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CONTINENTAL-SCALE MONTHLY THERMAL ANOMALIES IN EUROPE DURING THE YEARS 1951-2018 AND THEIR OCCURRENCE IN RELATION TO ATMOSPHERIC CIRCULATION

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Abstract

This study determines the frequency, location and spatial extent of such large-area monthly thermal anomalies, which are referred to in this paper as continental-scale thermal anomalies (CTAs). The research was based on monthly mean air temperature values from 210 weather stations over the 68-year period 1951-2018. A CTA is defined as an anomaly when the monthly mean temperature exceeded the long-term average by at least 2 standard deviations at a minimum of 40 stations. This study attempts to explain the occurrence of such CTAs (negative CTAs⁻ and positive CTAs⁺) in relation to the circulation conditions over Europe. In the years 1951-2018, there were 16 CTAs⁻ (mainly in winter and autumn) and 25 CTAs⁺ (predominantly in summer). One manifestation of climate warming is the ever less frequent occurrence of CTAs⁻ and a growing frequency and spatial extent of CTAs⁺. The immediate cause behind CTAs was the occurrence of characteristic synoptic situations, leading to intensified advection of cold or hot air masses, often driven by radiation factors. The formation of CTAs⁻ was much more often associated with very extensive and long-lasting anticyclonic systems, and that the associated synoptic situations over Europe lasted much longer than in the case of CTAs⁺.

Key words

contemporary warming • extreme temperatures • warm months • cold months • mean sea level pressure • Europe

Introduction

Out of the array of extreme climate events, the greatest interest is evoked by spells with temperatures significantly different from the long-term average at a given location. Although such positive and negative air temperature deviations are a natural feature of the climate, sometimes the magnitudes of such anomalies are very large and tend to extend over large areas. The occurrence of very high or very low temperatures unusual in a given area gives rise to multiple dangerous social and economic (Zvyagintsev et al., 2011) consequences, and also – perhaps most importantly – affects the functioning of the entire natural system (Maignan et al., 2008). In particular, the above is true for extremely hot summers and extremely severe winters. There is a rich record of such seasons and their dangerous consequences in historical chronicles (Girguś & Strupczewski, 1965; Phister, 1999).

Since the beginning of the 21st century, when climate warming gained momentum, the researchers' attention has focused almost exclusively on hot summers. In the first decade of this century, researchers published dozens of scientific studies on the causes, course and impacts of the extremely hot years of 2003 in Western Europe (Luterbacher et al., 2004; Twardosz & Batko, 2012) and 2010 in Eastern Europe (Dole et al., 2011; Gruza & Raňkova, 2011). Meanwhile, in the second decade, it mainly concerned the extremely hot years of 2015 (Hoy et al., 2016; Sippel et al., 2016; Luterbacher et al.; 2016; Krzyżewska & Dyer, 2018) and 2018 over vast areas of Central Europe (Sinclair et al., 2019; Twardosz, 2019). In addition, the year 2018 stood out in Europe for its extremely warm April and May, which proved to be the warmest such months from the beginning of temperature measurements (Twardosz, 2019). Towards the end of the second decade of the 21st century, we experienced an extremely hot June in 2019, especially in Central Europe, which was described, among other things, by Błażejczyk et al. (2021).

Despite the sustained warming (Twardosz et al., 2021), emerging periods of extreme cold remain a serious problem. Even though they are less frequent and intense than, for example, during the extremely cold winter of 1962/63 (Hirschi & Sinha, 2007), they still have dangerous economic and biometeorological implications. One such month was the unusually cold January 2017 in the Balkan Peninsula, which was one of the coldest and snowiest Januaries in this area (Anagnostopoulou et al., 2017).

The increasing frequency of thermal anomalies with a large spatial extent prompted the authors to study their occurrence throughout Europe and its immediate surroundings in the period from the mid-20th century to 2018. Although some of these anomalies have already been described in the literature of the subject, the results obtained by various authors are not fully comparable. They concern different locations and periods, and the criteria employed in research to identify thermal anomalies have often differed. Thus, the aim of this study is to identify the types, frequency, location and spatial extent of large-area monthly thermal anomalies starting from the mid-twentieth century, which are referred to in this study as continental-size thermal anomalies (CTAs). Additionally, a synoptic analysis of the occurrence of CTAs was carried out, in which particular attention was paid to the types, frequency and persistence of synoptic situations.

Data and methods

The input material for this research consisted of the average monthly air temperature values from meteorological stations across Europe (164 stations) and its immediate surroundings (46 stations) from 1951-2018. Of the 210 stations included in the study, the majority (182) are sites at altitudes below 300 m a.s.l., and 10 stations are located above 1000 m a.s.l. (Fig. 1). The database used in the study relies mainly on the publicly available and widely used European Climate Assessment & Dataset (ECA&D, <http://eca.knmi.nl/>; Klein Tank

