10 years. The highest increase occurred in winter, and it was 2.0–3.0°C/10 years (Førland *et al*. 2011).

The forecast warming in Svalbvard between 1961 and 2050 indicates an increase of temperature of 1.0°C/10 years in winter and 0.3°C/10 years in summer (Hanssen-Bauer 2002). An important sign of warming in the polar region is a reduced number of cold days by 11.4 days/10 years (Niedźwiedź *et al.* 2012) and an increasing number of warm days (about 3 days/10years), as well as more frequent occurrence of warm waves, as it was proved in this study.

Mean field of SLP in summer much differs from the mean SLP in other seasons, when the pressure gradient is much stronger (Bednorz and Kolendowicz 2013). In winter time, Arctic cyclones are deeper and shorter than in summer time. The cyclones from temperate latitudes are stronger than cyclones occurring in the region of the Arctic (Zhang *et al.* 2004). Analyzing the variability of atmospheric circulation over Spitsbergen proved the increase in the frequency of western circulation, especially in summer and autumn, and the increase in frequency of southern circulation in summer and winter. Simultaneously, increasing frequency of summer high-pressure systems at the end of the 20th century was reported (Niedźwiedź 2003). Kysely (2007) indicates the enhancing persistence of atmospheric circulation being one of the reasons for increasing frequency of temperature extremes, including occurrence of warm waves.

Longer and warmer heat waves occurring in the last decade of the analyzed period may be considered as a sign of climate warming, which has a significant impact on environment (ACIA 2005). One of the best recognized results of warming are reduction in area and thickness of Arctic ice of the continental glaciers and maritime glaciers, as well as a reduction of permafrost, which is visible in the increase in thickness of active layer. Consequently, morphological processes are activated (Humlum *et al.* 2003; Osterkamp and Jorgenson 2006; Etzelmüller *et al.* 2011). Furthermore, the present-day warming may cause advanced changes in the biosphere, *e.g.* reduction of the area of tundra by about 20–30% and introduction of bushy flora instead (Przybylak 2007a). At the same time, the increase in the air temperature in summer and more frequent appearance of warm waves may encourage the tourism development in polar areas, which are regarded as areas of high touristic values. According to the recent studies, the intensity of tourism in the polar regions particularly in Spitsbergen is growing (Dolnicki and Gawor 2012); summer warming may be favorable to this process.

Conclusions

Multiannual changes in the mean annual and mean summer temperature in Ny-Ålesund for the period of 1981–2010 amounted to 0.8°C/10 years and 0.4°C/10 years, respectively. A considerable increase in the number of warm waves was noted in the last decade (2001–2010) which may be considered as an effect of Arctic climate warming. The reasons of the warming process is not fully recognized, however the occurrence of warm periods seems to be strongly influenced by circulation patterns and the direction of air inflow.

While the extremely warm days were reported with similar frequency with cyclonic and anticyclonic situations, the warm waves were more frequent with the anticyclonic circulation types, due to their greater constancy. Extremely warm days appeared mainly with the inflow of air masses from the southern sector, caused by a high-pressure system spreading over the southern part of the studied area. Atmospheric circulation is essential for modifying the thermal conditions, particularly in the polar regions. Therefore, the growing number of extremely warm days in Ny-Ålesund can be associated with greater frequency of summer high-pressure systems at the end of the 20th century.

Concluding, the increasing frequency and length of warm waves can be caused by natural reasons related mainly to the air circulation and/or by anthropogenic reasons which are considered to be responsible for temperature increase and at the same time for increase in frequency and duration of warm periods. Determining the relative importance of each of factors seems impossible at the moment, however, the further research should be carried on complex relationships between global and local temperature trends and between local climate conditions and circulation patterns.

Acknowledgements. — The authors are thankful to the reviewers Professors Tadeusz Niedźwiedź and Øyvind Nordli for their valuable remarks and suggestions that helped to improve this paper.

References

ACIA 2005. *Acia Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge: 1042 pp.

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

BEDNORZ E. and FORTUNIAK K. 2012. Coreless winters in the European sector of the Arctic and their synoptic conditions. *Polish Polar Research* 33 (1): 19–34.

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

BENGTSSON L., SEMENOV V.A. and JOHANNESSEN O.M. 2004. The early twentieth-century warming in the Arctic – a possible mechanism. *Journal of Climate* 17: 4045–4057.

