since 1961

Baltica

BALTICA Volume 27 Number 1 June 2014 : 45–54
doi: 10.5200/baltica.2014.27.05

Heat and cold waves on the southern coast of the Baltic Sea

Arkadiusz Marek Tomczyk, Ewa Bednorz

Tomczyk, A. M., Bednorz, E., 2014. Heat and cold waves on the southern coast of the Baltic Sea. *Baltica, 27 (1), 45–54.* Vilnius. EISSN 1648-858X.
Manuscript submitted 24 February 2014 / Accepted 30 April 2014 / Published online 9 June 2014.

Abstract The objective of this study was to describe the characteristics of heat and cold waves on the southern coast of the Baltic Sea, and determine synoptic situations causing the occurrence of the waves. The analysis concerned six stations located on the southern coast of the Baltic Sea. In the study, an extreme warm day was defined as a day with the maximum temperature over the 95th annual percentile, while an extreme cold day as a day with the maximum temperature below the 5th annual percentile. A sequence of at least five extreme warm and cold days was considered, i. e. heat or cold waves, respectively. In the analysed multiannual period, on the southern coast of the Baltic Sea, there were from 11 (Świnoujście) to 28 (Arkona) heat waves recorded, while the number of cold waves was from 34 (Świnoujście) to 43 (Kołobrzeg). The occurrence of extreme warm and cold days creating heat and cold days was connected with positive anomalies of sea level pressure and isobaric surface 500 hPa, which showed the presence of the high pressure systems.

Keywords *• warm and cold waves • circulation • air masses • Baltic Sea coast*

✉ *Arkadiusz Marek Tomczyk (atomczyk@amu.edu.pl), Ewa Bednorz, Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Dzięgielowa 27, 61–680 Poznań, Poland*

INTRODUCTION

The last decade of the 20th century and the first decade of the 21st century were characterised by frequent occurrence of not only extremely hot months but also whole summer seasons (Twardosz, Kossowska-Cezak 2013). As the authors of the Fourth Report of IPCC (2007) emphasize, among the twelve warmest years in the whole series of instrumental record of global surface temperature, eleven years were from the period of 1996–2006. Simultaneously, according to the mentioned report, it is very likely that the frequency of extreme heat, heat waves and heavy precipitation events will increase (IPCC Report 2007). The previous research on air temperature changes in different regions of Europe showed an upward trend (Michalska 2011; Kürbis *et al*. 2009; Klein Tank, Können 2003; Wibig, Głowicki 2002; Fortuniak *et al*. 2001; Brázdil *et al*. 1996); however, the mechanisms of these changes have not been entirely explained.

The literature offers an extensive documentation concerning thermal conditions in the Baltic Sea region. Tylkowski (2013) analysed spatial and temporal variability of air temperature and precipitation on the southern coast of the Baltic Sea. Bielec-Bąkowska and Piotrowicz (2013) determined trends in temperature changes in Poland between 1951 and 2006. Ustrnul *et al*. (2010) evaluated the influence of atmospheric circulation on the occurrence of extreme air temperatures in Poland. Kriaučiūnienė *et al*. (2012) analysed variability of air temperature and precipitation in Lithuania, Latvia and Estonia. Kažys *et al*. (2011) analysed the occurrence of extreme warm days and nights in Lithuania between 1961 and 2010. Avotniece *et al*. (2010) investigated trends in changes in the occurrence of extreme weather events in Latvia. This study aims at describing the characteristics of heat and cold waves on the southern coast of the Baltic Sea, and determining synoptic situations causing the occurrence of the waves.

DATA AND METHODS

The analysis concerned six stations located on the southern coast of the Baltic Sea (Fig. 1). Everyday values of

Fig. 1 Location of meteorological stations.

Table 1 The value of the 5th and the 95th percentile of the maximum air temperature between 1971 and 2010.

Percentyl [T_{max}]	Hel	Łeba	Kołobrzeg	Świnoujście	Arkona	Rostock
5	–0.8	–0.7	–0.3	–0.4	0.1	0.2
95	23.8	24.0	24.2	24.8	22.0	24.6

the maximum, minimum and mean daily air temperature for the period of 1970–2010 were used. The source material for the Polish stations (Hel, Łeba, Kołobrzeg and Świnoujście) was gained from the records of Institute of Meteorology and Water Management, while for the German stations (Arkona, Rostock) it was gained from Deutscher Wetterdienst collections.

In the study, an extreme warm day was defined as a day with the maximum temperature over the 95th annual percentile, which ranged from 22.0 (Arkona) to 24.8°C (Świnoujście) (Table 1). A sequence of at least five extreme warm days was considered a heat wave. On the other hand, a day with the maximum temperature over the 5th annual percentile was defined as an extreme cold day, and a sequence of at least five days of the aforementioned category was perceived as a cold wave. A weather event, which occurrence is so rare in a particular area and in a particular season that it falls within a range of the 10th or the 90th percentile of the observed probability density function; or even more rare, is defined as an extreme event (IPCC Report 2007). A heat wave is the most often defined as: 1) a several days period with a maximum temperature exceeding a fixed threshold (*e.g*. 30.0°C; Kossowska-Cezak 2010; Kyselý 2002); 2) a period with an apparent temperature (AT) over 95th percentile, starting with a temperature increase by at least 2.0°C in comparison with the temperature on the previous day (Kuchcik, Degórski 2009); 3) a period where an average daily air temperature and an extreme temperature of the particular days differ from a normal temperature of a particular month at least by one standard deviation (Morawska-Horawska 1991).

On the basis of the source material, the basic climatic characteristics were calculated; that is, the average air temperature for the particular years and the number of extremely warm/cold days. Subsequently, at least five day sequences of extremely warm/cold days were selected, determining heat/cold waves. The next step was examining the variability of their occurrence in the multiannual period and calculating linear trends.