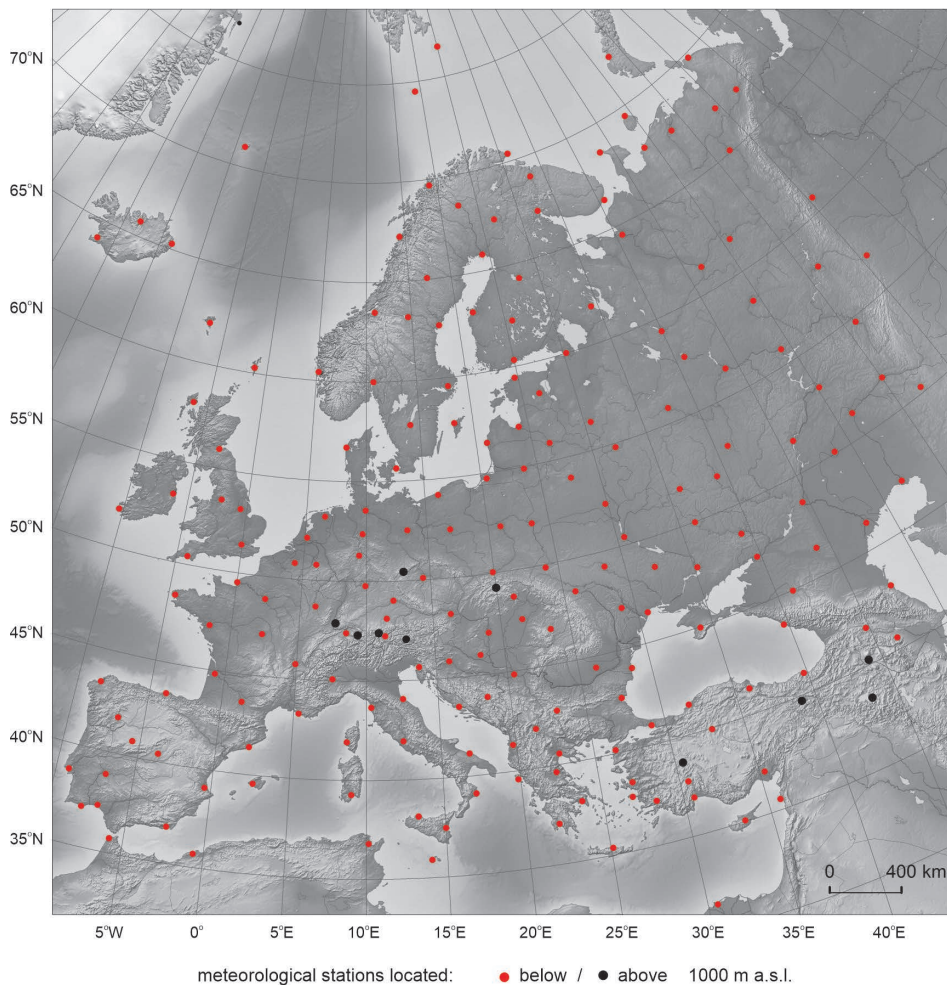


Figure 1. Weather stations included in the study

et al., 2002). The data contained in the Dataset are verified for homogeneity through several statistical tests. Use was also made of other online databases – National Climatic Data Center (NCDC), Ogimet and World Weather Records (WWR). The authors had previously relied on the thus-prepared dataset in a number of studies (Twardosz & Kossowska-Cezak, 2021; Twardosz et al., 2021). Therefore this study is based on real measurement data, rather than on grid data, which is extremely important in areas with a varied relief, such as the European continent. Temperature values in the lower

troposphere, especially in the near-surface air layer, strongly depend on local conditions and best reflect the actual thermal conditions of areas represented by weather stations.

In the first step of the research, the thermally anomalous months, namely anomalously cold months – ACMs, and anomalously warm months – AWMs, were identified. A strict statistical criterion was applied here, namely a monthly mean temperature differing by 2 standard deviations (SD) from the corresponding average for the whole period under study. The next stage involved selecting the months when the mean temperature

diverged from the long-term average by 3 and 4 SDs, based on which the anomalies were categorised in terms of severity. The analysis comprised only anomalies with a large spatial extent, referred to here as continental-size thermal anomalies (CTAs). A continental-size thermal anomaly or CTA (negative CTA- and positive CTA+) is defined as one recorded by at least 40 out of the 210 stations, which roughly corresponds to one quarter of Europe and one fifth of the total area of the European continent and its immediate surroundings.

For the CTAs that demonstrated the greatest spatial extent (at least 60 stations), the circulation conditions behind such huge air temperature deviations were described. To this end, use was made of mean sea level (SLP) air pressure distribution charts for Europe from the NCEP-NCAR Reanalysis dataset. In these charts, the pressure distribution is expressed in hPa and the isobars are plotted every 2 hPa (https://iridl.ldeo.columbia.edu/maproom/Global/Atm_Circulation/Sea_Level_Pres.html?bbox=bb%3A-20%3A35%3A40%3A75%3Abb, access: 9 December 2020). In addition, the research relied on synoptic weather maps of the northern hemisphere (sea-level and 500-millibar charts) developed by the US Department of Commerce NOAA and Europäischer Wetterbericht provided by Deutsche Wetterdienst, as well as day/hour weather charts for Europe made available by the German Weather Service (www1.wetter3.de) and the Polish Institute of Meteorology and Water Management (Biuletyn Synoptyczny).

When determining the relationships between the occurrence of CTAs and circulation over Europe, instead of the routinely deployed quantitative method that determines averaged pressure values for a given period, the frequency of occurrence of indicator values or types of circulation, use was made of a qualitative method based on the interpretation of circulation conditions as shown by synoptic maps. The method allowed us to determine, *inter alia*, the repeatability of specific synoptic situations in areas adjacent to a CTA and their changes

from day to day, which is difficult when use is made of averaged pressure values or identified types of circulation. The use of synoptic charts had another advantage, namely it better reflected circulation in the lower troposphere compared to maps from higher pressure levels.

General characteristics of the occurrence of CTAs

In the light of the strict statistical criterion for the identification of monthly thermal anomalies, it can be concluded that such months are quite frequent at individual stations in Europe. In about half of the months in the 68-year period of 1951-2018, such a month was recorded by at least one of the 210 stations (396 ACMs and 468 AWMs). However, most of them had a small spatial range comprising 1-5 stations (Fig. 2). Large-area anomalies are rare. Those that occurred at 40 stations and more (CTA) were only: 16 CTA- and 25 CTA+ (Fig. 2, Tab. 1-2). Yet, the largest ones covered over 80 stations, and the record-breaking one extended over almost 120 stations, i.e. more than half of the area of Europe and its immediate surroundings.

The CTAs- and CTAs+ included in further analysis showed a very clear annual trend (Fig. 3). Months with a CTA- occurred exclusively from September to March, with maximum frequencies in January, February, and October (3 CTAs- in each of these months over the 68 years). Thus, in Europe, summers do not see months with average temperatures below 2 standard deviations recorded over large expanses of the continent. CTAs+ occurred throughout the year, mainly from April to September, with a clear predominance in July and September (4 in each of these months over the 68-year period). One CTA+ per month was recorded over the period from October to January and March.

The number of CTAs- and CTAs+ varied very strongly over the 68 years (Fig. 4). Of the 16 CTAs-, 15 were seen in the second half of the 20th century, the last one appeared

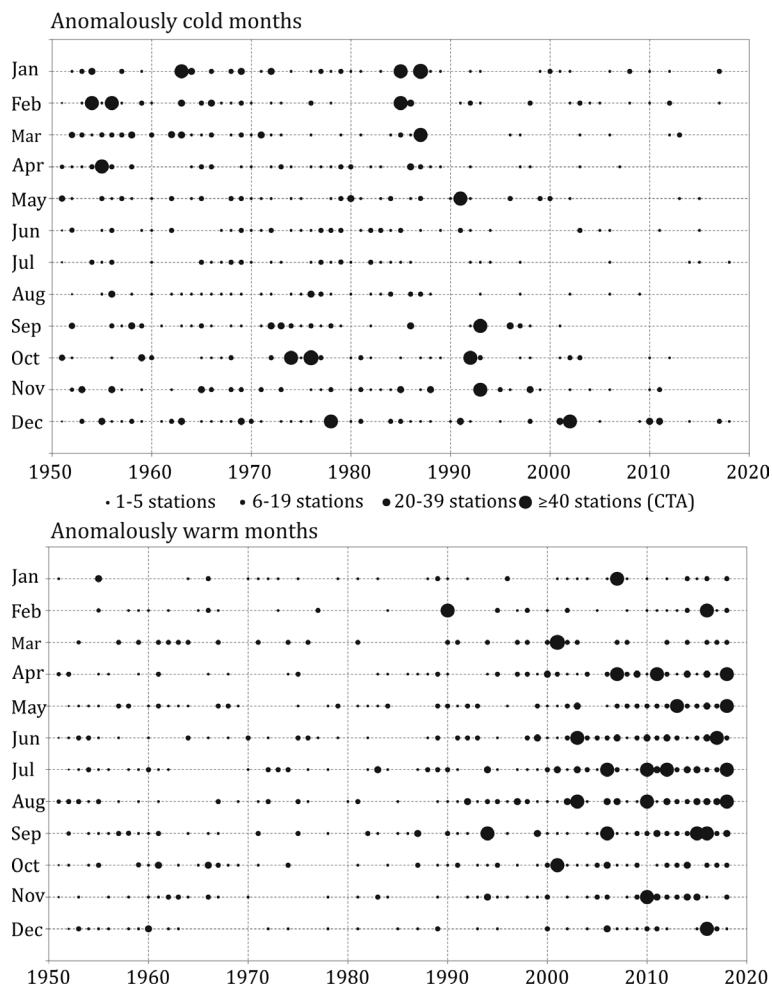


Figure 2. Occurrence of anomalously cool and anomalously warm months in numbers of stations during the study period

