EFFECT OF REGIONAL BARIC SYSTEMS ON THE OCCURRENCE OF BIOCLIMATIC CONDITIONS IN POLAND

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Abstract: The present study concerns the determination of the characteristics of bioclimatic conditions, as well as the synoptic situations related to the occurrence of thermal stress conditions, in Poland. The study was based on daily data obtained from the Institute of Meteorology and Water Management – National Research Institute from the period 1966–2020 for 37 synoptic stations in Poland. Based on the obtained data, values of the Universal Thermal Climate Index (UTCI) were calculated. The occurrence of heat stress increases from the north to the south, corresponding with the variability of influx of solar radiation, and is modified by factors at a smaller spatial scale. The results of this paper evidently point to the cooling effect of the waters of the Baltic Sea. In circulation conditions favouring strong and very strong heat stress, e.g. in two of the designated circulation types (T1 and T2), the occurrence of an expansive high-pressure ridge in the Atlantic-European area is typical, stretching from the region of the Azores High towards the north-east, with a secondary high developed within its boundaries. In the third of the designated circulation types (T3), the high-pressure area extends from the Azores eastwards, reaching the Black Sea. Each of the three circulation patterns associated with the unfavourable biometeorological conditions of very strong and extreme cold stress in Poland is characterised by strong pressure centres formed in the Euroatlantic region, triggering the airflow from the northern (T4) or eastern (T5, T6) sector.

Key words: bioclimatic conditions, UTCI, atmospheric circulation, Poland

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Introduction

The analysis of bioclimatic conditions assumes a steadily increasing importance with reference to human needs, particularly in the domains of spatial planning, tourism, public health, sports, bioforecasts, etc. Most biometeorological indices are not applicable to the entire year, unlike the Universal Thermal Climate Index (UTCI). Comparisons of different biometeorological indices with UTCI have been presented in numerous papers (Błażejczyk et al. 2012, 2014a, Bröde et al. 2013, Novak 2013, Matzarakis et al. 2014, Świątek 2014, Farajzadeh et al. 2015, Zare et al. 2018, 2019).

UTCI has been used, among other applications, for the assessment of perceived climate in the territory of selected countries and cities (Lindner 2011, Błażejczyk 2013, Lindner-Cendrowska 2013,

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Mąkosza 2013, Błażejczyk, Błażejczyk 2014, Błażejczyk et al. 2014b, Park et al. 2014, Owczarek 2021). It has also been applied in the investigation of correlations between thermal stress and a change in the concentration of air pollutants (Nidzgorska-Lencewicz, Mąkosza 2013, Nidzgorska-Lencewicz 2015) and mortality (Idzikowska 2011, Nastos, Matzarakis 2012, Błażejczyk 2013, Błażejczyk et al. 2013b, Urban, Kyselý 2014, Kuchcik 2021). The index was used by Okoniewska and Więcław (2013) in the assessment of the multiannual variability of bioclimatic conditions around noon in the second half of the previous century in Poland. It has also been applied in the assessment of the usefulness of biometeorological conditions for the purposes of tourism and recreation (Matzarakis, Nastos 2011, Lindner-Cendrowska 2013, Rutty, Scott 2014, Świątek 2014, Kažys, Malūnavičiūtė 2015, Ge et al. 2016). UTCI has, among other utilities, provided the basis for the assessment of the local climate of the Kłodzko Basin (Milewski 2013). Such research in the Polish coastal zone has also been conducted by, among other researchers, Nidzgorska-Lencewicz and Mąkosza (2013), Nidzgorska-Lencewicz (2015), Półrolniczak et al. (2016), Kolendowicz et al. (2018) and Koźmiński and Michalska (2019).

The effect of atmospheric circulation on bioclimatic conditions has been broadly investigated (Błażejczyk et al. 2003, Bartzokas et al. 2013, Nowosad et al. 2013, Bryś, Ojrzyńska 2016, Bartoszek et al. 2017, Katavoutas, Flocas 2018, Rozbicka, Rozbicki 2018, Owczarek 2019, Owczarek et al. 2019, Głogowski et al. 2020, Tomczyk, Owczarek 2020, Owczarek, Tomczyk 2022). Okoniewska (2021) evidenced that the most optimal biothermal conditions occur during the advection of marine polar air, extreme cold stress is caused by the inflow of polar continental and arctic air masses, and very strong heat stress by that of tropical air masses.

Research on extreme biometeorological conditions both in winter (Bartoszek et. al. 2017, 2020, Owczarek, Tomczyk 2022) and summer (Owczarek 2019, Krzyżewska et al. 2020, 2021, Tomczyk, Owczarek 2020, Tomczyk et al. 2020) in Poland has primarily been conducted at a regional scale. It shows a correlation of the occurrence of cold stress primarily with cyclonic circulation in south-east Poland, and air inflow from the western sector (Bartoszek et al. 2017). In northern Carpathians, the correlation is with anticyclonic circulation and advection from the north and north-west (Błażejczyk et al. 2020). Kolendowicz et al. (2018) and Półrolniczak et al. (2016) evidenced that the occurrence of extreme cold stress at the Baltic coast was predominantly related to the system of highs over northern Europe or a system of lows in that area, causing air inflow from the north. The occurrence of days with extreme UTCI values in Poland was primarily related to the presence of high-pressure systems blocking zonal circulation (Tomczyk, Owczarek 2020).

A change in the frequency of extreme biothermal conditions in recent years has been observed in Serbia by Pecelj et al. (2021), and in Poland by Krzyżewska et al. (2021). Kuchcik et al. (2021) recognised increase in maximum UTCI values in summer in the north-east, north-west and south of Poland, as well as in UTCI minimum values in the entirety of Poland in the period 1951–2018. Brecht et al. (2020) forecast more frequent occurrence of higher UTCI values related to an increase in air temperature and humidity. This creates a need for detailed research on extreme biometeorological conditions throughout the country affecting the health and functioning of society. Considering the above, the objective of this study was the determination of the characteristics of bioclimatic conditions in Poland, and identification of synoptic situations related to the occurrence of thermal stress conditions, namely strong and very strong heat stress and very strong or extreme cold stress.

Data and study methods

The study was based on daily data obtained from the Institute of Meteorology and Water Management – National Research Institute from the period 1966–2020 for 37 synoptic stations in Poland (Fig. 1). The study applied data from 12:00 UTC for meteorological parameters such as: air temperature (°C), relative humidity (%), wind speed ($m \cdot s^{-1}$) and total cloudiness (okta). All data series were homogenous.

First, based on the obtained data, values of the UTCI were calculated. The index is defined as equivalent air temperature at which, under

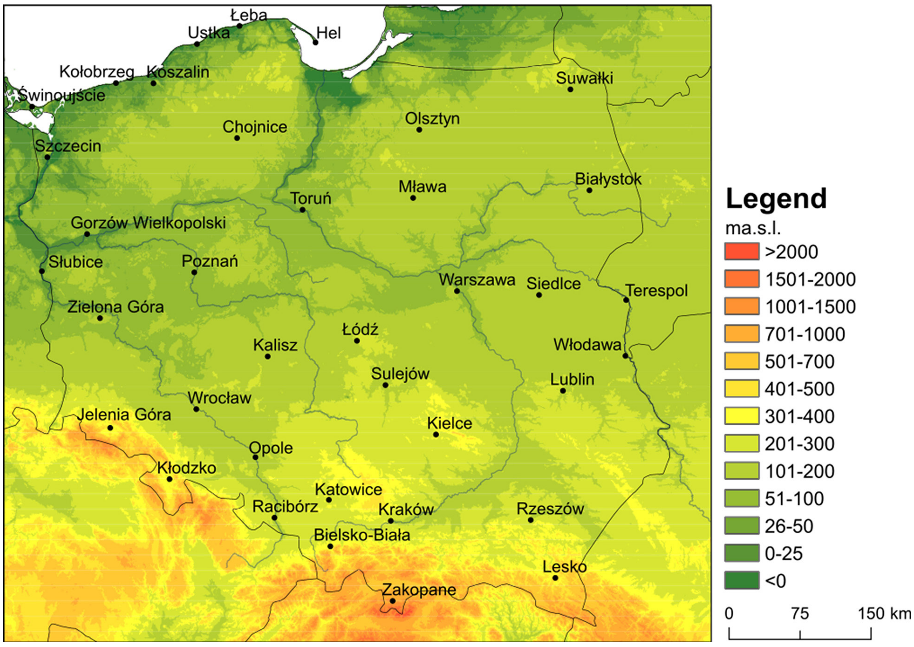

Fig. 1. Locations of the synoptic stations in Poland.