Relating the occurrence of mean daily temperature extremes to synoptic conditions, *the environment to circulation* approach was applied. In this method, the circulation classification is carried along specific environment–based criteria set for a particular environmental phenomenon, i.e. mean daily temperature extremes in this case (Yarnal 1993; Yarnal *et al*. 2001; Dayan *et al*. 2012). In order to determine pressure patterns favouring the occurrence of extreme warm and cold days, the values of sea level pressure (SLP) and the height of isobaric surface (z) 500 hPa (z500 hPa) were used. Daily SLP and z500 hPa data were derived from the collections of National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) analysis (Kalnay *et al*. 1996), available within the sources of Climate Research Unit. In the study, values of SLP and z500 hPa in 120 geographical grid points 5×5° for the area of 35–70°N latitude, 35W–40°E longitude were used. On the basis of the above–mentioned data, the maps of SLP and z500 hPa were drawn up for the summer season (July–August) and the winter season (December–March), together with composite maps for extreme warm and cold days creating heat and cold waves. Still, the analysis only considered those days on which the maximum temperature met the criterion of extreme warm or cold day at least in two stations.

Furthermore, on the basis of the daily patterns of SLP, different circulation types were distinguished separately for heat and cold waves, using the Ward's (1963) minimum variance method. This is a hierarchical clustering technique, most frequently used for climatic classification (Kalkstein *et al*. 1987) for identifying the atmospheric circulation patterns associated with occurrence of specific weather phenomena (*e. g*. Birkeland, Mock 1996; Bednorz 2008; Bednorz 2011; Suwała 2013). In the case of this study the clustered objects were the days consisting to the heat/cold waves and the clustering was based on the daily standardized SLP data. The standardisation was made to desezonalize the observations keeping the intensity of pressure field (Esteban *et al*. 2005). The maps of sea level pressure and height of isobaric surface 500 hPa, as well as, of anomalies were drawn up for the distinguished types of circulation. Air masses were verified on the basis of weather maps accessible in Daily Meteorological Biulletin of IMGW, available for the period of 1981–2010.

RESULTS

The mean annual air temperature on the southern coast of the Baltic Sea between 1971 and 2010 was 8.4°C and it oscillated between 7.9°C in Łeba and 9.1°C in Rostock. In the analysed period, the coldest was 1987, and the mean annual air temperature oscillated between 6.3°C (Łeba) and 7.4°C (Rostock) (Fig. 2). On the other hand, the warmest was 2007 with the mean annual temperature from 9.4°C (Łeba) to 10.4°C (Rostock). The course of mean annual air temperature in the analysed forty–year period was distinguished by its considerable year–to–year variability. However, the variability of annual temperature in the analysed period is similar, which is confirmed by the value of standard deviation that; apart from the station in Rostock (0.9°C) was 0.8°C. On average, the warmest month of a year was July (17.4°C), and the coldest one was January (0.2°C). The highest air temperatures in the analysed area exceeded 30.0°C, and the maximum was 38.0°C (Kołobrzeg; 10 August 1992). While the lowest air temperatures fell below –17.0°C, and the recorded minimum was –23.2°C (Łeba; 7 January 2003). The research study showed

