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ORIGINAL PAPER

Hot weather in Potsdam in the years 1896–2015

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Abstract The main objective of this article was the analysis of multiannual variability in the occurrence of hot days and heat waves in Potsdam in the last 120 years. The article used data concerning the maximum and minimum daily air temperature in Potsdam between 1896 and 2015, which were obtained from the Deutscher Wetterdienst database. A hot day was defined as a day with T_{max} >30 °C, and a heat wave was considered a sequence of at least three hot days. The analysed multiannual period showed a statistically significant increase in T_{max} in summer, which was 0.13 °C per 10 years. The observed increase in T_{max} translated into an increase in the number of hot days and, consequently, in the frequency of the occurrence of heat waves. Within the analysed multiannual period, the lowest number of heat waves was recorded between 1896 and 1905, while the highest was observed between 2006 and 2015.

1 Introduction

The climate warming currently being observed is, beyond doubt, with its changes manifesting in ever more frequent extreme weather events (IPCC 2013). The increase in the frequency of these phenomena is associated with an increase in mortality caused by biometeorological conditions affecting human body systems (Kuchcik 2001; Hajat et al. 2002; Kuchcik and Degórski 2009; Paldy and Bobvos 2009; Bobvos et al. 2015) and major economic losses (De Bono et al. 2004). These effects were clearly visible in the extreme heat waves of 2003 and 2006 in Western and Southern Europe (Vandentorren et al. 2004; Fouillet et al. 2006; Monteiro et al. 2013) and of 2010 in Russia (Shaposhnikov et al. 2014; Revich et al. 2015). As Barriopedro et al. (2011) show, the heat waves of 2003 and 2010, termed as "mega heat waves", broke the 500-year seasonal air temperature records across approximately 50% of the surface of Europe. This issue would appear to be particularly important in light of current forecasts indicating that, in the twenty-first century, heat waves will be not only more frequent, but also longer and more intense (Meehl and Tebaldi 2004; Beniston et al. 2007; Kyselý 2010; Zacharias et al. 2015).

The majority of available research studies concerning heat waves is based on the last 30-, 40- or 50-year period (Unkašević and Tošić 2015; Tomczyk and Bednorz 2016). Therefore, conducting a research study based on long series of data seems to be justified. Consequently, the station in Potsdam was chosen, which is one of only few stations in the world that is characterised by a homogeneous data series uninterrupted since the end of the nineteenth century. Series of measurements from this station are representative for the surrounding environment of different spatial and temporal scales (http://www.pik-potsdam.de). The objective of this study was to determine the long-term variability in the occurrence of hot days and heat waves in Potsdam over the last 120 years.

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2 Definition of heat waves, data and research methods

The literature contains various definitions of heat waves, which differ in their methodological assumptions. As Krzyżewska (2010) shows, this results from the fact that the onset of heat waves depends primarily on local climatic conditions, which vary with latitude, height above sea level and direction of air-mass inflow. In this article, a hot day was a day with T_{max} >30 °C, and a heat wave was a sequence of at least three such days. This definition has also been adopted in the works of, among others, Kyselý (2002) and Kossowska-Cezak (2010). However, a heat wave can also be defined as: (1) a several-day period of apparent temperature (AT) above the 95th percentile and beginning with a temperature increase of at least 2.0 °C on the previous day (Kuchcik and Degórski 2009); (2) a period of >5 consecutive days with T_{max} >5 °C above the 1961–1990 daily T_{max} norm (Frich et al. 2002; Unkašević and Tošić 2009); (3) a several-day period of maximum temperature above the 95th annual percentile (Tomczyk and Bednorz 2016).

This work uses maximum and minimum diurnal air temperature values (T_{max} and T_{min}) from the Potsdam station for the period 1896–2015. The data were obtained from the public-access Deutscher Wetterdienst database (http://www.dwd.de). The meteorological station is located to the south-west of town in Potsdam, at a distance of approximately 600 m from a built-up area which makes that an urban heat island is not present there (Kundzewicz and Huang 2010; http://www.pik-potsdam.de). In close vicinity to the area, there is a flat area surrounded by trees at a distance of 50–100 m. Meteorological measurements and observations were carried out at the station since 1 January 1893. The data have maintained their homogeneity. This is possible, among others, thanks to unchanged location of the station, unchanged surroundings of the station, unchanged methods, principles and date of observations (http://www.pik-potsdam.de).