in December 2002. The first CTA⁺ occurred in February 1990, and the remaining 24 in the 18-year period from 2001 to 2018. Based on the above trend of thermal anomalies, it can be concluded that the present-day warming manifests itself with a decreasing frequency of negative large-area monthly thermal anomalies and an increasing frequency of such positive anomalies. However, this process is asymmetrical, because the decrease in the frequency of CTAs⁻ proceeds at a slower pace than the increase in the frequency of CTAs⁺.

Characteristics of the CTA- cases

The calendar of all 16 CTAs⁻ identified in Europe over the 68-year period of 1951-2018 is presented in Table 1. An analysis of the calendar demonstrates that 12 of the CTAs⁻ involved air temperature anomalies of more than 3 SDs, and in 5 cases they were even 4 SDs. One of the largest anomalies in terms of area and severity was one from February 1956 (Tab. 1). This unusual thermal anomaly covered more than half of Europe (117 stations): from the British Isles to the Urals in the

Table 1. Calendar of negative Continental-Scale Monthly Thermal Anomalies (CTA-)

Year	Month	Number of stations with average temperature			The highest anomaly			
		$\geq 2\sigma$	$\geq 3\sigma$	$\geq 4\sigma$	Δt [°C]	station	σ_{\max}	station
1954	Feb.	56	16	–	-15.4	Aleksandrowv Gaj	3.6	Astrachań
1955	Apr.	43	–	–	-5.1	Vielikie Luki	2.7	Vielikie Luki
1956	Feb.	117	57	6	-12.6	Innsbruck	4.3	Toulouse, Innsbruck
1963	Jan.	73	13	1	-10.3	Kirovograd	4.1	Plymouth
1974	Oct.	58	18	1	-8.6	Säntis	4.1	Zugspitze
1976	Oct.	49	21	1	-9.4	Aktobe	4.2	Aktobe
1978	Dec.	46	3	–	-13.9	Pechora	3.2	Tartu
1985	Jan.	54	2	–	-13.2	Kajaani	3.1	Kandalaksa
	Feb.	57	–	–	-11.9	Sodänkyla	2.7	Sodänkyla
1987	Jan.	69	5	–	-13.0	Volgograd	3.1	Kaliningrad
	Mar.	69	8	–	-8.4	Zaporoz'e	3.2	Simferopol
1991	May.	43	–	–	-4.3	Zugspitze	2.6	Zugspitze
1992	Oct.	49	5	–	-8.5	Sodänkyla	3.2	Sodänkyla
1993	Sep.	41	–	–	-4.7	Tambor	2.7	Tartu
	Nov.	82	23	2	-10.4	Aktobe	4.7	Makhaczkala
2002	Dec.	41	2	–	-10.1	Uralsk	3.6	Makhaczkala

σ – standard deviations (SD)

north and from the Pyrenees Peninsula to the western and northern shores of the Black Sea (Fig. 5). On half of the area covered by this anomaly, i.e. in its south-western part, the average temperature in February 1956 was lower than the long-term average by 3 SDs, and in the area of south-eastern France (5 stations) and Innsbruck even by 4 SDs. In Toulouse and Innsbruck, the relative anomaly reached 4.3 SDs. In most of the area it was the coldest February from 1951 onwards (Twardosz & Kossowska-Cezak, 2021) and, according to Pfister (1999), the coldest in the history of measurements. Extremely low air temperatures, dropping even below -40°C (Andrews, 1956), caused human deaths, the freezing of lakes and rivers, and damage to plants (Dizerens et al., 2017). In the second and third decades of February, navigation on the Rhine was halted because the Rhône-Rhine Canal and the lower and middle reaches of the River Rhine froze.

A slightly smaller area (82 stations) was covered by a CTA- in November 1993, extending along the central strip of Europe from the Atlantic coasts of France, through central Europe and the Baltic countries, Ukraine and European Russia to the Urals, the eastern part of the Black Sea coast and the Caucasian countries (Fig. 5). On more than a quarter of the area covered, the anomalies exceeded 3 SDs. The monthly mean temperature values in Eastern Europe were below -10°C . At the time, Makhaczkala saw the greatest relative anomaly of monthly mean temperature in Europe over the entire 68-year period.

The third largest CTA in terms of spatial extent occurred in January 1963. It covered about one third of the area of the European continent and its immediate surroundings (73 sites), from Bordeaux and Valentia in the west to Moscow and Zaporizhia in the east and from Split and Sofia in the south

Table 2. Calendar of positive Continental-Scale Monthly Thermal Anomalies (CTA+)

Year	Month	Number of stations with average temperature			The highest anomaly			
		$\geq 2\sigma$	$\geq 3\sigma$	$\geq 4\sigma$	Δt [°C]	station	σ_{max}	station
1990	Feb	50	-	-	10.5	Kajaani, Arhangelsk	2.5	Kajaani
1994	Sep	46	9	-	4.9	Kharkiv	3.4	Burgas
2001	Oct	41	-	-	4.2	Feldberg	2.7	Nancy
2001	Mar	44	10	-	6.2	Afyon	3.7	Palencia
2003	Jun	62	28	4	7.5	Lyon	4.3	Lyon, Zurych
	Aug	68	18	-	6.4	Lyon	3.8	Bourges
2006	Jul	62	9	-	5.6	Aachen	3.4	Bourges
	Sep	45	3	-	4.1	Tartu, Aachen, Feldberg	3.4	Waddington
2007	Jan	42	-	-	11.2	Uralsk	2.7	Uralsk
	Apr	44	15	-	6.7	Feldberg	3.7	Bourges, Paryż
2010	Jul	62	17	-	7.4	Moscow	3.8	Moscow
	Aug	64	16	-	6.8	Kursk	3.8	Kiev, Kursk
	Nov	48	-	-	7.1	Kharkiv, Elista	2.8	Odessa, Kharkiv
2011	Apr	67	1	-	5.4	Björnöya	3.0	Thorshavn
2012	Jul	44	12	1	5.4	Sofia	4.0	Sofia
2013	May	52	3	-	5.7	Elista	3.3	Elista
2015	Sep	46	6	-	5.1	Rostov on the Don	3.5	Zonguldak
	Dec	44	9	-	6.9	Sonnblick	3.6	Brest
2016	Feb	43	-	-	12.7	Amderma, Vorkuta	2.9	Korfu
	Sep	41	4	-	5.1	Kassel	3.5	Kassel
2017	Jun	46	3	-	5.2	Madrid	3.5	Vienna
2018	Apr	84	29	-	6.1	Fichtelberg	3.7	Vienna, Cluj
	May	83	25	2	5.5	Stockholm	4.2	Jönköping
	Jul	56	10	-	5.7	Murmansk	3.8	Sosnovets Island, Yerevan
	Aug	45	2	-	4.2	Kosice	3.4	Praha