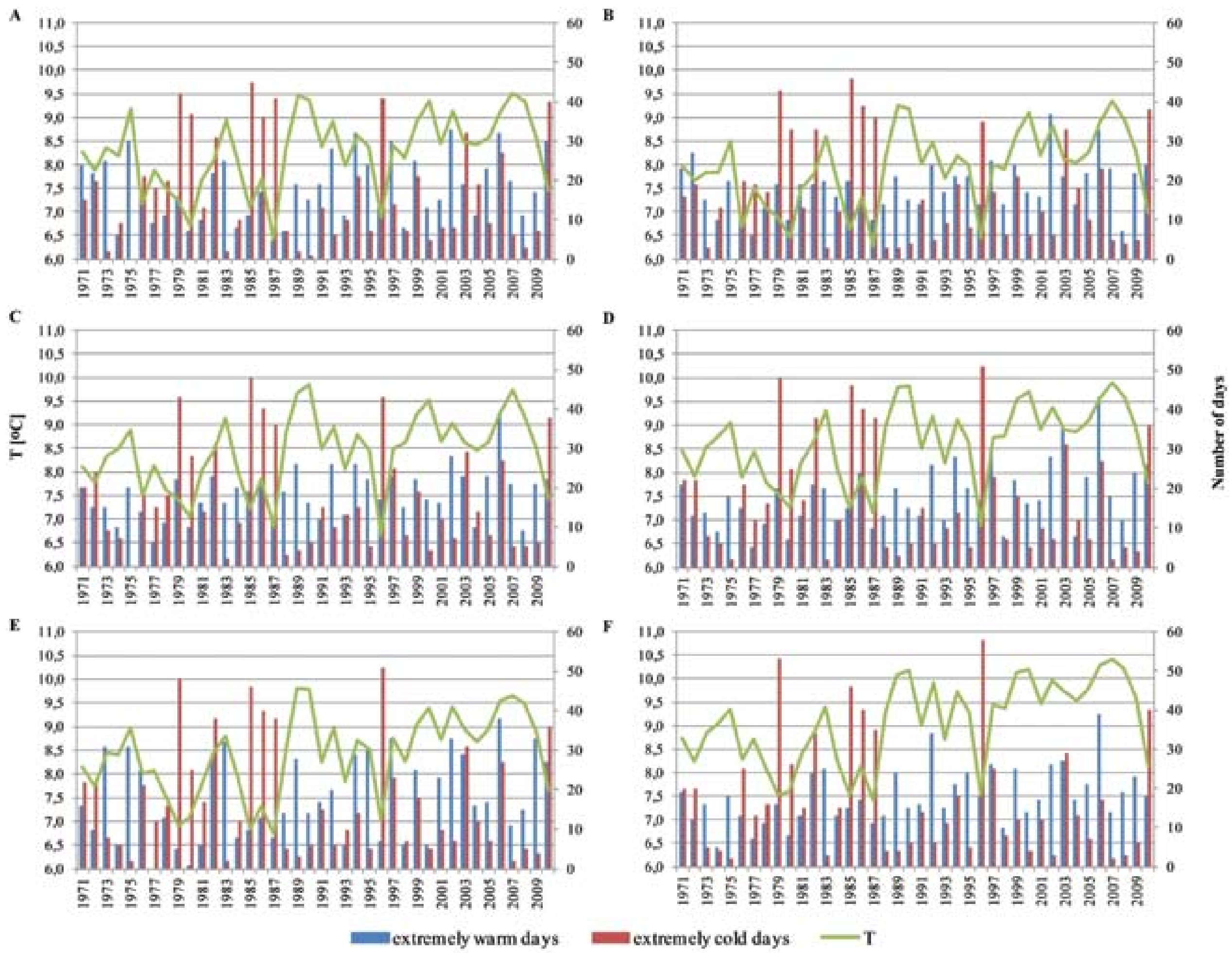

Fig. 2 Multiannual course of annual number of extreme warm and cold days and the mean annual air temperature: A. Hel; B. Łeba; C. Kołobrzeg; D. Świnoujście; E. Arkona; F. Rostock.

a statistically significant increase in the mean annual air temperature within the analysed area, and the value of changes was 0.3°C per 10 years. When analysing changes in the particular stations, it was found that the smallest increase took place in Kołobrzeg (0.25°C/10 years), and the most considerable one was recorded in Rostock (0.42°C/10 years). Trends in changes of the mean annual air temperature; investigated in relation to ten–year periods, showed its considerable decrease in the 1970s; subsequently, its increase between 1981–2000, and a slight decrease in the first decade of the 21st century.

On average, extreme warm days (T_{max} >95 percentile) occurred on the southern coast of the Baltic Sea on 18 days a year. The smallest number of days of the aforementioned category was recorded in 1977 and it oscillated between 0 (Arkona) and 9 (Hel) (Fig. 2). On the other hand, the most considerable number of those days was recorded in 2006, and it oscillated between 32 (Hel) and 43 (Świnoujście). The course of annual number of extreme warm days in the analysed multiannual period was distinguished by great year–to–year variability. The variability of number of days of the above mentioned category within the analysed area was diverse and that was found on the basis of the values of standard deviation; namely, they were from 6 to 11 days. The extreme warm days occurred from April to October, with the maximum in July and August. The obtained results confirmed the statistically significant increase in the number of extreme warm days on the southern coast of the Baltic Sea, and it was 2.3 days per 10 years. In the particular stations, these changes were from 1.4 days/10 years in Hel to 3.0 days/10 years in Świnoujście. In Hel and Arkona these changes were not statistically significant.

From among extreme warm days, there were sequences of at least five days of the aforementioned category distinguished that form heat waves. Between 1971 and 2010, there were from 11 heat waves in Świnoujście to 28 heat waves in Arkona recorded on the southern coast of the Baltic Sea (Table 2). The shortest duration of heat waves was recorded in Łeba (87 days in total), and the longest one was recorded in Arkona and Hel (in total, there were; respectively, 263 and 200 days). The least considerable number of heat waves was recorded between 1971 and 1980. In the mentioned decade, only one heat wave (five days) was recorded in Kołobrzeg; on the other hand, there were as much as six heat waves (36 days) in Hel. The highest number of heat waves occurred in the first decade of this century, and it oscillated between 3 in Kołobrzeg and 10 in Arkona. In the analysed period, heat waves lasting over 10 days were recorded in every station, and the longest heat wave in Arkona lasted for 24 days (19 July–12 August). Almost equally long heat wave was recorded in 1997 in Arkona (23 days; 6–28 August) and in 1994 in Hel (22 days; 21 July–11 August). The longest heat waves occurred in 1997 and in 1994. 53% of all heat waves constituted 5–day and 6–day waves. Heat waves were recorded from the turn of May and June to the turn of August and September; still, their most frequent occurrence was in July (46%) and August (40%).

On average, the extreme cold days (T_{max} <5 percentile) on the southern coast of the Baltic Sea occurred on 17 days in the season. The smallest number of days of the above–mentioned category was recorded in season 1974/1975, and it oscillated between 0 (Hel, Łeba, Kołobrzeg) and 2 (Świnoujście, Arkona, Rostock) (Fig. 3). On the other hand, the highest number of such days occurred in winter of 1995/1996, and it oscillated between 35 (Łeba) to 58 (Rostock). The course of seasonal number of extreme cold days in the analysed period was characterized by great year–to–year variability. The variability of the number of days of the aforementioned category in the analysed period was quite similar, and this was showed by the values of standard deviation that were from 13 to 15 days. The extreme cold days occurred from November to March, with the maximum in January. The re-

Table 2 Characteristics of cold and heat waves (N – number; D – duration).

Years	Hel		Łeba		Kołobrzeg		Świnoujście		Arkona		Rostock	
	N	D	N	D	N	D	N	D	N	D	N	D
Cold waves												
1970/71–1979/80	12	89	12	83	11	96	11	91	11	81	13	115
1980/81–1989/90	9	113	10	109	13	124	10	137	9	119	11	122
1990/91–1999/00	9	66	9	56	10	63	5	61	10	65	8	73
2000/01–2009/10	9	76	7	62	9	74	8	63	6	46	7	51
1970/71–2009/10	**39**	**344**	**38**	**310**	**43**	**357**	**34**	**352**	**36**	**311**	**39**	**361**
Heat waves												
1971–1980	6	36	2	10	1	5	2	12	5	35	2	14
1981–1990	5	30	3	15	4	24	2	12	6	47	4	22
1991–2000	8	79	2	24	5	40	3	43	7	90	7	44
2001–2010	7	55	7	38	3	26	4	38	10	91	7	50
1971–2010	**26**	**200**	**14**	**87**	**13**	**95**	**11**	**105**	**28**	**263**	**20**	**130**

