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ORIGINAL PAPER

Heat waves in lowland Germany and their circulation-related conditions

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Abstract The research study aimed at assessing multiannual variability of heat wave occurrence in the lowland part of Germany between 1966 and 2015 and determining the role of atmospheric circulation in their occurrence. The analysis was conducted with the use of two independent datasets, that is, the dataset of Germany's National Meteorological Service, Deutscher Wetterdienst, and American meteorological reanalysis database of the National Centre for Environmental Prediction/National Centre for Atmospheric Research. This article defines a hot day as a day with maximum temperature of >30 °C, and a heat wave as a sequence of at least three such days. The observed warming translated into an increase in a number of hot days and, consequently, an increase in the frequency of heat wave occurrence. In the analysed 50-year period, the smallest number of heat waves was observed between 1976 and 1985, and the largest number between 2006 and 2015 in the lowland part of Germany. The occurrence of heat waves in lowland Germany was related to anticyclonic circulation.

1 Introduction

Heat waves are considered extreme weather events (IPCC 2013) not only with regard to extremely high values of air temperature observed during these events but also, and most of all, due to their grievous impact on human life and economy (Perkins and Alexander 2013). When discussing only the beginning of the 21st century, one may notice at least a few heat waves which brought about great damages. Western Europe experienced very dangerous heat waves in 2003 during which, among others, in Germany, new air temperature records were set, and mean monthly temperature anomalies exceeded 6 °C in many places (Beniston 2004; Fink et al. 2004; Schär and Jendritzky 2004; Rebetez et al. 2009). Hot weather caused a rapid increase in the death rate (number of casualties was estimated to be 30,000) and great losses in the agricultural sector (Trigo et al. 2005; García-Herrera et al. 2010). Equally great anomalies occurred during hot weather in July 2006. These covered the area located north of the one from August 2003 so their impact was not so grievous (Rebetez et al. 2009). The hot weather in 2010 in Eastern Europe (Barriopedro et al. 2011; Russo et al. 2015) contributed to a massive increase in the death rate (number of casualties was estimated to be 55,000), losses in agriculture, as well as, occurrence of numerous fires and an increase in air pollution. The summer of 2015 was extremely hot and dry in Central and Eastern Europe, and it was record-breaking, among others, in South-Eastern Germany and Poland. The hot weather period spanned from the end of June to the half of September, with numerous breaks, and was the reason for all-time low state of the rivers and losses in agriculture (Hoy et al. 2016).

There was an increase in mortality rate during heat waves observed in many European cities. In Munich, this was estimated to be, on average, 7.6% (D'Ippoliti et al.

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2010). As the studies of Gabriel and Endlicher (2011) have shown, conducted in Brandenburg and Berlin (North-Eastern Germany), negative impact of hot days on health are visible not only within highly urbanized areas (although it is the most severe there), but also in rural areas.

According to many research studies, the observed warming of the Earth's climate (IPCC 2013) is also related to an increase in frequency, duration and intensity of heat waves on a global scale and in the particular regions of the Globe (Alexander et al. 2006; Perkins et al. 2012). Della-Marta et al. (2007a) claim that between 1880 and 2003 in Western Europe, duration of heat waves doubled and the frequency of occurrence of hot days almost trebled. The articles concerning the region of Central Europe, including Germany, also mention an increase in frequency, duration and intensity of heat waves in the past decades (Lhotka and Kyselý 2015; Hoy et al. 2016; Tomczyk and Bednorz 2016).

In the temperate climate zone, the most often discussed factor causing the occurrence of thermal extreme events, including heat waves, is atmospheric circulation (Kyselý 2008; Huth et al. 2008; Ustrnul et al. 2010). According to Della-Marta et al. (2007b) the heat waves in Western Europe are related to the high-pressure area settling over Scandinavia and Central and Western Europe. Kyselý (2008) has proven that the occurrence of long-term and intensive heat waves in Central and Western Europe is promoted by maintenance of atmospheric circulation types connected with centres of high-pressure and inflow of air masses from east. The great significance of the presence of high-pressure area in connection to heat wave occurrence in Central Europe has been also noticed by Tomczyk and Bednorz (2016). Some researchers claim that the reasons for heat waves are the so-called blocking situations, that is, a high-pressure centre holding over a particular area for a long time which obstructs the zonal flow of air masses (Porębska and Zdunek 2013). These were a reason for, among others, the aforementioned heat waves in 2003 and 2010 (Black et al. 2004; Schneidereit et al. 2012). Climate projections based on different scenarios of climate changes show that heat waves are going to occur more often in Europe in the next decades, and they are going to be longer and more intensive (Meehl and Tebaldi 2004; Amengual et al. 2014). Thus the necessity of detailed research, especially, in the context of mechanisms leading to their occurrence.

The research objective of this article was the assessment of multiannual variability of heat wave occurrence in the lowland part of Germany and determination of the role of atmospheric circulation in this occurrence. In addition, the thermal and pressure conditions of the 2003 summer season, which was the warmest season between 1966 and 2015 in the majority of the area, were analyzed in detail.

2 Data and research methods

The analysis was conducted with the use of two independent datasets. Daily values of the maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperature in the period of 1966–2015 from 12 meteorological stations located in northern and central Germany (Fig. 1) was obtained from the collections of Germany's National Meteorological Service, Deutscher Wetterdienst (http://www.dwd.de), while daily values of sea level pressure (SLP), height of the 500 hPa isobaric level (z500 hPa) and temperature on the 850 hPa isobaric level (T850) were collected from American meteorological reanalysis database of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996). This data was obtained for nodes of a 2.5° × 2.5° geographical grid for the area of 25–75°N latitude and 35°W–65°E longitude.

Heat waves are subject of many contemporary research studies; however, there have been no universal methods of their determination yet, and the literature on the subject offers many definitions based on different criteria and using both maximum, minimum and mean daily air temperature (Perkins and Alexander 2013). The methods of determining heat waves can be divided into three groups: (1) using a specific, presumed temperature threshold which value should refer to possible effects; (2) based on statistical distribution of temperature in a particular point (using the multiannual mean value and multiplicity of standard deviation); (3) based on probability of occurrence of certain temperature values in a particular point (with the use of values of selected percentiles) (Stephenson 2008; Perkins and Alexander 2013). In the article, the first of the mentioned groups was chosen. This method consists in separating a series of days with a maximum daily air temperature that exceeds a certain thermal threshold. On this basis, the heat wave was defined as a sequence of at least 3 days with a maximum air temperature above 30 °C. The selection of a threshold seems to be justified with regard to little climatic diversity of the discussed area and the fact it has been used in studies concerning this part of Europe—among others, in France, the Netherlands, Czech Republic, Poland and Germany (Kyselý 2004; Poumadere et al. 2005; Wibig et al. 2009; Kundzewicz and Huang 2010; Porębska and Zdunek 2013; Tomczyk 2017). The minimum 3-day duration of a wave is the most often used in the climatological research studies (among others, Kyselý 2004, 2008; Perkins and Alexander 2013), and, as it has been proven, a human body starts its negative reaction to the stress of heat after exactly 3 days (Hajat et al. 2002; Nairn and Fawcett 2015).

The first stage of the research was calculating mean values of $T_{\max}$ in summer (JJA) in particular stations as