reference conditions, the basic physiological parameters of the human organism would adopt the same values as in actual conditions. It is a unidimensional value reflecting the response of the organism to multidimensionally described meteorological and physiological information (Błażejczyk et al. 2012, Bröde et al. 2012). It is assumed that heat exchange between the human body and the surroundings only depends on air temperature (Ta) at a constant level of the remaining meteorological parameters (Błażejczyk et al. 2012, Bröde et al. 2012). The index is based on the multinodal model of human temperature regulation by Fiala et al. (1999, 2001), composed of two subsystems of regulation of heat exchange: passive and active. UTCI values are a measure of thermal stress of the organism, and are expressed in degree Celsius. The calculation of the index employed the package BioKlima 2.6 (Błażejczyk, Błażejczyk 2006).

The calculated values provided the basis for the determination of the UTCI category (Table 1) for each day, followed by the determination of the frequency of occurrence of such categories in the study period in individual stations. At the next stage, the frequency of occurrence of two extreme classes recorded in a given area was determined, namely strong and very strong heat stress and very strong and extreme cold stress. Then, changes in the annual number of days included in the categories in the period 1966–2020 were analysed, and the statistical significance was verified by means of a non-parametric Mann–Kendall test (Mann 1945) at a significance level of 0.05.

The identification of regional circulation patterns associated with unfavourable biometeorological conditions employed the reanalysis data, at a resolution of 2.5° × 2.5° on sea level pressure (SLP) and 500 hPa geopotential height (z500 hPa), collected from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (Kalnay et al. 1996). Moreover, air temperature at the 850 hPa geopotential level (T850), usually equal to approximately 1500 m a.s.l., was obtained from the same source and applied to the analysis.

The ‘environment to circulation’ approach was applied in referring the occurrence of unfa-

Table 1. Universal Thermal Climate Index (UTCI) assessment scale of human heat stress (Błażejczyk et al. 2013a).

UTCI (°C)	Stress category	UTCI (°C)	Stress category
>+46	Extreme heat stress	0 to +9	Slight cold stress
+38 to +46	Very strong heat stress	−13 to 0	Moderate cold stress
+32 to +38	Strong heat stress	−27 to −13	Strong cold stress
+26 to +32	Moderate heat stress	−40 to −27	Very strong cold stress
+9 to +26	No thermal stress	<−40	Extreme cold stress

vourable biometeorological conditions to circulation patterns (Yarnal 1993, Yarnal et al. 2001, Dayan et al. 2012). In this method, the classification of atmospheric conditions is made according to specific environment-based criteria set for a particular environmental phenomenon, in this case the occurrence of heat/cold stress. Days with two extreme classes of heat stress (strong and very strong heat stress/very strong and extreme cold stress) occurring in at least 10 Polish stations (out of the 37 chosen for the analysis) were selected, and composite maps of the SLP and z500 hPa mean as well as SLP, z500 hPa and T850 anomalies were constructed. All anomalies were computed for each day separately as a difference between a given day value and a given day 55-year climatology.

Furthermore, different circulation types were designated for days with heat/cold stress, using the Ward's (1963) minimum variance method. It is a hierarchical clustering technique most frequently used for climatic classification (Kalkstein et al. 1987). The method permits identification of atmospheric circulation patterns associated with the occurrence of specific weather phenomena (e.g. Esteban et al. 2005, Bednorz 2011, Tomczyk et al. 2019). In this study, the clustered objects were days with heat/cold stress, and the clustering was based on daily SLP data. The primary idea of the clustering of data objects (in this case days) is the use of the minimum distance method. Clusters should consist of objects separated by small distances, relative to the distance between clusters. The distance measure commonly used in cluster analysis is the Euclidean distance in the multidimensional space of the data vectors (Wilks 1995). Finally, composite maps of the synoptic conditions were produced for each distinguished type.

Results

General characteristics of biometeorological conditions

Conditions with different categories of cold stress prevailed over a bigger part of the year in Poland (Fig. 2). It particularly concerned winter months. In 10 stations (i.e. in 27% of the stations chosen for the analysis), in the studied multiannual period, at least 1 month was recorded in which 100% of days were qualified as days with cold stress. The situation was observed in only 2 months in a year, i.e. January and December. All days in both months with cold stress were recorded in Chojnice, Koszalin, Suwałki and Ustka. In at least one of these months, such a situation

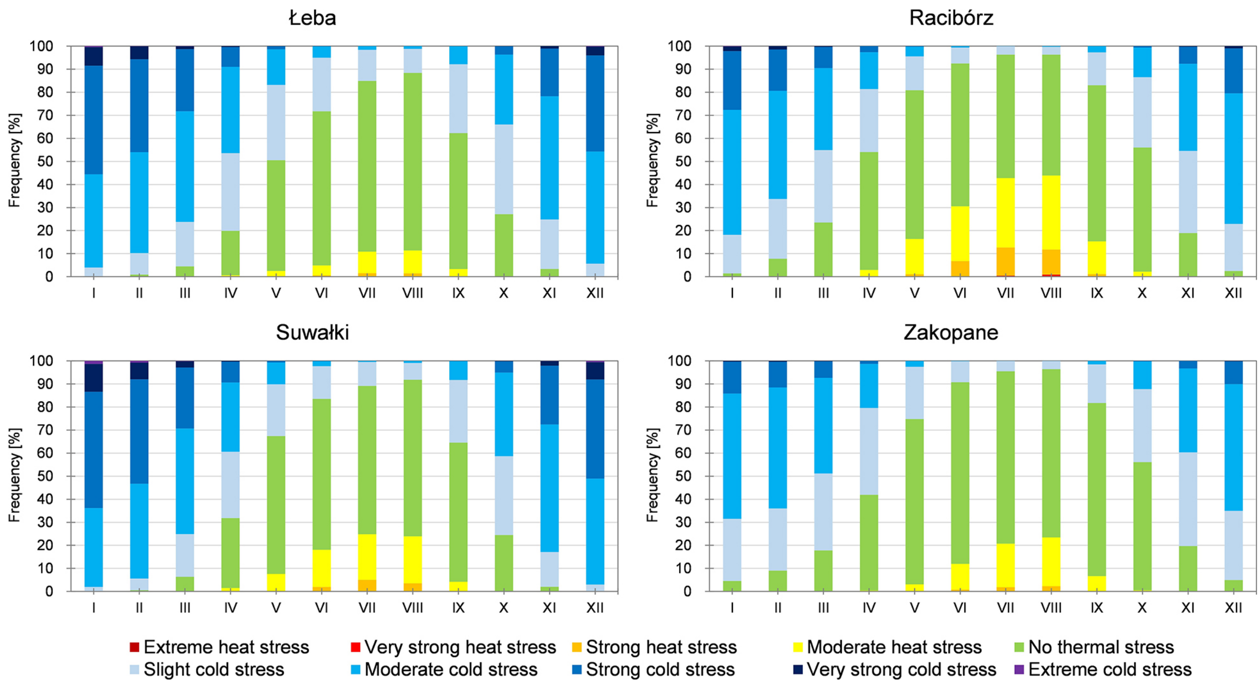

Fig. 2. Share of days with particular Universal Thermal Climate Index categories during the year in selected stations in Poland in the period 1966–2020.

was recorded in Hel, Łeba, Siedlce, Terespol, Toruń and Włodawa. Days with extreme cold stress were primarily observed in winter months. Moreover, in several stations, individual days occurred outside that period, i.e. in March (Jelenia Góra, Łeba, Suwałki), April (Świnoujście) and November (Bielsko-Biała, Suwałki).