σ - standard deviations (SD)

to Edinburgh and Bergen in the north (Fig. 5). The western part of this area observed the greatest drop in temperature, in excess of 3 SDs at 13 stations and even 4 SDs in Plymouth (Tab. 1). In the western part of the area, it was the coldest January in the 68-year period, and in some stations, for example in Warsaw, even the coldest winter month from the middle of the 20th century. It was the second extremely cold month after December 1962 over much of the area (Twardosz & Kossowska-Cezak, 2021). January

1963 was also an exceptionally snowy month (Hirschi & Shina, 2007).

The CTAs in January and March 1987 had a similar spatial range as that in January 1963, extending over 69 stations each. The first of them occurred in the area stretching from France, through the countries on the northern side of the Alps and Scandinavia, to the central part of European Russia (Fig. 5). The largest temperature anomalies were noted in the eastern part of the coverage of that CTA-, reaching up to -13°C in Volgograd, and

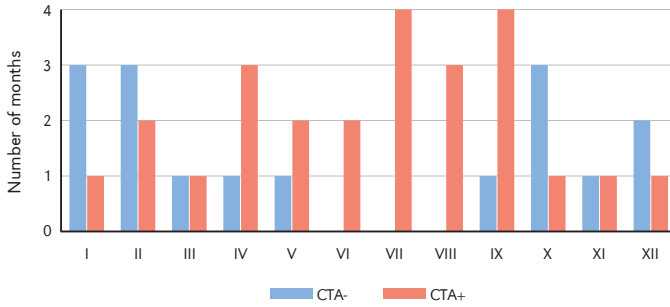


Figure 3. Annual pattern of monthly CTA- and CTA+

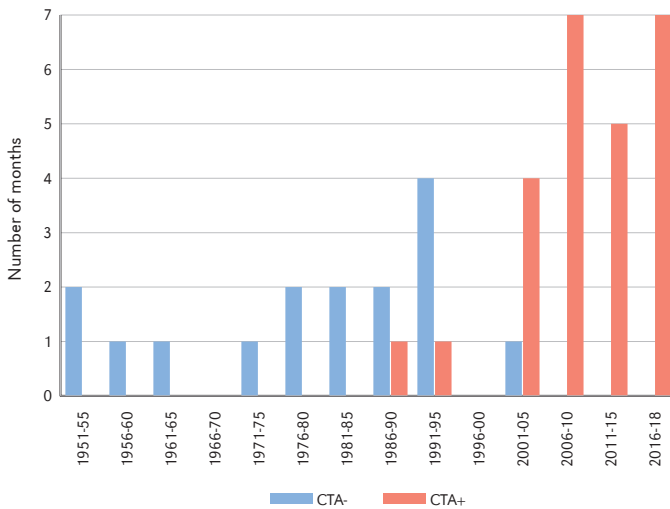


Figure 4. Long term pattern of months with CTA- and CTA+

even exceeding 3 SDs at 5 stations at various locations. The most severe frosts were recorded in the middle of that month (Brugge, 1987).

In March 1987, the CTA- covered a compact area stretching from central Europe and south of it to Sicily, the Peloponnese and Turkey. The greatest relative anomalies (more than 3 SDs) were found mainly in the south of this area (8 stations, Tab. 1).

The CTA- in October 1976 is noteworthy (Fig. 5). Although it was observed at a smaller number of stations (49) than those mentioned earlier, in almost half of the area (21 stations) these anomalies exceeded 3 SDs, and in one – in Aktobe – even 4 SDs. It also covered a compact area, mainly European Russia.

Characteristics of the CTA+ cases

Table 2 presents the calendar of all 25 CTAs+ identified in Europe during the 68-year study period, while Figure 6 shows the extents of the largest 9 CTAs+. The table clearly shows that 20 CTAs+ involved air temperature anomalies exceeding 3 SDs, and 3 even 4 SDs. Although CTAs+ are more common than CTAs-, they are much less likely to reach such huge temperature anomalies over a vast area. Among the CTAs+, those that occurred in April and May 2018 are the top-ranking ones as the largest anomalies in terms of area (84 and 83 stations, respectively) and intensity – 29 and 25 stations with a monthly

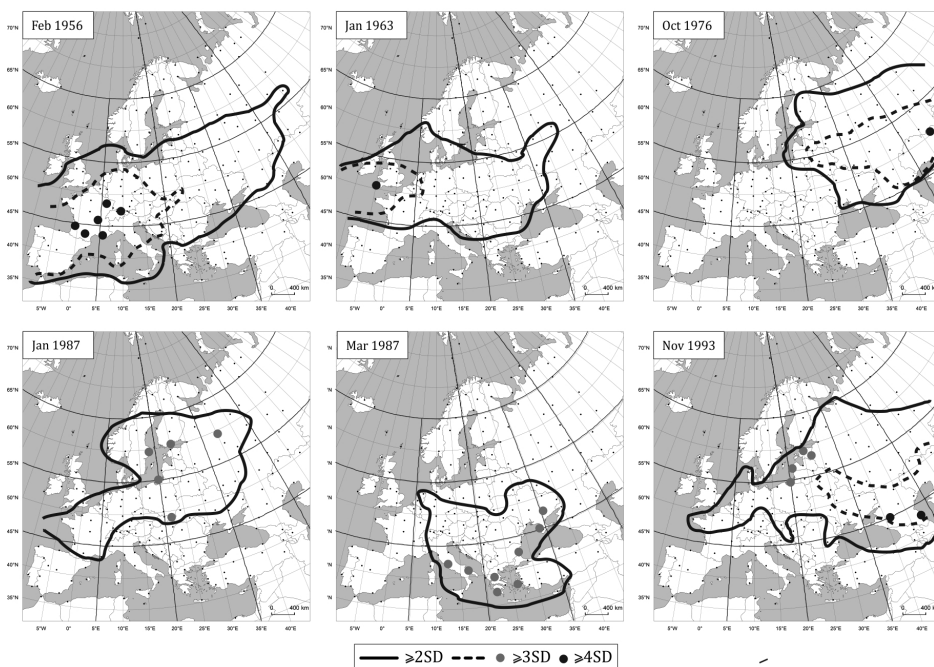


Figure 5. Spatial extent of selected CTA- (> 60 stations)

mean temperature deviation of more than 3 SDs, and in May even 4 SDs at 2 stations (Oslo and Jönköping). Both these CTAs+ covered mainly the central and southern parts of Europe. The April CTA+ covered compact areas, from France to Ukraine in the north and from the islands in the western Mediterranean to Crete and western Asia Minor. At the time, south-eastern Poland saw the largest absolute average temperature anomalies (6.5°C; Twardosz, 2019). In May, the CTA+ extended further north to cover all of Scandinavia and the Baltic states. New air temperature records were set in many places (Sinclair et al. 2019). Based on the secular series of air temperatures from Kraków spanning the years 1792-2018, it can be observed that April and May 2018 were the warmest in more than two hundred years (Twardosz, 2019). Such an early onset of 2-month-long conditions of unusually warm weather proved to have a highly adverse biometeorological effect, because the human body is not yet adapted to such heat after the winter

period (Twardosz & Kossowska-Cezak, 2021). It should also be emphasised that the early appearance of hot and usually dry weather after a mild and snowless winter aggravated drought, which impacted many areas of the economy (Sinclair et al. 2019; Twardosz 2019).

