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ORIGINAL PAPER

Strong heat and cold waves in Poland in relation with the large-scale atmospheric circulation

Arkadiusz M. Tomczyk[1] · Ewa Bednorz[1] · Marek Półrolniczak[1] · Leszek Kolendowicz[1]

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Abstract

Occurrence of heat and cold waves in Poland in the years 1966–2015 (1966/1967–2015/2016) was described, and their circulation conditions were determined in this study. A heat wave is defined as a period of at least 3 days with Tmax > 30.0 °C and a cold wave as a period of at least 3 days with Tmax <− 10.0 °C. Heat waves occurred most often in central and southern Poland and cold waves in north-eastern Poland. The occurrence of both heat and cold waves is related to high pressure systems. Anticyclonic blocking patterns both in winter and summer inhibit the zonal flow of air masses and intensify the meridional flow. Positive sea level pressure anomalies occurred over the study area, in the case of heat waves up to 3 hPa and in the case of cold waves up to 11 hPa. Perpendicular profiles showing geopotential height and air temperature anomalies in the troposphere were identified for the selected cases of extreme temperature episodes. Centres of geopotential height positive/negative anomalies were detected at the level of 300–250 hPa geopotential height, right over the area of the positive/negative surface temperature extremes.

1 Introduction

The currently observed global warming is particularly manifested in an increase in air temperature and increase in the frequency of extreme weather phenomena (IPCC 2013). According to NOAA (2018), in the period 1880–2016, 9 out of 10 warmest years are those after 2000, and the warmest year was 2016. Numerous studies on changes in air temperature in Europe evidently suggest the occurrence of warming, particularly in the last approximately dozen years (Irannezhad et al. 2015; Tošić et al. 2016). A similar direction of changes was also confirmed by numerous studies in central Europe (Kundzewicz and Huang 2010; Avotniece et al. 2012; Jaagus et al. 2014; Lhotka and Kyselý 2015a).

The changes of extreme values of air temperature in Poland correspond with the changes in thermal conditions throughout entire central Europe (Bielec-Bąkowska and Piotrowicz 2013). In Poland, the strongest warming is observed in spring and summer (Michalska 2011; Wójcik and Miętus 2014; Owczarek and Filipiak 2016). Further increase in air temperature is also predicted in the next several decades. According to Piniewski et al. (2017), depending on the adopted scenario of climate changes in the years 2071–2100, an increase in maximum air temperature in summer can vary from 1.5 °C (RCP 4.5) to 2.9 °C (RCP 8.5) and in the case of minimum temperature from 1.8 °C (RCP 4.5) to 3.4 °C (RCP 8.5).

The effect of progressing warming is increasingly frequent occurrence of persistent hot weather. Strong heat waves in Europe and Poland in recent years include those from 2003, 2006, 2010 and 2015. Numerous studies indicate not only more frequent but also longer duration of heat waves in the twenty-first century (Meehl and Tebaldi 2004; Zacharias et al. 2015; Muthers et al. 2017). Due to the above, extreme heat waves can be expected in Poland in the future, similar to those from 2003 south-western Europe and 2010 in Russia, described by Barriopedro et al. (2011) as “mega heat waves”. The observed warming is also manifested in a decrease in the frequency of occurrence of cold days and cold waves (Matuszko and Piotrowicz 2012; Lhotka and Kyselý 2015b; Migała et al. 2016).

In the climatological literature, one can find a number of studies regarding the occurrence of thermal waves in Poland, the vast majority of which concerns heat waves. In these

✉ Arkadiusz M. Tomczyk
atomczyk@amu.edu.pl

[1] Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University in Poznań, B. Krygowskiego 10, 61-680 Poznan, Poland

studies, the authors focused primarily on the analysis of the frequency of heat waves and the determination of general atmospheric conditions during their occurrence (Kuchcik 2006; Wibig et al. 2009a; Tomczyk 2014; Wibig 2018). In several studies, a detailed analysis of thermal and circulation conditions was made during selected waves, often called the "mega heat waves" (Sulikowska et al. 2016; Krzyżewska and Dyer 2018). Much less studies were devoted to the occurrence of cold waves and their conditions (Wibig et al. 2009b; Tomczyk 2016). Bearing in mind the literature review presented above, it is justified to characterise the conditions of strong heat and cold waves in Poland.

The objective of the study was the description of the occurrence of heat and cold waves in Poland in the years 1966–2015 (1966/1967–2015/2016) and determination of the circulation conditions of their occurrence. Moreover, detailed analyses of baric conditions were performed for the longest heat and cold waves. Vertical structure of anomalies for geopotential heights and air temperature anomalies was also described for the selected cases of heat and cold extremes. Research leading to recognising anomalies of geopotential height, particularly the positions and tracks of their centres, can facilitate better understanding of the occurrence of temperature extremes and in consequence extend their predictability (Qian et al. 2015, 2016; Chen et al. 2017).

2 Data and methods

The research was conducted with the application of two independent data sets. Daily values of the maximum (Tmax) and minimum (Tmin) air temperature in the period 1966–2016 from 16 meteorological stations in Poland (Fig. 1) were obtained from the archive datasets of the Institute of Meteorology and Water Management—National Research Institute. Daily values of sea level pressure; geopotential heights of 1000 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa and 70 hPa; and air temperatures at the mentioned heights were obtained from the database of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996).

Heat waves are a subject of many modern studies. No universal methods of their designation still exist, however, and the literature provides many definitions based on both relative and absolute thresholds. Considerably, less papers concern cold waves that also have no single or uniform definition. Considering the above, the definition of both heat wave and cold wave was decided to be based on absolute thermal thresholds. Based on such assumptions, a heat wave was defined as a sequence of at least 3 days with Tmax > 30.0 °C and a cold wave as a sequence of at least 3 days with Tmax <− 10.0 °C. The above definitions were already adopted in earlier studies (Wibig et al. 2009a; Porębska and Zdune 2013; Bartoszek and Krzyżewska 2017).

First, based on source materials, hot days and very cold days were designated, and their sequences of at least 3 days were identified. Then, the basic characteristics of occurrence of heat and cold waves were calculated, i.e. number of waves and their duration in particular years and decades, term of their occurrence, as well as mean Tmax and Tmin for particular heat and cold waves.

In the next step, for the purpose of determining baric conditions favouring the occurrence of heat and cold waves, maps of mean distribution and anomalies of sea level pressure (SLP), geopotential height of 500 hPa (z500 hPa) and air temperature at a level of 850 hPa (T850) on the days constituting heat and cold waves were prepared. Anomalies were designated as differences between mean value of SLP, z500 hPa, and T850 for heat and cold waves, and mean value of the above elements in summer (June–August) and winter (December–February) in the analysed multi-annual period. To retain spatial consistency and eliminate single cases of waves with a local range, all analyses covered only days that occurred in at least 20% of the analysed stations. Similar maps were prepared for selected heat waves (24.07–6.08.1994 and

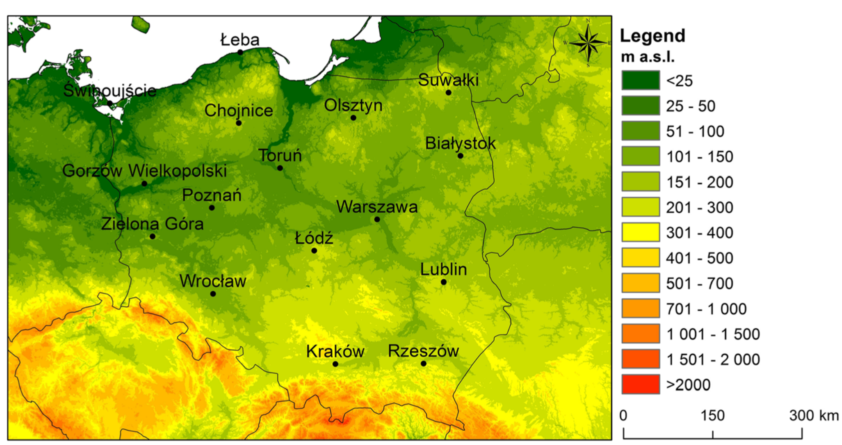


Fig. 1 Locations of the meteorological stations

3–15.08.2015) and cold waves (8–18.01.1987 and 26.12.1996–2.01.1997). The synoptic characteristics for heat and cold waves were supplemented with vertical cross sections through the troposphere with anomalies of air temperature and geopotential height anomalies for selected days of heat and cold waves. It was the hottest and coldest in the analysed waves. Anomalies for the cross sections were calculated as differences in values from a particular day and mean values for a given date from the multi-annual period. The similar method was applied earlier in the case studies concerning the occurrence of heat waves in south-western Europe (Tomczyk et al. 2017).

