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

Arkadiusz Marek Tomczyk, Ewa Bednorz

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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

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.


DATA AND METHODS

The analysis concerned six stations located on the southern coast of the Baltic Sea (Fig. 1). Everyday values of
Table 1 The value of the 5th and the 95th percentile of the maximum air temperature between 1971 and 2010.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Hel</th>
<th>Leba</th>
<th>Kolobrzeg</th>
<th>Świnoujście</th>
<th>Arkona</th>
<th>Rostock</th>
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<tbody>
<tr>
<td>5</td>
<td>0.8</td>
<td>0.7</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
<td>0.2</td>
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<tr>
<td>95</td>
<td>23.8</td>
<td>24.0</td>
<td>24.2</td>
<td>24.8</td>
<td>22.0</td>
<td>24.6</td>
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</table>

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

the maximum, minimum and mean daily air temperature for the period of 1970–2010 were used. The source material for the Polish stations (Hel, Leba, Kolobrzeg 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).
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 deseasonalize 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 Bulletin 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 Leba 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 (Leba) and 7.4°C (Rostock) (Fig. 2). On the other hand, the warmest was 2007 with the mean annual temperature from 9.4°C (Leba) 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 (Leba; 7 January 2003). The research study showed

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![Fig. 2](image-url) Multiannual course of annual number of extreme warm and cold days and the mean annual air temperature: A. Hel; B. Leba; 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\text{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.

On average, extreme cold days (T\text{max} <5 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 cold 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 cold days occurred from November to March, with the maximum in January.

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

<table>
<thead>
<tr>
<th>Years</th>
<th>Hel</th>
<th>Leba</th>
<th>Kołobrzeg</th>
<th>Świnoujście</th>
<th>Arkona</th>
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<td>1980/81–1989/90</td>
<td>9</td>
<td>113</td>
<td>10</td>
<td>109</td>
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<td>1990/91–1999/00</td>
<td>9</td>
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<td>9</td>
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<td>2000/01–2009/10</td>
<td>9</td>
<td>76</td>
<td>7</td>
<td>62</td>
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<td>1971–1980</td>
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<td>1981–1990</td>
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<td>1991–2000</td>
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<td>79</td>
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<td>2001–2010</td>
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<td>1971–2010</td>
<td>26</td>
<td>200</td>
<td>14</td>
<td>87</td>
<td>13</td>
<td>95</td>
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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 Leba 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), Leba (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 centre 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.
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 northwest 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.
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.

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References


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 Kolobrzeg 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 Sea recorded from 11 (Świnoujście) to 28 (Arkona) heat waves and from 34 (Świnoujście) to 43 (Kolobrzeg) 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.