In 86% of the stations in the period from May to September, more than half of days in the analysed multiannual period were days with no thermal stress. In the remaining stations, the period was somewhat different. In Opole, Słubice and Zakopane, it lasted from May to October, in Racibórz from April to October and in Łeba it was the shortest, lasting from June to September.

Days with heat stress particularly occurred from April to October (Fig. 2). The exception is a group of 12 stations where individual days with moderate heat stress were recorded in March. Additionally, in Lesko, such a day also occurred in November. The greatest share of days with different heat stress categories was observed in the summer period, i.e. from June to August. Except for two stations (Kalisz and Wrocław), only during these three months, days with very strong heat stress were recorded. In both of the stations, one such day was recorded in September. The highest number of days with very strong heat stress was determined in Słubice (37 days) and Wrocław (30 days). No days in this category only occurred in Zakopane.

Among 37 analysed stations, 92% showed an increase in the number of days with heat stress, and 95% showed an increase in the number of days with no thermal stress in the analysed multiannual period. Among stations with an increase in the number of such days, statistically significant changes were recorded in the former case in 65% of the stations, and in the latter in 71% of the stations. In 95% of the stations, a decrease in the number of days with cold stress was determined, whereas 94% of the changes were statistically significant.

Occurrence of days with strong and very strong heat stress and their circulation conditions

In the years 1966–2020, the average annual number of days with strong and very strong heat stress in Poland reached 5.6 days. The analysed days occurred the most seldom at the south coast of the Baltic Sea and in areas located in south-west Poland, especially along the Oder River valley (Fig. 3). In particular stations, the average number of days with strong and very strong heat stress varied from 1.1 days in Łeba to 10.3 days in Racibórz. More than 10 days were

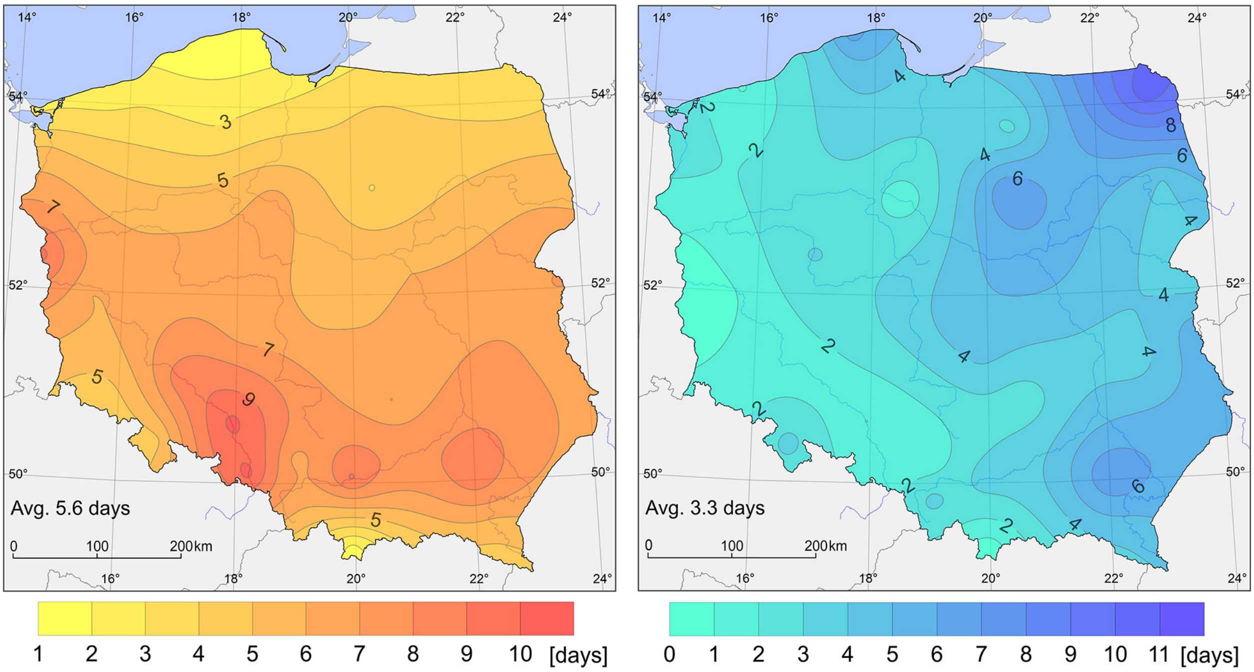

Fig. 3. Average annual number of days with strong and very strong heat stress (map on the left) and days with very strong and extreme cold stress (map on the right).

also recorded in Opole (10.2 days). The years 1994 and 2015 stood out in terms of the number of the analysed days. In those years, a maximum number of such days was recorded, i.e. in 49% and 41% of the stations, respectively. In 1994, the number of days of the analysed category varied from 2 days in Kołobrzeg to 25 days in Rzeszów, and in 2015 from 1 day in Hel to 32 days in Racibórz. Such days were observed the most seldom in the first half of the analysed period. The years that particularly stood out were 1980 and 1978. These were the only years when, in more than half of the stations, no day with strong or very strong heat stress was recorded. The maximum number of the analysed days in the first year reached 3 days (Racibórz), and in the second one 5 days (Opole). In 86% of the stations, the number of days with strong and very strong heat stress increased. The most intensive changes were recorded in Kraków and Rzeszów (1.7 days · 10 years^{-1}) (Fig. 4). No changes were observed in the remaining stations, and in the case of two stations (Łeba and Zakopane), due to a low number of cases, the changes were not quantifiable.

Throughout the study period 1966–2020, 424 days with strong and very strong heat stress were recorded in at least 10 stations in Poland. Conditions of heat stress were associated with positive SLP anomalies over Europe and a vast high-pressure ridge spreading zonally from the Azores High towards the east and north-east. In the composite maps constructed for days with heat stress, the highest SLP anomalies exceeding 4 hPa occurred east and north-east of Poland, where a secondary anticyclonic centre is located, with SLP reaching >1018 hPa (Fig. 5). At the same time, weak negative SLP anomalies extended over the British Isles and the North Atlantic. The anticyclone spreading over Europe reached the middle troposphere, whereas z500 hPa persisted higher than average. The isohipses of z500 hPa were bent northwards, and anomalies of z500 hPa were positive over most of the continent, exceeding 100 m over Poland and the south Baltic Sea. Summer anticyclonic conditions over Europe usually cause higher than normal air temperatures, as in this case, documented by positive anomalies of T850 over most of the continent. The highest T850 anomalies exceeding 6°C occurred over south-west Poland, primarily caused by anticyclonic conditions, and secondarily by southern advection of air masses, forced by clockwise circulation around the anticyclone.

