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IMPACT OF ATMOSPHERIC CIRCULATION ON THE OCCURRENCE OF VERY STRONG AND EXTREME COLD STRESS IN POLAND

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Abstract: The primary objective of the study was the determination of the spatial and multiannual variability of occurrence of days with very strong and extreme cold stress in Poland according to the Universal Thermal Climate Index (UTCI), as well as determination of baric conditions favouring their occurrence. The study was based on data from the years 1966/67 to 2018/19 from the Institute of Meteorology and Water Management – National Research Institute and National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR). The research showed a statistically significant decrease in the number of days with very strong and extreme cold stress on half of the analysed stations, and a slight tendency or no changes on the remaining stations. The occurrence of days with extreme cold stress in Poland, as revealed by the analysis was primarily related to the presence of high-pressure systems blocking zonal circulation. The study resulted in the designation of three circulation types, i.e. two types related to anticyclonic systems and one cyclonic type.

Key words: bioclimatology, UTCI, atmospheric circulation, cold stress, winter, Poland

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Introduction

Modern climate changes are manifested in an intensive increase in air temperatures and temperature of the Earth and Ocean surface (IPCC 2021). It is estimated that during 2006–2015, global mean surface temperature was higher by 0.87°C than the mean value from the period 1850–1900 (IPCC 2019). The progressing warming contributes to the occurrence of extreme weather conditions that considerably affect human health and life. Such phenomena include heat waves increasingly frequently occurring in many regions over the world, including Poland (Wibig 2018, Tomczyk et al. 2019) and Europe in general (Tomczyk, Bednorz 2019, Matzarakis et al. 2020, Twardosz, Kossowska-Cezak 2021).

Despite the observed warming, several-day-long periods with very low air temperature are observed. On the majority of meteorological stations in Poland, the highest number of cold waves, defined as a sequence of at least

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3 days with T_{max} below −10°C, was recorded in the seasons 1966/1967 to 1985/1986 (Tomczyk et al. 2019). The duration of the longest waves on particular stations varied from 6 days to 14 days. A decreasing frequency of the occurrence of cold spells, as determined by different methods, has been observed (Owczarek, Filipiak 2016, Tomczyk et al. 2019). However, cold episodes have been observed during numerous winter seasons in recent years. As examples of such cold episodes that occurred in Poland, we may mention the ones that took place in 2016, 2017 (Report of the Government Centre for Security, 2016, 2017), 2018 (Tomczyk, Bednorz 2019) and 2021 (IMGW-PIB 2022). There is a risk of hypothermia, heart failure, myocardial infarction or even death associated with cold thermal conditions (Błażejczyk et al. 2020a, Kuchcik 2020).

Unfortunately, the papers cited above discuss extreme weather phenomena only based on one meteorological element, namely air temperature. It is recommended that research on human-biometeorological conditions needs to apply indices that take into account various meteorological parameters, because the human organism abiding outdoor is affected by thermal stimuli, modified by air humidity and wind speed. The effect of wind on the intensification of convection heat loss from the organism is particularly manifested at very low air temperature (Tikuisis, Osczevski 2003, Shitzer 2018). Even wind with very low speed (approximately 3 m $\cdot$ s^{-1}) increases the risk of hypothermia in the case of staying outdoors for a longer period of time without proper protection. At a temperature below −20°C, the risk of frostbite of exposed body parts increases even within 10–30 min (Environment Canada 2020, National Weather Service 2020). A fast decrease with an increase of wind speed, particularly at low air temperature, was also evidenced in the case of Universal Thermal Climate Index (UTCI) values (Novak 2013). UTCI values calculated based on simulations of different meteorological conditions in the conditions of a standard meteorological station (Błażejczyk, Błażejczyk 2014) show that wind with a speed of 4 m $\cdot$ s^{-1} has a cooling effect only in sunny weather and high air humidity. At a wind speed of 8 m $\cdot$ s^{-1}, irrespective of air humidity, its cooling effect is always observed. One should also remember the stimulus effect of atmospheric pressure, which was analysed in clinical studies on the occurrence of pain, e.g. the increase of headache incidences connected with increase of air pressure was demonstrated by Yang et al. (2011) and Elcik et al. (2017). On the other hand, in the work of Mukamal et al. (2009), it can be found that lower air pressure per about 7 hPa increases the risk of nonmigraine headache and hospitalisation.