3 Results

3.1 Characteristics of occurrence of heat waves

In the years 1966–2015 in the territory of Poland, the number of heat waves and their duration were considerably variable. The highest number of heat waves occurred in Poznań, Toruń, and Wrocław (42 heat waves in each of the cities). Their total duration was respectively 180, 166 and 177 days (Table 1). A similar number of heat waves were also determined in Rzeszów (41 waves). The lowest number occurred on the coast of the Baltic Sea. In Łeba, only one heat wave was recorded (4 days), and in Świnoujście, four heat waves (in total 14 days). Mean duration of heat waves varied from 3.5 days in Świnoujście to 4.5 days in Łódź.

On all stations (except for Łeba, where one 4-day heat wave was recorded), the shortest heat waves, i.e. those lasting 3 days, occurred the most frequently (Fig. 2a). Only in Łódź and Olsztyn, 3-day heat waves constituted less than 50% of all waves. The highest contribution of the shortest waves was determined in Świnoujście (75%). Their contribution of more than 60% was also observed in Zielona Góra (69.7%), Rzeszów (65.9%) and Gorzów Wielkopolski (62.2%). In each Polish station, apart from the two coastal ones, waves lasting more than 1 week were recorded. The highest number of 1-week waves was recorded in Poznań and Rzeszów (6 cases each). The duration of the longest heat waves on particular stations (excluding Łeba) varied from 5 days in Świnoujście to 16 days in Rzeszów and Wrocław (Table 1). Both in Rzeszów and in Wrocław, the longest wave occurred in 1994, respectively from 24 July to 8 August 1994 and from 22 July to 6 August 1994. On particular stations, the longest heat waves occurred at the turn of July and August 1994 and in August 2015 (mainly in the south of the country), as well as in July 2006 (mainly in the west of the country).

On the majority of stations (14 out of 16), the lowest number of heat waves was recorded in the years 1976–1985 (Fig. 2b). In this period, there were no heat waves observed in Białystok, Hel, Łeba, Lublin, Olsztyn, Suwałki and Świnoujście, whereas the most waves were observed in Poznań and Wrocław (six waves). Moreover,

Table 1 Characteristics of heat waves in Poland (1966–2015)

Station	Heat waves			The longest heat wave (days) with the occurrence dates	
	Total number	Total length (days)	Mean length (days)		
Białystok	17	74	4.4	9	25 July–2 August 1994
Chojnice	13	51	3.9	10	24 July–2 August 1994
Gorzów Wielkopolski	37	157	4.2	11	23 July–2 August 1994, 18–28 July 2006
Kraków	33	139	4.2	12	4–15 August 2015
Lublin	21	93	4.4	11	3–13 August 2015
Łeba	1	4	4.0	4	10–13 July 2010
Łódź	29	131	4.5	15	23 July–6 August 1994
Olsztyn	20	81	4.1	8	26 July–2 August 1994
Poznań	42	180	4.3	11	19–28 July 2006
Rzeszów	41	178	4.3	16	24 July–8 August 1994
Suwałki	14	57	4.1	7	27 July–2 August 1994
Świnoujście	4	14	3.5	5	9–13 July 2010
Toruń	42	166	4.0	11	24 July–3 August 1994
Warszawa	35	150	4.3	11	3–13 August 2015
Wrocław	42	177	4.2	16	22 July–6 August 1994
Zielona Góra	32	129	4.0	12	22 July–2 August 1994

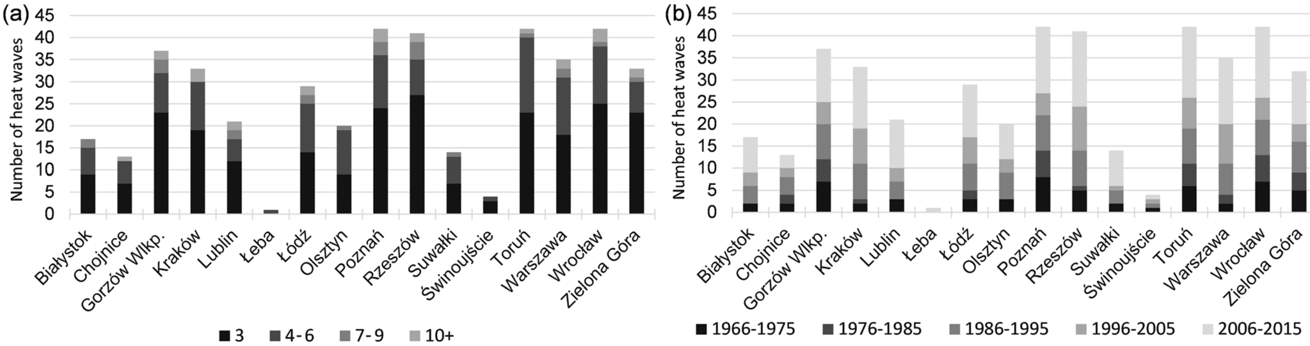


Fig. 2 Number of heat waves by duration (**a**) and number of heat waves in decades (**b**) in Poland (1966–2015)

on several stations, the similar number of waves was observed in the next three decades. On 15 out of 16 stations, the highest number of heat waves occurred in the years 2006–2015, varying from 1 in Hel, Łeba and Świnoujście to 17 in Rzeszów.

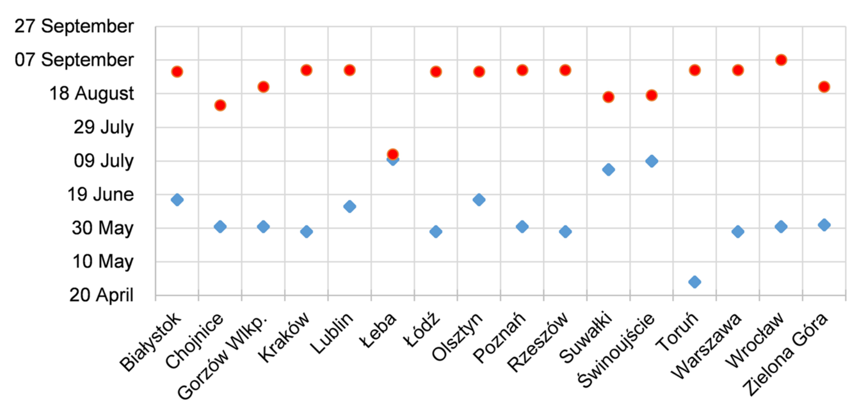
In the years 1966–2015 in Poland, heat waves occurred from the end of April to the beginning of September (Fig. 3). They were the most frequently recorded in July, and their contribution varied from 45% in Kraków and Wrocław to 64% in Suwałki. The only heat wave in Łeba occurred in July. On the majority of stations, the first heat wave was usually recorded in the first half of June and the last one in the second half of August. The earliest heat wave was determined in Toruń in 2012, from 28 to 30 April, and the latest in Wrocław in 1973, from 5 to 7 September. The above data suggest that the potential period of occurrence of heat waves in Poland lasted from 28 April to 7 September, i.e. 133 days. On particular stations (excluding Łeba), the duration of the term ranged from 40 days in Świnoujście to 127 days in Toruń.

Mean Tmax during the analysed heat waves in Poland amounted to 32.2 °C and Tmin 17.1 °C. The highest mean Tmax and Tmin were determined in Łeba (32.8 °C and 20.2 °C, respectively), although only one heat wave was recorded on the station. Apart from that, the highest mean Tmax for all heat waves was recorded in Kraków (32.4 °C) and the highest Tmin in Zielona Góra (19.4 °C). On the majority of stations, heat waves with the highest mean Tmax were determined in the 1990s. They were waves from 1992 and 1994 (Fig. 4). The warmest waves occurred in Zielona Góra on 8–10 August 1992, with mean Tmax 35.6 °C. Equally high mean Tmax was recorded in Poznań, Toruń and Gorzów Wielkopolski. The heat wave from 2015 was the warmest wave in the analysed multi-annual period in the south of the country, i.e. in Wrocław (34.7 °C) and Rzeszów (34.3 °C). The highest mean Tmin was recorded on the majority of stations during heat waves in summer 2010. Similarly, as in the case of the highest mean Tmax, the highest mean Tmin was recorded during a heat wave in 1992 in Zielona Góra (21.6 °C). Heat waves with mean Tmin ≥ 20 °C also occurred in Gorzów Wielkopolski, Warsaw, Łeba and Łódź.