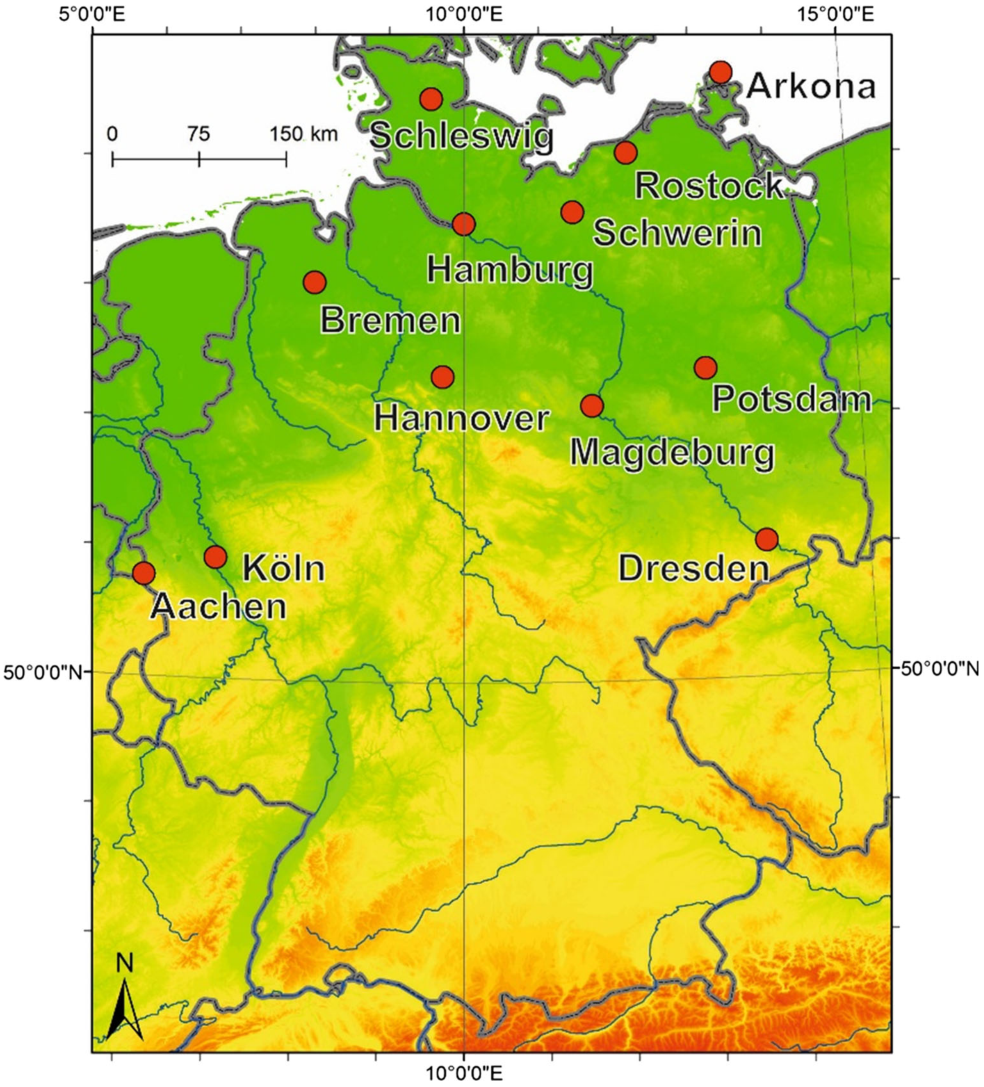


Fig. 1 Locations of the meteorological stations

well as assessing its spatial diversity and multiannual variability. Quantities of changes were defined by means of the coefficient of linear regression. Another step was determining hot days (T_{max} >30 °C) and heat waves (a sequence of at least 3 hot days). The frequency of their occurrence was determined and a potential period of their occurrence in the discussed stations was defined. The analysis of multiannual variability of hot days was carried out by means of Mann–Kendall test, and statistical significance of the determined trends was found with Sen's method.

At the next stage of the research, to determine pressure conditions conducive to heat wave occurrence, the maps of sea level atmospheric pressure average distribution and anomalies, height of the 500 hPa isobaric level and temperature on the 850 hPa isobaric level on the days forming heat waves were drawn up. Similar maps were drawn up for the summer season in years 1966–2015 and for the summer of 2003. The composite maps included the days when the maximum temperature fulfilled the criterion of a hot day in at least ¼ of the stations. Using this criterion is related to exclusion of phenomena which occurred locally. Using Ward's method, consisting in grouping the particular days with regard to the value of sea level pressure by means of the minimum variance method (Ward 1963), two types of circulation conducive to the occurrence of heat waves within the analysed area were distinguished. To achieve that, the standardised SLP values were used. The standardisation was made to equalize seasonal variability, simultaneously, keeping the intensity of pressure field (Esteban et al. 2005). For the determined circulation types, there were mean SLP, z500 hPa and T850 maps drawn up, together with the maps of anomalies. Additionally, for the selected days in the determined circulation types, there were 48-h back trajectories of air particles traced by means of NOAA HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php). Trajectories were traced for the three selected stations, that is, Bremen, Köln and Potsdam. The back trajectory analysis enables one to determine the area of the origin of air masses on the selected days, which constitutes a supplement to information displayed by weather maps.

3 Results

3.1 The maximum temperature in the summer

Between 1966 and 2015, in lowland Germany, the mean $T_{\max}$ in summer (June–August) was 22.0 °C and ranged from 19.1 °C in Arkona to above 23.0 °C in south-eastern part of the domain and in Köln (Table 1). Extreme daily temperatures in particular stations, expressed by 99th percentiles, varied widely from station to station. The percentile value was the smallest in the northernmost stations, for example, in Arkona, where temperatures above 24.8 °C can be considered very rare (<1%). On the other hand, in some stations located in the southern part of the research area, percentiles' values exceeded 31.0 °C (up to 32.3 °C in Potsdam), meaning that temperatures around 30 °C were much more likely there (Table 1).

The multiannual course of the mean summer $T_{\max}$ showed its considerable year to year fluctuations (Fig. 2). The scope of its deviations from the multiannual mean ranged from −5.3 °C (Rostock, 1987) to 4.6 °C (Potsdam, 2003). In all the considered stations $T_{\max}$ variability was similar, what was proven by hardly diversified values of standard deviation falling within the range of 1.0–1.3 °C (Table 1). Between 1966 and 2015, there was an increase in summer $T_{\max}$ observed in all stations, but it was the most intensified in the south-western part of the research area (up to 0.35 °C/10 years in Köln) (Table 1). The $T_{\max}$ trend was statistically significant in most of the stations and its magnitude was influenced the most by relatively high $T_{\max}$ values in the 21st century (Table 1; Fig. 2). In 8 out of 12 stations, the warmest season was recorded in 2003, and then the mean $T_{\max}$ ranged from 24.0 °C (Schwerin) to 26.7 °C (Köln). In the two northernmost stations, the warmest summer occurred in 2006, and in Rostock and Magdeburg, located in the eastern part of the analysed area, the warmest summer season was in 1992 (Table 1). On the other hand, the coldest summer in the case of 8 out of 12 stations took place in 1987, and the mean $T_{\max}$ ranged from 16.9 °C (Arkona) to 21.1 °C (Magdeburg) (Table 1).

3.2 Hot days

Hot days occured the most frequently in south-western and south-eastern parts of the research domain, with exception of Aachen (Table 2). There were 366 such days in Dresden, above 400 in Köln and Magdeburg, up to 504 in Potsdam (what amounts to 10 hot days per year). On the other hand, hot days were the rarest in the northern part of the research area, especially in Arkona, where only seven such days were noted (Table 2). When analysing a number of hot days in the particular decades, it was stated that these were the rarest between 1976 and 1985 (in the case of 8 out of 12 stations), and the most frequent between 2006 and 2015 (in the case of 9 out of 12 stations) (Table 2). Only in Aachen and Köln the highest number of hot days was observed decade earlier. The analysis of the particular summer seasons showed that in all the considered stations, years 1994 and 2003 can be described with a relatively large number of hot days (Fig. 3). Against the multiannual period, they

Table 1 Mean summer (JJA) $T_{\max}$, its standard deviation and tendency, the highest and the lowest value along with the year of occurrence and 99th daily $T_{\max}$ percentile in lowland Germany (1966–2015)

Station	Mean $T_{\max}$ (°C)	Std. dev. (°C)	Tend. (°C/10 years)	Highest mean $T_{\max}$ (°C)		Lowest mean $T_{\max}$ (°C)		99th perc. (°C)
Aachen	22.0	1.3	0.31*	25.5	2003	19.6	1978	30.8
Arkona	19.1	1.0	0.21*	21.2	2006	16.9	1987	24.8
Bremen	22.1	1.3	0.20	24.6	2003	19.7	1987	30.3
Dresden	23.1	1.2	0.16	25.8	2003	21.0	1980	31.5
Hamburg	21.7	1.3	0.27*	24.4	2003	19.4	1987	30.1
Hannover	22.4	1.2	0.27*	25.4	2003	20.4	1987	30.7
Köln	23.2	1.3	0.35*	26.7	2003	20.7	1978	31.8
Magdeburg	23.4	1.3	0.28*	26.1	1992	21.1	1987	31.8
Potsdam	23.7	1.3	0.22	26.4	2003	21.2	1993	32.3
Rostock	20.7	1.0	0.29*	23.1	1992	18.4	1987	29.2
Schleswig	20.5	1.2	0.30*	23.3	2006	17.8	1987	28.0
Schwerin	21.9	1.2	0.21	24.00	2003	19.5	1987	30.2

* Statistically significant ($p \leq 0.05$)

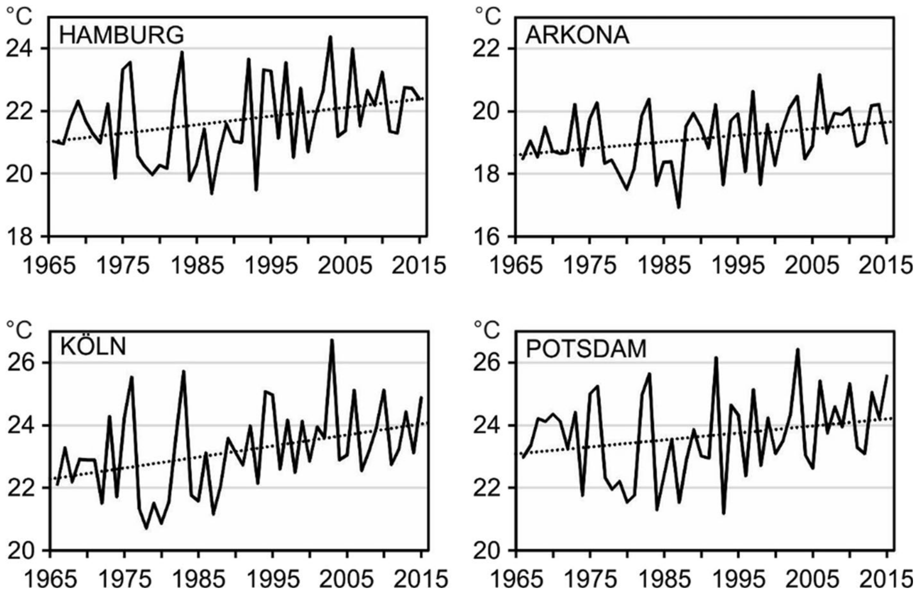


Fig. 2 Temporal variability and linear trends (*dotted lines*) of mean summer (JJA) $T_{\max}$ at the selected stations (1966–2015)