An example of such a human-biometeorological index is the UTCI (Błażejczyk et al. 2010). The index is commonly applied in research on human-biometeorological conditions. In Poland, such studies have been conducted at the local (Dobek, Krzyżewska 2015, Bartoszek et al. 2017) and regional (Półrolniczak et al. 2016, Kolendowicz et al. 2018, Owczarek et al. 2019, Błażejczyk et al. 2021) scales, as well as at the scale of the entire country (Błażejczyk, Kunert 2011, Błażejczyk et al. 2018, Kuchcik et al. 2021). The studies primarily focused on the frequency of occurrence of particular stress categories in different time-scales. Periods of at least 30 years were usually taken into account (e.g. Dobek, Krzyżewska 2015, Półrolniczak et al. 2016), but so were shorter time-periods, e.g. 10 years (Idzikowska 2010). The frequency of occurrence of all thermal stress categories was analysed (Kolendowicz et al. 2018), or only selected categories were considered (Kuchcik 2020, Tomczyk, Owczarek 2020). Annual values were presented, but sometimes also seasonal (Błażejczyk, Błażejczyk 2014) or monthly ones (Nowosad et al. 2013, Bartoszek et al. 2017).

Similar studies have been conducted in many regions of Europe, including in the Czech Republic (Urban et al. 2019), Greece (Nastos et al. 2017), Germany (Walikewitz et al. 2018), Serbia (Pecelj et al. 2021) and Italy (Petralli et al. 2020). Di Napoli et al. (2018) analysed the variability of biothermal conditions in Europe, and evidenced the correlation between such variability and human health.

Atmospheric circulation is one of the primary factors shaping weather and climatic conditions at mid-latitude (Niedźwiedź 1981, Yarnal 1993). Therefore, numerous studies have also investigated its effect on human-biometeorological conditions (Bartoszek et al. 2017, Kolendowicz et al. 2018, Owczarek 2019, Tomczyk, Owczarek 2020). So far, research regarding extreme conditions of human-biometeorological situations in winter in Poland has been primarily conducted at a regional scale. In south-eastern Poland, Bartoszek et al. (2017) evidenced that extreme, very strong and strong cold stress was most frequently recorded at cyclonic and transitional circulation from the west and north-west, and cyclonic from the south and south-west. The highest frequency of cold stress days in the northern Carpathians was mostly related to advection of air from the north and north-east during the anticyclonic types of circulation (Błażejczyk et al. 2020a, b). Kolendowicz et al. (2018) and Półrolniczak et al. (2016) evidenced that the occurrence of extreme cold stress at the coast of the Baltic Sea was primarily related to a high-pressure system over northern Europe, or a low-pressure system in the area. Such systems provided for advection of cold air masses from the north.

Numerous studies focused on the analysis of human-biometeorological conditions primarily in the summer season (Krzyżewska et al. 2019, 2021, Owczarek 2019, Tomczyk, Owczarek 2020, Tomczyk et al. 2020) as a consequence of the progressing warming (Hoy et al. 2020, Krauskopf, Huth 2020, Tomczyk, Bednorz 2020). Despite a decrease in the frequency of cold extremes in winter, it is justified to analyse biometeorological conditions during their occurrence, because they still cause cold stress to the human organism. As evidenced above, such episodes have been recorded in recent years. Less frequent occurrence of negative air temperature results in weakening thermal stimuli in winter, leading to the loss of the adaptation, or increase in sensitivity of organisms to such stimuli (Flemming 1983, Błażejczyk, Kunert 2011). Due to this, detailed investigation of extreme human-biometeorological conditions in winter throughout the country will be of particular importance for the health and life of different social groups. Considering the above information, the study objectives are:

1. the determination of the spatial and multiannual variability of occurrence of days with very strong and extreme cold stress in Poland, and
2. identification of atmospheric circulation patterns favouring the occurrence of such stress in Poland.