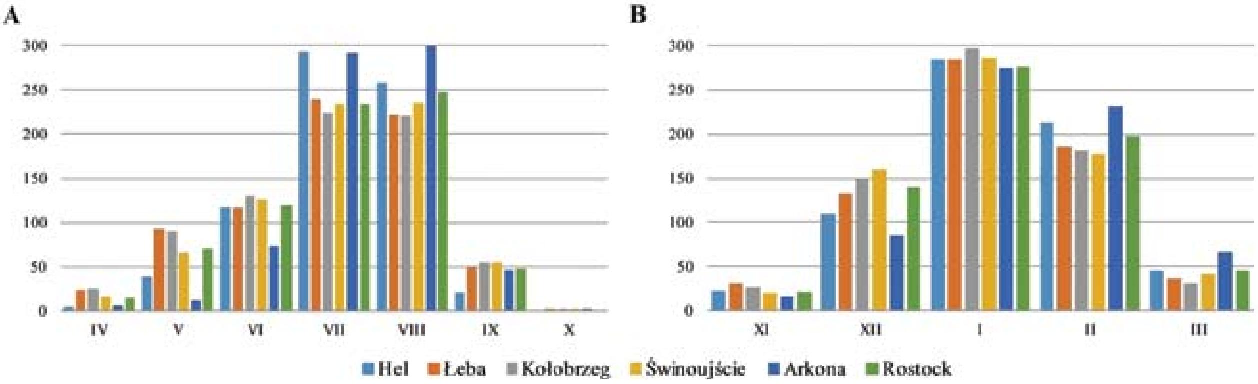

Fig. 3 Monthly course of the number of days: A – extreme warm; B – extreme cold.

search showed a statistically insignificant decrease in extreme cold days within the analysed area, and that was 1.2 days per 10 years. In the particular stations, the pace of decrease in the number of days of the aforementioned category was from 0.7 days/10 years (Hel) to 1.6 days/10 years (Rostock).

From among extreme cold days, there were sequences of at least five days of the aforementioned category distinguished that form cold waves. In the multiannual period and within the area subject to investigation, there were 34 cold waves distinguished in Świnoujście and 43 cold waves in Kołobrzeg (Table 2). The shortest duration of cold waves was recorded in Łeba and Arkona (in total; respectively, 310 and 311 days), the longest one was found in Rostock (361 days in total). The smallest number of heat waves was recorded in 2000/01–2009/10, while the highest number of them in 1970/71–1979/80. In the analysed period, there were cold waves lasting over 20 days recorded in every station; and the longest wave, lasting 28 days, was recorded in 1986 in Arkona (4 February–3 March) and in Świnoujście (5 February–4 March). Almost equally long cold waves were recorded in 1985 in Hel (22 days), Łeba (21 days) and Kołobrzeg (20 days). The most frequent were 5–day and 6–day waves which constituted; respectively, 24% and 16% of all waves. The cold waves occurred from November to March, with the maximum in January (52%).

Synoptic conditions of heat and cold waves

The mean sea level pressure in Euro-Atlantic Sector between 1971 and 2010, in the summer time (June–August) reached the highest value in the area of the Azores Islands (>1023 hPa) (Fig. 4A). The SLP decreased in the northerly direction, and the centre of low pressure was located on the southern west of Iceland (<1010 hPa). The horizontal gradient of SLP was much less considerable over the continent than over the Atlantic Ocean. In the summer season, the averaged isobaric surface 500 hPa was inclined towards the northern–west. The maximum height with 500 hPa was recorded over the Azores Islands (>5850 m), and the minimum was found over the northern Atlantic (<5525 m). The aforementioned pressure system caused the west circulation; typical for Europe, both in the middle and bottom troposphere.

The occurrence of heat waves on the south coast of the Baltic Sea was connected with a ridge of high pressure lying across Europe, in the vicinity of which a local high–pressure area was formed with its centre over the Baltic Sea (>1018 hPa) (Fig. 4B). Contour lines of isobaric surface 500 hPa located over the continent bent northward creating a clear elevation over Central Europe. During the occurrence of heat waves, the pressure over the analysed area was higher than the average summer season pressure, which has been confirmed on the sketches of SLP anomaly maps, with a value of 3–4 hPa within the southern coast area. Simultaneously, pressure over the Atlantic was lower than the average, negative anomalies in the center amounted to <–3 hPa. The isobaric surface 500 hPa settled over the continent higher than usually during the summer season and the positive anomalies over the Baltic exceeded 100 m. The pressure pattern described above caused an inflow of warm and dry continental air masses from the north-east in the low troposphere. Tropical air masses advection from the south-west occurred in higher troposphere layers.

Days with a maximum temperature exceeding the 95th annual percentile, lasting a minimum of five days, in at least two stations were grouped by the mean sea level pressure value and on this basis, two types of circulation conducive to the occurrence of heat waves on the southern coast of the Baltic Sea have been determined. 106 type one extreme warm days creating heat waves were recorded. Their occurrence was connected to the anticyclone settling over the Central and Northern Europe with the center over the northern Baltic (>1017 hPa) (Fig. 4C). Research area was created within the range of positive SLP anomalies, with the value of 1–3 hPa. Central Europe was under the influence of warm air masses, and the isobaric surface 500 hPa over the coast settled 80 m higher than the average during the summer season.