Table 2 Number of hot days in decades, total and average together with their tendency and the highest number observed within a year in lowland Germany (1966–2015)

Station	Hot days									
	1966–1975	1976–1985	1986–1995	1996–2005	2006–2015	Σ	Average (days/ year)	Δ (days/ 10 years)	The highest number within a year	
Aachen	33	36	52	71	58	250	5	0.7*	18	1976
Arkona	1	1	1	2	2	7	0.1	–	1	Several
Bremen	43	33	46	42	55	219	4	0.5	15	1994
Dresden	70	61	88	55	92	366	7	0.0	24	2015
Hamburg	28	27	42	44	48	189	4	0.5*	18	1994
Hannover	40	37	58	54	66	255	5	0.8*	16	1994, 2003
Köln	60	68	90	93	92	403	8	0.8	21	2003
Magdeburg	73	72	98	76	116	435	9	1.0*	22	2003
Potsdam	97	75	97	101	134	504	10	1.1	23	2003
Rostock	23	15	23	25	27	113	2	0.0	8	2010
Schleswig	30	27	44	37	54	192	1	–	7	1994
Schwerin	7	1	15	12	16	51	4	0.5*	18	1994

* Statistically significant ($p \leq 0.05$)

are especially distinguished in the northern part of the analysed area (among others Schleswig, Hamburg, Schwerin). On the other hand, in the south, there were more summer seasons with a relatively large number of hot days (among others 1976, 1994, 2006, 2010, 2015) (Fig. 3). The largest number of hot days within a season in particular stations ranged from 1 in Arkona to 24 in Dresden in the summer of 2015 (Table 2). In the area extending from Köln, through Hannover, to Potsdam the highest number of hot days was observed in 2003 (up to 23 days in Potsdam), in the north-western part of the research area hot days were the most numerous in 1994 (up to 18 in Hamburg and Schwerin) and in the remaining stations in other previously mentioned seasons.

Due to summer $T_{\max}$ warming in the analysed period there was an increase in a number of hot days observed, which was statistically significant in five stations located mainly in the central part of the research domain (Table 2). The most considerable changes were recorded in Magdeburg and Potsdam (up to 1.1 days per 10 years), the

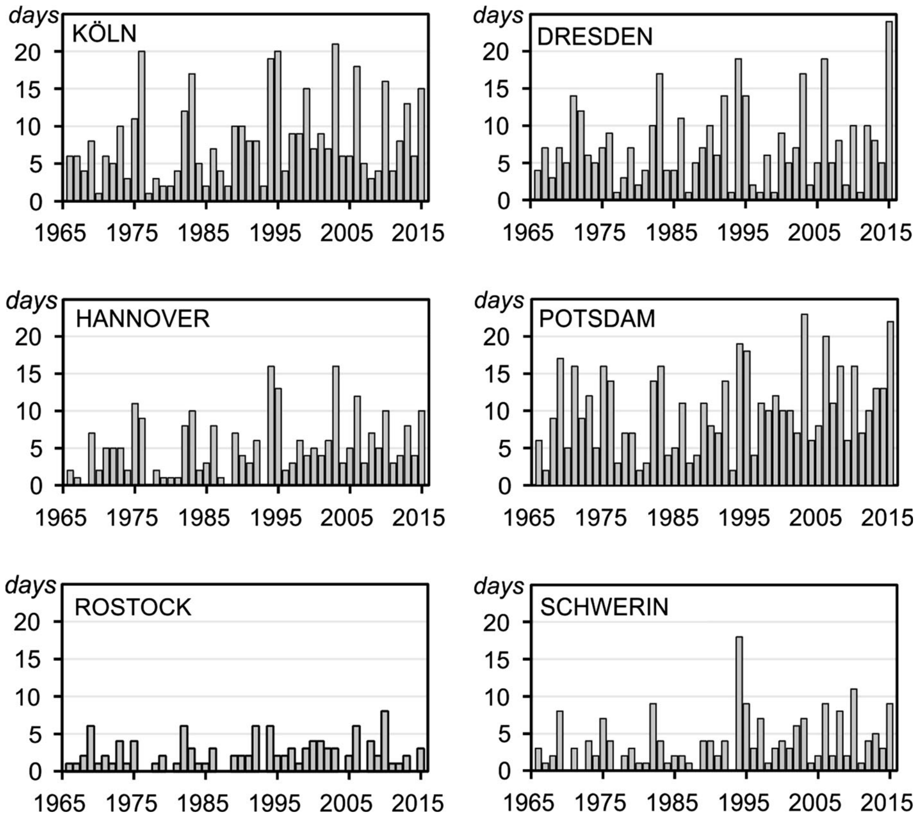


Fig. 3 Temporal variability of hot days in selected stations (1966–2015)

increase of hot days was slightly slower in south-western and central part of the research area (0.5–0.8 days per 10 years) and there was no change observed in Dresden and Rostock (trends in Arkona and Schleswig were not calculated due to few cases of hot days).

Within the investigated area, hot days occurred from April to September; however, these were the most frequent in July and August (respectively, 47 and 33% of all hot days) (Fig. 4). In the analyzed period, the earliest occurrence of a hot day was on 21 April (Bremen, Köln, Magdeburg), and the latest was on 20 September (Aachen, Köln, Potsdam). The shortest potential period of hot days occurrence was observed in Arkona (only 58 days) while the longest one in Magdeburg, Potsdam (152 days each) and Köln (153 days) (Fig. 5).

3.3 Heat waves

A number of heat waves and their duration varied from station to station. They were the most numerous in Potsdam (57 heat waves, that is 9.5 heat waves per 10 years) where, in total, they lasted for 251 days (Table 3). Similar numbers of heat waves were recorded in Magdeburg (49) and Köln (40). On the other hand, there were few heat waves in

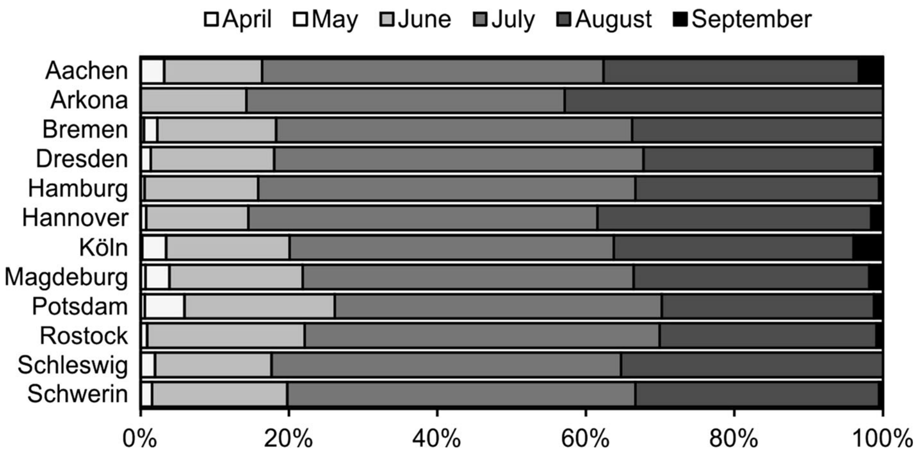


Fig. 4 Percentage of hot days occurring in particular months in lowland Germany (1966–2015)

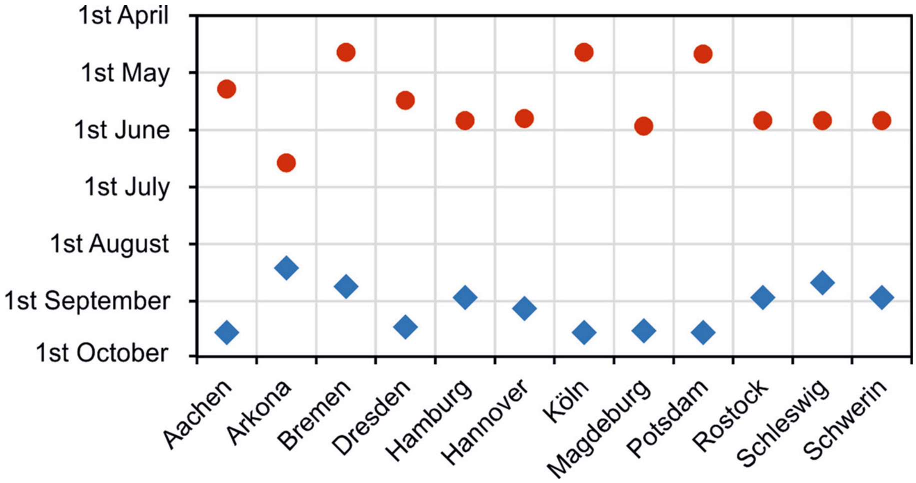


Fig. 5 Potential period of the occurrence of hot days in lowland Germany; *red dots* the earliest occurrence of a hot day, *blue diamond* the latest occurrence of a hot day (1966–2015)

the northern part of the considered area—in Rostock (4), Schleswig (1) and Arkona, where no heat wave was observed. On the average heat waves were the longest in Köln (4.6 days), Aachen and Bremen (4.5 days) (excluding Schleswig where only one 5-day long heat wave was noted), while Rostock was characterized by the shortest mean heat wave duration (3.5 days) (Table 3).