3.2 Circulation conditions of heat waves

The occurrence of heat waves in Poland in the analysed years was usually related to the persistence of a wedge of high pressure over Europe, within which an anticyclone developed with a centre located north-west of Poland (> 1017 hPa) (Fig. 5). Geopotential isolines of 500 hPa over Central Europe were bent northwards, developing an elevation over the study area, suggesting the presence of warm air masses. During the occurrence of heat waves, pressure over the study area was higher than the summer season average, as confirmed by the prepared maps of

Fig. 3 Potential period of occurrence of heat waves in Poland; blue diamonds—the earliest beginning of a heat wave; red dots—the latest ending of a heat wave (1966–2015)



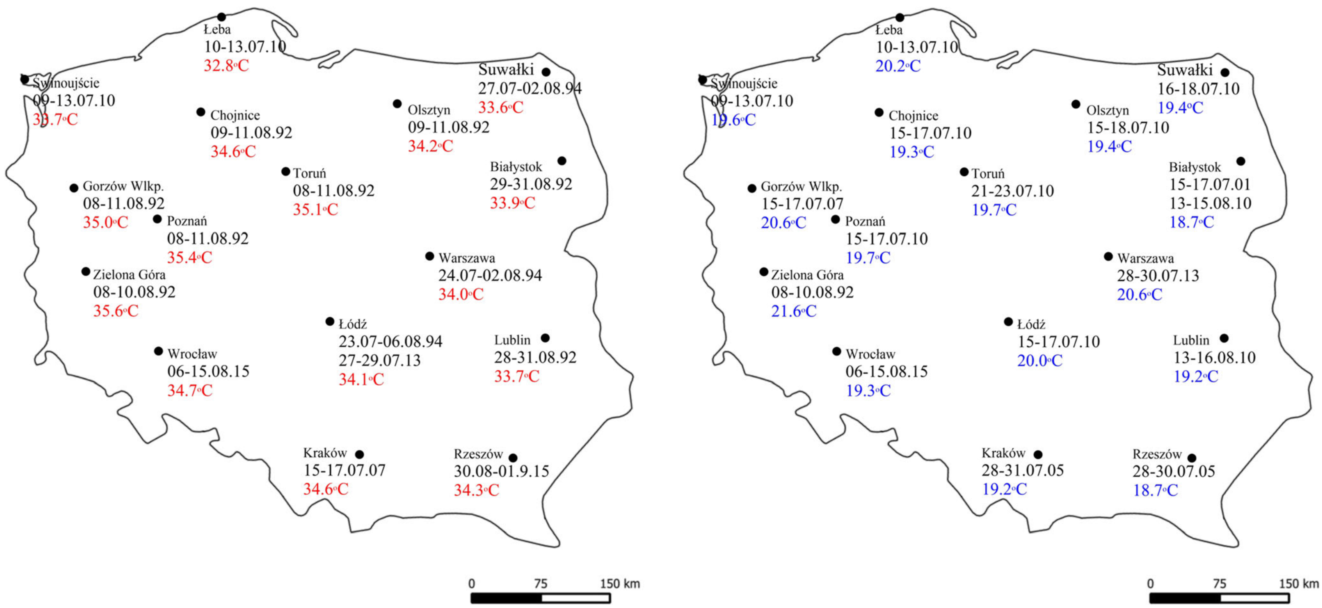


Fig. 4 Highest average Tmax (map on the right) and Tmin (map on the left) during heat waves with their date of occurrence (°C)

SLP anomalies which varied from 0 to > 3 hPa over the study area. Pressure over the Atlantic was lower than average, and negative anomalies in the centre amounted to <− 2 hPa. Positive anomalies were also recorded in the case of z500 hPa which exceeded 105 m in the centre of the system. The presence of warm air masses was also confirmed by positive anomalies of T850 which exceeded 6 °C over Poland. The described pressure pattern ensured the inflow of warm and dry continental air masses in the lower troposphere from the south-eastern sector. In higher layers of the troposphere, advection of warm air masses from the southern sector occurred.

3.3 Selected heat waves and their circulation conditions

The heat wave from the turn of July and August 1994 covered the entire country except for the coast of the Baltic Sea. The beginning of the hot period progressed from the south-west to north-east. The heat wave began the earliest in Wrocław and Zielona Góra (22 July) and the latest in Suwałki (27 July) (Fig. 6). The end of the wave occurred on the same day over a major part of the area (2 August). Only in south and central Poland, the end occurred later—in Wrocław and Łódź on 6 August and in Rzeszów on 8 August. As already mentioned earlier, the analysed heat wave lasted the longest in Wrocław and Rzeszów, i.e. 16 days.

An equally long heat wave occurred in August 2015 and affected south and east Poland to the greatest degree. The beginning of the wave varied between 2 (Poznań) and 6 August (Wrocław and Zielona Góra) and the end between 6 (Olsztyn) and 16 August (Rzeszów) (Fig. 6). The aforementioned wave lasted the longest in Rzeszów and Łódź, i.e. 13 days. It lasted almost equally long in Kraków (12 days) as well as in Lublin and Warsaw (11 days).

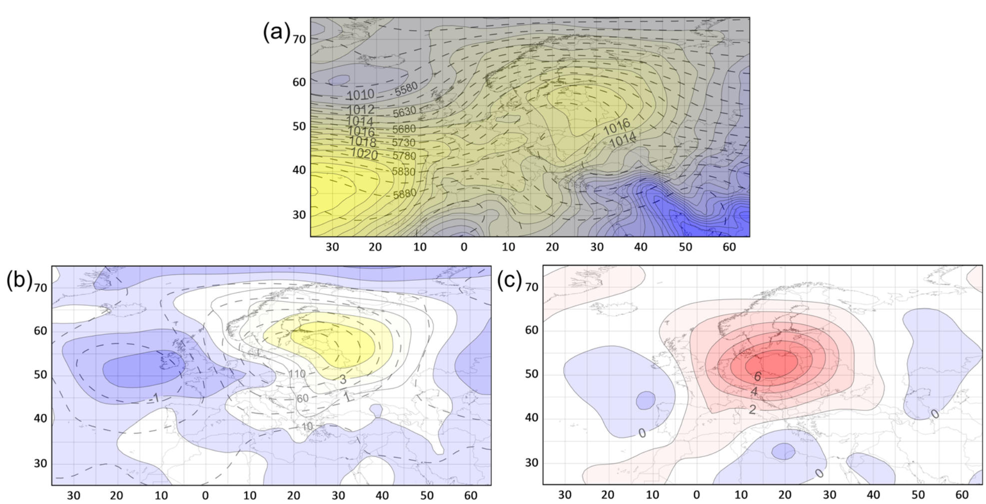


Fig. 5 Mean SLP (in hPa; colour scale) and z500 hPa (in gpm; dashed lines) (**a**); anomalies of SLP (in hPa; colour scale) and z500 hPa (in m; dashed lines) (**b**); anomalies of T850 (in °C; **c**) for heat waves

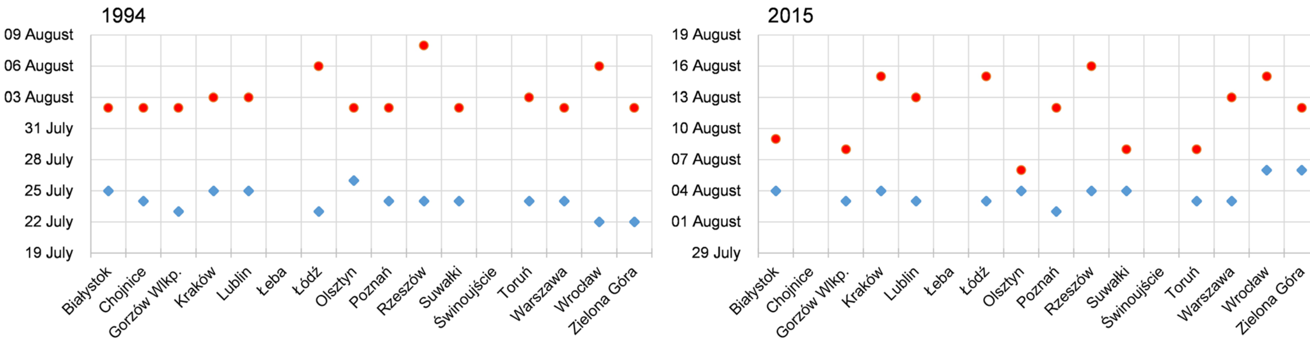


Fig. 6 Beginning (blue diamonds) and end (red dots) of selected heat waves in Poland

The occurrence of both heat waves was related to high pressure systems. During the wave from 1994, the centre of the anticyclone persisted over the Baltic Sea (> 1018 hPa) (Fig. 7) and the entire baric system was extended towards the north-east, reaching the Barents Sea. During the wave from 2015, the high pressure system persisted over a major part of north, central and east Europe, and the anticyclonic centre was located over west Russia (> 1020 hPa). The occurrence of the heat wave from 2015 was related to a somewhat stronger high than in 1994, as suggested by SLP anomalies. In both cases, similar values of SLP anomalies were recorded in the study area. The isolines of 500 hPa geopotential level over central Europe were bent northwards, developing an elevation over the study area, suggesting the presence of warm air