Although the subsequent CTAs+ had a smaller spatial reach (fewer than 70 stations), they differed in terms of the size of the anomaly. The most notable ones included 4 CTAs+ in western Europe (June and August 2003, July 2006 and April 2011), two in eastern Europe (July and August 2010), and one in the central-southern part of the continent (July 2012).

June 2003 ranks highest among the above CTAs+. In that month, in almost half of the stations (28 out of 62) the anomaly exceeded 3 SDs, mainly in France, southern Germany, Switzerland, Austria and Italy, and at 4 stations in the central part, it even reached 4 SDs (Fig. 6). It was the warmest June from 1951 onwards in most of the area (Twardosz & Kossowska-Cezak, 2021).

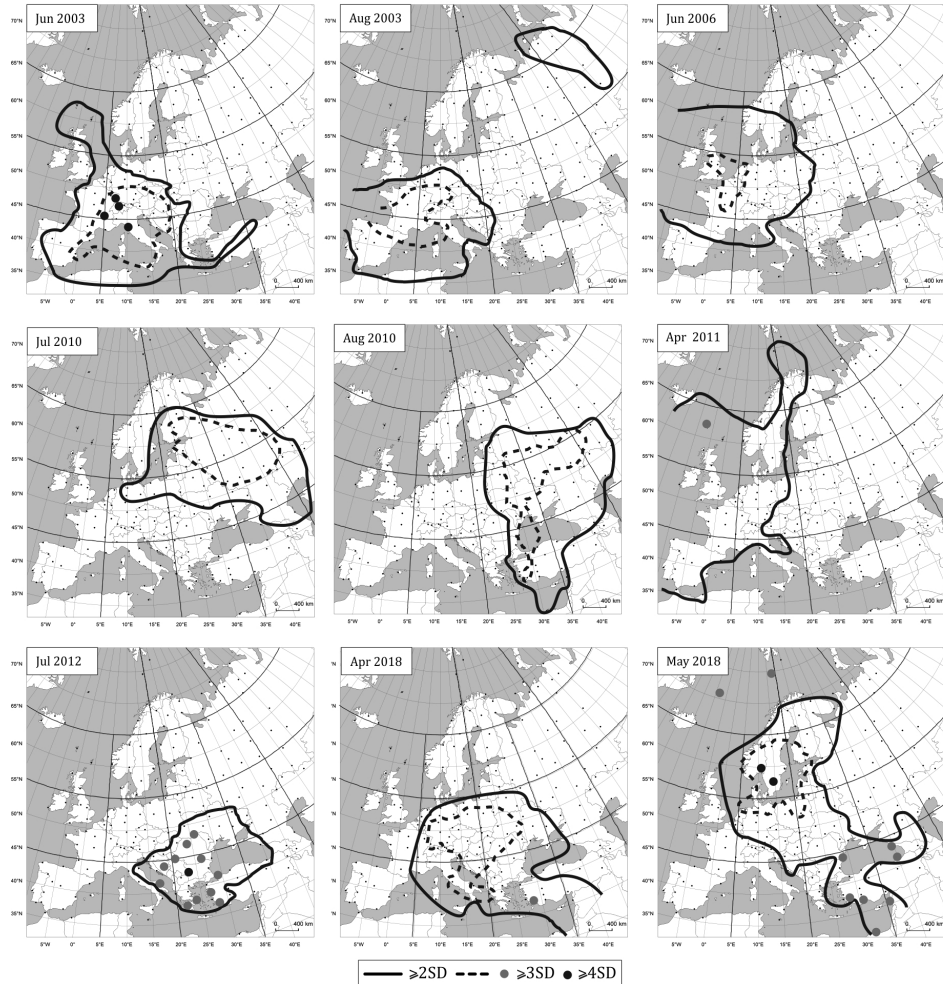


Figure 6. Spatial extent of selected CTA+ (> 60 station)

A month later, in August 2003, another CTA+ occurred in the same area. Although the area covered by mean temperatures above 3 SDs was much smaller during that anomaly and there were no cases of anomalies with 4 SDs, it had much more severe biometeorological and economic consequences (Luterbacher et al., 2004; Twardosz & Batko, 2012). This was due to the extremely strong heat wave that hit Western Europe, mainly France, in the first two weeks of August with record high values of the maximum and especially of the minimum temperature. In the second half of August, the intensity of the heat

was far lower, which significantly mitigated the monthly air temperature anomaly.

The CTA+ which ranked third, covered more than 60 stations, was that identified in July 2006. The greatest relative anomalies (3.8 SDs) occurred once again in central France.

In 2010, vast thermal anomalies were observed in two consecutive months, namely July and August, and they extended over large areas of eastern Europe (Fig. 6). In both of these cases, the extent of the temperature anomalies was similar, i.e. slightly more than 60 stations, about a third of which recorded

an anomaly of more than 3 SDs (with the highest anomaly reaching 3.8 SDs). The CTA+ recorded in July covered an area from the Baltic coast to the eastern Black Sea and the Caspian Sea. Meanwhile in August, it essentially covered the same areas as in July, although it did not extend so far north and west, but reached further east as far as the southern Urals. In most of the area, July and August were the hottest months in the 68-year period under investigation (Twardosz & Kossowska-Cezak, 2021).

The last CTA+ that covered over 60 stations was the one in April 2011. It stretched over vast areas of western Europe, but the anomalies did not exceed 3 SDs with the exception of one station.

The case of the CTA+ in July 2012 is also noteworthy. Although it covered a much smaller area than previously described, it was the third CTA+ in the 68-year timespan where the mean temperature exceeded 4 SDs (Sofia). The extremely high temperatures, with a large deficit of precipitation, triggered extensive fires in this area (Dong et al., 2013).