Based on these data, average summer T_{max} (June–August) and number of hot days were calculated, from which heat waves were subsequently identified. Long-term trends in the changes in these climate parameters were identified, and the character of their changes was evaluated using a linear regression model. Then, the statistical significance of the slope was assessed using t Student's test at the level $p \leq 0.05, p \leq 0.01$. T_{max} anomalies were also calculated as a difference between the average T_{max} of a given month and the long-term average T_{max} for that month. In the next stage, a thermal classification of months and years was carried out, according to the method proposed by Lorenc (1994) and modified by Migała et al. (2016). In this method, the evaluation of thermal conditions is carried out on the basis of a comparison between the average T_{max} of a given period on the one hand, and the average T_{max} of the multi-year period under analysis increased or decreased by a multiple of the standard deviation on the other. In this classification, five classes were distinguished, namely: very warm $t > T + 1.5\sigma$; warm $T + 1.5\sigma \geq t > T + 0.5\sigma$; normal $T + 0.5\sigma \geq t \geq T - 0.5\sigma$; cold $T - 0.5\sigma > t \geq T - 1.5\sigma$; very cold $t < T - 1.5\sigma$.

In addition to this, the type of circulation was defined for hot days, using the Grosswetterlagen (GWL) series developed by Hess and Brezowsky (Werner and Gerstengarbe 2010). This classification comprises 30 Grosswetterlagen circulation types grouped by the direction of air-mass advection (Table 1). Circulation types for the particular days were obtained from two sources, that is, for the 1896–2009 period from the Potsdam Institute for Climate Impact Research and for the 2010–2015 period from the online databases (http://www.orniwetter.info). Based on the above data, the frequency of occurrence of hot days within the specific circulation types was established, as well as the probability of these days occurring within each specific type.

3 Results

3.1 The maximum temperature in the summer

In Potsdam, the average T_{max} for the summer (June–August) was 23.2 °C in the years 1896–2015. The coolest summer was recorded in 1902, with an average of 20.5 °C. Similarly, cool seasons were recorded in 1907, 1923 and 1962 (20.7 °C) (Fig. 1a). According to the adopted thermal classification, these seasons were classified as very cold. Additionally, the summers of 1916, 1956 and 1993 also fell into that group. In turn, the warmest summer was recorded in 2003, with an average T_{max} of 26.4 °C. Similar thermal conditions were also seen in the summer of 1992 (26.2 °C). These seasons, along with those of 1947, 1983, 2006, 2010 and 2015, were classed as very warm seasons.

Figure 1b shows the exchange of average T_{max} anomalies together with a moving (5-year) average, based upon which warmer and cooler periods can be distinguished alternately. The cooler periods, in which negative anomalies predominated, occurred from the turn of the twentieth century to the beginning of the 1930s and at the turn of the 1960s, as well as in the 1980s. Subsequently, a clear rise in T_{max} is observed from the mid-1990s. The lowest average T_{max} belonged to the decade of 1916–1925 (22.3 °C) and the highest to 2006–2015 (24.4 °C). Over the studied multi-year period, a statistically significant increase in summer T_{max} was identified at a rate of 0.13 °C per decade.

Table 1 Types of Grosswetterlagen circulation (Werner and Gerstengarbe 2010)

Grosswettertype (GWT)	Symbol	Grosswetterlage (GWL)
West	WA	West circulation, anticyclonal
	WS	West circulation, cyclonal
	WZ	Southern west circulation
	WW	Angled west circulation
Southwest	SWA	Southwest circulation, anticyclonal
	SWZ	Southwest circulation, cyclonal
Northwest	NWA	Northwest circulation, anticyclonal
	NWZ	Northwest circulation, cyclonal
Central Europe high	HM	Central European high
	BM	Central European ridge
Central Europe low	TM	Central European low
North	NA	North circulation, anticyclonal
	NZ	North circulation, cyclonal
	HNA	Norwegian sea high, anticyclonal
	HNZ	Norwegian sea high, cyclonal
	HB	British Isles high
	TRM	Central Europe trough
Northeast	NEA	Northeast circulation, anticyclonal
	NEZ	Northeast circulation, cyclonal
East	HFA	Fennoscandian high, anticyclonal
	HFZ	Fennoscandian high, cyclonal
	HNFA	Norwegian sea/Fennoscandia high, anticyclonal
	HNFZ	Norwegian sea/Fennoscandia high, cyclonal
Southeast	SEA	Southeast circulation, anticyclonal
	SEZ	Southeast circulation, cyclonal
South	SA	South circulation, anticyclonal
	SZ	South circulation, cyclonal
	TB	British Isles low
	TRW	Western Europe trough
	U	Undefined

In June, the average T_{max} was 22.2 °C and fluctuated between 15.6 °C in 1923 and 27.2 °C in 1917. This month was classed as very cold in 1916, 1918, 1923 and 1984, but as very warm in 1915, 1917, 1930, 1947, 1970, 1992 and 2003. An increase in T_{max} was identified over the period under analysis, although the changes were not statistically significant. On average, the warmest month of the year was July (58 instances) with an average T_{max} reaching 23.9 °C. The lowest average T_{max} for this month was found in 1898 (19.3 °C) and the highest in 2006 (30.5 °C). This month was classed as very cold in 1898, 1902, 1907, 1954, 1962, 1965, 1979 and 1984, but as very warm in 1976, 1983, 1994, 2006, 2010 and 2014. Over the studied period, a statistically significant ($p < 0.05$) increase in T_{max} was identified at a rate of 0.14 °C per decade. August was slightly cooler than July; the average T_{max} was 23.4 °C and fluctuated between 19.5 °C in 1902 and 28.8 °C in 2015. This month was classed as very cold in 1896, 1902, 1912 and 1956, but as very warm in 1911, 1944, 1971, 1975, 1997, 2002, 2003, 2009 and 2015. Over the studied multi-year period, the increase in T_{max} was 0.19 °C per decade and statistically significant ($p < 0.01$).