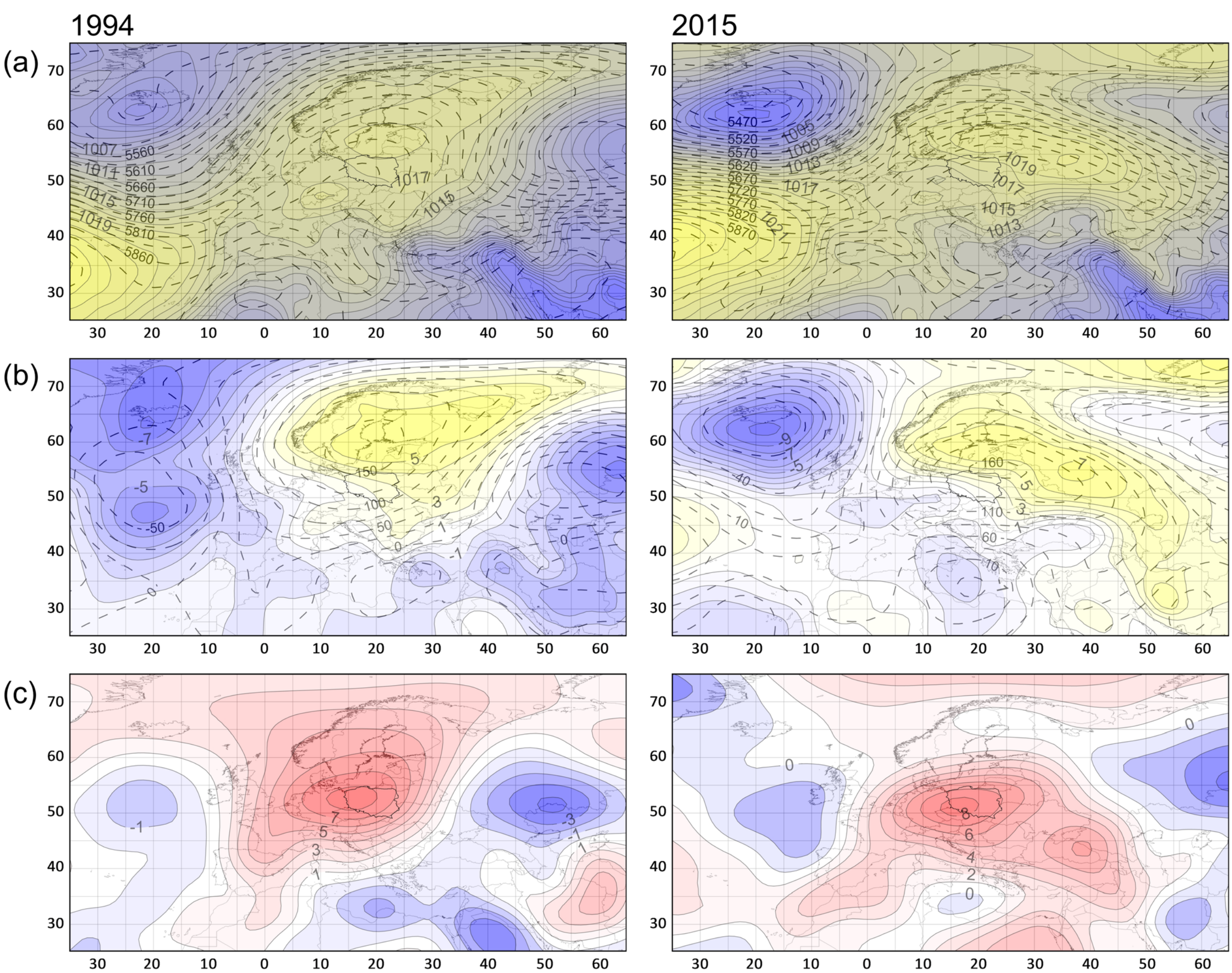


Fig. 7 Mean SLP (in hPa; colour scale) and z500 hPa (in gpm; dashed lines) (**a**); anomalies of SLP (in hPa; colour scale) and z500 hPa (in m; dashed lines) (**b**); anomalies of T850 (in °C; **c**) for selected heat waves

masses. The advection of warm air masses is also confirmed by positive anomalies of T850, reaching 8 °C over Poland. In 1994, the range of warm air masses covered particularly central and north Europe and in 2015 central and south Europe.

The studied surface air temperature extremes in Poland were accompanied by the downward extension of positive height anomalies from their centre in the upper troposphere. The vertical cross sections through the troposphere performed for 31 July 1994 and 8 August 2015, i.e. two of the hottest days during the period 1966–2016, show positive anomalies of geopotential heights throughout the troposphere over the areas of the surface thermal extremes occurrence. The maximum values of anomalies (exceeding 250 m), however, were observed for 300–250 hPa geopotential height. This situation suggests that the strongest signal of the presence of heat waves was detected in the upper troposphere at a height of approximately 10 km (Fig. 8). The highest positive T850 anomalies exceeding 8 °C were recorded over south Baltic Sea. In the parallel and meridional tropospheric cross sections, the greatest positive air temperature anomalies occurred at isobaric levels up to 850 hPa (maximum > 12 °C). At the level of the maximum geopotential anomalies, air temperature anomalies were close to 0 °C. Above these neutral values, a sharp border area occurred with negative temperature anomalies. The greatest negative air temperature anomalies were observed above the level of 300 hPa in the upper area of positive geopotential anomalies, right over their maximum values. The pattern of air temperature anomalies can be explained by air dynamics observed in the high (anticyclonic) pressure system, where the horizontal divergence of air masses in its upper part causes adiabatic cooling and results in negative temperature anomalies. Positive anomalies in the lower part of the high pressure system are consequences of the subsidence of air masses, activating adiabatic heating.

3.4 Characteristics of occurrence of cold waves

In the years 1966/1967–2015/2016 in Poland, the number of cold waves and their duration were considerably variable. The highest number of cold waves was recorded in north-east Poland with a maximum in Suwałki (32 waves). Their total duration amounted to 173 days (Table 2). Cold waves also occurred relatively frequently in Białystok (21 waves; 108 days). The lowest number of cold waves occurred on the coast of the Baltic Sea. Only one cold wave was recorded in Świnoujście (lasting 3 days). No occurrence of cold waves was determined for Łeba in the analysed multi-annual period. Mean duration of cold waves (excluding Świnoujście) varied from 3.8 days in Gorzów Wielkopolski and Poznań to 5.4 days in Suwałki.

On the majority of stations in the analysed years, the shortest cold waves occurred, i.e. those lasting 3 days. The highest contribution (excluding Świnoujście) of 3-day cold waves was determined for Gorzów Wielkopolski and Poznań (Fig. 9a). They constituted 80% and 75% of all waves, respectively. On the majority of stations (12 out of 16), waves lasting at least 1 week were recorded. The highest number of such waves was recorded in Suwałki (nine waves) and Białystok (four waves). The duration of the longest cold waves on particular stations (excluding Świnoujście) varied from 6 days in Kraków and Wrocław to 14 days in Suwałki. On the majority of stations, the longest cold wave was recorded in winter 1986/1987. In Suwaki, it lasted from 5 to 18 January 1987. Similar duration of the wave was observed in Olsztyn (13 days) and Białystok (12 days).

On the majority of stations, the highest number of cold waves was recorded in the first two decades, i.e. in the years 1966/1967–1985/1986 (Fig. 9b). On five stations, however, (Łódź, Olsztyn, Rzeszów, Toruń, Warsaw), the highest number (three or four cases) of cold waves occurred in the years 2006/2007–2015/2016. A decreasing frequency of occurrence of cold waves has been observed in recent years. Apart from coastal stations—Łeba and Świnoujście, where hardly any cold waves appear at all, in two other lowland sites (Wrocław and Zielona Góra), no cold wave was recorded in the last 20-year period and in Gorzów Wielkopolski in the last decade.

In the years 1966/1967–2015/2016 in Poland, cold waves occurred from the middle of December to the beginning of March (Fig. 10). They were the most frequently recorded in January, and their contribution varied from 45% in Toruń and Warsaw to 75% in Wrocław. The only cold wave in Świnoujście occurred in December. The earliest cold wave was observed in Białystok and Suwałki in 2009 from 17 to 21 December and the latest in Suwałki in 1987 from 2 to 4 March. The above data suggest that the longest potential period of occurrence of cold waves occurred in Suwałki and amounted to 78 days. In the remaining area (excluding the coast), the duration of the period varied from 28 days in Wrocław to 58 days in Białystok, Lublin and Rzeszow.

In Poland, mean Tmax during the analysed cold waves amounted to − 13.1 °C and Tmin − 20.3 °C. The lowest mean Tmax was recorded in Warsaw (− 13.9 °C), and the lowest mean Tmin in Wrocław (− 22.9 °C) (Fig. 11). On the majority of stations, cold waves with the lowest mean Tmax were recorded in winter 1978/1979 and 1986/1987. The coldest wave (in terms of Tmax) occurred in Białystok from 30 December 1978 to 2 February 1979, with a mean of − 17.7 °C. Almost equally, low mean Tmax was observed in Suwałki during the wave, amounting to − 17.3 °C. The lowest mean Tmin was mainly recorded during waves in winter 1969/1970, 1984/1985, 1986/1987 and 2005/2006. The coldest wave (in terms of Tmin) occurred in Rzeszów on 11–13 February 1985, with a mean of − 27.9 °C. Almost equally low mean Tmin was observed in Suwałki and Białystok during the wave from 30 January to 2 February 1970 (− 29.1 °C and − 28.9 °C, respectively).