Data and methods

The study was based on daily data from the period from October to April in the years 1966/67 to 2018/19 from 40 meteorological stations in Poland (Fig. 1). The study employed data series from 12:00 UTC, such as: air temperature (°C), relative humidity (%), wind speed (m · s^{-1})

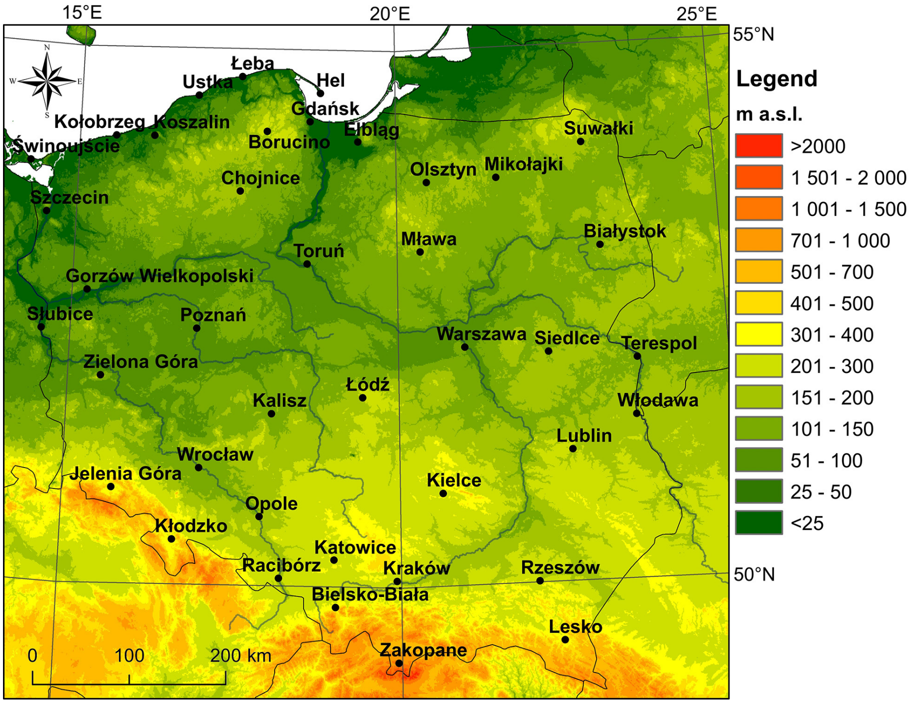

Fig. 1. Location of meteorological stations.

and total cloudiness (Oct.). 12:00 UTC is a standard observation term providing data for research in the scope of biometeorology and bioclimatology. This time of day corresponds to most types of outdoor human activity in Poland (Kuchcik 2020). The air temperature at midday is usually not the lowest during the day; so, if very cold stress occurs then, it can be supposed that the exposure of the human body to the effects of cold stress may last longer. Data from that time had been commonly applied in earlier studies for the assessment of the human-biometeorological situation for a given day (Błażejczyk et al. 2013, Owczarek 2019). It was assumed that the measurements of wind speed were always carried out at a standard height of 10 m above ground level. All data series were homogenous, and were obtained from the data base of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

The aforementioned data provided the basis for the calculation of the UTCI. It is defined as equivalent air temperature at which, in reference conditions, the basic physiological parameters of the organism would adopt the same values as in actual conditions. It is a one-dimensional value reflecting the response of the organism to multidimensionally described meteorological and physiological information (Błażejczyk et al. 2012, Bröde et al. 2012). The index is based on the Fiala et al. (1999, 2001) multinode model of human heat transfer and temperature, composed of two subsystems of heat transfer regulation: passive and active. The passive subsystem considers physical elements of heat transport within the organism and on its surface. The active subsystem considers the physiological mechanisms of thermoregulation, e.g. sweating, shivering that change the value of heat flux. UTCI values are a measure of organism heat stress, and are expressed in degrees Celsius. As reference conditions, the paper adopted mean radiant temperature equal to air temperature, wind speed at a height of 10 m above ground level equal to 0.5 $m \cdot s^{-1}$ and water vapour pressure corresponding to 50% of relative air humidity (Bröde et al. 2012). The adopted physiological parameters included metabolic heat production corresponding to human body movement at a speed of 1.1 $m \cdot s^{-1}$, and clothing thermal insulation relevant to the surrounding conditions.