3.2 Hot days

In Potsdam in the years 1896–2015, there were eight hot days recorded annually. Their number in particular seasons ranged from 0 in 1916 and 1965 to 26 in 1947 (Fig. 2a). Over 20 hot days were also observed for 2003 and 2015. The fewest such days occurred in the years 1896–1905, with a total of 49. However, the greatest number of such days was observed in the years 2006–2015 (134 days), 1996–2005 (101 days) and 1946–1955 (100 days). Over the studied multi-year period, a statistically significant ($p < 0.01$) increase in hot days was identified, at a rate of

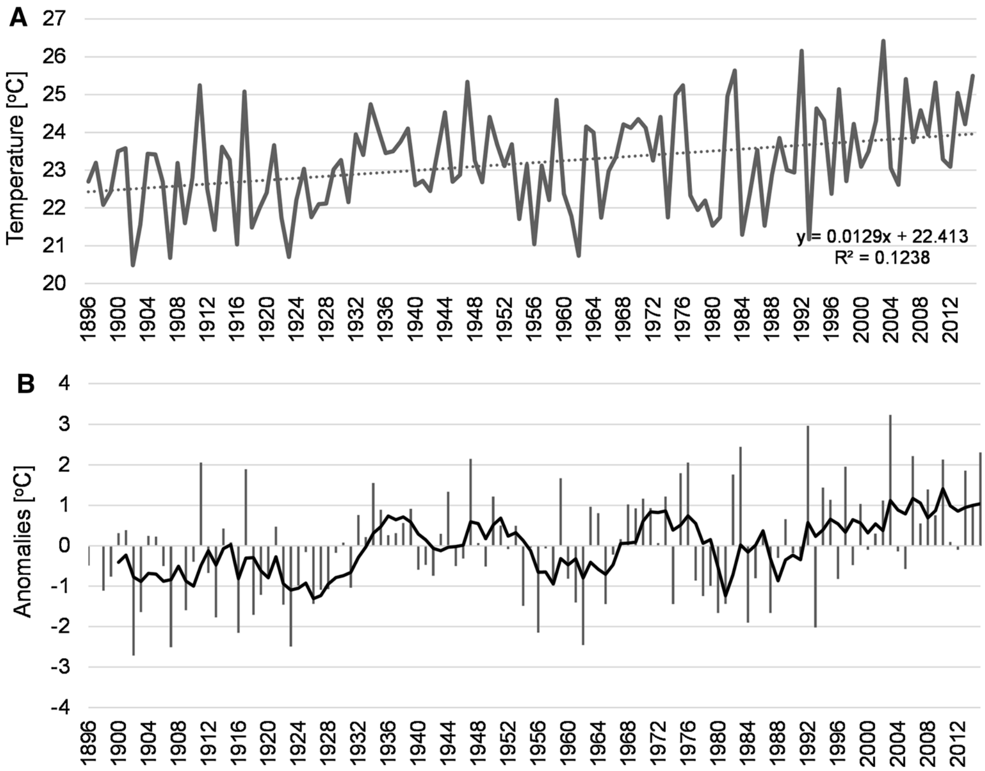

Fig. 1 **a** Average summer T_{max} in Potsdam; **b** average T_{max} anomalies, with moving (5-year) average