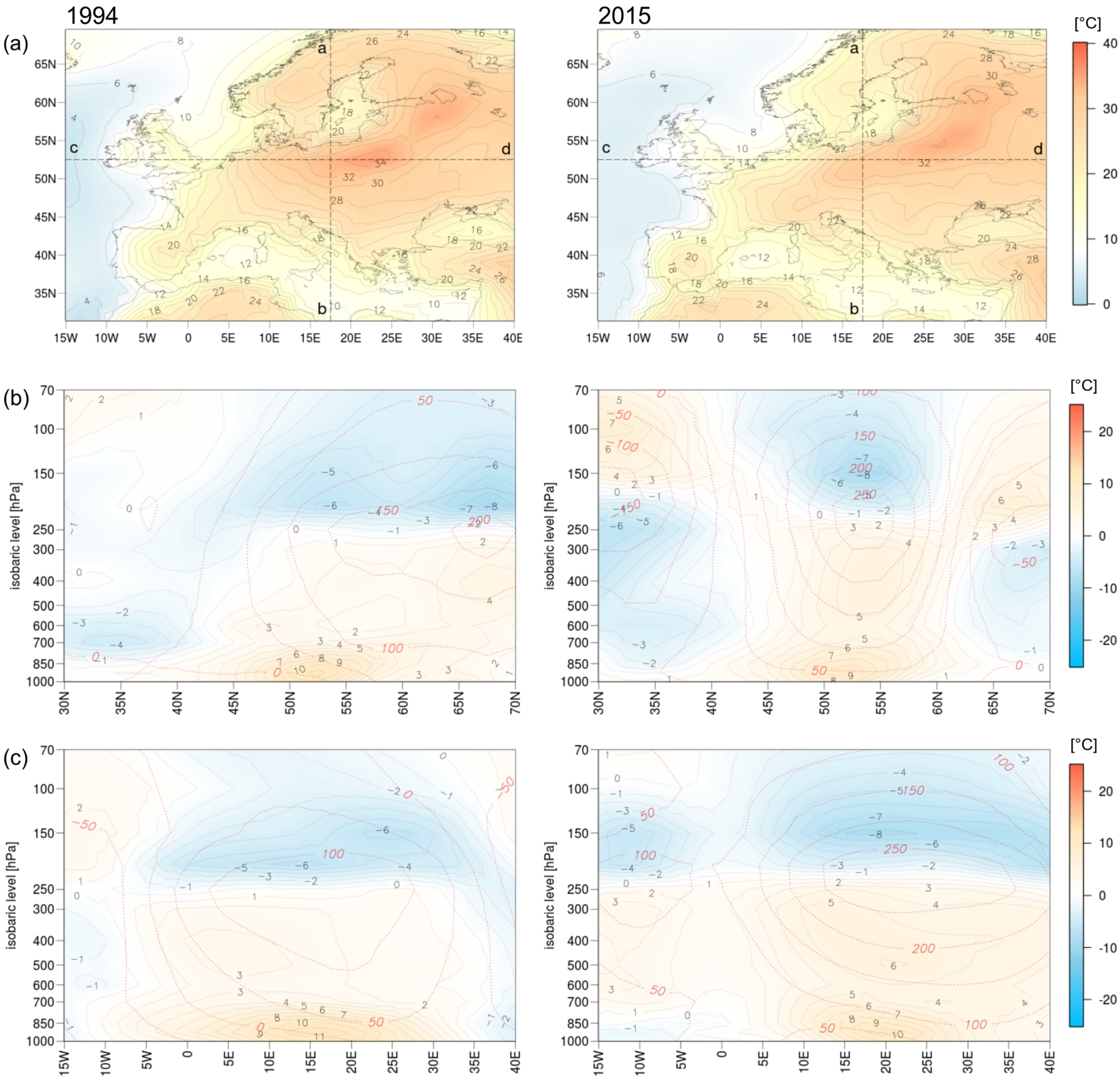


Fig. 8 Mean daily surface air temperature (**a**) and vertical sections of the troposphere with anomalies of air temperature (in °C; colour scale) and geopotential height (in m; dotted lines) along the 17.5° W meridian (**b**) and the 52.5° N parallel (c) on 31 July 1994 (left column) and 8 August 2015 (right column)

3.5 Circulation conditions of cold waves

The occurrence of cold waves in Poland in the analysed years was usually related to the persistence over the majority of the continent of a wedge of high pressure related to the high from over west Russia. A low pressure system persisted over the Mediterranean Sea (in the centre < 1010 hPa) (Fig. 12). Over the study area, SLP varied from 1022 to 1026 hPa. During the occurrence of cold waves, pressure over the study area was higher than average in the winter season. Over the study area, SLP anomalies ranged from 3 to > 11 hPa. In the centre of the system, SLP was higher by > 15 hPa. The isolines of 500 hPa geopotential level over central Europe were bent towards south-west, developing an evident subsidence over the study area, suggesting the presence of cold air masses. The isobaric surface 500 hPa persisted lower than on average in winter, suggesting the presence of cold air masses. This is also confirmed by negative anomalies of T850 with the centre located over central Europe (<− 7 °C). The described pressure pattern generated advection of air masses from the eastern sector, also suggested by the course of anomalies of T850.

Table 2 Characteristics of cold waves in Poland (1966/1967–2015/2016)

Station	Colds waves			The longest cold waves (days) with the occurrence dates	
	Total number	Total length (days)	Mean length (days)		
Białystok	21	108	5.1	12	7–18 January 1987
Chojnice	10	43	4.3	8	10–17 January 1987
Gorzów Wielkopolski	5	19	3.8	7	11–17 January 1987
Kraków	10	45	4.5	6	5–10 January 1985, 27 December 1996–1 January 1997, 1–6 February 2012
Lublin	13	66	5.1	8	10–17 January 1987, 26 December 1996–2 January 1997
Łeba	–	–	–	–	–
Łódź	9	45	5.0	8	10–17 January 1987, 26 December 96–2 January1997
Olsztyn	14	69	4.9	13	7–19 January 1987
Poznań	8	30	3.8	7	11–17 January 1987
Rzeszów	10	46	4.6	8	30 January–6 February 2012
Suwałki	32	173	5.4	14	5–18 January 1987
Świnoujście	1	3	3.0	3	22–24 December 1969
Toruń	11	45	4.1	9	10–18 January 1987
Warszawa	11	54	4.9	10	8–17 January 1987
Wrocław	4	18	4.5	6	11–16 January 1987
Zielona Góra	4	20	5.0	8	11–18 January 1987

3.6 Selected cold waves and their circulation conditions

On the large majority of stations, the longest cold wave occurred in winter 1986/1987. The beginning of the wave progressed from the north-east towards the south and west of the country. It began the earliest in Suwałki (on 5 January) and the latest in Gorzów Wielkopolski, Kraków, Poznań, Rzeszów, Wrocław and Zielona Góra (on 11 January) (Fig. 13). The end of the cold wave occurred the earliest in the south (Kraków, Rzeszów)—on 15 January, and the latest in the north-east (Olsztyn)—on 19 January. The discussed wave was not recorded on the coast of the Baltic Sea. It lasted the longest in north-east Poland (Suwałki—14 days, Olsztyn—13 days, Białystok—12 days). During the cold wave, mean Tmax varied from − 16.2 °C in Kraków and Wrocław to − 13.5 °C in Gorzów Wielkopolski and mean Tmin from − 25.6 °C in Białystok to − 19.3 °C in Gorzów Wielkopolski.

An equally long (on three stations the longest) cold wave was recorded at the turn of 1996 and 1997 (Fig. 13). Similarly, as in the case of the wave from 1987, and also in this case, the wave was not recorded on the coast or in west and south-west Poland. On the majority of stations, it began on 26 December 1996 and ended on 1 January 1997. Only in Gorzów Wielkopolski, Lublin and Łódź, it ended 1 day later, i.e. on 2 January. The discussed wave lasted the longest in Lublin and Łódź—8 days. During the occurrence of the wave, mean