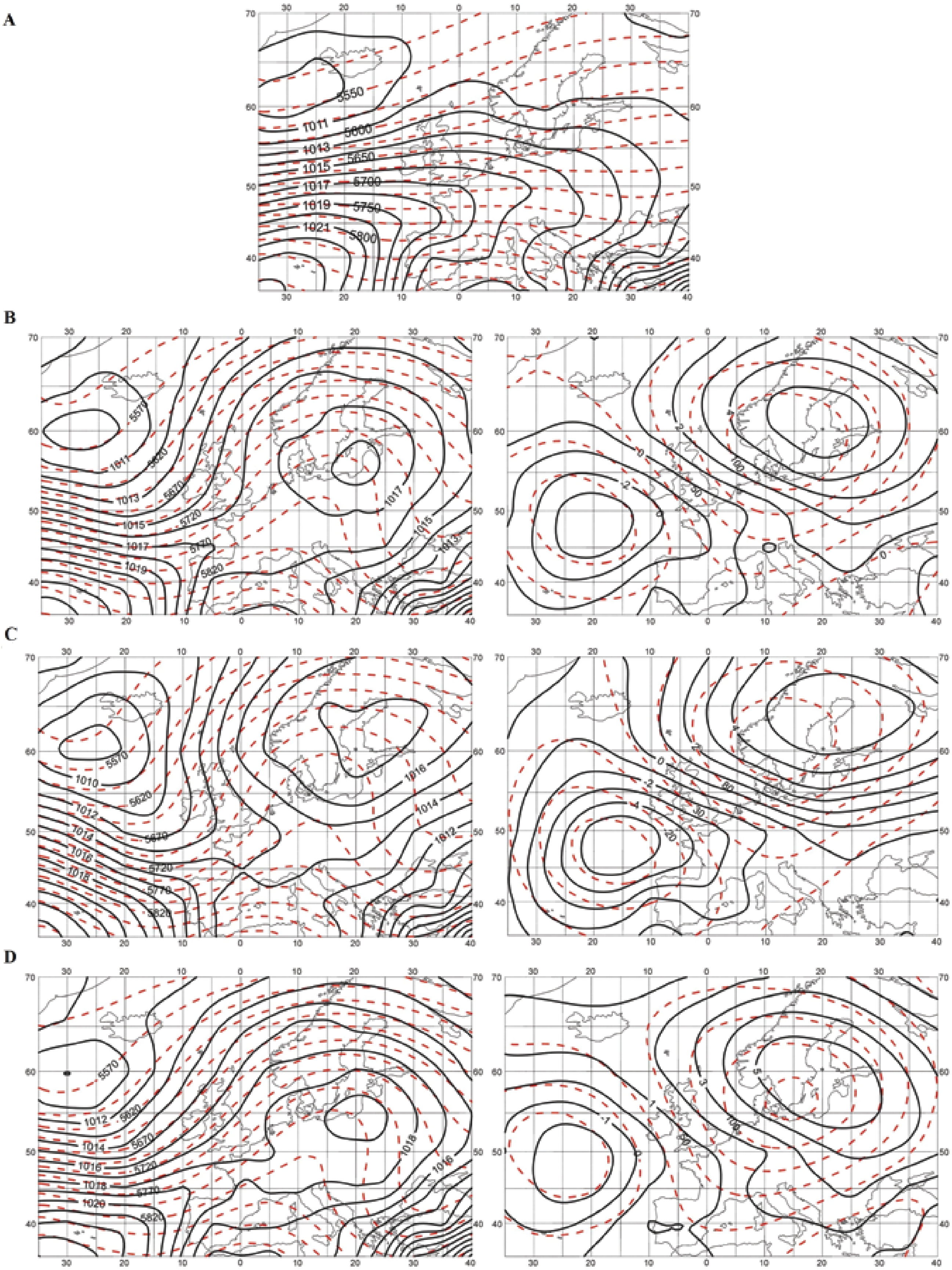

Fig. 4 Mean sea level pressure, altitude of isobaric surface 500 hPa and anomaly maps (right column): A – summer season; B – all days creating heat waves; C – extreme warm type 1 days; D – extreme warm type 2 days.

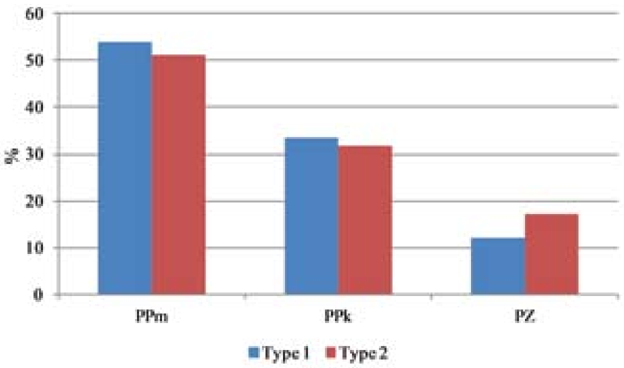

Fig. 5 Share of air masses (PPm – marine polar air, PPk – continental polar air, PZ – tropical air) during days creating heat waves type 1 and 2.

This system caused an advection of mainly marine polar (during 53.8% of type 1 days) and continental polar air masses (33.4%) (Fig. 5). Type 2 included 159 days and their occurrence was connected with anomalies of SLP as well as isobaric surface 500 hPa over the southern Baltic more significant than in type 1. The southern Baltic was within the range of a local anticyclone (>1019 hPa), formed in a high pressure wedge (Fig. 4D). The contour lines and the anomalies (>125 m in the center) of the isobaric surface 500 hPa indicate the presence of warm air masses over the continent. During days classified as type 2, marine polar (51.0%) and continental polar air masses (31.7%) occurred most frequently. Advection of tropical air masses occurred more frequently than within type 1 (17.3%) (Fig. 5). The distinguished circulation types differ in the location of pressure systems, and this results in the inflow of air masses from other source areas. This is reflected in more considerable share of polar continental air masses in type 1; while in type 2 there is higher share of tropical air masses.

During the analyzed period in the winter (December–March), within the Euro-Atlantic sector, the average SLP reached its highest value in the Azores Islands region (>1020 hPa) and decreased in the northern direction (Fig. 6A). Low pressure center was located over the north Atlantic, southeast from Iceland (<998 hPa). A high level of gradient pressure occurred between the indicated barometric centers located over the ocean, which decreased gradually over the continent. The averaged z500 hPa during the winter season sloped northward. It settled highest over the Azores (>5685 m), and lowest over the northern Atlantic (<5200 m).