Furthermore, three patterns of the SLP field (T1, T2 and T3) were designated for days with strong and very strong heat stress in Poland (Fig. 6). Type 1 (T1) represents 188 days with heat stress, and generally shows conditions similar to those described above for all days with strong and very strong heat stress, namely a high-pressure ridge spreading throughout Europe with a secondary anticyclonic centre developed in the east. The eastern centre of high pressure extends from Belarus to west Russia, where SLP exceeds 1018 hPa (SLP anomalies >4 hPa). Positive air

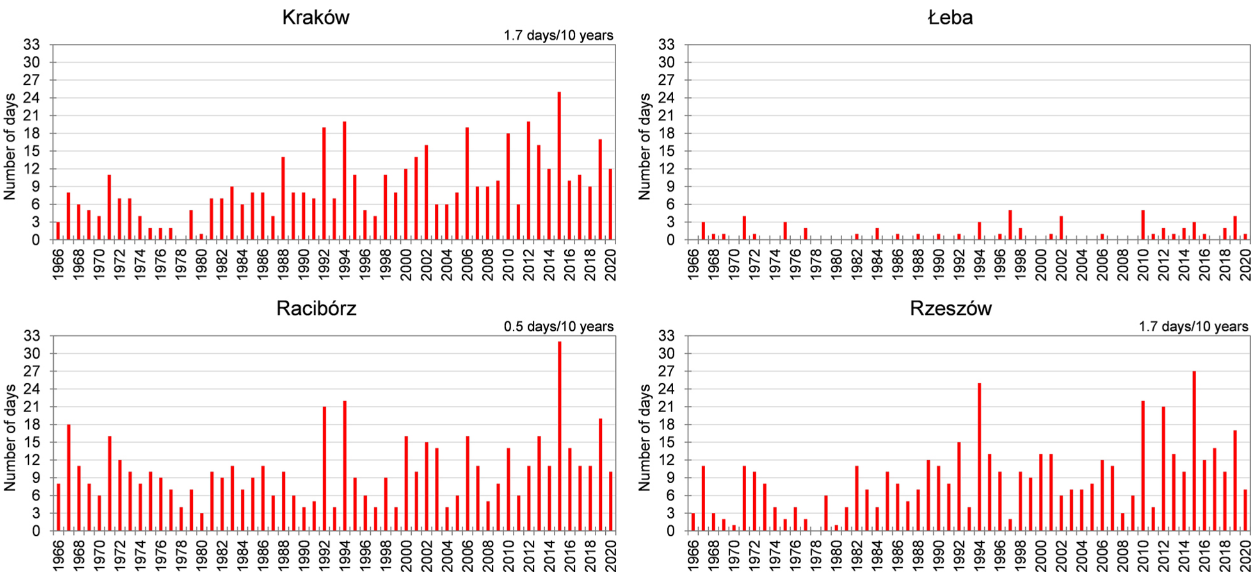

Fig. 4. Number of days with strong and very strong heat stress in selected stations in the period 1966–2020.

temperature anomalies at Z850 cover a major part of Europe, and are the highest (>6°C) over the western part of Poland.

In type 2 (T2 in Fig. 6), covering 127 days, the high-pressure ridge over Europe is shifted to the north-west, and the local anticyclonic centre with SLP exceeding 1020 hPa is located over south Finland and the north Baltic Sea (Finnish and Bothnia Gulfs). Positive SLP anomalies mainly cover north Europe, exceeding 6 hPa

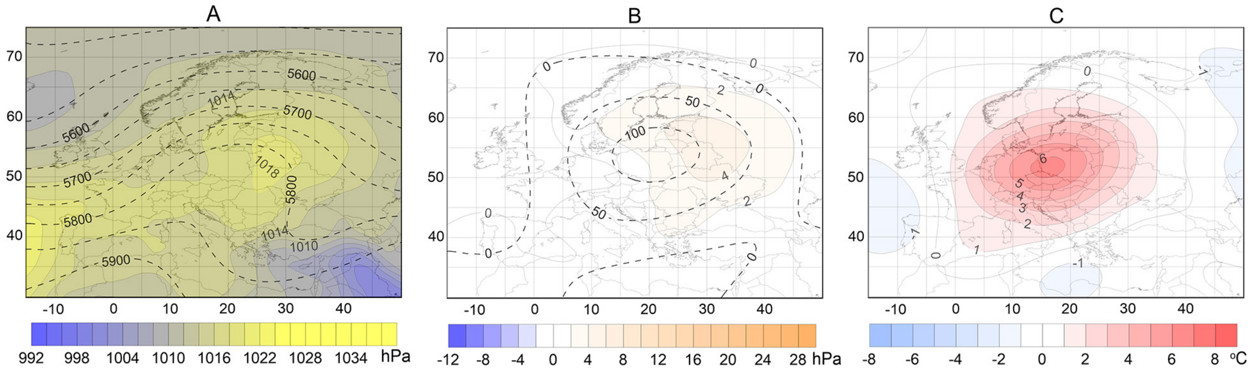

Fig. 5. Mean (A), anomaly maps of sea level pressure (SLP, hPa, colour shades) and z500 hPa (gpm · m^{-1}, dashed lines) (B) and anomaly map of T850 (°C) (C) for days with strong and very strong heat stress in at least 10 stations in Poland.

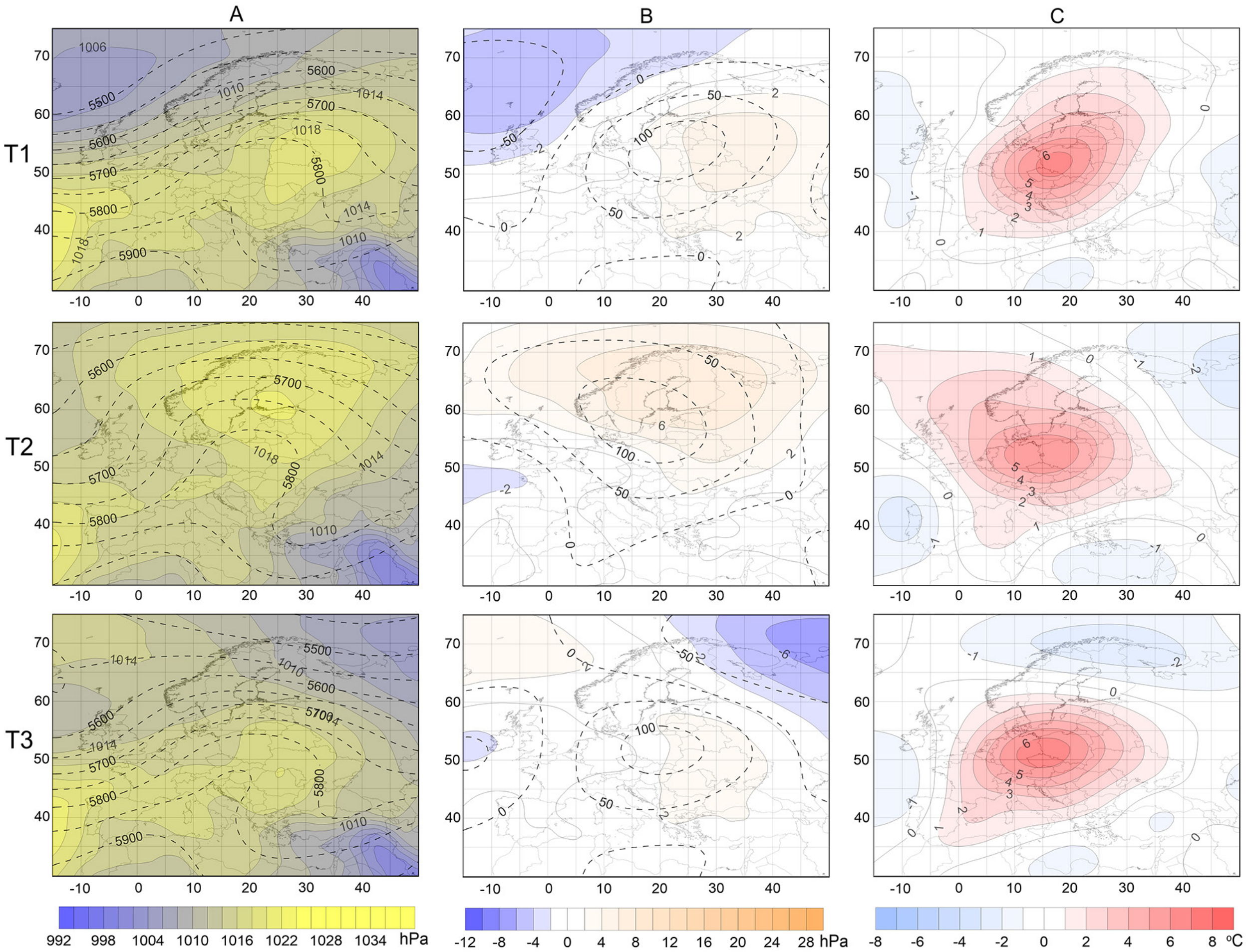

Fig. 6. Mean (A), anomaly maps of sea level pressure (SLP, hPa, colour shades) and z500 hPa (gpm · m^{-1}, dashed lines) (B) and anomaly map of T850 (°C) (C) for three circulation types (T1, T2 and T3) associated with strong and very strong heat stress in Poland.