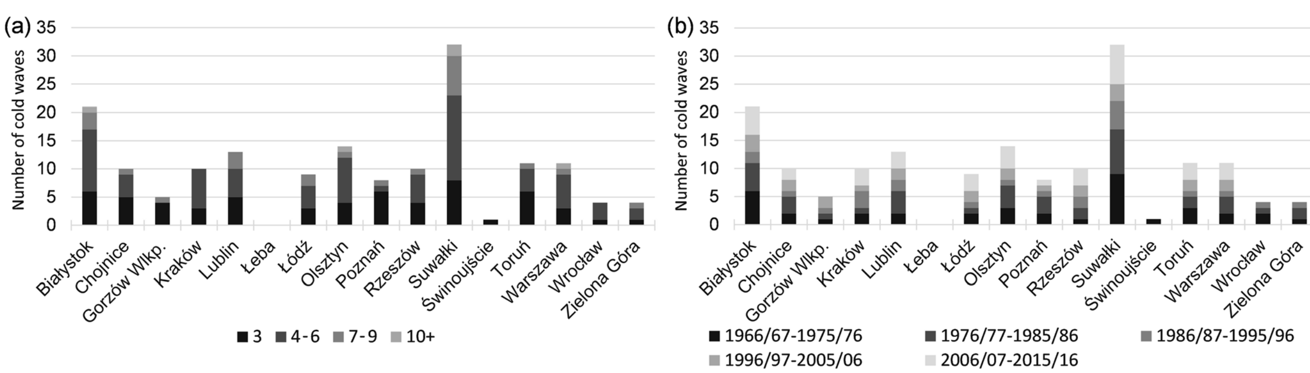


Fig. 9 Number of cold waves by duration (**a**) and number of cold waves in decades (**b**) in Poland (1966–2015)

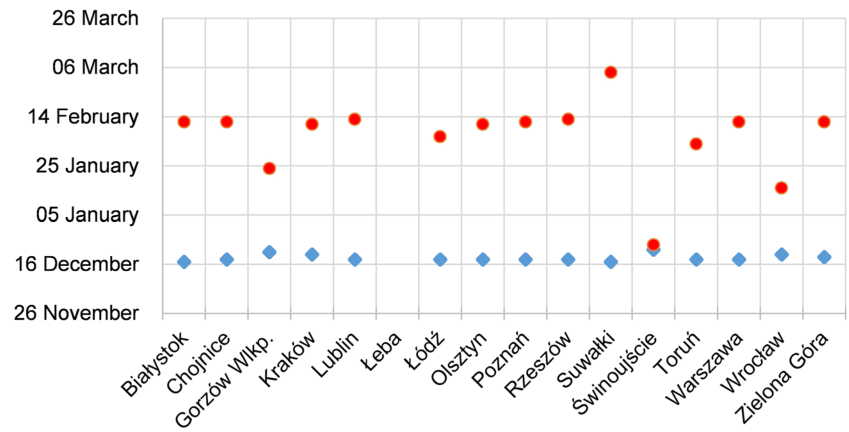


Fig. 10 Potential period of occurrence of cold waves in Poland; blue diamonds—the earliest beginning of a cold wave; red dots—the latest ending of a cold wave (1966/1967–2015/2016)

Tmax varied from − 16.2 °C in Suwałki to − 11.3 °C in Toruń and mean Tmin from − 24.6 °C in Suwałki to − 18.0 °C in Gorzów Wielkopolski.

The occurrence of selected cold waves (i.e. from 1987 and 1996/1997) was related to the area of high pressure. In the first case, a high pressure system persisted over north Europe (in the centre > 1036 hPa), and a low pressure system over south Europe, with a centre over the Tyrrhenian Sea (< 1008 hPa) (Fig. 14). In the second case, the area of high pressure extended from east Europe to Iceland, with a high pressure system over the Atlantic (> 1028 hPa). In both cases, a major part of the continent was within the range of positive SLP anomalies. In the centre of the systems, anomalies of SLP exceeded 28 hPa (in the first case) and 26 hPa (in the second case). Over the study area, SLP anomalies during the first wave varied from 1 to 10 hPa and during the second one from 6 to 12 hPa. Isolines of z500 hPa in both cases were bent towards the south-west, developing an evident subsidence over the study area, suggesting the presence of cold air masses. The advection of cold air masses is also suggested by negative anomalies of T850 which were greater in the case of the cold wave from winter 1996/1997. The described pressure pattern ensures advection of cold continental air masses from the east in the first case and from the north-east in the second. Such conditions of air mass inflow are also confirmed by the course of anomalies of T850.

During positive surface air temperature extremes described in the previous sections, the strong positive geopotential height anomaly in the upper troposphere is related to the strong positive temperature anomaly below it. The opposite pattern is observed at negative temperature extremes, when surface cold anomalies are coupled with a negative centre of geopotential height anomalies in the upper troposphere, located right over the area of the cold surge occurrence. The vertical cross sections through the troposphere performed for 11 January 1987 and 28 December 1996, i.e. two of the coldest days during the period 1966–2016, show negative height anomalies occurring at every isobaric level over the areas of

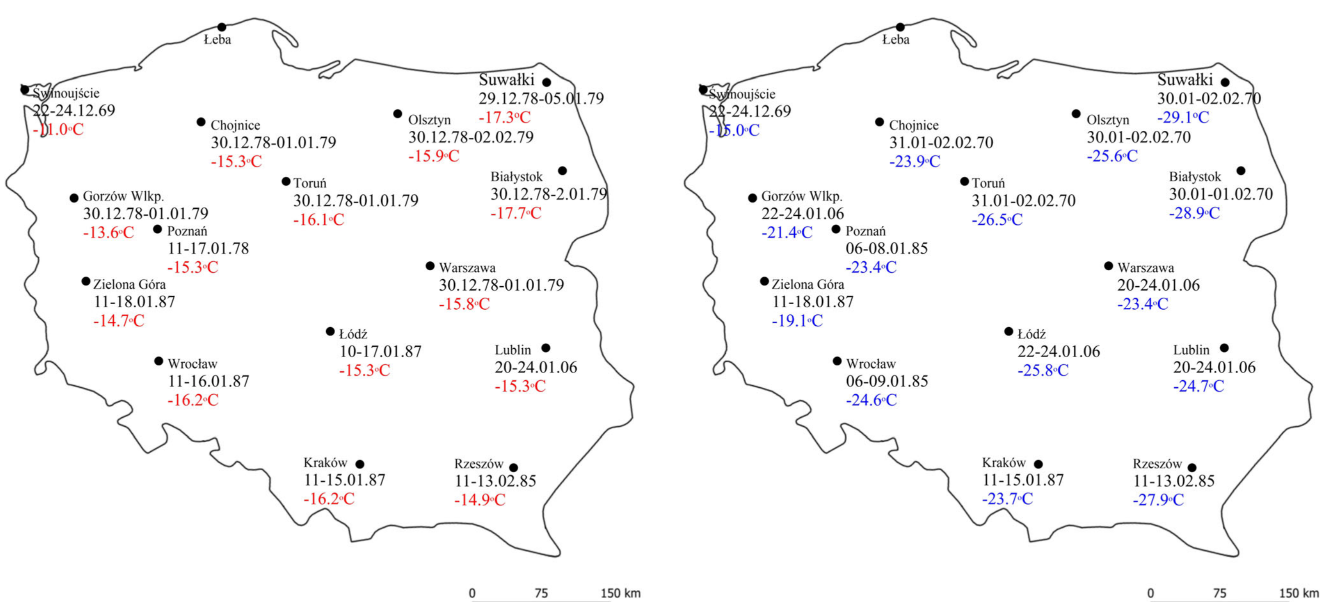


Fig. 11 Lowest average Tmax (map on the right) and Tmin (map on the left) during cold waves with their date of occurrence (°C)

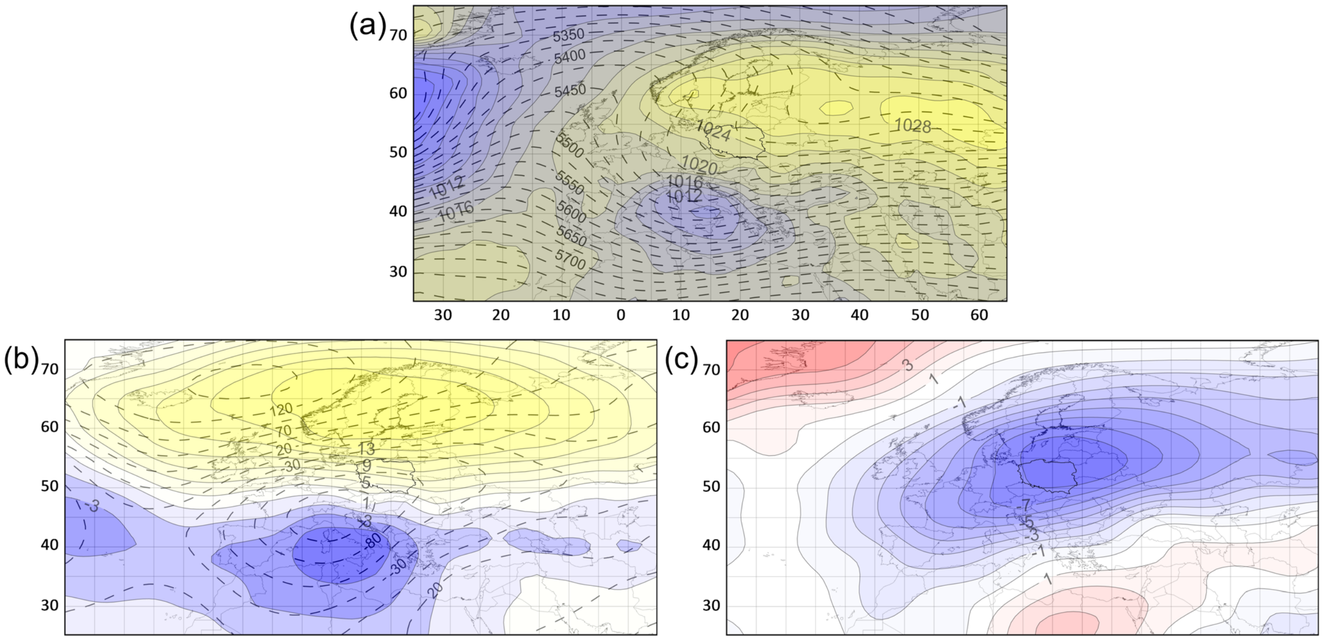


Fig. 12 Mean SLP (in hPa; colour scale) and z500 hPa (in gpm; dashed lines) (**a**); anomalies of SLP (in hPa; colour scale) and z500 hPa (in m; dashed lines) (**b**); anomalies of T850 (in °C; **c**) for the cold waves