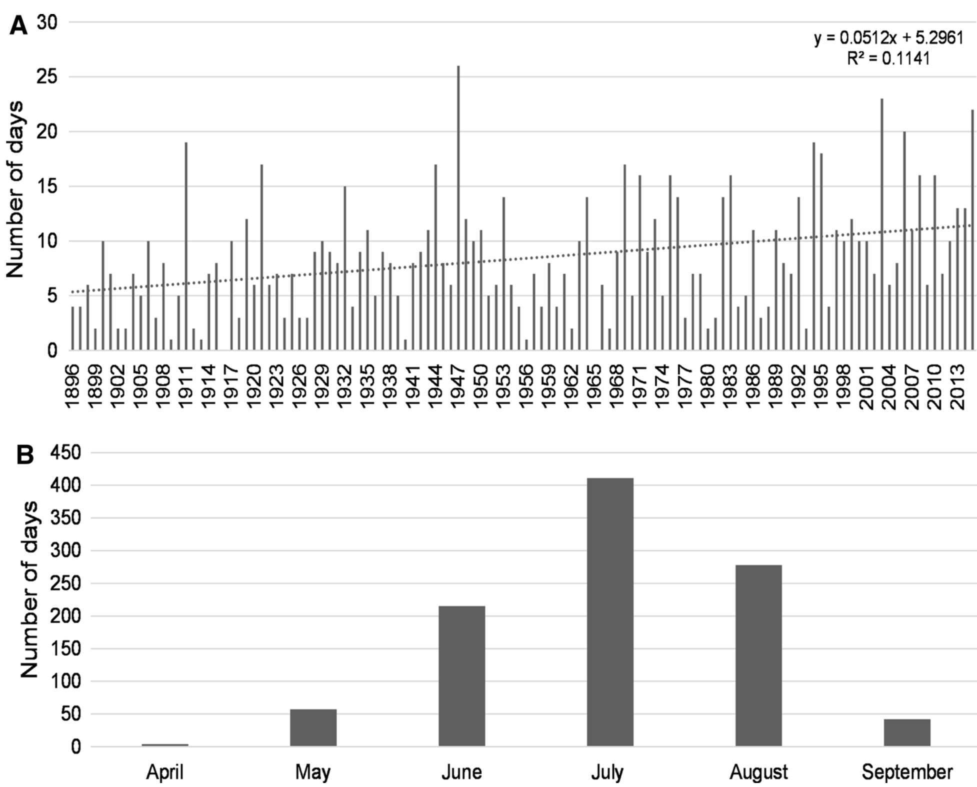

Fig. 2 **a** Number of hot days in 1896–2015; **b** total number of hot days in individual months

0.5 days per decade. Analysis of the changes in particular months of the year revealed a statistically significant increase in July (0.3 days per decade; $p < 0.01$) and in August (0.2 days per decade; $p < 0.05$). In June, a drop in the number of days in this category was recorded, although the changes were not statistically significant. Hot days were observed between April and September, although they were most numerous in July, which saw as much as 40.8% of all such days (Fig. 2b). The earliest a hot day was recorded was on 22 April, 1968, while the latest days were on 20 September of 1947 and 2003. From the above, the potential span of their occurrence was 152 days.

3.3 Atmospheric circulation

In the summers of 1896–2015, the most commonly observed circulation types were, on average, WZ (18.1%), as well as BM (8.1%), HM (7.9%) and WA (7.5%) (Fig. 3a). Meanwhile, the least common types, occurring with a frequency below 1%, were the following: SEZ (0.2%), SZ (0.2%), SA (0.3%), SEA (0.5%) and HFZ (0.9%). In the above period, the prevailing summer circulation was cyclonic (51.7%), over anticyclonic (47.3%). Meanwhile, hot days occurred about twice as often during anticyclonic circulation (66.2%) than during cyclonic (32.3%). These days were most commonly observed during