BIRKELAND K.W. and MOCK C.J. 1996. Atmospheric circulation patterns associated with heavy snowfall events, Bridger Bowl, Montana, U.S.A. *Mountain Research and Development* 16: 281–286.

DAYAN U., TUBIA A. and LEVY I. 2012. On the importance of synoptic classification methods with respect to environmental phenomena. *International Journal of Climatology* 32: 681–69.

DOLNICKI P. and GAWOR Ł. 2012. Tourist value of selected regions of Spitsbergen. *Annales Universitatis Paedagogicae Cracoviensis, Studia Geographica III*: 70–76 (in Polish).

ESTEBAN P., JONES P.D., MARTIN-VIDE J. and MASES M. 2005. Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *International Journal of Climatology* 25: 319–329.

ETZELMÜLLER B., SCHULER T.V., ISAKSEN K., CHRISTIANSEN H.H., FARBROT H. and BENESTAD R. 2011. Modeling the temperature evolution of Svalbard permafrost during the 20th and 21st century. *The Cryosphere* 5: 67–79.

FELDSTEIN S.B. 2002. The recent trend and variance increases of the annular mode. *Journal of Climate* 15: 88–94.

FRÖHLICH C. and LEAN J. 1998. The Sun's Total Irradiance: Cycles and trends in the past two decades and associated climate change uncertainties. *Geophysical Research Letters* 25: 4377–4380.

FØRLAND E.J., BENESTAD R., HANSSEN-BAUER I., HAUGEN J.E., and SKAUGEN T.E. 2011. Temperature and precipitation development at Svalbard 1900–2100. *Advances in Meteorology:* 1–14.

HANSSEN-BAUER I. and FØRLAND E.J. 1998. Long-term trends in precipitation and temperature in the Norwegian Arctic: can they be explained by changes in atmospheric circulation patterns? *Climate Research* 10: 143–153.

HANSSEN-BAUER I. 2002. Temperature and precipitation in Svalbard 1912–2050: measurements and scenarios. *Polar Record* 38 (206): 225–232.

HUMLUM O., INSTANES A. and SOLLID J.L. 2003. Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. *Polar Research* 22 (2): 191–215.

IPCC 2007. Climate Change 2007: The Physical Science Basis. *In*: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge and New York: 996 pp.

JOHANNESSEN O.M., BENGTSSON L., MILES M.W., KUZMINA S.I., SEMENOV V.A., ALEKSEEV G.V., NAGURNYI A.P., ZAKHAROV V.F., BOBYLEV L., PETTERSSON L., HASSELMANN K. and CATTLE H.P. 2004. Arctic climate change: observed and modelled temperature and sea ice variability. *Tellus* 56 A (4): 328–341.

KALKSTEIN L.S., TAN G. and SKINDLOV J.A. 1987. An evaluation of three clustering procedures for use in synoptic climatological classification. *Journal of Applied Meteorology and Climatology* 26: 717–730.

KALNAY E., KANAMISTU M., KISTLER R., COLLINS W., DEAVEN D., GANDIN L., IREDELL M., SAHA S., WHITE G., WOOLLEN J., ZHU Y., LEETMAA A., REYNOLDS R., CHELLIAH M., EBISUZAKI W., HIGGINS W., JANOWIAK J., MO K.C., ROPELEWSKI C., WANG J., JENNE R. and JOSEPH D. 1996. The NMC/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77: 437–471.

KYSELY J. 2007. Implications of enhanced persistence of atmospheric circulation for the occurrence and severity of temperature extremes. *International Journal of Climatology* 27: 689–695.

MARSZ A.A. and STYSZYŃSKA A. 2009. Oceanic control of the warming processes in the Arctic – a different point of view for the reasons of changes in the Arctic climate. *Problemy Klimatologii Polarnej* 19: 7–31.

MARSZ A.A. and STYSZYŃSKA A. 2011. Spatial distribution and the scale of the Atlantic Arctic warming in a 30-year period from 1980 to 2009 and its comparison with the "great warming of the Arctic" in the 30s of the 20th century. *Problemy Klimatologii Polarnej* 21: 91–114 (in Polish).

NIEDŹWIEDŹ T. 2003. Contemporary variability of atmospheric circulation, temperature and precipitation in Spitsbergen. *Problemy Klimatologii Polarnej* 13: 79–92 (in Polish).

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).