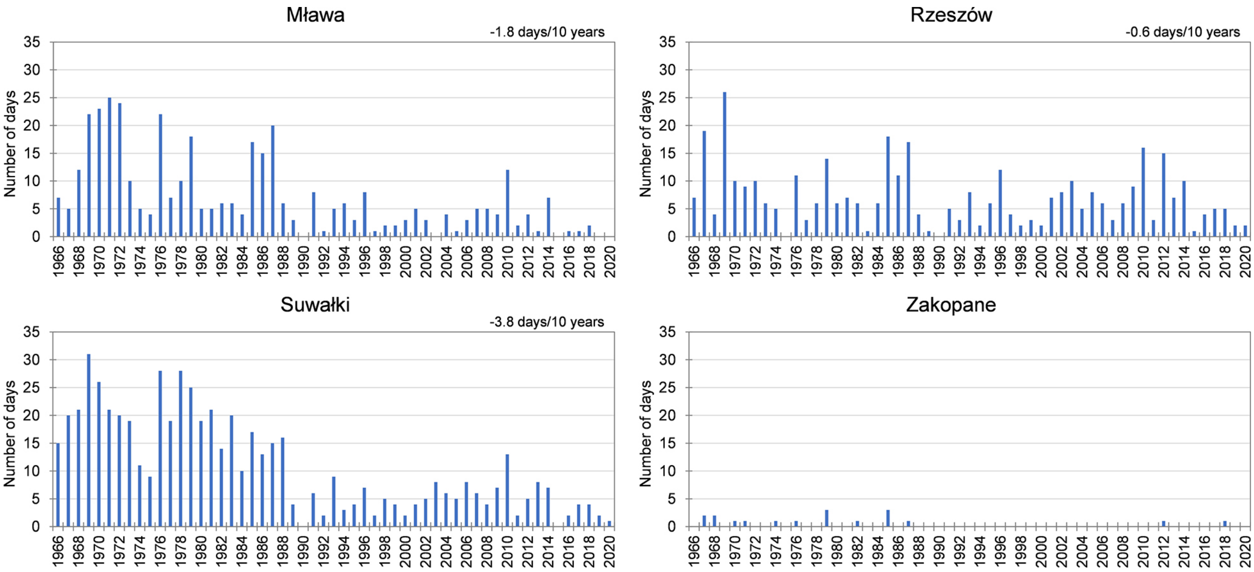

Fig. 7. Number of days with very strong and extreme cold stress in selected stations in the period 1966–2020.

over Scandinavia. Anomalies of T850 extend over a larger part of the study area than in the case of type 1, although they are weaker and exceed 5°C over central and west Poland and north Germany.

In the least numerous type 3 (109 days, T3 in Fig. 7), the high-pressure ridge is shifted southwards, and extends zonally east of the Azores High. SLP reaches >1014 hPa over the vast area extending from central Poland to the Black Sea. In type 3, weak positive SLP anomalies (hardly exceeding 2 hPa) are observed east and south-east of Poland, while negative SLP anomalies in the north-east reach −6 hPa (probably not influencing bioclimatic conditions in Poland). As in both previous types, positive anomalies of z500 hPa follow the positive anomalies of SLP, exceeding 100 m at most. In type 3, positive temperature anomalies occur over central Europe, exceeding 6°C over the Polish–German–Czech border.

In each of the three types, three components account for unfavourable biometeorological conditions of strong and very strong heat stress in Poland. First, it is strong solar radiation flux under a clear sky due to subsidence in an anticyclone. Second, a weak pressure gradient over Poland suppresses the wind speed, which might have a cooling effect, and third, the advection of warm air masses from the southern (type 1), south-eastern (type 2) or south-western (type 3) sector.

Occurrence of days with very strong and extreme cold stress and their circulation conditions

In the analysed multiannual period, the number of days with very strong and extreme cold stress in Poland averaged 3.3 days. The analysed days occurred the most seldom in west Poland, and particularly in south-western regions (Fig. 3). They were recorded the most frequently in east Poland with a maximum in north-eastern regions and at the east coast of the Baltic Sea. In particular stations, their average number varied from 0.3 days in Zakopane to 10.7 days in Suwałki. In the analysed period, days with very strong and extreme cold stress occurred the most frequently in the second half of the 1960s, as well as in the 1970s and the 1980s; and the years 1979 and 1969 stood out on the background of the multiannual period. In the former, the number of the analysed days varied from 2 days in Racibórz to 25 days in Suwałki. In 1969, their number ranged from 0 days in Opole, Racibórz and Zakopane to 31 days in Suwałki. In 1979, 35% of the stations showed the highest number of days of the analysed category, and in 1969 the share was 27% of the stations. Days with very strong and extreme cold stress occurred the most seldom in the last years of the analysis with a minimum in 2020 and 2015. In those years, in 84% of the stations, no days in the analysed category were recorded. In 27 stations, the number of observed cases permitted the determination of the rate and trend of changes. Among these stations, 89% showed a decrease in the number of the analysed days. The most intense changes were observed in Suwałki (−3.8 days · 10 years^{-1}) and Mława (−1.8 days · 10 years^{-1}) (Fig. 7).

The number of days with very strong and extreme cold stress occurring in at least 10 stations in Poland throughout the study period is 182 days. The biometeorological conditions of cold stress were associated with a dipole pattern

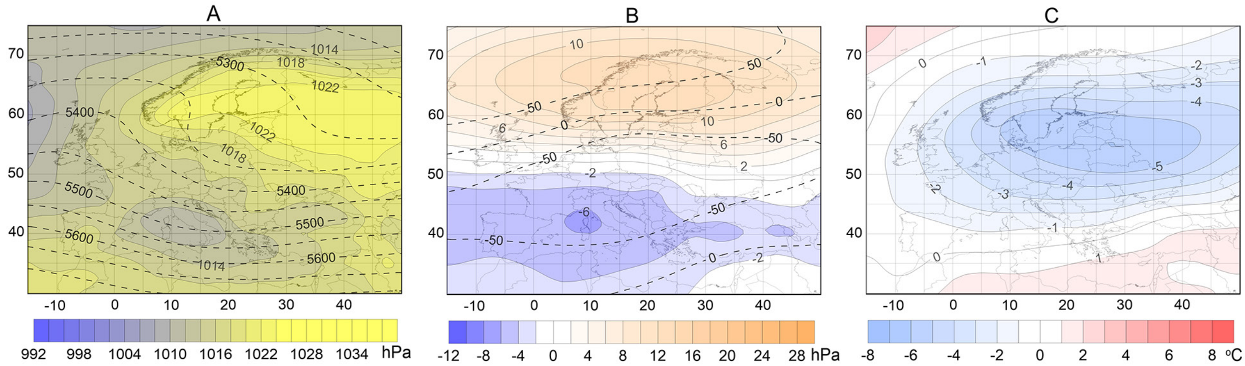

Fig. 8. Mean (A), anomaly maps of sea level pressure (SLP, hPa, colour shades) (B) and z500 hPa (gpm · m^{-1}, dashed lines) and anomaly map of T850 (°C) (C) for days with very strong and extreme cold stress in at least 10 stations in Poland.