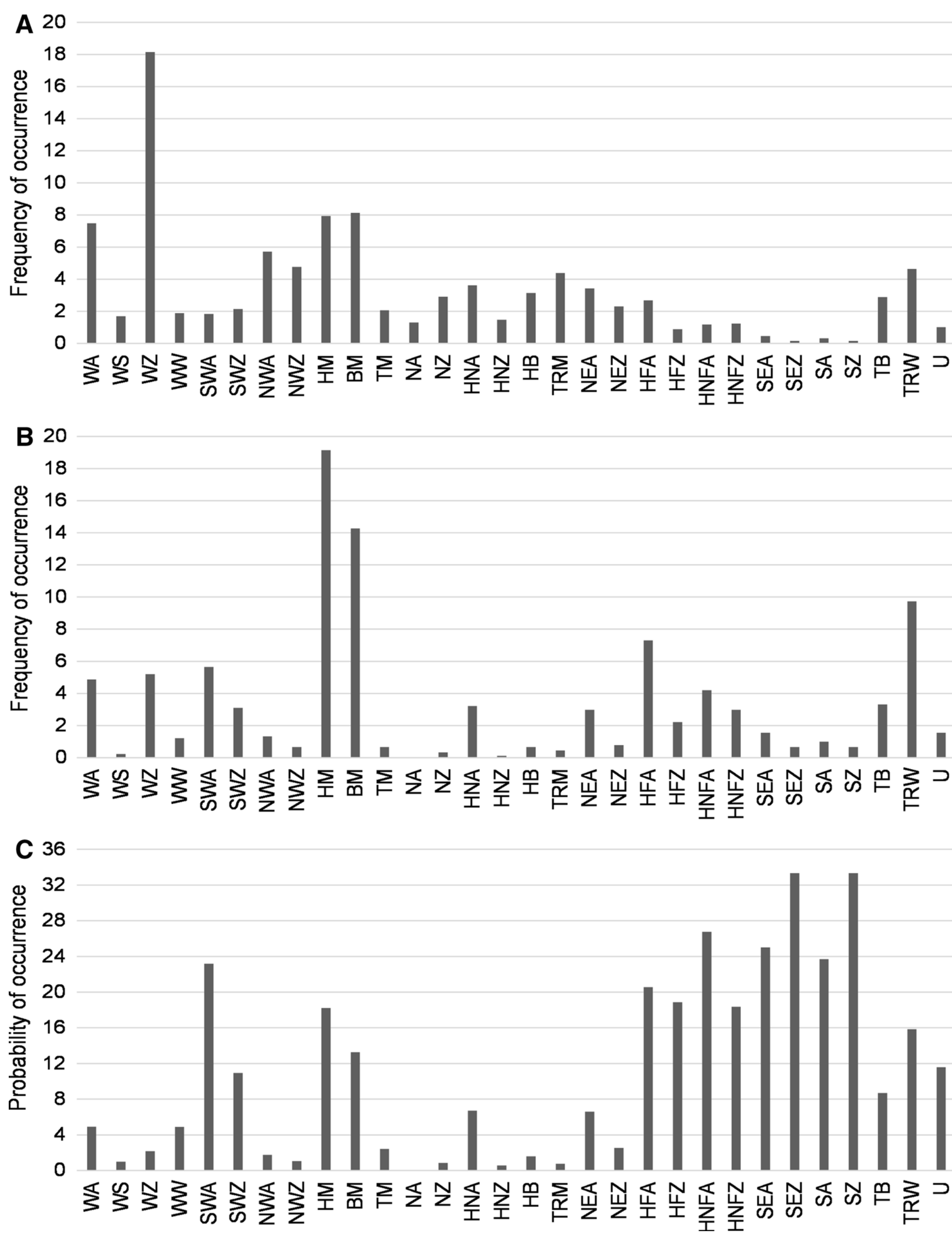

Fig. 3 **a** Frequency of occurrence of individual circulation types in summer; **b** frequency of occurrence of hot days under individual circulation types; **c** probability of occurrence of hot days under individual circulation types

types HM (19.1%), BM (14.3%), TRW (9.7%) and HFA (7.3%) (Fig. 3b).

There was greater probability of the occurrence of hot days observed with anticyclonic circulation than with cyclonic circulation. During summer anticyclonic circulation, the greatest probabilities were noted, on average, for types HNFA (26.8%) and SEA (25%) (Fig. 3c). However, the situation looked somewhat different for individual months. The greatest probability of occurrence was observed for type SEA (20%) in June and types SEA (47.1%), SA (40%) and HNFA (34.6%) in July, whereas for August it was HNFA (33.3%), SWA (26.6%) and SA (26.3%). On the other hand, during summer cyclonic circulation, the greatest probabilities were noted, on average, for types SEZ (33.3%) and SZ (33.3%). The greatest probability of occurrence was observed for type SZ (42.9%) and SEZ (30%) in June and for types HFZ (34.2%), HNFZ (27.3%), TRW (27%) and SZ (25%) in July, whereas for August it was SEZ (37.5%) and SA (3.3%).

3.4 Heat waves

In Potsdam in 1896–2015, 114 heat waves were identified, lasting a combined total of 467 days. The fewest heat waves were recorded in the years 1896–1905 (5 heat waves) and lasted 15 days, while the most were recorded in the years 2006–2015 (18 heat waves) and lasted 82 days (Fig. 4). Heat waves occurred with a similar frequency in the years 1946–1955 (15 heat waves) and lasted 58 days. Heat waves occurred from May to September, though mostly in July, which accounted for 44.7% of all heat waves. In contrast, only two heat waves were noted for May and four for September. The earliest heat wave occurred from 20 to 22 May 1953, while the latest was from 12 to 16 September 1947. From the above data, the potential span of their occurrence was 120 days. In the analysed period, 3-day waves were the most common, representing 52.6% of all cases. Heat waves lasting 10 days or more were observed only four times. The longest wave lasted 21 days, from 23 July to 3 August 1969.

The average T_{max} during the analysed heat waves was 32.4 °C, while the T_{min} was 17.2 °C. The highest average T_{max} was recorded during a heat wave from 20 to 22 August 1943 at 36 °C. A similarly high average T_{max} was found for the following heat waves: 1–3.08.1943 (35.7 °C), 8–10.08.1992 (35.6 °C), 8–12.07.2010 (35.9 °C) and 6–8.08.2015 (35.2 °C). Meanwhile, the highest average T_{max} was recorded during a heat wave lasting from 25 to 27 June 1935, at 20 °C. A slight increase in T_{max} was identified in the heat waves over the period under analysis, although the changes were not statistically significant. However, in the case of T_{min}, a statistically significant increase was identified.