The occurrence of cold waves within the analysed multiannual period was connected with the settling of a high pressure wedge over Central and Northern Europe (Fig. 6B). Sea level pressure exceeded 1020 hPa over the researched area and was higher than the winter average by approximately 6 hPa. Such pressure pattern caused an inflow of cold, continental air masses from the south-east, simultaneously blocking the western circulation. The contour lines of z500 hPa indicate an advection of cold air masses from the north–west over Central Europe. The Central, Eastern and Southern Europe remained within the reach of negative z500 hPa anomalies.

Extreme cold days creating cold waves recorded at least in two stations were grouped in two distinct types with respect to sea level pressure. Type 1 included 228 days, which occurred in relation to a high pressure point with a center located northeast from Poland (>1030 hPa) (Fig. 6C). The southern coast of the Baltic remained within the reach of positive SLP anomalies (>12 hPa) and z500 hPa (>40 m). The described system caused an inflow of mainly continental polar air masses (50.0% days) (Fig. 7). 205 days were classified as type 2 extreme cold and their occurrence was connected with anomalies of SLP and z500 hPa less significant than within type 1 (Fig. 6D). A low pressure bay settled over the majority of Europe. The Baltic Sea region maintained within the anticyclone (>1017 hPa in the center). The described system caused an advection of mainly arctic air (51.7%) (Fig. 7).

DISCUSSION

Changes in air temperature mentioned in this article are similar to the results of previous research. Tylkowski (2013) showed that the increase in the mean annual temperature in the coastal area oscillated between 0.28°C/10 years on Gdańsk Shoreline and 0.32°C/10 years on Szczecin Shoreline. Michalska (2011) determined the increase in the average annual air temperature on the majority of Poland's territory as 0.20°C/10 years.

An increase of extreme warm days and a simultaneous decrease of cold days have also been confirmed in other studies regarding extreme climatic phenomena in Latvia (Avotniece *et al.* 2010). Kažys *et al.* (2011), obtained similar results analyzing the occurrence of extreme warm and cold nights in Lithuania. The increase in the frequency of days with an exceptionally high temperature and the decrease of days with an exceptionally low temperature in Poland was confirmed in the research conducted by Bielec-Bąkowska, Piotrowicz (2013), Kossowska-Cezak, Skrzypczuk (2011) and Ustrnul *et al.* (2011).

The obtained results concerning the atmospheric circulation during the occurrence of extreme warm and cold days are coincident with the previous research conducted in Central Europe. Kažys *et al.* (2011) proved that a 1/3 of extreme warm weather cases in Lithuania were connected to the advection of air masses from the south-east. A similar inflow direction of air masses was identified for Latvia (Avotniece *et al.* 2010) and Estonia (Jaagus 2006). Ustrnul *et al.* (2010) indicated, that the occurrence of