Circulation conditions of continental thermal anomalies

Most of Europe is located in moderate to high latitudes, which means that, apart from radiation factors, the thermal conditions of the continent are mainly determined by circulation, especially during the cold half of the year. Furthermore, Europe is the smallest continent and a very fragmented one, which means that the location of centres of action plays a crucial role (the Azores High and the Icelandic Low over the Atlantic Ocean and the Siberian High – in the cold half of the year, and the South Asian Low – in the warm season). They shape the most important features of atmospheric circulation in this region of the world and influence the directions of advection of air masses in Europe and the weather in the various areas of the continent (Barry & Carleton, 2001). Anticyclonic systems, in the form of blocking systems, and

the formation, evolution and movement from west to east of families of dynamic lows separated by high-pressure ridges exert a particularly strong influence. Such variable circulation leads to a high changeability of weather conditions.

This renders circulation-related determinants of the weather, especially on the European continent, a very popular subject of research among climatologists. When it comes to extreme values of the individual meteorological elements, the short periods in which they occurred are usually analyzed. By contrast, this study addresses the circulation-related conditions of monthly periods when temperatures significantly diverged from the long-term average over a large territory. The research was based on both the mean distribution of the pressure field in a given month and the circulation conditions changing from day to day. When analysing extreme temperatures, especially if they occur simultaneously over a large area, attention is usually paid to the occurrence of pressure systems, their strength, impact range and persistence. However, the recurrence of certain synoptic situations over a longer period of time is a crucial element too. It is precisely these features of circulation that this paper focuses on when analysing the occurrence of the continental-size thermal anomalies (CTAs) described above.

Among the temperature anomalies identified in the study period, those involving very low temperature values (CTAs-) were less frequent. All the cases studied occurred in the 20th century and the cold six-month period of the year, although only half of them were observed in the winter months. The latter include exceptional CTAs- which occurred in winter months, i.e. in **February 1956** and in **January 1963** and **1987** (Tab. 1; Hirschi & Sinha, 2007; Dizerens et al., 2017). They were caused by the long-lasting very strong (with pressure in the centre of the system often exceeding 1045 hPa) and vast high pressure systems, often covering over half of Europe. As can be seen in the mean pressure distribution chart, highs with their centre

over the Atlantic and the Siberian High were of the greatest importance (Fig. 7). However, an analysis of daily changes in the positions of the systems has shown that their location was not unchangeable and that their centers would sometimes also move to Scandinavia. There were also short spells when they were replaced by low pressure systems or when highs from the Atlantic merged with highs from Russia to form an elongated zone of high pressure. At the same time, southern Europe remained under the influence of low-pressure systems. As a result, for most days of the month when the CTA-cases under discussion occurred, frosty Arctic air blew into Europe from the north, or polar continental air arrived from the east. Those advection produced the obvious effect of record-high negative monthly temperature anomalies over vast areas of Europe (Fig. 5), totally blocking the inflow of air from the Atlantic. In January 1963, the Icelandic Low almost completely disappeared. The result was the highest negative value of the North Atlantic Oscillation index ($NAO = -4.09$; Twardosz & Kossowska-Cezak, 2020).

Anticyclonic systems also led to low temperature values in two autumn months – **October 1976 and November 1993**. In both cases, the decisive role in weather formation was played by very strong highs (with pressure even higher than 1050 hPa), the centres of which were usually located over Scandinavia or Eastern Europe (Fig. 7). Their range would typically cover Scandinavia, eastern and central Europe, sometimes reaching the Black Sea. In 1993, in the second half of the month, the high's influence on the weather reached as far as Spain. However, for most of the periods analysed, the western part of the continent was under the influence of active lows from the Atlantic. Such a distribution of pressure systems caused long-lasting freezing weather over vast areas of central and especially eastern Europe, associated with the influx of Arctic air from the north and polar continental air from Asia. The temperature, which was very low for this time of year, also persisted in Western Europe.

It can be concluded, base on of the average pressure distribution, that the extremely low temperatures (lower by as much as ca. 7°C than the long-term average; Twardosz & Kosowska-Cezak, 2019) recorded mainly in central and southern Europe in **March 1987**, were mainly due to the presence of a high over the eastern part of the European continent, which caused advection of cold air (Fig. 7). A detailed analysis has shown that the impact of lows moving across the Atlantic and Scandinavia, which sometimes extended as far as southern Europe, was equally important. Depending on the pressure centre which predominated in a given period, masses of very cool Arctic air from the north and northwest or continental air from the eastern sector flowed into the area in question. Those circulation conditions produced not only lower air temperatures, but also heavy snowfall in the south of the continent (Tselepidaki et al., 1990).

The spatial distribution of pressure systems was the main determinant of the direction of advection of air masses in the cold half of the year. The greatest role was played by anticyclonic systems, which at times took the form of blocking systems. However, one should not forget the strong outward radiation of energy in the presence of such extensive high-pressure systems. It was an additional factor contributing to the drop in air temperature, especially during long winter nights, in the areas where the CTAs-described occurred.

In the warm half of the year, where nine exceptional cases of temperature well above the long-term average were identified, the radiation factor was also crucial on account of the long day and the high position of the sun above the horizon. However, the fact is that hot masses of tropical air moved towards Europe and the role of active low-pressure systems was also important. The latter were usually moved along the northernmost areas of Europe. In the south, the most common was a fuzzy high-pressure zone or a wedge of the Azores High, which at times reached far inland. Such distributions of pressure

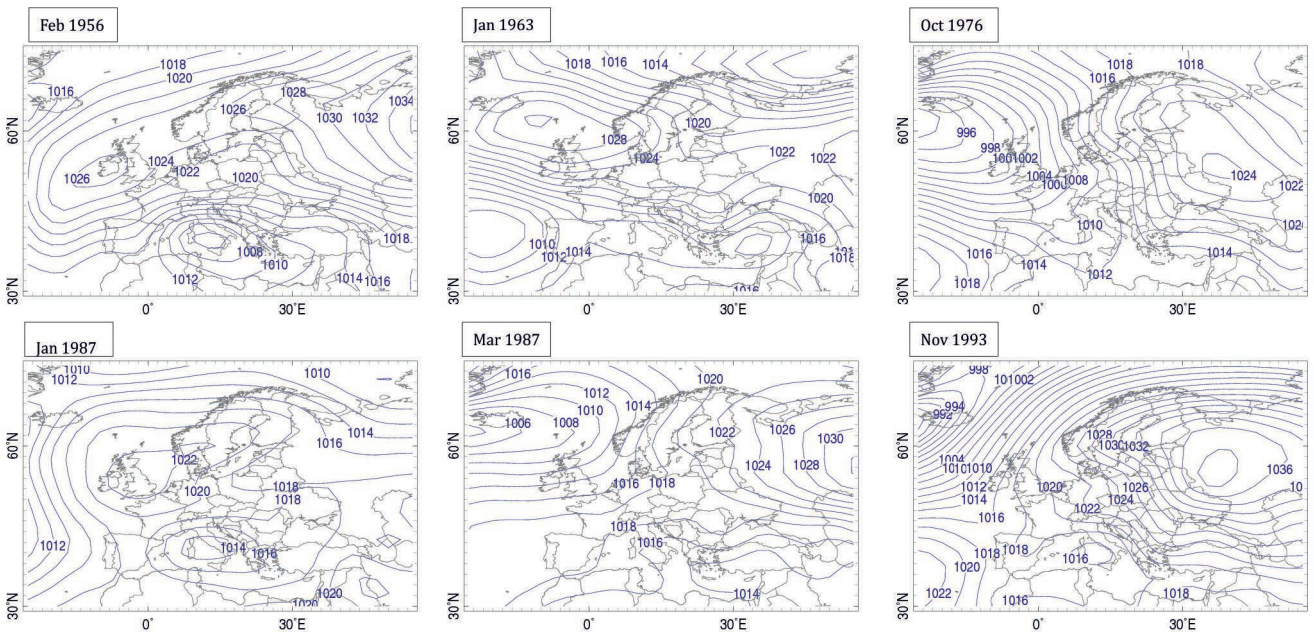


Figure 7. Mean sea level pressure (in hPa) during the CTA- in the period 1951-2018 (NCEP-NCAR Reanalysis)

caused air to inflow from the Atlantic Ocean, especially above 50°N.