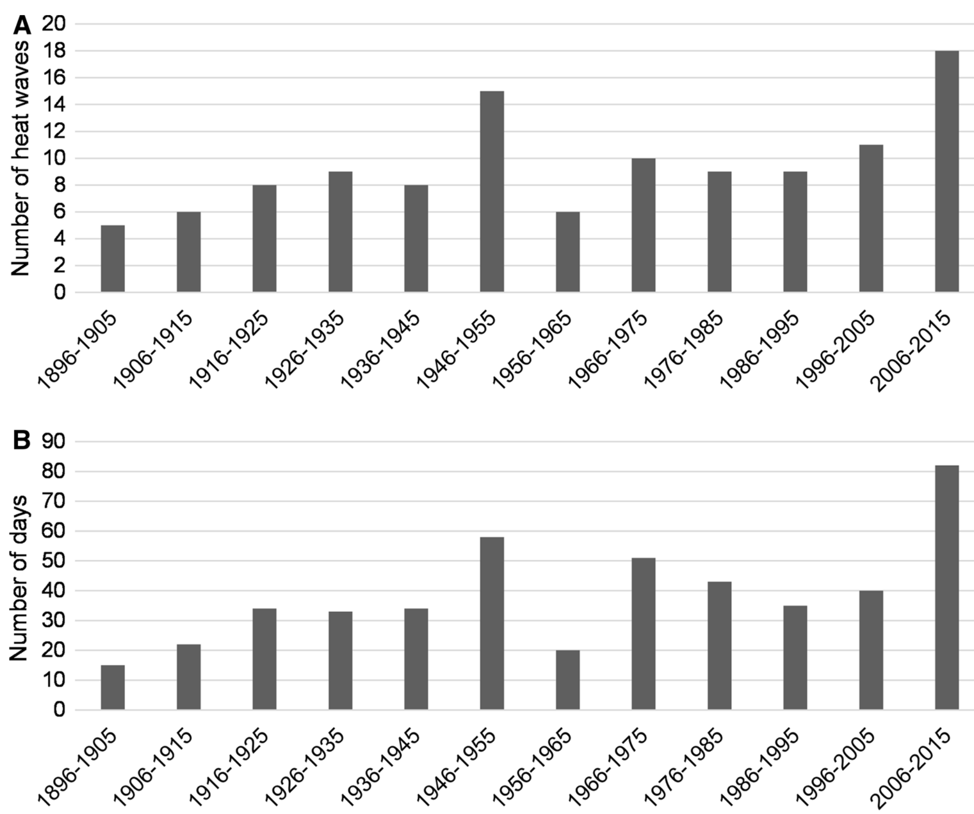

Fig. 4 **a** Number of heat waves; **b** duration of heat waves, by decade

3.5 Synoptic conditions of selected heat waves

A detailed analysis of synoptic conditions was carried out for the warmest and longest heat waves in the studied period. As previously mentioned, the warmest heat wave occurred from 20 to 22 August 1943, during which time the average T_{max} was 36 °C and T_{min} was 18.7 °C The highest observed T_{max} was on 21 August (37.4 °C) and T_{min} on 22 August (20.9 °C). According to the Grosswetterlage series, the analysed heat wave was associated with type TB. During that period, the weather conditions were shaped predominantly by a low, centred over the British Isles (<995 hPa). The isohypses of the 500 hPa pressure surface over Central Europe bent towards the north, forming a clear upward slope, indicating the presence of warm air masses (Fig. 5a). The presence of warm air masses over Central Europe is also visible on maps of air temperatures on the 850 hPa pressure surface (Fig. 5b). These conditions caused an inflow of warm air masses from the southeast.

The longest of the heat waves was observed from 23 July to 3 August 1969 and lasted 12 days, during which the average T_{max} was 32 °C, and T_{min} 18 °C. According to the Grosswetterlage circulation series, the heat wave was associated with type HM (23 and 24 July) at onset, then with type HFZ (25–31 July) and HFA (1–3 August). The centre of the high forming the hot weather in the analysed wave was located over the Baltic Sea (Fig. 6a). During that time, the isohypses of the 500 hPa pressure surface over Central Europe were bent towards the northeast, forming a clear upwards slope over that part of the continent. This indicates the presence of warm air masses, as also indicated by maps of air temperatures on the 850 hPa pressure surface (Fig. 6b). The described heat wave was mainly associated with the inflow of continental air masses from the eastern sector.