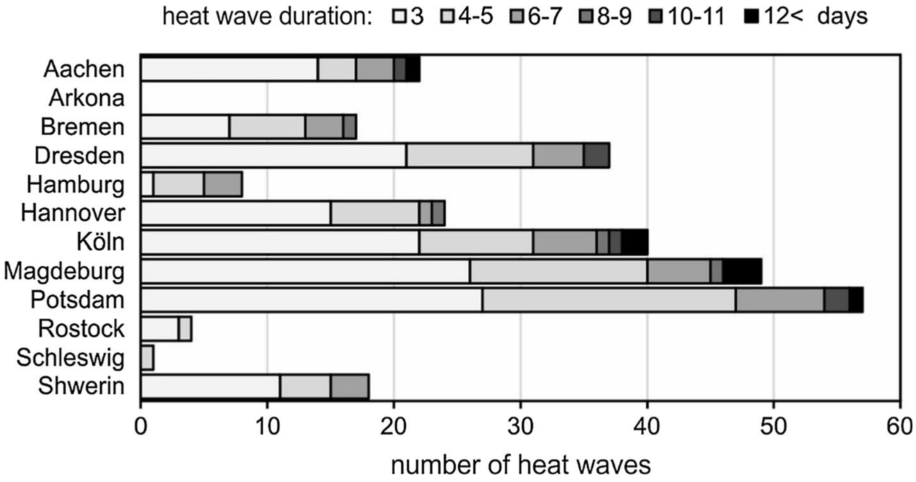
In all the stations where heat waves were observed, these lasting 3 days were the most frequent (they constituted up to 51% of all heat waves) (Fig. 6). Heat waves lasting 4 or 5 days were also quite common—at least one was observed in every station. Heat waves of longer duration (over a week) were sporadic (6% of all heat waves) and were observed mainly in the southern part of the considered area (Fig. 6). The longest heat wave duration in particular stations ranged from 5 days in the northern part of the research domain to more than 10 days in its southern part. All these heat waves were noted during five summer seasons: 1969, 1975, 1976, 1994 and 2006 (Table 3). The heat wave of the longest duration occured between 24th June and 8th July 1976 in Köln and Aachen and lasted 15 days.

In most of the stations, the smallest number of heat waves was observed between 1966 and 1975, and it ranged from 1 in Aachen and Schleswig to 10 in Potsdam (Fig. 7). On the other hand, the largest number of heat waves was noted between 2006 and 2015. In that decade, they were especially numerous in the south-eastern part of the

Table 3 Heat waves frequency and duration characteristics and the longest heat waves along with dates of occurrence in lowland Germany (1966–2015)

Station	Heat waves				The longest heat wave (days) with the occurrence dates	
	Total number	Mean freq. per 10 years	Total length (days)	Mean length (days)		
Aachen	22	3.7	98	4.5	15	24.06–8.07.1976
Arkona	–	–	–	–	–	–
Bremen	17	2.8	76	4.5	9	4–12.08.1975
Dresden	37	6.2	154	4.2	11	18–28.07.2006
Hamburg	17	2.8	66	3.9	7	22–28.07.1994
Hannover	24	4.0	92	3.8	9	4–12.08.1975
Köln	40	6.7	185	4.6	15	24.06–8.07.1976
Magdeburg	49	8.2	217	4.4	12	23.07–3.08.1969 1.07–1.08.1994 17–28.07.2006
Potsdam	57	9.5	251	4.4	12	23.07–3.08.1969
Rostock	4	0.7	14	3.5	5	29.07–2.08.1969
Schleswig	1	0.2	5	5.0	5	8–12.08.1975
Schwerin	18	3.0	70	3.9	7	28.07–3.08.1969 22–28.07.1994

Fig. 6 Number of heat waves of particular duration in lowland Germany (1966–2015)

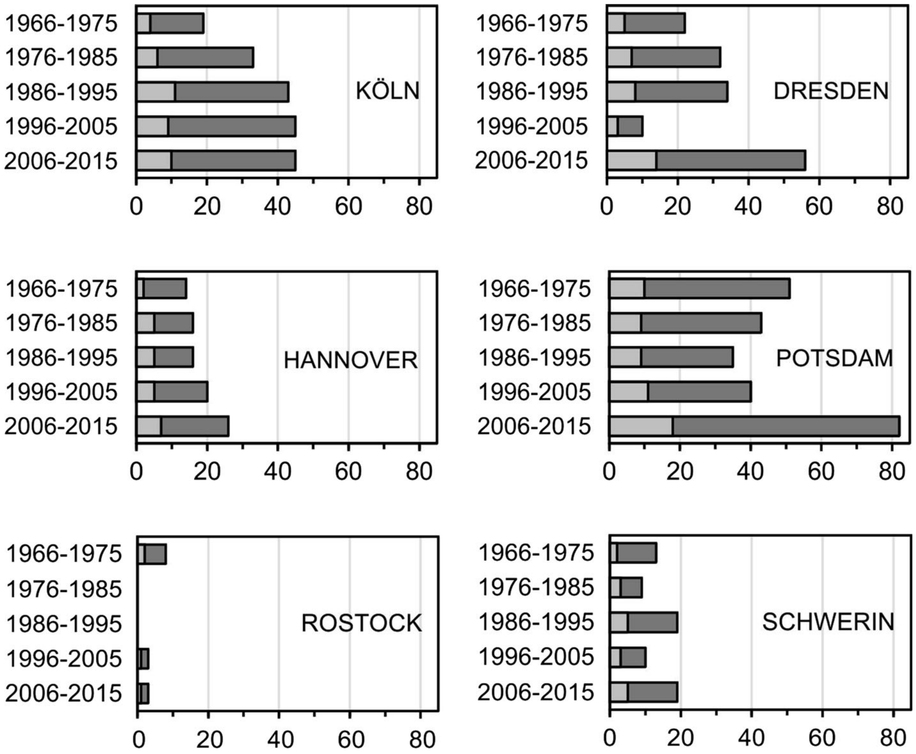


considered area, and the largest part occurred in Potsdam (18 waves). In most of the stations, the heat waves were also the longest in that period.

In the analysed multiannual period, the heat waves occurred from May to September; however, these were the most frequently recorded in July (53% of all heat waves) (Fig. 8). In most of the stations, the first heat wave was most often recorded in the first half of June, while the last one in the second half of August. The earliest heat wave in the analysed multiannual period was recorded in Aachen and Köln, from 11 to 13 May 1998, while the latest one in Köln, from 11 to 14 September 1999. Using the dates of beginnings and ends of heat waves, the potential period of their occurrence was determined and this was the shortest in Schleswig (only 5 days as there was only 1 heat wave), and the longest in Aachen (126 days) and Köln (127 days) (Fig. 9).

The highest mean $T_{\max}$ during heat waves was observed in Magdeburg and Potsdam; it was 35.9 °C and occurred during heat waves of (respectively) 14–16 July 2007 and 8–12 July 2010 (Table 4). In the northern part of the research area it was considerably lower, for example, 31.4 °C in Schleswig during the heat wave of 8–12.08.1975. On the other hand, the highest $T_{\min}$ was recorded in Rostock and it was 21.6 °C during the wave of 10–12 July 2010. Considering daily $T_{\max}$ extremes

Fig. 7 Number of heat waves (*light grey*) and number of hot days contributing to heat waves (*dark grey*) shown in decades in selected stations (1966–2015)



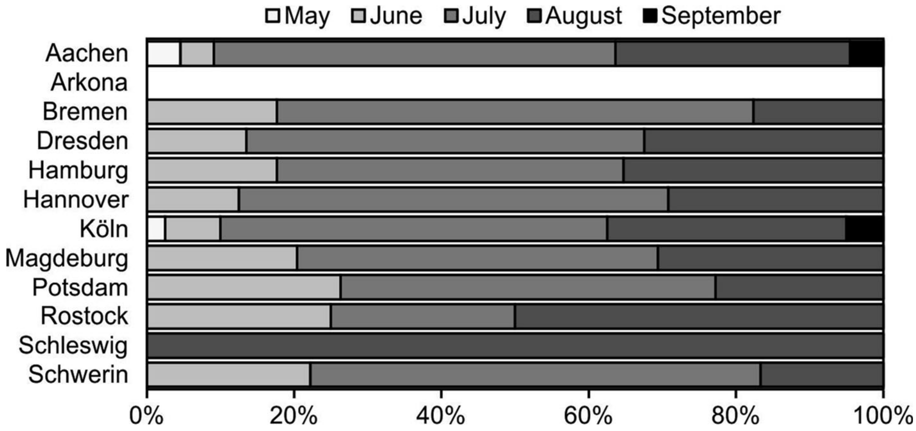


Fig. 8 Percentage of heat waves occurring in particular months in lowland Germany (1966–2015)