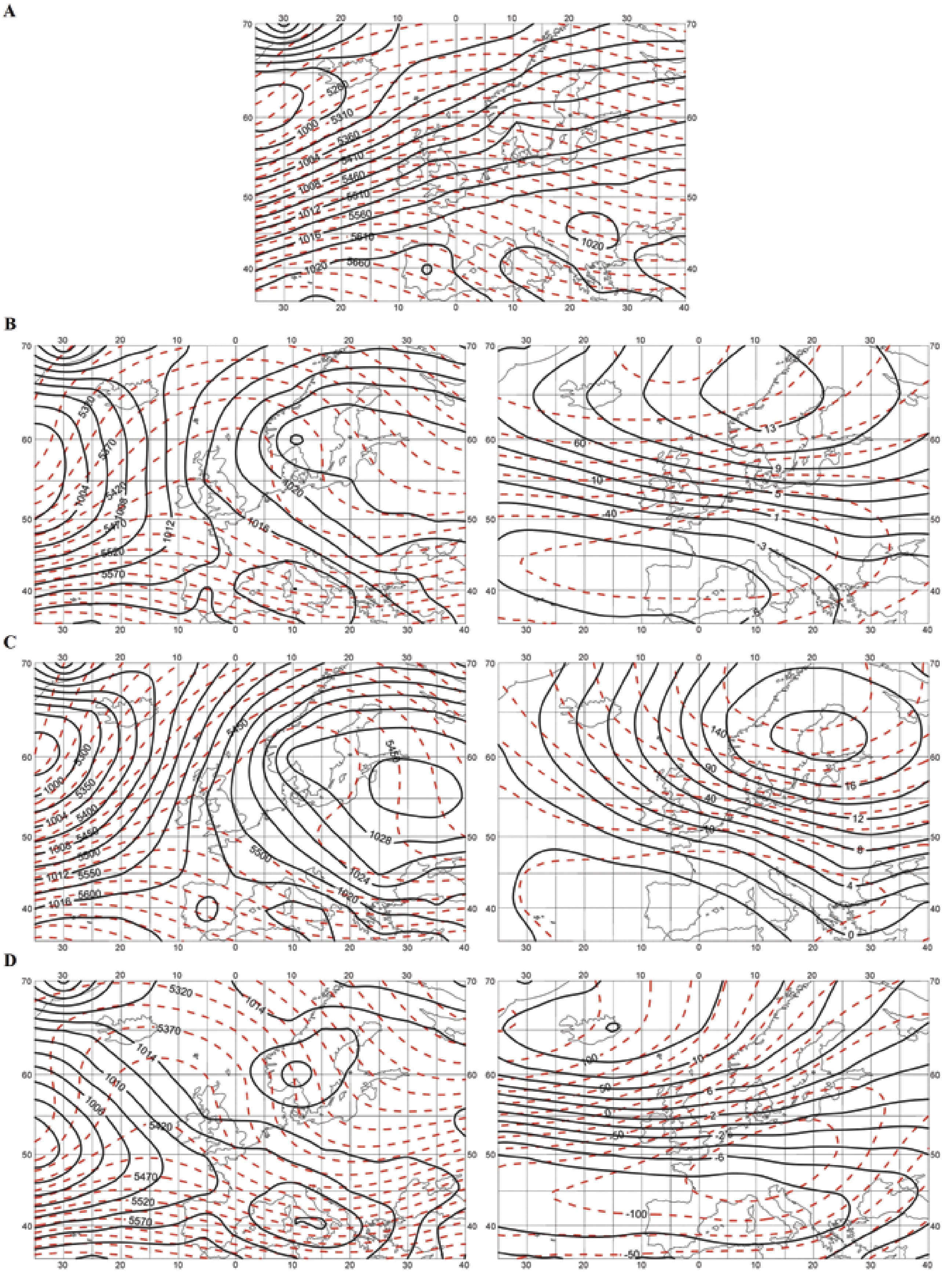

Fig. 6 Mean sea level pressure, altitude of isobaric surface 500 hPa and anomaly maps (right column): A – winter season; B – all days creating cold waves; C – extreme cold type 1 days; D – extreme cold type 2 days.

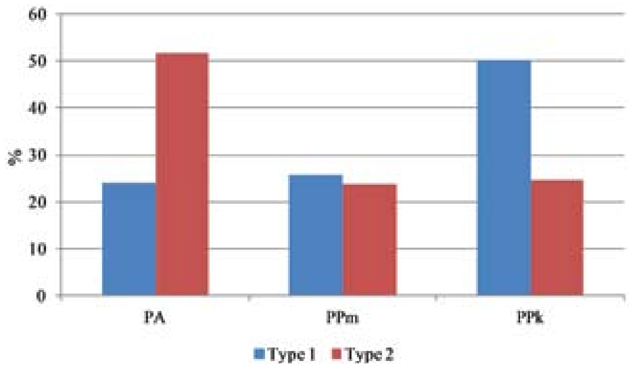

Fig. 7 Share of air masses (PA – arctic air, PPm – marine polar air, PPk – continental air) during days creating cold waves type 1 and 2.

highest temperatures is related to the anticyclone situation with no clear advection, and a blurred pressure field usually occurring over Poland. A high pressure situation is favorable to the occurrence of the lowest temperatures, causing an inflow of air masses from the eastern sector. Wibig (2007) has proved that the occurrence of summer heat waves in central Poland is connected to positive anomalies in isobaric surface 700 hPa and to the inflow of air masses from the south–east, usually hot and dry in the summer. Warm weather on Hel is created by the advection of air masses from the south or west, while cold weather by the inflow of air masses from the north or east (Baranowski, Kirschenstein 2009).

CONCLUSIONS

The results concerning variability of air temperature and the occurrence of extreme warm and cold days stated in this study confirms other findings concerning changes of the air temperature in Europe. Within the researched area, the increase of average annual air temperature ranged between 0.25°C/10 years in Kołobrzeg and 0.42°C/10 years in Rostock.

Extreme warm days on the southern coast of the Baltic Sea occurred between April and October with the maximum occurrence in July. Studies confirmed a statistically significant increase in the number of extreme warm days in the analyzed stations (with the exception of Hel and Arkona). Extreme cold days occurred from November to March with the maximum in January. The analysed station recorded a decrease in the number of extremely cold days, not statistically significant however.

During the analyzed multiannual period, the southern coast of the Baltic recorded from 11 (Świnoujście) to 28 (Arkona) heat waves and from 34 (Świnoujście) to 43 (Kołobrzeg) cold waves. In the majority of stations, the lowest number of heat waves was recorded during 1971–1980, and the highest number during 2001–2010. Cold waves occurred most frequently during 1970/71–1979/80 and least frequently during 2000/01–2009/10. The occurrence of extreme warm and cold days creating heat and cold waves was connected to the positive SLP and z500 hPa anomalies, which indicates the existence of high pressure systems. The anomalies were followed by an advection of dry, continental air masses from south-east and north-east.

Acknowledgements

The authors are thankful to Dr. Jūratė Kriaučiūnienė (Kaunas) and Professor Maris Klavinš (Rīga) for valuable remarks and suggestions that allowed improve the quality of this paper. This work was partly supported by the Polish National Science Centre under grant number 2011/01/B/ST10/01923.

References

Avotniece, Z., Rodinov, V., Lizuma, L., Briede, A., Kļaviņš, M., 2010. Trends in the frequency of extreme climate events in Latvia. *Baltica 23 (2)*, 135–148.

Baranowski, D., Kirschenstein, M., 2009. Thermic weather types in Hel and atmospheric circulation types. *Baltic Coastal Zone 13*, 99–107.

Bednorz, E., 2008. Synoptic conditions of snow occurrence in Budapest. *Meteorologische Zeitschrift 17 (1)*, 39–45. http://dx.doi.org/10.1127/0941-2948/2008/0262

Bednorz, E., 2011. Occurrence of winter air temperature extremes in Central Spitsbergen. *Theoretical and Applied Climatology 106*, 547–556. http://dx.doi.org/10.1007/s00704-011-0423-y

Bielec–Bąkowska, Z., Piotrowicz, K., 2013. Temperatury ekstremalne w Polsce w latach 1951–2006 [Extreme temperatures in Poland 1951–2006]. *Prace Geograficzne 132*, 59–98. [In Polish].