4 Discussion and summary

In Potsdam in the years 1896–2015, the average T_{max} for the summer (June–August) was 23.2 °C and changed from 20.5 °C (1902) to 26.4 °C (2003). Over the studied multi-year period, a statistically significant increase in summer T_{max} was identified at a rate of 0.13 °C per decade. The greatest change in T_{max} was observed in August at 0.19 °C per decade. A similar direction of change was also observed in the average annual air temperature (Kundzewicz and Huang 2010; Tomczyk and Jasik 2016). The observed increase in T_{max} translated into an increase in hot days. In the analysed years, an annual average of eight hot days was observed. Their number in particular seasons ranged from 0 in 1916 and 1965 to 26 in 1947. Over the studied multi-year period, a statistically significant increase in hot days was identified at a rate of 0.5 days per decade.

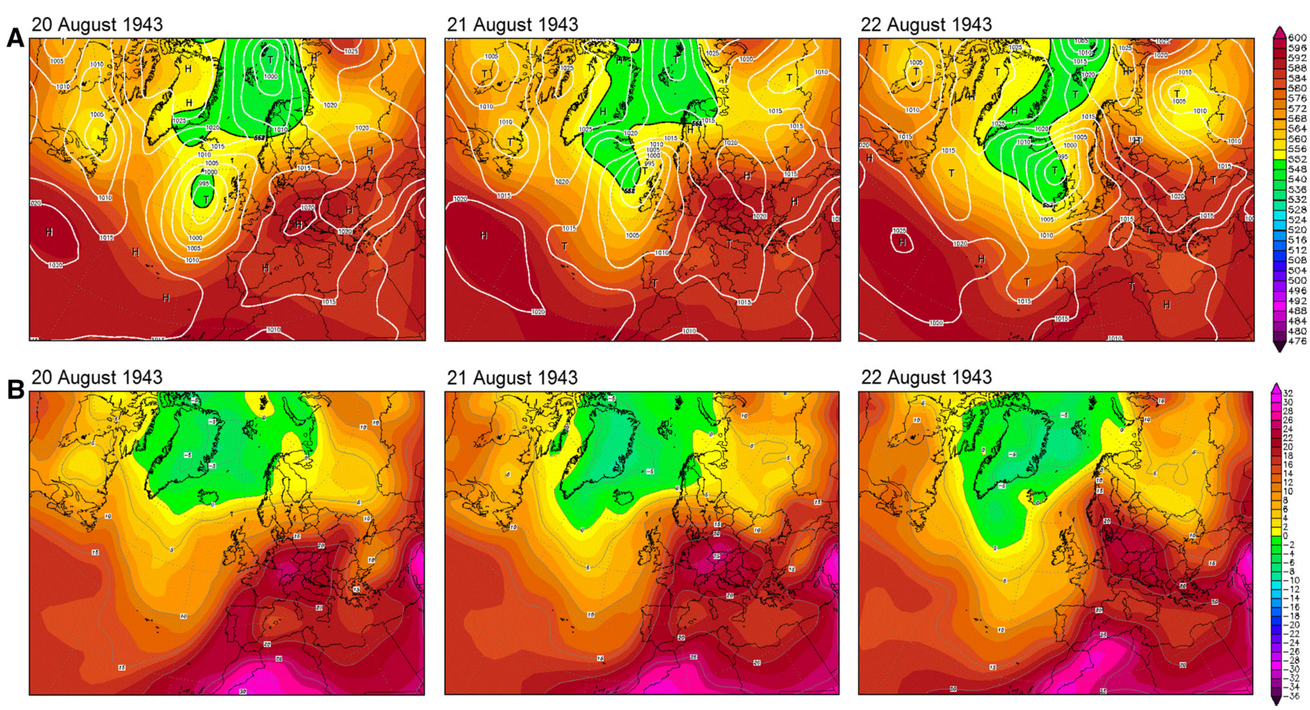

Fig. 5 Baric conditions during the warmest heat waves: **a** GFS model of: 500 hPa baric topography (*colour scale*); pressure sea level (*white line*); **b** air temperatures on the 850 hPa pressure surface Source: http://www.wetterzentrale.de