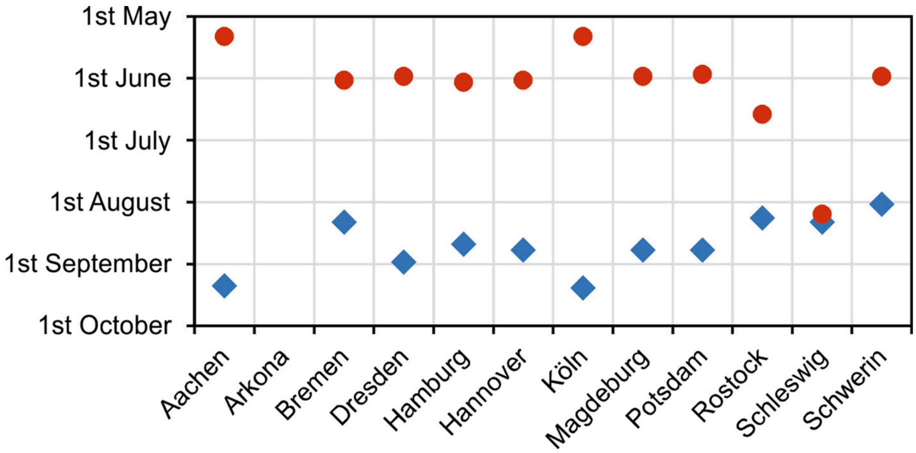


Fig. 9 Potential period of the occurrence of heat waves in lowland Germany; *red dots* the earliest beginning of a heat wave, *blue diamond* the latest ending of a heat wave (1966–2015)

Table 4 Highest average T_{max} and T_{min} during heat waves and highest daily T_{max} and T_{min} along with the dates of occurrence in lowland Germany (1966–2015)

Station	Heat waves				Highest daily T_{max} (°C) with the occurrence date		Highest daily T_{min} (°C) with the occurrence date	
	Highest mean T_{max} (°C) with the occurrence date		Highest mean T_{min} (°C) with the occurrence date					
Aachen	33.6	8–12.07.2010	20.0	24–26.07.2006	36.8	12.08.2003	24.2	09.08.1992 19.08.2012
Arkona	–	–	–	–	31.3	16.08.1974	22.1	10.07.2010
Bremen	35.7	4–12.08.1975 7–12.08.2003 6–8.08.2015	19.4	2–4.07.2015	37.6	09.08.1992	21.5	11.07.2010
Dresden	35.7	6–8.08.2015	20.0	14–17.07.2007 2–5.07.2015	37.4	07.08.2015	23.5	16.07.2007
Hamburg	33.8	19–21.06.2000	19.1	12–14.07.1994 22–28.07.1994	37.3	09.08.1992	24.4	28.07.1994
Hannover	34.0	7–12.08.2003	19.9	8–12.07.2010	37.4	09.08.1992	22.7	11.07.2010
Köln	35.0	1–5.07.2015	19.1	18–20.08.2012	38.8	12.08.2003	21.9	02.07.2015
Magdeburg	35.9	14–16.07.2007	19.1	16–28.07.2003	38.1	16.07.2007 4.07.2015	21.8	11.07.2010
Potsdam	35.9	8–12.07.2010	19.3	13–16.08.2015	38.6	09.08.1992	21.9	20.08.2012
Rostock	33.9	10–12.07.2010	21.6	10–12.07.2010	36.9	09.08.1992	22.5	28.07.1994
Schleswig	31.4	8–12.08.1975	17.4	8–12.08.1975	33.5	21.07.1992	21.2	01.08.1994
Schwerin	33.4	19–21.06.2000	20.1	8–12.07.2010	36.9	09.08.1992	22.9	10.07.2010

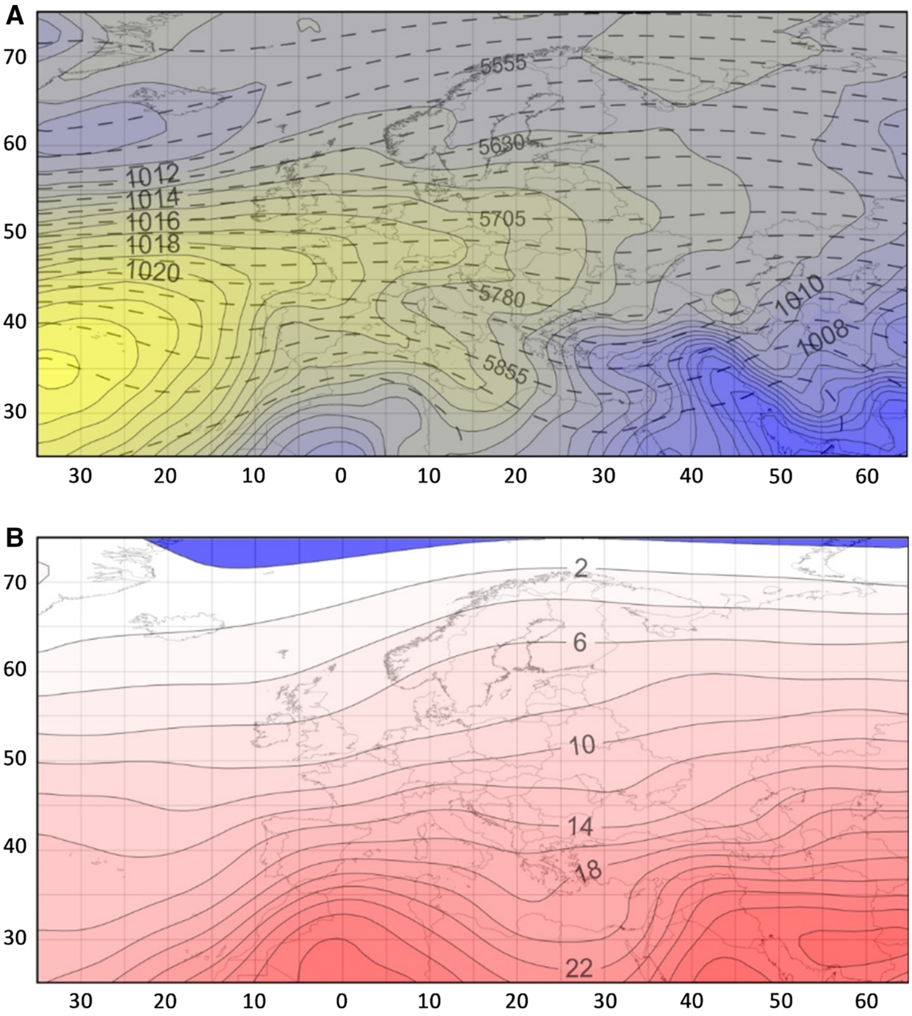


Fig. 10 Mean summer (June–August) **a** SLP in hPa and z500 hPa in m and **b** T850 (°C)

(occurring whether during heat waves or not) these were the highest in Köln and Potsdam (above 38.5 °C) and the lowest in Arkona (31.3 °C). In case of T_{min} the south-north differences were considerably smaller (24.4 °C in Hamburg comparing to 21.2 °C in Schleswig). In the majority of the analysed stations, both the highest T_{max} and T_{min} (both mean and absolute values) were recorded in the second half of the research period.

3.4 Atmospheric circulation

Between 1966 and 2015, in the Euro-Atlantic Sector, the mean sea level pressure in the summer season (June–August) ranged from <1010 hPa in the Icelandic Low to >1024 hPa in the Azores High (Fig. 10a). Between the above-mentioned pressure systems, over the Atlantic Ocean, there were big pressure gradients. Smaller gradients were observed over the Continent. SLP ranged from 1014 to >1017 hPa over the analysed area. A supplement to the description of atmospheric circulation in higher layers of troposphere were z500 hPa maps. In the warmer air masses, pressure is dropping slower with height than it is in cooler ones; therefore, z500 hPa in warmer masses is laying higher. In the analysed period, height of the 500 hPa isobaric level was inclined towards the north. Its maximum height was recorded over the Mediterranean Sea (>5880 gpm), and the minimum was found over the northern Atlantic (<5500 gpm). Air temperature on the 850 hPa isobaric level decreased from the south (>20 °C) to the northwest (<0 °C) (Fig. 10b). The aforementioned pressure system caused the west circulation; typical for Europe, both in the middle and bottom troposphere.