occurrence of cold waves. On 11 January 1987, the maximum negative values, exceeding 400 m, were observed for 300–250 hPa geopotential height (Fig. 15). The described situations show that the strongest signals of cold waves presence were detected in the upper troposphere at an approximate height of approximately 10 km. The highest negative T850 anomalies in both cases were recorded over central Europe (exceeding 8–9 °C). In the parallel and meridional tropospheric sections, considerable negative air temperature anomalies were observed in the air mass right below the centre of the negative geopotential height anomaly. The highest values of anomalies reach 16–20 °C at the lowest isobaric levels up to 850 hPa. In the upper troposphere, weak positive anomalies of air temperature were observed despite geopotential heights shifted downward. Positive anomalies of air temperature on a geopotential height of over 300 hPa recorded on 28 December 1996 (and weaker on 11 January 1987) were caused by the horizontal convergence of air masses above the subsidence zone in the anticyclonic system formed over the area with a cold wave.

4 Discussion and summary

The conducted research showed high spatial variability of occurrence of hot and cold waves in Poland in the years 1966–2015. The highest number of heat waves concerned stations located in the central and southern part of the study area and the lowest—coastal stations. Cold waves usually occurred in north-east Poland and the most seldom on the coast and in the west of the country.

The observed warming (Tomczyk and Bednorz 2016; Wypych et al. 2017) translated into increasingly frequent occurrence of heat waves and increasingly seldom occurrence of cold waves. In the analysed period of 50 years, the lowest number of heat waves was observed in the years 1976–1985

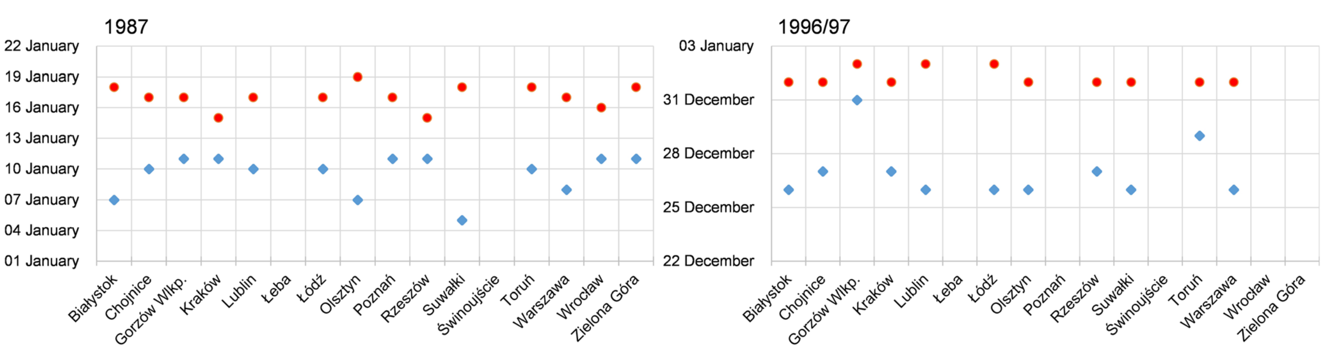


Fig. 13 Beginning (blue diamonds) and end (red dots) of selected cold waves in Poland

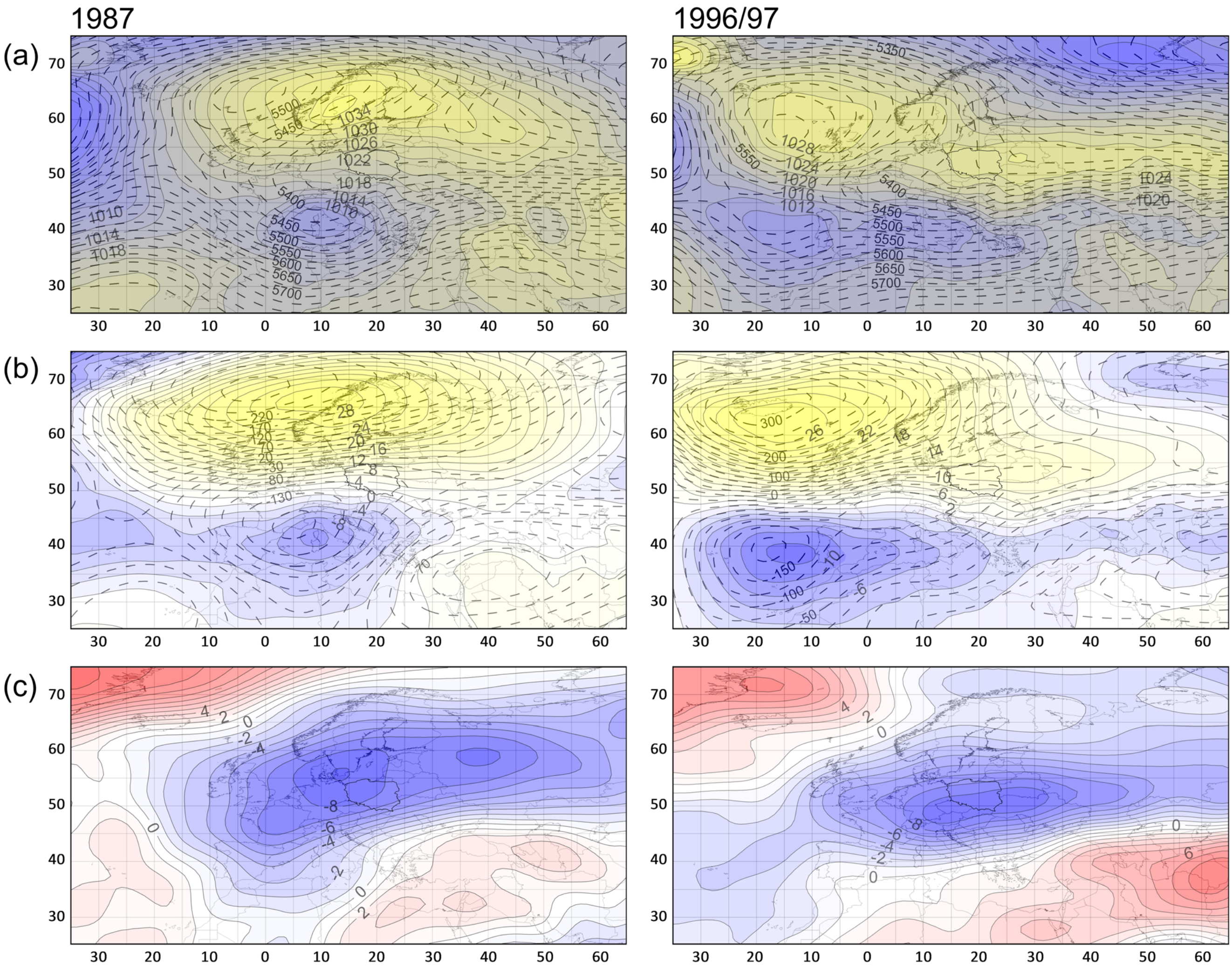


Fig. 14 Mean SLP (in hPa; colour scale) and z500 hPa (in gpm; dashed lines) (**a**); anomalies of SLP (in hPa; colour scale) and z500 hPa (in m; dashed lines) (**b**); anomalies of T850 (in °C; **c**) for selected cold waves

and the highest in the years 2006–2015. An increase in the number of heat waves was also evidenced in earlier studies from the territory of Poland (Tomczyk 2014; Sulikowska et al. 2016; Graczyk et al. 2017; Wibig 2018). A similar direction of changes was recorded in neighbouring countries, e.g. in Germany (Tomczyk and Sulikowska 2017), Czech Republic (Kyselý 2010) and Ukraine (Shevchenko et al. 2014). On the majority of stations in Poland, the highest number of cold waves was observed in the first two decades of the analysed multi-annual period (1966/1967–1985/1986) and the lowest in the two last decades (1966/1997–2006/2015). A decrease in the number of cold waves in Poland was also mentioned by other authors (Wibig 2007; Wibig et al. 2009b; Tomczyk and Bednorz 2014). A similar direction of changes was determined in other regions of central Europe (Lhotka and Kyselý 2015b; Spinoni et al. 2015).