The dynamic changes in the synoptic situations which occurred in the above cases (CTAs+) hinder the identification of the underlying characteristic (typical) features of circulation. However, certain regularities closely linked to the mutual position of low- and high-pressure systems over Europe can be identified. In **June and August 2003**, high temperatures in western and southern Europe went hand in hand with extensive low-pressure systems whose centres were located over the Atlantic and the north-east areas of the continent (Fig. 8). These systems were separated by high-pressure ridges, which caused hot air masses to flow from the south and south-west. For several August days, a high with pressure in the centre exceeding 1020 hPa lingered over north-eastern Europe, as a result of which also this part of Europe experienced high temperatures (Twardosz & Batko, 2012).

In **July 2006 and April 2011**, anomalously high temperature values in Western Europe and partly in Scandinavia were associated with the frequent occurrence of an extensive ridge of the Azores High, which covered almost all of Europe, and with highs over the Scandinavian Peninsula (Fig. 8). They were fostered by the advection of air from the south or east, and lows, which most frequently moved over northern Europe, usually added to the inflow of air from the south. A similar situation occurred in **May 2018**. However, the May 2018 highs were both stronger (the pressure in the centre even exceeded 1035 hPa), vaster (sometimes they covered almost the entire continent), and shifted towards the north of Europe. Very often, the centre was located over Scandinavia, the Baltic Sea, and Central Europe.

Similar circulation conditions occurred in **July and August 2010**. The extremely high temperature in Central and Eastern Europe and in the Black Sea area was associated with the frequent occurrence of blocking highs over north-eastern Europe and a ridge of the Azores High entering the continent from the south-west (Fig. 8). At times, the

above systems were separated by dynamic lows from the Atlantic, and the resultant synoptic situations caused inflows of dry and warm continental air from the east or the south.

The abnormally high temperatures in southern Europe in July 2012 were caused by the presence of highs over central and eastern Europe and by the influx of dynamic lows from the Atlantic in the first half of the month (Dong et al., 2013). They caused the advection of warm air from the south. The second half of July saw the formation of a ridge of the Azores High over the southern part of the continent, very clearly visible on the mean pressure distribution map (Fig. 8), which caused the influx of dry and hot air from the east. Meanwhile, Northern Europe saw circulation conditions conducive to the occurrence of large excesses of precipitation (Dong et al., 2013). The April 2018 CTA+ in the same region was associated with a completely different atmospheric circulation. A leading role was played by high pressure systems that extended mainly over southern and eastern Europe, and sometimes also Scandinavia. In parallel, dynamic low-pressure systems were moving over Western and Northern Europe. As a result, the central and southern parts of the continent were under the influence of the advection of air masses from the east and south, which were usually accompanied by mildly cloudy weather.

Discussion and Conclusions

Continental-scale thermal anomalies (CTAs) belong to a group of dangerous climatic events with multiple dangerous biometeorological, natural and economic implications. This study analyses their annual and long-term trends, as well as their interconnection with the atmospheric circulation.

In the years 1951-2018, there were 16 CTAs- and 25 CTAs+. CTAs- mainly occurred in the winter and autumn, and CTAs+ in summer, which means that they show a different annual pattern, which is a characteristic feature. CTAs underwent pronounced long-term