Between 1966 and 2015, the occurrence of heat waves in lowland Germany was related to a ridge of high-pressure lying over the continent with its centre over the Azores Islands, within which there was a local high-pressure area formed with its centre over the Baltic Sea (>1020 hPa) (Fig. 11a). On those days, positive SLP anomalies with the centre over southern Sweden (>7 hPa) were observed over the majority of the Continent. SLP ranged from 1017 to >1019 hPa over the analysed area and was higher than on average in summer by 1–5 hPa (Fig. 11b). That system

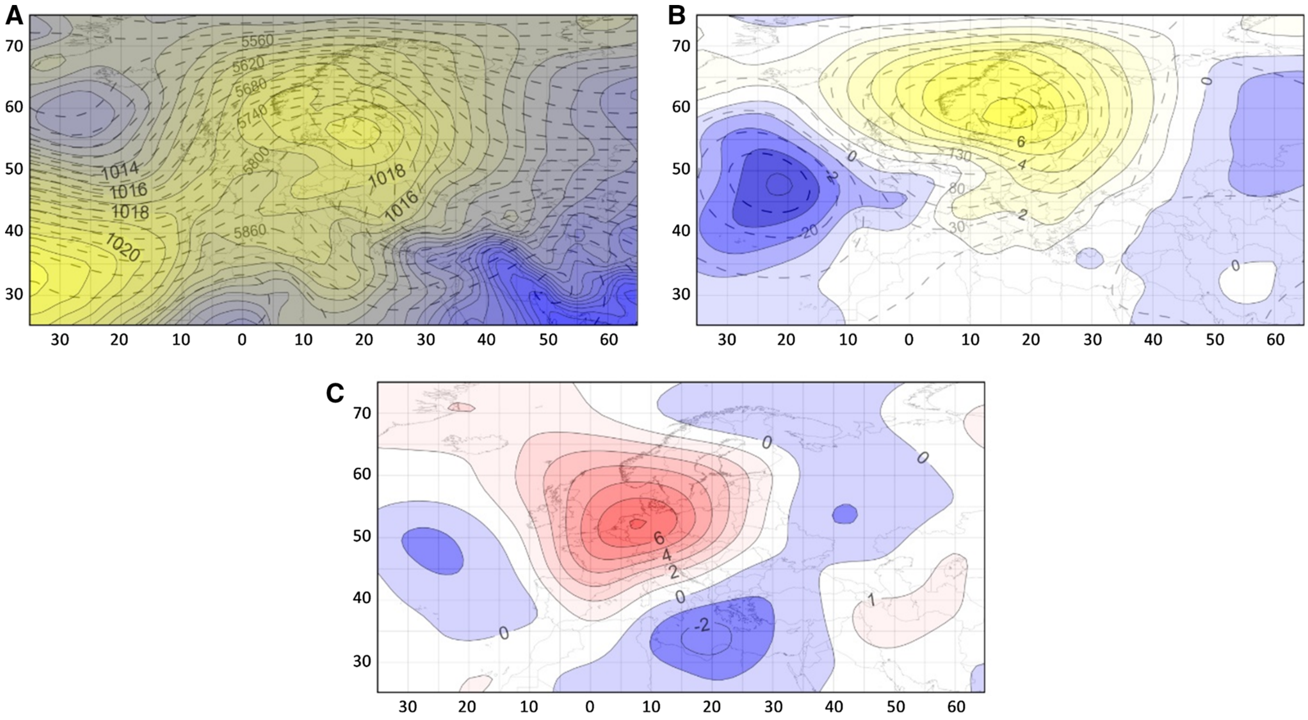


Fig. 11 **a** Mean SLP (hPa) and z500 hPa (gpm), **b** SLP (in hPa) and z500 hPa (m) anomalies, **c** anomalies of T850 (°C) for the heat wave days

caused the advection of warm and dry continental air masses from the eastern sector. The contour lines of the 500 hPa isobaric level over the analysed area bent northwards creating its clear elevation (>5820 gpm). The pattern of z500 hPa contour lines shows south-western air flow in the middle troposphere layer. The research area stayed within the reach of z500 hPa positive anomalies, which ranged from 105 to >150 m which proves warm air masses lying on the analysed days. The presence of these air masses are also confirmed by T850 positive anomalies, which centre was located over north-western Germany (>7 °C) (Fig. 11c).

Hot days forming heat waves were grouped with regard to the sea level pressure distribution and, on this basis, two types of circulation were distinguished (Fig. 12). A dominating type (126 days) of circulation causing the occurrence of the aforementioned days was type 1 (T1) with a wide ridge of high pressure, within which there was a local high-pressure area formed over the Baltic Sea and northern Poland (>1019 hPa), where SLP was higher by almost 5 hPa than on average in summer in the analysed multiannual period. Over the analysed area, SLP anomalies ranged from 1 to 5 hPa. On the other hand, type 2 (T2) included 38 hot days during which Europe was under the influence of a strong high with the centre over the northern Baltic Sea (1025 hPa). In the case of T2, similar to T1, there were SLP positive anomalies recorded; however, compared to T1, these were much stronger and in the centre of the system, they exceeded 13 hPa (over the analysed area up to 8 hPa). The contour lines of the 500 hPa isobaric level 500 hPa over the Central Europe bent northwards and north-eastwards creating its clear elevation over the analysed area. Both z500 hPa and T850 positive anomalies indicate the presence of warm air masses in this part of the continent. Both in type 1 and 2, T850 maximum anomalies were recorded over north-western Germany and these were >7 °C. Advection of air masses from the southwest was dominating in type 1 while in type 2 it was from the eastern sector. The aforementioned directions of air flow were also shown by 48-h back trajectories of air particles for the selected days, i.e., in type 1 for 26 July 1994 and 4 July 2015 and type 2 for 3 June 1979 and 28 July 2008. All the trajectories show air mass settling which is typical of high-pressure systems (Fig. 13).

3.5 Heat waves of 2003

In the summer of 2003 daily $T_{\max}$ in lowland Germany was above the long-term daily mean for 73.4% of days on the average. The summer was the most anomalous in the south-western part of the research area represented by Aachen and Köln, where it was hotter than normal for 80.4% of days (Table 5; Fig. 14). Hot days were noted in all the stations except Arkona and heat waves occurred in 8 out of 12 stations. Both hot days and heat waves were the most numerous in Magdeburg and Potsdam. The first heat waves