Birkeland, K. W., 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. http://dx.doi.org/10.2307/3673951

Brázdil, M., Budíková, M., Auer, I., Böhm, R., Cegnar, T., Faško, P., Lapin, M., Gajić-Čapka, M., Zaninović, K., Koleva, E., Niedźwiedź, T., Ustrnul, Z., Szalai, S., Weber, R. O., 1996. Trends in maximum and minimum daily temperatures in Central and South–eastern Europe. *International Journal of Climatology 16*, 765–782. http://dx.doi.org/10.1002/(SICI)1097-0088-(199607)16:7<765::AID-JOC46>3.0.CO;2-O

Dayan, U., Tubia, A., Levy, I., 2012. On the importance of synoptic classification methods with respect to environmental phenomena. *International Journal of Climatology 32*, 681–694. http://dx.doi.org/10.1002/joc.2297

Esteban, P., Jones, P. D., Martin-Vide, J., Mases, M., 2005. Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *International Journal of Climatology 25*, 319–329. http://dx.doi.org/10.1002/joc.1103

Fortuniak, K., Kożuchowski, K., Żmudzka, E., 2001. Trendy i okresowości zmian temperatury powietrza w Polsce w drugiej połowie XX wieku [Trends and periodicity of changes in air temperature in Poland in the second half of 20th century]. *Przegląd Geofizyczny XLVI, z. 4*, 283–303. [In Polish].

IPCC, 2007. Climate change. The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel in Climate Change, Cambridge University Press, Cambridge.

Jaagus, J., 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large–scale atmospheric circulation. *Theoretical and Applied Climatology 83*, 77–88. http://dx.doi.org/10.1007/s00704-005-0161-0

Kalkstein, L. S., Tan, G., 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. http://dx.doi.org/10.1175/1520-0450-(1987)026<0717:AEOTCP>2.0.CO;2

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., Joseph, D., 1996, The NMC/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society 77*, 437–471. http://dx.doi.org/10.1175/1520-0477-(1996)077<0437:TNYRP>2.0.CO;2

Kažys, J., Stankūnavičius, G., Rimkus, E., Bukantis, A., Valiukas, D., 2011. Long–range alternation of extreme high day and night temperatures in Lithuania. *Baltica 24 (2)*, 71–82.

Klein Tank, A., Können, G. P., 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. *Journal of Climate 16*, 3665–3680. http://dx.doi.org/10.1175/1520-0442-(2003)016<3665:TIIODT>2.0.CO;2

Kossowska-Cezak, U., 2010. Fale upałów i okresy upalne-metody ich wyróżniania i wyniki zastosowania [Heat waves and heat periods–distinguishing methods and results of application]. *Prace Geograficzne 123*, 143–149. [In Polish].

Kossowska-Cezak, U., Skrzypczuk, J., 2011. Pogoda upalna w Warszawie (1947–2010) [Hot weather in Warsaw (1947–2010)]. *Prace i Studia Geograficzne 47*, 139–146. [In Polish].

Kriaučiūnienė, J., MeilutytėBarauskienė, D., Reihan A., Koltsova, T., Lizuma, L., Šarauskienė, D., 2012. Variability of regional series of temperature, precipitation and river discharge in the Baltic States. *Boreal Environment Research 2 (17)*, 150–162.

Kuchcik, M., Degórski, M., 2009. Heat-and cold-related mortality in the north-east of Poland as an example of the socio-economic effects of extreme hydrometeorological events in the Polish Lowland. *Geographia Polonica 82*, 69–78.

Kürbis, K., Mudelsee, M., Tetzlaff, G., Brázdil, R., 2009. Trends in extremes of temperature, dew point, and precipitation from long instrumental series from Central Europe. *Theoretical and Applied Climatology 98*, 187–195. http://dx.doi.org/10.1007/s00704-008-0094-5

Kyselý, J. 2002., Temporal fluctuations in heat waves at Prague – Klementinum, the Czech Republic, from 1901–1997, and their relationships to atmospheric circulation. *International Journal of Climatology 23*, 33–50. http://dx.doi.org/10.1002/joc.720

Michalska, B., 2011. Tendencje zmian temperatury powietrza w Polsce [Recent trends of air temperature in Poland]. *Prace i Studia Geograficzne 47*, 67–75.

Morawska–Horawska, M., 1991. Fale ciepła i chłodu w Krakowie w stuleciu 1881–1980 [Waves of warmth and coldness in Cracow in century 1881–1980]. *Wiadomości Instytutu Meteorologii i Gospodarki Wodnej XIV (1–4)*, 127–136. [In Polish].

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.

Tylkowski, J., 2013. Temporal and spatial variability of air temperature and precipitation at the Polish coastal zone of the southern Baltic Sea. *Baltica 26 (1)*, 83–94.

Twardosz, R., Kossowska–Cezak, U., 2013. Exceptionally hot summers in central and eastern Europe (1951–2010). *Theoretical and Applied Climatology 112*, 617–628. http://dx.doi.org/10.1007/s00704-012-0757-0

Ustrnul, Z., Czekierda, D., Wypych, A., 2010. Extreme values of air temperature in Poland according to different atmospheric circulation classifications. *Physics and Chemistry of the Earth 35*, 429–436. http://dx.doi.org/10.1016/j.pce.2009.12.012

Ustrnul, Z., Wypych, A., Kosowski, M., 2011. Ekstrema termiczne i opadowe w Polsce w świetle różnych metod wyróżniania wartości ekstremalnych [Thermal and precipitation extremes in Poland in the light of various methods used to distinguish extreme values]. *Wiadomości Meteorologii, Hydrologii, Gospodarki Wodnej V (1–2)*, 55–68. [In Polish].

Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association 58*, 236–244. http://dx.doi.org/10.1080/01621459.1963.10500845

Wibig, J., Głowicki, B., 2002. Trends of minimum and maximum temperature in Poland. *Climate Research 20*, 123–133. http://dx.doi.org/10.3354/cr020123

Wibig, J., 2007. Fale ciepła i chłodu w środkowej Polsce na przykładzie Łodzi [Waves of warmth and coldness in Central Poland on the example of Łódź]. *Acta Universitatis Lodziensis, Folia Geographica Physica 8*, 27–61. [In Polish].

Yarnal, B., 1993. Synoptic Climatology in Environmental Analysis. Belhaven Press, London.

Yarnal, B., Comrie A. C., Frakes B., Brown D. P. 2001. Developments and prospects in synoptic climatology. International Journal of Climatology 21, 1923–1950. http://dx.doi.org/10.1002/joc.675