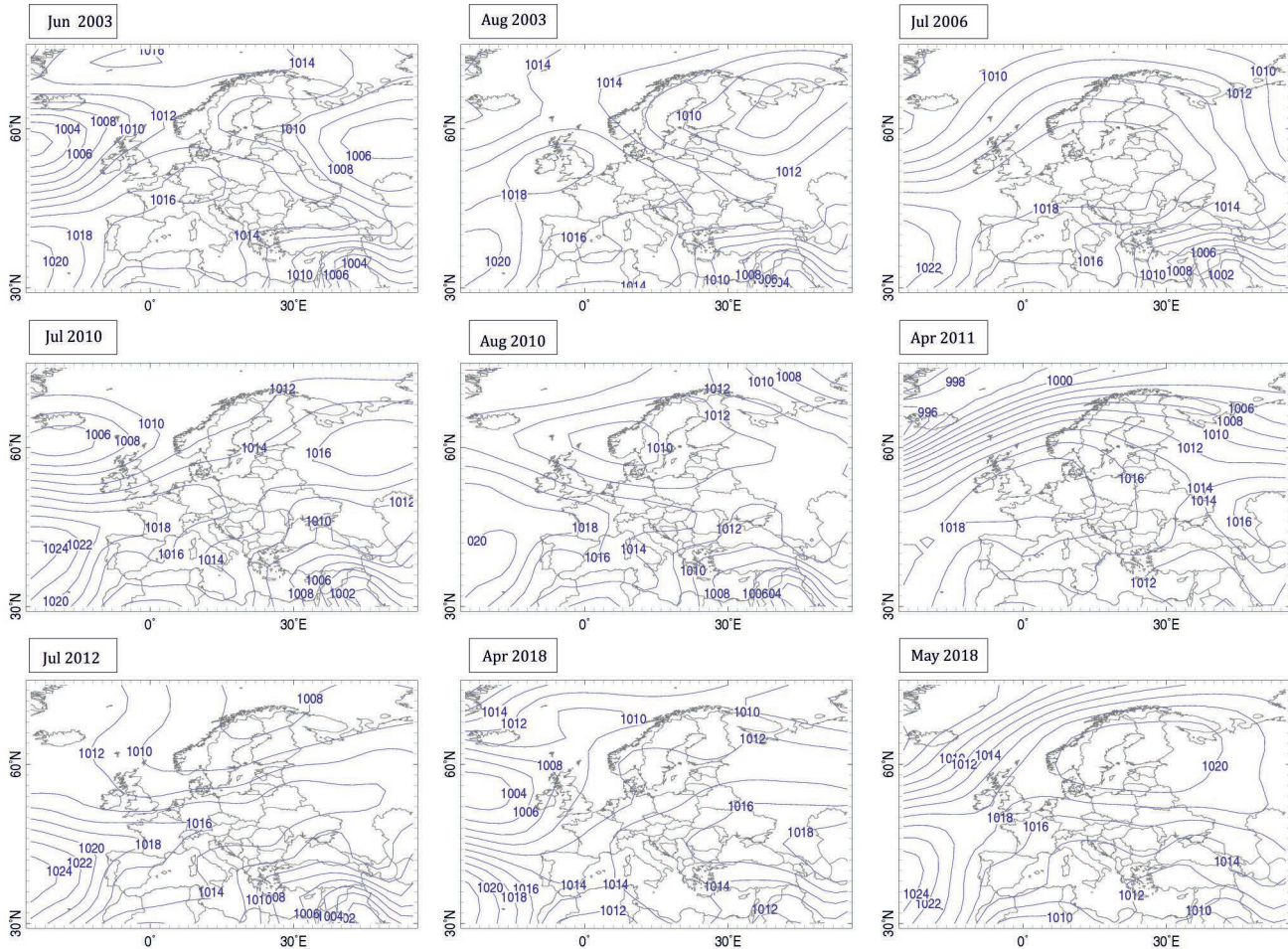


Figure 8. Mean sea level pressure (in hPa) during the CTA+ in the period 1951-2018 (NCEP-NCAR Reanalysis)

changes. Out of the 16 CTAs-, 15 occurred before 1993, and only one in the 21st century (December 2002). Out of 25 CTAs+ only two occurred in the 20th century (in 1990 and 1994), and among the remaining 23, as many as 12 were recorded in the last 8 years, including 4 in 2018. Such changes over the years confirm the much commented on global warming, which is manifested in Europe, inter alia, by increasingly warmer winters and ever more frequent and longer heat waves (Kundzewicz & Huang 2010; Štěpánek et al., 2011; Hoy et al., 2017; Tomczyk et al., 2019). However, it should be emphasised that an increase in the number of exceptionally hot days is not always associated with an increase in the absolute values of maximum temperature (Wibig, 2021).

It is of note that the recent warming of the European climate is not only evidenced by a decrease in the frequency of CTAs- and growth in the frequency of CTAs+, but also by a change in the size of the area covered by these thermal anomalies. Particularly noticeable growth in the extent of CTAs+ and their frequency was recorded during 2-month sequences over a similar area. This was the case in July and August 2010 and in April and May 2018. The last of the CTAs+ prove both that they begin earlier and last longer. Such an early onset of extremely hot periods (as early as April and/or May) has particularly adverse biometeorological effects. As is noted by Muthers et al. (2017), after the winter the human body is not yet adapted to such heavy heat stress. It must also be remembered that early hot and usually dry weather after a mild and snowless winter aggravates drought, which entails multiple adverse effects across a range of branches of the economy (Sinclair et al., 2019; Twardosz, 2019). The results obtained are consistent with the outcomes of research by Sulikowska and Wypych (2021), which have shown that the considerable increase in the frequency and intensity of spells with exceptionally high temperatures observable since the mid-twentieth century has gone hand in hand with an increase in their spatial range.

One of the record-breaking anomalies in terms of area and size is the CTA- that occurred in February 1956 and covered more than half of Europe, from the Urals to the British Isles. On half of the area covered by the CTA-, the average temperature in February 1956 was lower than the long-term average by as much as 3 SDs.

Typically, the area covered by a CTA- had a large latitudinal extent (W-E), while in the case of a CTA+ the area tended to be stretched longitudinally. The characteristic way in which CTAs stretch stems from geographical conditions, mainly the latitudinal orientation of mountain ranges on the European continent, which makes it easier for cold continental air masses to move from the east even as far as south-west Europe (which was the case with the CTA- in February 1956). However, the mountain ranges do not constitute a major obstacle to the movement of hot lighter air masses from the south northward, which are often responsible for CTAs+. It should also be emphasised that crossing a mountain barrier by warm and humid air may produce the foehn effect on the northern side, which adds to the increase in temperature, e.g. in April and May 2018. However, it should be remembered that changes in the frequency, intensity and spatial coverage of extreme thermal conditions, including CTAs, proceed in slightly different ways from one geographic region and season of the year to another (Sulikowska & Wypych, 2021).

The research conducted has revealed that the occurrence of a CTA is most frequently associated with the occurrence of characteristic synoptic situations over Europe. Strong, extensive and persistent anticyclonic systems played a special role in such cases. In winter, they were often associated with the predominance of meridional circulation (negative NAO and AO phase) and the advection of air from the east or north (Cattiaux et al., 2010; Buchan et al., 2014). This led to a very strong drop in air temperature, which was not only conditioned by advection, but also by strong outward radiation of heat from the ground during long winter nights in cloudless

high-pressure weather. Longer spells of such advection, which are usually caused by the build-up of high-pressure blocking systems, would lead to periods with anomalously low air temperatures in various parts of the continent, which is also confirmed by other studies (Gumiński, 1931; Bardin, 2007).

Stationary high-pressure systems equally frequently caused CTAs in the summer, although the role of low-pressure systems was no less important (Wibig 2021). As a result of their interaction, some areas of Europe experienced an advection of hot tropical air, which was the direct cause of the occurrence of the CTA+ identified. In addition, it must be emphasised that the growth of temperature in the summer is also fostered by insolation, which grows as a result of the small degree of cloudiness on long summer days, typical of highs. Many researchers also attribute the primary causes of such events to the thermal conditions prevailing in the ocean (Black & Sutton, 2007), especially to the temperature of its surface waters (Dole et al., 2011), changes in cloud cover (Tang et al., 2012), and incoming solar radiation, as well as to the increase in the concentration of greenhouse gases in the atmosphere (Jones et al., 2008; Gruza & Ran'kova, 2011).

It is also worth noting that the formation of CTAs- was much more often associated with very extensive and long-lasting anticyclonic systems, and that the associated synoptic situations over Europe lasted much longer than in the case of CTAs+. In the summer, the circulation over the European continent changed much more frequently in the months identified, but the mutual pattern of the individual pressure centres and the associated advection of air recurred many times. Such changes occurring in the long run result in the average distribution of air pressure

at sea level. It should be considered as an important tool for explaining the general features of circulation over a given area which contribute to the spatial distribution of the values of the various elements of climate. However, it does not always fully reflect the dynamic changes in circulation, which means that sometimes we get a somewhat distorted picture of the location of the most important pressure centres and of the directions of air advection. It is particularly noticeable in the summer season, when even the short-term presence of a strong anticyclonic system was mirrored in the distribution of mean pressure values, e.g.: in August 2003 and July 2006 (Wibig, 2021).

For the above reason, existing research on the relationship between the occurrence of extreme thermal conditions and atmospheric circulation has most often focused on analysing the pressure field at sea level and selected pressure levels on days when such conditions occurred (Porębska & Zdunek, 2013; Tomczyk & Owczarek, 2020), and sometimes also on the preceding days (Chen et al., 2017; Tomczyk et al., 2019). However, it follows from the present study that it is of equal importance to investigate the circulation conditions and the recurrence of particular synoptic situations, which then translate into extreme thermal conditions on vast areas, for longer (e.g. monthly) periods.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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