NIEDŹWIEDŹ T. 2013. *Calendar of Circulation Types for Spitsbergen*. Database of University of Silesia in Katowice, Department of Climatology, Sosnowiec. Available online at http://klimat.wnoz.us.edu.pl/.

NORDLI P.O., LIE O., NESJE A. and DAHL S.O. 2003. Spring-summer temperature reconstruction in western Norway 1734–2003: a data synthesis approach. *International Journal of Climatology* 23: 1821–1841.

NORDLI Ø. 2010. The Svalbard Airport temperature series. *Bulletin of Geography, Physical Geography Series* 3: 5–25.

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

OSTERKAMP T.E. and JORGENSON J.C. 2006. Warming of permafrost in the Arctic Widlife Refuge, Alaska. *Permafrost and Periglacial Processes* 17 (1): 65–69.

OVERLAND J.E. and SERREZE M.C. 2012. Advances in Arctic atmospheric research. *In*: P. Lemke, H.W. Jacobi (eds) *Arctic climate change*. Springer, New York: 11–27.

OVERLAND J.E., WOOD K.R. and WANG M. 2011. Warm Arctic-cold continents: climate impacts of the newly open Arctic Sea. *Polar Research* 30 (1): 1–14.

PALMER T.N. 1999. A nonlinear dynamical perspective on climate prediction. *Journal of Climate* 12: 575–591.

POLYAKOV I.V., BEKRYAEV R.V., ALEKSEEV G.V., BHATT U.S., COLONY R.L., JOHNSON M.A., MASKSHTAS A.P. and WALSH D. 2003. Variability and trends of air temperature and pressure in the maritime Arctic 1875–2000. *Journal of Climate* 16 (12): 2067–2077.

POLYAKOV I.V., ALEKSEEV G.V., TIMOKHOV L.A., BHATT U.S., COLONY R.L., SIMMONS H.L., WALSH D., WALSH J.E. and ZAKHAROV V.F. 2004. Variability of the intermediate Atlantic water of the Arctic Ocean over the last 100 years. *Journal of Climate* 17 (23): 4485–4497.

PRZYBYLAK R. 2000. Temporal and spatial variation of surface air temperature over the period of instrumental observations in the Arctic. *International Journal of Climatology* 20 (6): 587–614.

PRZYBYLAK R. 2003. *The Climate of the Arctic.* Kluwer Academic, Dordrecht: 270 pp.

PRZYBYLAK R. 2007a. Contemporary climate change in the Arctic. *In*: A. Styszyńska and A.A. Marsz (eds) *Zmiany klimatyczne w Arktyce i Antarktyce w ostatnim pięćdziesięcioleciu XX i ich implikacje środowiskowe*. Akademia Morska, Gdynia: 93–110 (in Polish).

PRZYBYLAK R. 2007b. Recent air-temperature changes in the Arctic. *Annals of Glaciology* 46: 316–324.

PRZYBYLAK R. and WYSZYŃSKI P. 2009. Atmospheric pressure in the Arctic in the period of the First International Polar Year 1882/83. *Problemy Klimatologii Polarnej* 19: 81–98 (in Polish).

SHABBAR A. 2006. The impact of El Niño-Southern Oscillation on the Canadian climate. *Advances in Geosciences* 6: 149–153.

SOON W.W.H. 2005. Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years. *Geophysical Research Letters* 32: L16712.

SUWAŁA K. 2013. The influence of atmospheric circulation on the occurrence of hail in the North German Lowlands. *Theoretical and Applied Climatology* 112 (3–4): 363–373.

TURNER J., OVERLAND J.E. and WALSH J.E. 2006. An Arctic and Antarctic perspective on recent climate change. *International Journal of Climatology* 27 (3): 277–293.

WARD J.H. 1963. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association* 58: 236–244.

YARNAL B. 1993. *Synoptic climatology in environmental analysis*. Belhaven, London: 195 pp.

YARNAL B., COMRIE A.C., FRAKES B. and BROWN D.P. 2001. Developments and prospects in synoptic climatology. *International Journal of Climatology* 21: 1923–1950.

ZHANG X., WALSH J.E., ZHANG J., BHATT U.S. and IKEDA M. 2004. Climatology and inter-annual variability of Arctic cyclone activity: 1948–2002. *Journal of Climate* 17: 2300–2317.

Received 18 February 2014
Accepted 7 July 2014