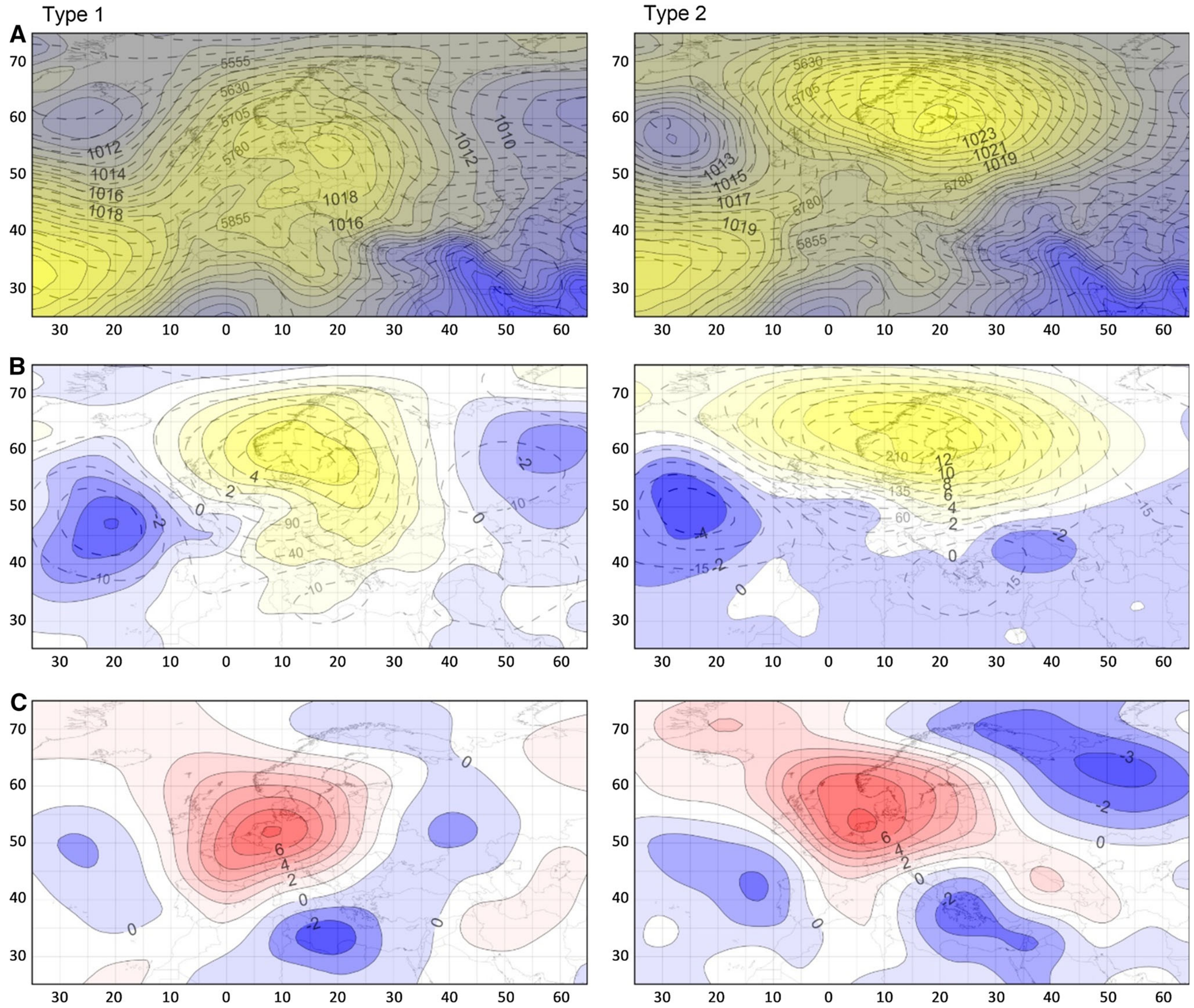
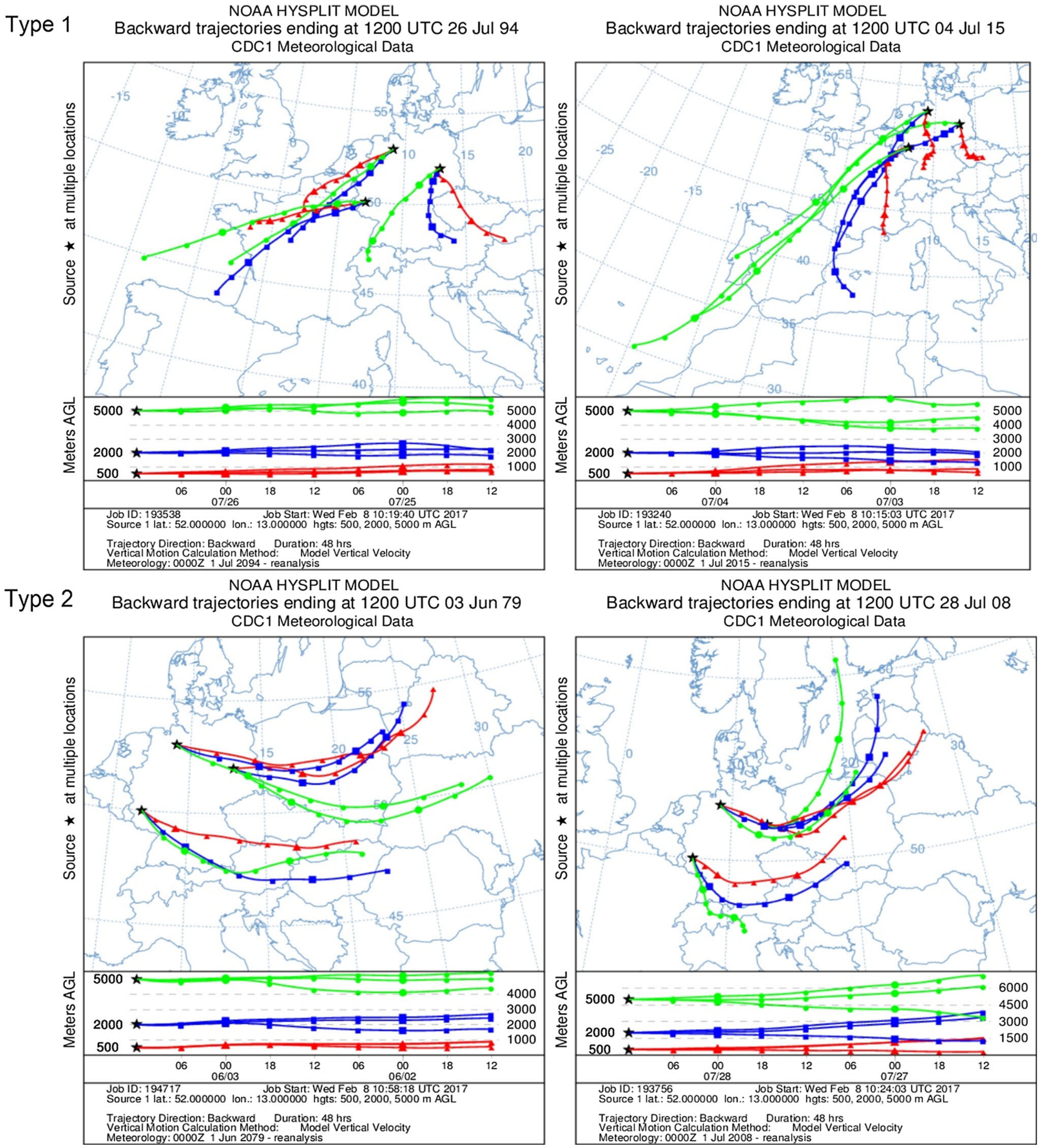


Fig. 12 **a** Mean SLP (hPa) and z500 hPa (gpm), **b** SLP (in hPa) and z500 hPa (m) anomalies, **c** anomalies of T850 (°C) for the synoptic type 1 and 2 causing heat waves in the considered area

at these two stations were noted at the very beginning of June, when T_{max} exceeded 30.0 °C in almost all the stations located in the eastern and central parts of the research area. Second very hot period occurred in the middle of July, when hot days were observed in all the stations (except Arkona) (Table 5; Fig. 14). The largest number of hot days and heat waves in lowland Germany during this summer were observed in the first half of August. In that time in Köln the longest heat wave was observed (12 days; 2.08–13.08). This period was also the hottest during the whole summer as T_{max} reached its highest values in almost all stations. In more than a half of them T_{max} exceeded 35.0 °C and in Köln it peaked at 38.8 °C (Table 5; Fig. 14).

In the summer of 2003, a high-pressure ridge, extending up to Eastern Europe, settled over the majority of the Euro-Atlantic sector (Fig. 15). A low-pressure system with the center (<1008 hPa) in the south-western Iceland laid over the North Atlantic. Eastern Europe, on the other hand, was under the influence of the trough of low-pressure. In the analyzed season SLP over the Atlantic, Western and Eastern Europe was lower than the average in the summer in the discussed multi-year period. The occurrence of positive anomalies was observed over the analysed area, but they did not exceed 1 hPa. The aforementioned system caused advection of hot air masses from the southwest. Contour lines of isobaric surface 500 hPa over the majority of the continent bent northward creating its clear elevation. The pattern of z500 hPa contour lines shows south-western air flow in the middle troposphere layer. The presence of warm air masses over the majority of the continent is confirmed


Type 1

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 26 Jul 94
CDC1 Meteorological Data

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 04 Jul 15
CDC1 Meteorological Data

Type 2

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 03 Jun 79
CDC1 Meteorological Data

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 28 Jul 08
CDC1 Meteorological Data

Fig. 13 48-h backward trajectories for the selected days in the synoptic type 1 and 2 causing heat waves in the considered area

by positive z500 hPa anomalies, which in the center (German–French border) exceeded 60 m. The presence of warm air masses is also indicated by positive T850 anomalies, which in the center (over France) exceeded 4 °C. At the same time Eastern Europe remained within the reach of cool air masses.

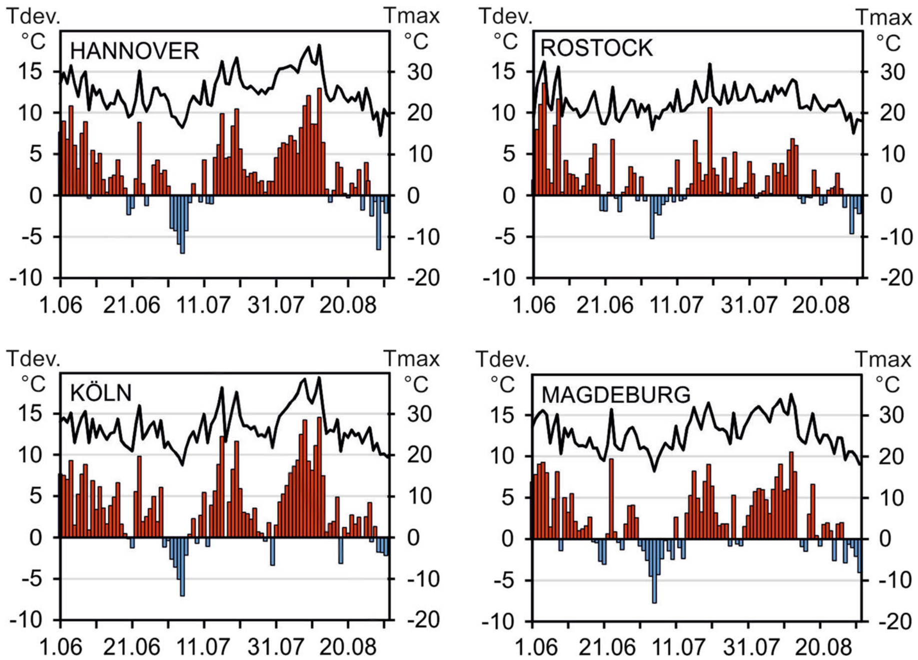
4 Summary and discussion

The conducted analyses showed great spatial diversity of the temperature extremes in the lowland Germany over the period 1966–2015, which refers to the spatial distribution of the maximum air temperature ($T_{\max}$) in summer. The

Table 5 Thermal characteristics of the summer of 2003: mean summer T_{max}, days with T_{max} above long-term average (%), highest daily T_{max} and number of heat waves along with the dates of occurrence in lowland Germany