The research revealed that the most intensive heat waves occurred in 1992, 1994, 2006, 2010 and 2015. On the majority of stations in the analysed multi-annual period, the longest heat wave occurred in 1994. Research by Lhotka and Kyselý (2015a) showed that the said heat wave was the most serious wave since the 1950s, followed by the heat wave from 2006. The heat wave from 1994 also covered west Ukraine (Shevchenko et al. 2014). On many stations in Europe, also in Poland, the record values were exceeded in summer 2015. The summer was recorded as extreme particularly in south-east Germany and Poland, where the hot period lasted, with breaks, from the end of June to mid-September (Hoy et al. 2017). Russo et al. (2015) considered the heat wave from 2015 as the most serious one in Europe since 1950. Summer 2015 was exceptionally hot throughout Poland, particularly in the south-west of the country (Sulikowska et al. 2016). The most intensive cold waves occurred in 1978/1979, 1987, 1996/1997 and 2012. In a major part of the country, the longest cold wave occurred in 1987. Also, Krzyżewska and Wereski (2014) reported long waves of cold days among others in 1987 in the scope of her research on heat and cold waves in south-east Poland. In spite of the observed changes,

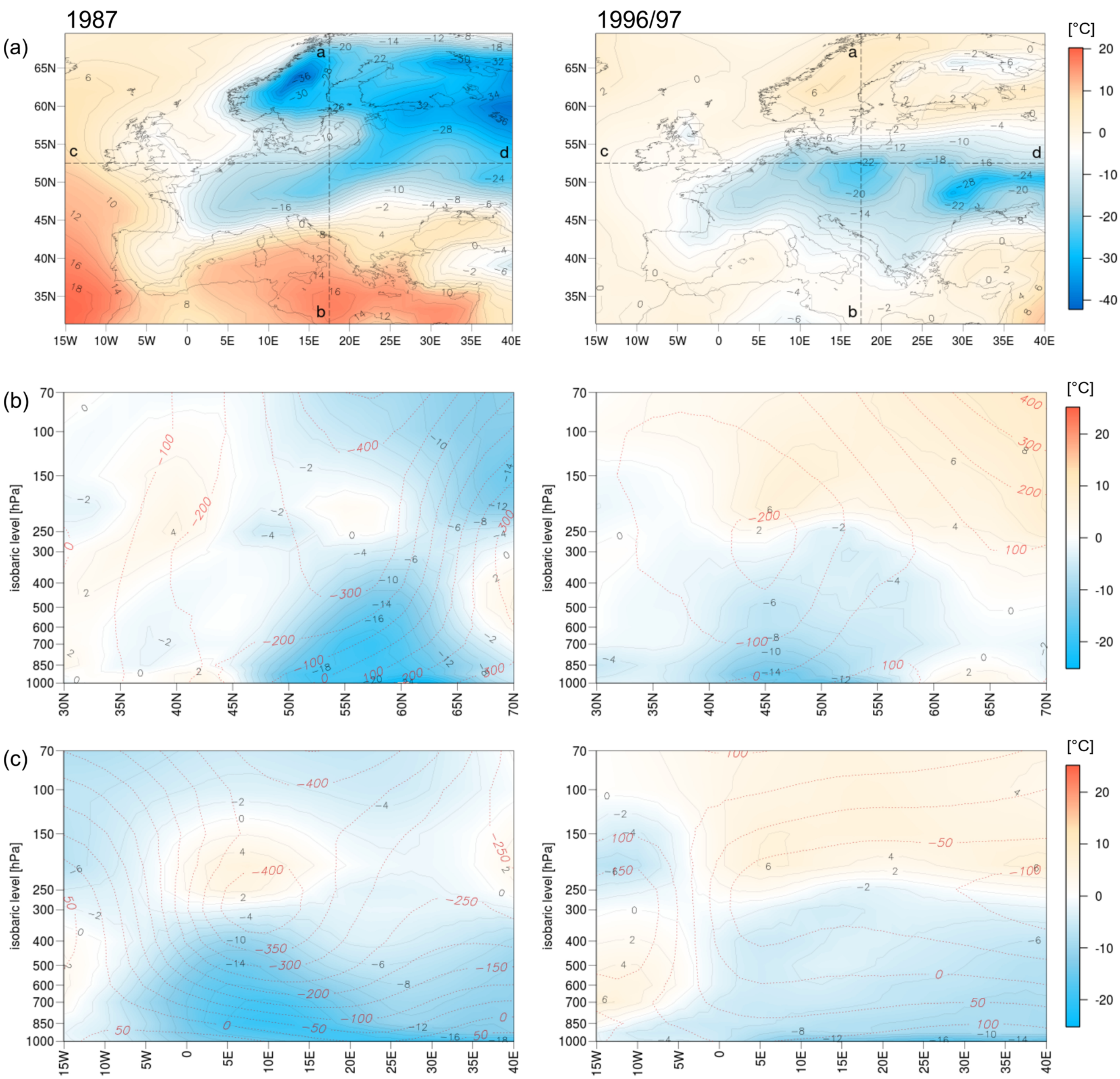


Fig. 15 Mean daily surface air temperature (**a**) and vertical sections of the troposphere with anomalies of air temperature (in °C; colour scale) and geopotential height (in m; dotted lines) along the 17.5° W meridian (**b**) and the 52.5° N parallel (**c**) on 11 January 1987 (left column) and 28 December 1996 (right column)

several day-long periods with very low temperatures have been still recorded in Poland during winter seasons of recent years, as exemplified by January 2016 and 2017 in Poland (Informacja tygodniowa, Zagrożenia—Skutki—Ocena 2016, 2017).

The occurrence of both heat and cold waves is related to high pressure systems. Anticyclonic blocking patterns both in winter and summer inhibit the zonal flow of air masses and intensify the meridional flow. In central Europe, this means the presence of arctic or polar continental air masses in winter and tropical air masses in summer. In the case of summer heat waves, pressure anomalies were ranged from 0 to > 3 hPa over the study area. Considerably greater anomalies were recorded during cold waves (from 3 to > 11 hPa). Apart from continental advections, the described baric systems provided strong insolation in summer and intensive heat loss in winter with low or no cloudiness, which is characteristic of anticyclonic weather. This is also confirmed by the performed cross sections through the troposphere. The greatest anomalies of air temperature occurred at the surface layers of the troposphere, in the case of hot days positive anomalies up to 12 °C and in the case of very cold days negative anomalies up to − 20 °C.

The presence of warm air masses during heat waves is confirmed by positive anomalies of z500 hPa and T850. Colder than average air masses during cold waves are suggested by negative anomalies of z500 hPa and T850. According to Ustrnul et al. (2010), the occurrence of the highest temperatures in Poland is related to the anticyclonic situation without evident advection and the lowest in situations of high with advection of air masses from the eastern sector. Similar results were obtained by Tomczyk and Bednorz (2014) analysing the circulation conditions of heat and cold waves on the south coast of the Baltic Sea. Strong highs and blockade situations, disturbing zonal circulation, have particular importance for the occurrence of extreme values of air temperature, including heat and cold waves (Porębska and Zdune 2013; Bielec-Bąkowska 2014; Wibig 2018).

The occurrence of the longest heat waves was related to considerably greater anomalies of atmospheric pressure field and air temperature than on average during heat and cold waves. Duchez et al. (2016), analysing the heat wave from 2015, evidenced that oceanic anomalies and the resulting strong meridional sea surface temperature gradient could cause the spread of the Rossby's wave leading to Jet Stream stationarity, which translated into an increase in pressure and extreme air temperature over central Europe.

In this study, anomalies of baric conditions accompanying extremes of the surface air temperature throughout the troposphere were detected. The maximum geopotential height anomaly in the upper troposphere appeared to be closely associated with surface extreme temperature episodes. Centres of geopotential height anomalies were located right over the area of the positive/negative surface temperature extremes. In accordance with the hydrostatic relation, during positive surface air temperature events, the strong positive geopotential height anomaly in the upper troposphere was related to the strong positive temperature anomalies below it. On the other hand, the opposite vertical structure with a negative centre of geopotential height anomalies in the upper troposphere and a cold air column below it was recognised during negative extremes of the surface air temperature in Poland. Qian et al. (2016) and Chen et al. (2017) discovered similar structures accompanying heat waves and cold surges in China. They found that geopotential height anomalies usually appear several (up to 20) days prior to extreme temperature events. As the structure of geopotential height and temperature anomalies complies with the hydrostatic balance, surface temperature anomalies can be derived from height anomalies in the troposphere. Consequently, detecting anomalies of geopotential height—particularly the early formation, positions and, tracks of their centres—could essentially extend the predictability of surface heat and cold extremes occurrence (Qian et al. 2015, 2016; Chen et al. 2017).

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