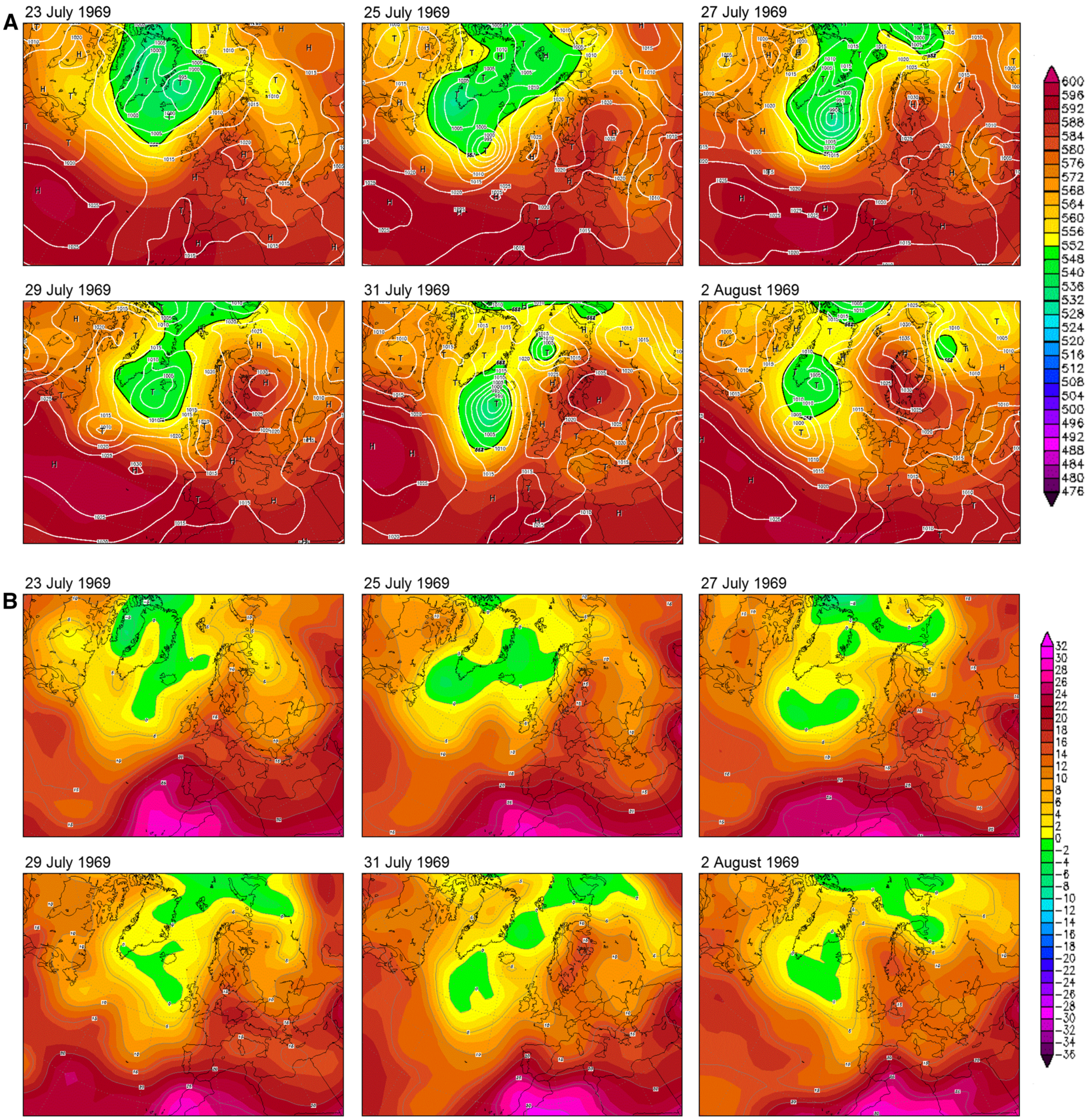

Fig. 6 Baric conditions during the longest heat waves: **a** GFS model of: 500 hPa baric topography (*colour scale*); pressure sea level (*white line*); **b** air temperatures on the 850 hPa pressure surface Source: http://www.wetterzentrale.de

The presented results are in line with earlier studies which have revealed an increase in the number of summer days, hot days and warm nights accompanied by a fall in the number of cold days and nights (Kundzewicz and Józefczyk 2008; Kundzewicz and Huang 2010). The results also confirm studies from other regions based on a considerably shorter period (Rodríguez-Puebla et al. 2010; Avotniece et al. 2012; Unkašević and Tošić 2015; Tomczyk et al. 2016).

The probability of occurrence of hot days was observed to be greater with anticyclonic circulation than with cyclonic, due to the greater stability of highs. In summer, more long-lasting circulation types, such as highs over Central or Eastern Europe, contribute to the occurrence of more intense and longer heat waves, resulting from the advection of warm air masses and strong insolation (Kyselý 2008). The summer inflow of continental air masses from the eastern sector over Central Europe is associated with the occurrence of extreme temperatures or heat waves (Wibig 2007; Ustrnul et al. 2010; Porebska and Zdune 2013).

In the period under analysis, 114 heat waves were identified, lasting a combined total of 467 days. The fewest heat waves were recorded in the years 1896–1905 (5 heat waves) and lasted 15 days, while the most were recorded in the years 2006–2015 (18 heat waves) and lasted 82 days. In turn, the longest heat wave in the period under analysis was recorded from 23 July to 3 August 1969 and the warmest from 20 to 22 August 1943. The increase in the number and duration of heat waves at the beginning of the twenty-first century has been demonstrated in Serbia (Unkašević and Tošić 2015), Ukraine (Shevchenko et al. 2014), the Carpathian region (Spinoni et al. 2015), and Central and Northern Europe (Tomczyk and Bednorz 2016; Tomczyk et al. 2016).

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