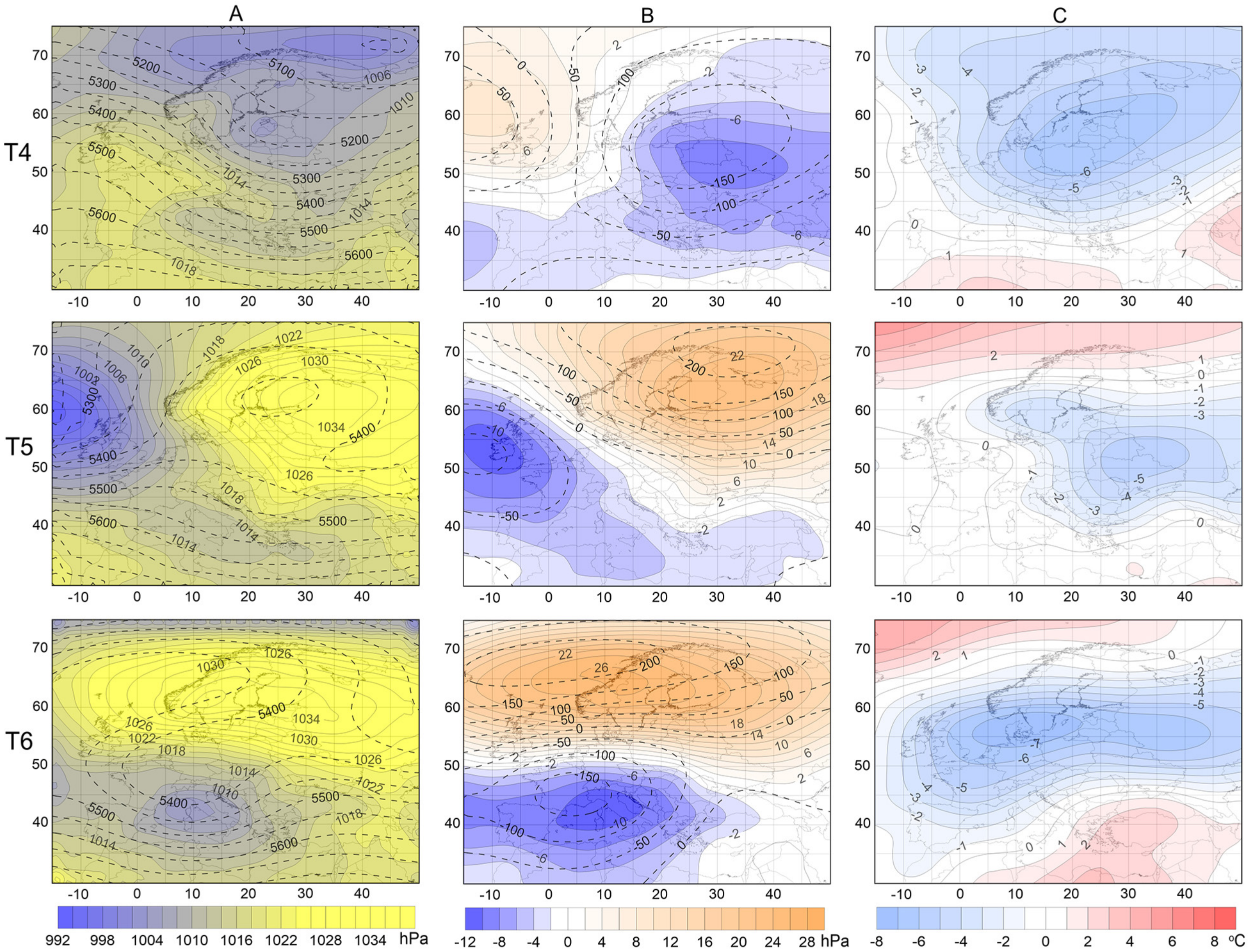

Fig. 9. Mean (A), anomaly maps of sea level pressure (SLP, hPa, colour shades) and z500 hPa (gpm · m^{-1}, dashed lines) (B) and anomaly map of T850 (°C) (C) for three circulation types (T4, T5 and T6) associated with very strong and extreme cold stress in Poland.

of SLP anomalies with a positive centre over Scandinavia (anomalies >12 hPa) and a negative centre (<−6 hPa) over the Mediterranean (Fig. 8). The high-pressure ridge exceeding 1022 hPa expands from north-east Europe through north Baltic to Scandinavia, and a local cyclonic centre with SLP dropping to 1–12 hPa is located over the western Mediterranean. Such an SLP pattern triggers intense (due to larger than normal pressure gradient) eastern airflow over central Europe, bringing cold polar continental air masses. Anomalies of T850 are negative in a major part of Europe, exceeding −6°C in the area from west Russia to the south Baltic and north-east Poland. The T850 anomaly field corresponds to the anomalies of z500 hPa, and in the cool air masses along the zonal belt extending throughout the study area, z500 hPa is lowered by >50 m.

Similar to the case of heat stress, the detailed analysis permitted distinguishing three patterns of the SLP field (T4, T5 and T6 in Fig. 9) occurring on days with very strong and extreme cold stress in Poland. Each type represents a dipole pattern of positive and negative SLP anomalies, similar to the composite map in Figure 8, although the locations of the positive and negative centres are different.

In type 4 (T4 in Fig. 9), consisting of 73 days, higher than normal pressure, with SLP anomalies exceeding 8 hPa, appeared over the North Atlantic, while negative SLP anomalies were observed throughout Europe, dropping under −8 hPa east of Poland. The low-pressure system with a centre over the Barents Sea expanded south. One secondary cyclonic centre formed in the east Baltic region, and another one over the Mediterranean. A wedge of high pressure encompassed south-west Europe, reaching the British Islands. Such a pressure pattern enhanced northern circulation, and cool air masses covered a prevalent area of Europe, excluding the Mediterranean section. Anomalies of T850 dropped below −6°C in the area from north-west Russia to Poland and the south Baltic. In the same area of cool air, the highest decline of geopotential heights was observed, and z500 hPa anomalies exceeded −150 m.

Type 5 (55 days, T5 in Fig. 9) represents a pattern quite opposite to T4, with SLP anomaly centres located conversely. Strong positive SLP anomalies encompassed northern Europe, exceeding 22 hPa in east Scandinavia and northwest Russia. A high-pressure system spread over north and east Europe, and in the anticyclonic centre over north-east Russia SLP exceeded 1034 hPa. At the same time, a deep cyclone was situated in the west of the study area, and SLP dropped below 994 hPa in its centre over the North Atlantic. Negative SLP anomalies were observed in south-west Europe, reaching −10 hPa over Ireland. An eastern and south-eastern flow, forced by the described pressure pattern, brings cold polar continental air to the eastern and central parts of Europe, where negative air temperature anomalies reach −5°C.

In type 6 (T6 in Fig. 9), consisting of 54 days, a south-north dipole pattern of SLP anomalies was observed, and Europe was zonally divided into areas of positive and negative anomalies. In the positive centre over Norway and the Norwegian Sea, SLP was higher by >26 hPa, while the negative centre over the central Mediterranean was weaker, with anomalies reaching approximately –10 hPa. Both the Scandinavian vast anticyclone with SLP reaching 1036 hPa in the centre and the Mediterranean cyclone (<1006 hPa in the centre) generated strong eastern circulation in Europe that brought cold polar continental air masses flowing zonally to the west, as suggested by the pattern of T850 anomalies (up to −7°C between the North and Baltic Seas).