Station	Mean summer T_{max} (°C)	% days with anomaly	Highest daily T_{max} along with date of occurence		Number of hot days	Dates of heat waves along with their duration (days)	
Aachen	25.5	80.4	36.8	12.08	14	3.08–12.08	10
Arkona	20.5	75.0	27.2	13.08	–	–	–
Bremen	24.6	75.0	35.8	12.08	9	7.08–12.08	6
Dresden	25.8	69.6	36.0	13.08	17	2.08–4.08	3
Hamburg	24.4	71.7	34.4	12.08	11	7.08–12.08	6
Hannover	25.4	76.1	36.5	12.08	16	1.08–05.08	5
						7.08–12.08	6
Köln	26.7	80.4	38.8	12.08	19	2.08–13.08	12
Magdeburg	22.7	66.3	35.1	12.08	22	3.06–5.06	3
						19.07–21.07	3
						1.08–4.08	4
						7.08–13.08	7
Potsdam	26.4	68.5	35.5	13.08	21	2.06–5.06	4
						19.07–21.07	3
						1.08–4.08	4
						7.08–9.08	3
Rostock	22.6	71.7	32.4	1.06	3	–	–
Schleswig	22.7	76.1	31.9	20.07	4	–	–
Schwerin	24.0	69.6	33.2	12.08	7	–	–

Fig. 14 Daily maximum temperature (*right axis*) and its deviations from the long-term (1966–2015) average during the summer of 2003 in selected stations



stations located in the southern part of the research area (especially Köln, Potsdam and Magdeburg) were characterized by the highest mean T_{max} and the largest number of hot days and heat waves. Aachen and Dresden, despite their location further to the South, were described by somewhat lower frequency of temperature extremes, what was a consequence of slightly higher elevation. Temperature extremes were the least frequent in the northern part of

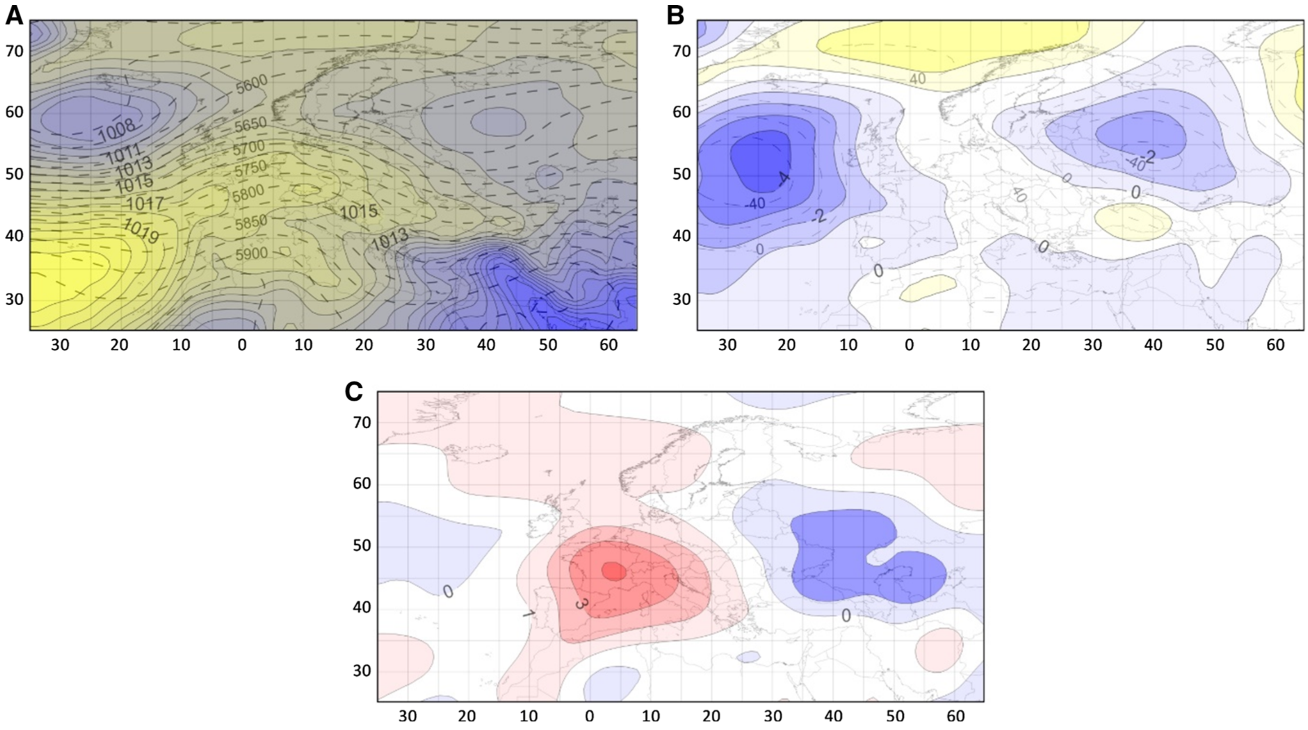


Fig. 15 **a** Mean SLP (hPa) and z500 hPa (gpm), **b** SLP (hPa) and z500 hPa (gpm) anomalies, **c** anomalies of T850 (°C) in the summer of 2003

the considered area, especially in Arkona. Lower temperatures in this region of Germany are a joint result of the location to the North and cooling sea influence.

There was an upward trend of the summer $T_{\max}$ observed (0.25 °C per 10 years on the average), which was statistically significant in the most of the considered stations and was the most intensive in the south-western part of the research area (up to 0.35 °C per 10 years in Köln). $T_{\max}$ increase was especially visible in the last 20 years of the considered period, when its values usually exceeded the long-term (1966–2015) average in particular stations. Summer $T_{\max}$ warming was accompanied by an increasing frequency of hot days in most of the stations, which was the most rapid in south-eastern part of the research domain (up to 1.1 days per 10 years in Potsdam). This tendency resulted in increased frequency of heat wave occurrence. In the analysed 50-year period, in the lowland part of Germany, the smallest number of heat waves was observed in years 1976–1985, while the largest one in 2006–2015.

The obtained results concerning temporal variability and tendencies of temperature extremes are confirmed by the results of research of other authors, obtained both for the area of Germany (Kundzewicz and Józefczyk 2008; Kundzewicz and Huang 2010; Tomczyk 2017) and the neighbouring countries, e.g., Poland (Wibig et al. 2009; Michalska 2011; Tomczyk 2014; Wójcik and Miętus 2014; Wypych et al. 2017), Czech Republic (Kyselý 2010), and France (Vidal et al. 2010). As Tomczyk (2017) has shown, within the last 120 years in Potsdam, the largest number of heat waves was recorded between 2006 and 2015, although hot days were most numerous in 1947. Wypych et al. (2017) found positive trends in mean summer $T_{\max}$ in Poland (0.4 °C on the average) and number of days with extreme temperature (1.2 days per 10 years) which are similar (regarding the magnitude) to the demonstrated for lowland Germany. Summer seasons with enhanced heat wave characteristics identified for different parts of lowland Germany correspond to the European results, describing the summers of 1976, 1992, 1994, 2003, 2006, 2010 and 2015 as extremely hot in particular European regions (Kyselý 2010; Barriopedro et al. 2011; Russo et al. 2015; Hoy et al. 2016; Wypych et al. 2017).

The occurrence of heat waves in Northern Germany was related to a ridge of high-pressure lying over Europe, within which there was a local high-pressure area formed with its centre over the Baltic Sea. The detailed analysis of circulation showed two types of circulation, that is, type 1 with a wide ridge of high pressure, within which there was a local high-pressure area formed with its centre over the Baltic Sea and northern Poland, and type 2 with a strong high with the centre over the northern Baltic Sea. Over the analysed area, there were SLP, z500 hPa and T850 positive anomalies. Similar pressure systems were determined by Tomczyk and Bednorz (2014) who have analysed atmospheric circulation during heat and cold waves on the south coast of the Baltic Sea. An alternative circulation type causing the occurrence of heat waves in Central Europe is a low-pressure area with its centre to the west of Ireland (Tomczyk and Bednorz 2016). Most of all, the occurrence of heat waves is related to anticyclonic weather which is characterised by great insolation, cloudlessness or a small cloud cover and what makes surface and air heating possible (Black et al. 2004; Fink et al. 2004; Rebetez et al. 2009; Porębska and Zdunek 2013; Unkašević and Tošić 2015).

We identified the summer of 2003 to be one of the most severe summer seasons in lowland Germany, especially in its south-western part. This confirms the findings of Schönwiese et al. (2004) who examined time series 1761–2003 representative of Germany and found the summer of 2003 to be the hottest on record. Our results, concerning both temperature anomalies and circulation conditions in the summer of 2003 are in accordance with a large number of European studies which examined this season in details (e.g., Black et al. 2004; Beniston 2004; Schär and Jendritzky 2004).

Numerous studies have shown that European societies are very vulnerable to the occurrence of hot days and heat waves (Trigo et al. 2005; D'Ippoliti et al. 2010; García-Herrera et al. 2010; Barriopedro et al. 2011; Hoy et al. 2016), therefore, this subject has been in the focus of attention of many scholars. With regard to the observed increase in the frequency of heat wave occurrence in Europe in the past decades, further studies are necessary to explain the mechanisms of forming of heat waves.

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