Each of the three circulation patterns associated with the unfavourable biometeorological conditions of very strong and extreme cold stress in Poland is characterised by strong pressure centres formed in the Euroatlantic region, triggering the airflow from the northern (T4) or eastern (T5, T6) sector. Cold arctic or polar continental air masses coming to central Europe, due to strong pressure gradients, are associated with strong wind conditions, which escalates the cold stress. Furthermore, in the anticyclonic conditions observed in type 5, strong heat flux into the higher layers of the atmosphere results in a significant decrease in surface air temperature.

Discussion and summary

The paper presents patterns of the spatial and temporal variability of occurrence of conditions strenuous for the organism related to strong or very strong heat stress and very strong or extreme cold stress. The occurrence of heat stress increases from the north to the south, corresponding with the variability of influx of solar radiation, and is modified by factors at a smaller spatial scale. The results of this paper evidently point to the cooling effect of the waters of the Baltic Sea. The average annual number of days with the analysed heat stress varied from approximately 1 day at the Baltic Sea coast, 6–7 days in central Poland, to even >10 days in the south of Poland. Similar patterns have been described in literature at different time scales, but the number of days determined in those studies has often been different than that provided herein. For example, in July in Warsaw, the number of days with strong and very strong heat stress in the period 1971–1990 did not exceed 2 days (Błażejczyk, Kunert 2011), in the years 1966–2015 it was 2.5 days (Tomczyk, Owczarek 2020) and in the years 2001–2018 it reached almost 4 days (Krzyżewska et al. 2021). Two more days with strong and very strong heat stress than in this paper were determined in south-west Poland in the period 1971–2019 (Miszuk 2021). Błażejczyk (2006) points to a gradual intensification of heat stress in southern Poland. Results presenting the spatial variability of the occurrence of cold stress strongly affecting the thermoregulation system of the organism show that it is caused by the variability of the degree of continentalism, variability of water temperature in the Baltic Sea, and local factors such as height a.s.l. and land relief diversity. The north-eastern part of Poland stands out, where on average, the highest number (up to 8) of days with the analysed category of heat stress occurs in a year. In January in the period 1971–1990 in north-east Poland it was on average approximately 3 days (Błażejczyk, Kunert 2011), and in winter in the years 1966–2019 approximately 5 days (Owczarek, Tomczyk 2022). In Warsaw in January in the period 1971–1990, an average of 2 such days occurred, and at the Baltic Sea coast 1 day (Błażejczyk, Kunert 2011). Similar differences between central Poland (4.5 days) and the Baltic Sea coast (approximately 2 days) were determined with reference to the entire winter season in the years 1991–2000 (Błażejczyk, Błażejczyk 2014). Station Zakopane shows an exceptionally low number of days with the analysed category of cold stress (0.3 days on average). In winter seasons, the frequency of occurrence of very strong cold stress in Zakopane does not exceed 0.5% (Wereski et al. 2020, Owczarek, Tomczyk 2022). Such low values may result from the distribution of wind speed, which is a factor potentially considerably intensifying cold stress. The average annual wind speed in Zakopane in the years 1966–2018 was 1.4 m · s^{-1}, and in winter at noon it reached 1.9 m · s^{-1} (Wibig 2021). The frequency of moderate winds (with speeds from 4 m · s^{-1} to 10 m · s^{-1}) was 6.7% at noon, and even less in the morning and evening (3%). Very high frequency of calms is also observed: 43.5% in the morning and 10.8% at noon. The valley location of the station might be a factor contributing to the reduction of wind speed and the frequency of silence. Similar results were shown in other stations, also located in mountain valleys (Wibig 2021). Irregularities in wind speed measurements in Zakopane were also observed, however, resulting from the incorrect location of the anemometer (Lorenc 1996, Wibig 2021). A characteristic pattern of the temporal variability of the discussed biometeorological conditions is a multiannual increase in the frequency of occurrence of strong and very strong heat stress, and a simultaneous decrease in the occurrence of very strong and extreme cold stress. Both the aforementioned changes are statistically significant over the majority of the territory of Poland. In the case of heat stress, the rate of increase was estimated at 0.5 days · 10 years^{-1} to almost 2 days · 10 years^{-1}. Considering a multiannual period shorter by 5 years than that in this paper, its statistically significant increase was determined in 50% of the stations in Poland, and in 65% of the stations in this paper. A faster rate of changes was also recorded, by 0.6–2.3 days · 10 years^{-1} (Tomczyk, Owczarek 2020). A similar direction and rate of changes have also been observed in other papers, e.g. a significant increase in the number of days with strong heat stress in south-east Poland in the years 1971–2019 at a rate of 0.7 days · 10 years^{-1} (Miszuk 2021), and at the Baltic Sea coast in the period 1981–2010 by 3–6 days · 10 years^{-1} (Półrolniczak et al. 2016). Since 2005, in south-east Poland, very strong heat stress has been occurring twice as frequently than in the 1980s (Nowosad et al. 2013), and in the years 2010–2018 the number of days with strong and very strong heat stress in Poland varied from 17 days in Łeba to 127 days in Rzeszów; and in some stations it was even twice as high as in the period 2001–2009 (Krzyżewska et al. 2020). In the case of cold stress conditions a decrease in their frequency of occurrence is observed, and the rate of these changes was faster, from approximately 2 days · 10 $years^{-1}$ to almost 4 days · 10 $years^{-1}$, particularly in north-east Poland. A similar character of changes was determined in south-west Poland, where in the period 1971–2019 the rate of changes reached >2 days · 10 $years^{-1}$, and in Karkonosze—only in the case of extreme cold stress—even >4 days · 10 $years^{-1}$ (Miszuk 2021). A decrease in the frequency of occurrence of cold stress conditions was also recorded in south-east Poland, where in the period 1977–2006 the rate of the decrease reached 9 days · 10 $years^{-1}$ (Bartoszek et al. 2017), and at the Baltic Sea coast, where in the years 1981–2010 the rate of changes in the occurrence of days with strong cold stress reached 2 days · 10 $years^{-1}$ (Półrolniczak et al. 2016). This is confirmed in the research of Błażejczyk and Twardosz (2010), who reported a gradual softening of the bioclimatic conditions in winter. Although results of earlier studies are often difficult to compare due to different spatial and temporal scales, as well as the applied methods, the recorded patterns in spatial and temporal variability are coherent, and correspond with general multiannual changes in climate elements, and particularly thermal conditions.

Both in average circulation conditions favouring strong and very strong heat stress, and in two of the designated circulation types (T1 and T2), the occurrence of an expansive high-pressure ridge in the Atlantic-European area is typical, stretching from the region of the Azores High towards the north-east, with a secondary high developed within its boundaries. The centre of the high can be located over east Europe or over the south-eastern part of the Scandinavian Peninsula. In the third of the designated circulation types (T3), the high-pressure area extends from the Azores eastwards, reaching the Black Sea. Simultaneously with the aforementioned expansive areas of positive SLP anomalies over the North Atlantic, an area of negative anomalies occurs that, depending on the location of its centre, can reach the western boundary of the continent or cover the entirety of north Europe.

Similar circulation types were designated with reference to a period 5 years shorter than that in this study, whereas the number of cases of the analysed heat stress differed in particular circulation types (Tomczyk, Owczarek 2020). The greatest difference concerns the share of circulation with a high located over east Europe, accounting for 44% of cases, whereas in the shorter period the share covered 35% of cases. A similar share of cases of intensification of heat stress related to the occurrence of extensive high-pressure systems over Europe, favouring stable weather, was also observed in south Europe. In Greece, approximately 35% of such cases were recorded during the occurrence of a high-pressure system from the Iberian Peninsula to south Baltic Sea and east Europe (Bartzokas et al. 2013), with a range similar to that of the high ridge presented in this paper. The system of isohips of 500 hPa isobaric surface designated in types 1 and 2, located >100 m higher than average, is similar to the system of isohips of 300 hPa isobaric surface that was identified as a condition favouring the occurrence of strong and very strong heat stress (Tomczyk, Owczarek 2020). The occurrence of strong and very strong heat stress in Poland is therefore in most cases related to the occurrence of baric systems blocking western zonal airflow, and favouring advection of warm air from the southern directions. This is suggested by the determined positive values of temperature anomalies at a level of 850 hPa, with a concentric arrangement of isanomals. Blockage systems contribute to the occurrence of extremely high air temperature values (Pfahl, Wernli 2012, Pfahl 2014, Brunner et al. 2017), and particularly heat waves (Porębska, Zdunek 2013, Tomczyk, Bednorz 2016, Zschenderlein et al. 2019, Błażejczyk et al. 2022). The obtained results confirm the strong effect of thermal conditions on thermal stress of the human organism, which, in weak gradient areas of higher-than-average pressure with low cloudiness, is strengthened by the radiation factor and weakening or even lack of the cooling effect of wind. Earlier research on the occurrence of strong and very strong heat stress in south-east Poland showed that it is related to two circulation types designated based on the analysis of the SLP field (Bartoszek et al. 2017). One of them involves a high with a location similar to that in type 1, favouring advection from the south. In the second one, Poland is within the range of an extensive weak gradient area with a local high with a centre north of Poland, but located at a lower latitude than the centre of the high designated in type 2. The dominant effect of longitudinal advection on the occurrence of high UTCI values in south-east Poland was evidenced by Nowosad et al. (2013). At the south coast of the Baltic Sea, strong and very strong heat stress occurred in relation to two circulation types with a characteristic system of isohips of 500 hPa isobaric surface similar to that presented herein, with anomalies reaching 120 m higher than on average (Półrolniczak et al. 2016). In the SLP field, a high was observed over the north-eastern border of Poland, or shifted towards the north-east. Both the aforementioned circulation types are approximate to type 1 designated in this paper, but with a high located northward. They were interpreted as favouring advection of warm air from the south. Moreover, the occurrence of the analysed heat stress at the Baltic Sea coast can be related to the extensive high-pressure area with a range approximate to that of type 3, with a high ridge extending further north than in type 1, or a high over north Europe favouring advection from the east (Kolendowicz et al. 2018). With reference to particular directions of advection of geostrophic wind, it was evidenced that it is usually related to advection from the south and south-east (Owczarek et al. 2019). Similarly, the occurrence of strong and very strong heat stress in Warsaw is in most cases related to anticyclonic circulation types favouring advection from the south and south-east (Rozbicka, Rozbicki 2018). In summer months, the presence of centres of higher-than-average pressure in the area of the Baltic Sea or north-east Europe, with location similar to that in type 2 herein, and weak advection from the south-east or east, can contribute to an increase in the number of days with moderate, strong or very strong heat stress by >5 days in a month (Owczarek 2018). The meridional circulation with the southern component brings an increase in heat stress in spring, summer and autumn (Błażejczyk et al. 2003).

In the case of cold stress, its considerable intensification can be determined by both longitudinal and latitudinal advection. In 60% of cases (types 5 and 6) of occurrence of very strong or extreme cold stress, Poland is under the effect of a high-pressure system with a centre over the south-western or south-eastern part of the Scandinavian Peninsula. Simultaneously, a system of negative SLP anomalies is observed with different locations – with a centre west of the British Islands or in the area of the Mediterranean Sea. Intensification of cold stress is favoured by considerable cooling as a result of intensive advection of cold continental air from the east and north-east. In the case of the designated type 6, temperature at the level of 850 hPa in the south Baltic area reaching the north-western edge of Poland is >7°C lower than on average. Similar to the case of this paper, the occurrence of cold stress due to advection from eastern directions has also been reported in earlier studies. For example, in Warsaw, occurrence of cold stress in winter was usually observed during anticyclonic situations with advection from the south-east, although the category of strong cold stress was also considered (Rozbicka, Rozbicki 2018). A circulation type similar to the designated type 5, in that the occurrence of cold stress in south-east Poland is favoured, is reported by Bartoszek et al. (2017), but with main baric centres differing in location, namely, the centre of the high over north Europe being located further east, and the centre of the low over the North Atlantic being located further south, than in type 5."Such a circulation type favours continental air advection from the south-east, with the cooling effect manifested in the >3°C lower-than-average minimum temperature in the station in Lublin. The occurrence of very strong and extreme cold stress at the south coast of the Baltic Sea due to the presence of a strong high in the Scandinavian and Baltic areas generated airflow from the south-east. This type is the most similar to type 6 designated herein, but the negative anomalies of 500 hPa isobaric surface are approximately 30 m lower. Particularly strong cold stress can also occur due to the flow of cool air from the north-west and north. Such advection is favoured by the corresponding-to-type-4 system of negative anomalies in the SLP field with a centre north of the Scandinavian Peninsula and a simultaneously occurring extensive area of positive anomalies with a centre over the North Atlantic covering west Europe. The distributions of anomalies of the isobaric surface having a height of 500 hPa, as well as temperature at a level of 850 hPa, suggest cooling not only throughout Poland, but almost reaching the southern edge of the continent. The occurrence of cold stress due to the presence of an area of negative anomalies in the SLP field with a centre in the area of the Scandinavian Peninsula or south Baltic was also evidenced with reference to south-east Poland in two circulation types (Bartoszek et al. 2017). If the centre of a low-pressure system is located at the north-eastern border of Poland or over central Baltic, together with the high-pressure area over the Azores, a system develops that favours advection from the north-west. Type 4 designated herein is the most similar to these two types. It accounts for 40% of cases of very strong or extreme cold stress over a major territory of Poland. Earlier research has also described circulation types favouring intensification of cold stress, showing a high gradient area of intensive western airflow the development, of which is supported by a strong low-pressure system with a centre over the Norwegian Sea. Due to the above, the role of wind speed in shaping thermal stress at the Baltic Sea coast was emphasised (Kolendowicz et al. 2018), as well as in south-east Poland (Bartoszek et al. 2017). This paper presents no evident situation of advection from the west affecting the occurrence of the analysed categories of cold stress. The zonal circulation with the western component clearly moderates the conditions that are biothermal in winter (Błażejczyk et al. 2003).

The results of this paper, as well as those of several previous studies, suggest that the most important aspect of occurrence of the strongest thermal stress of the organism is the increasingly frequently occurring very strong heat stress, often related to the occurrence of anticyclonic circulation types, including blockage situations. Due to the evidenced increase in the frequency of occurrence of such situations since the beginning of the 20th century (Bielec-Bąkowska 2014, Brunner et al. 2018), negative consequences of strong heat stress of the organism can occur increasingly often, including an increase in mortality, which has been repeatedly described in the literature (Błażejczyk et al. 2018, Kuchcik 2021). Moreover, they can be difficult to estimate due to the still-prevalent difficulties in forecasting the accurate location, intensity and duration of blockage situations (Brunner et al. 2018, Lupo 2021). On the other hand, the results also show that despite a systematic decrease in the frequency of occurrence of very strong cold stress, it can still occur. It is therefore worth emphasising the need for forecasting and monitoring of biometeorological conditions and changes in bioclimatic conditions.

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Author's Contribution

AMT: conceptualization, data curation, formal analysis, investigation, project administration, writing – original draft, writing – review and editing; EB: conceptualization, data curation, formal analysis, investigation, writing – original draft, writing – review and editing, correspondence with editor; KSP: writing – original draft, writing – review and editing; MO: writing – original draft, writing – review and editing.

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