The calculation of the UTCI value employed the BioKlima 2.6 package (Błażejczyk, Błażejczyk 2006). Calculation algorithms were implemented to the software with the application of the sixth-degree exponential function (Błażejczyk et al. 2013). The meteorological data provided the basis for the determination of daily values of UTCI at 12 UTC in the analysed period, followed by the seasonal and monthly frequency of occurrence of UTCI below −27°C. Based on the assessment scale of thermal stress according to UTCI, such index values cover a combination of very strong and extreme cold stress categories. UTCI values from below −27 to −40°C correspond to very strong cold stress. In turn, UTCI below −40°C indicates extreme cold stress (Bröde et al. 2012). In conditions of very strong cold stress, frostbite of exposed facial skin can occur within 2 h when UTCI equals −27°C (Bröde et al. 2012, Błażejczyk et al. 2013). It is recommended to intensify activity and protect face and extremities against cooling, use warmer clothing and reduce outdoor exposure time. As the value of the UTCI decreases, further physiological responses are observed: gradual decrease in rectal temperature, numbness of facial skin and occurrence of shivering. The risk of frostbite increases corresponding to the decrease in UTCI: when UTCI equals −35°C, facial skin temperature decreases to −5°C within 120 min. The extreme cold stress UTCI threshold value equals −40°C, and when this value is reached, face skin frostbite can occur within 30 min, while decrease in rectal temperature by more than −0.3 $K \cdot h^{-1}$ is observed. It is recommended that when conditions of extreme cold stress are prevalent, time spent in open spaces be reduced to the necessary minimum. The multiannual variability of the annual number of days with combined very strong and extreme cold stress, with UTCI below −27°C at 12 UTC, was analysed on all stations subject to the study. Statistical significance was analysed by means of a non-parametric Mann-Kendall test (Mann 1945, Wibig et al. 2009) at a significance level of 0.05.

The determination of baric conditions favouring the occurrence of the analysed days was based on daily sea level pressure values (SLP), height of isobaric surface of 500 hPa (z500 hPa) and air temperature at isobaric surface of 850 hPa (T850). In the study, values of SLP, z500 hPa and T850 in 861 geographical grid points 2.5 × 2.5° for the area of 25°N–75°N latitude, 35 W–65°E longitude were used. The data were obtained from the collection of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996), available in the archives of NOAA ESRL PSD (Earth System Research Laboratory Physical Science Division).

The aforementioned data provided the basis for the preparation of average maps of SLP and z500 hPa for all days with very strong and extreme cold stress. They were then supplemented with maps of anomalies of SLP, z500 hPa and T850. The anomalies were calculated as the difference between the mean value of each of the above elements on a particular day and its mean value on a given day in the multiannual period of 1981–2010. The adopted period of reference is recommended by the World Meteorological Organization (WMO), which recommends adopting the most valid period of 30 years for climatological studies (finishing in a year ending with 0). The next stage involved the determination of circulation types through grouping particular days in terms of SLP values with the application of the minimum variance method known as the Ward (1963) method. Such grouping was performed based on standardised SLP values. Thus, the location and spatial arrangement of low- and high-pressure systems became a main distinguishing feature instead of the SLP absolute values (Esteban et al. 2005). After the designation of circulation types, it was verified whether the types are statistically significantly different. For this purpose, *t* test for independent samples was applied. This method was used in previous research on atmospheric circulation (Tomczyk, Bednorz 2019, Tomczyk, Owczarek 2020). Next, for the designated circulation types, maps of mean SLP and z500 hPa were prepared, as well as maps of their anomalies, and anomalies of T850. Similar maps were prepared for selected days with extreme UTCI values.

Results

Variability of very strong and extreme cold stress

UTCI values at 12:00 UTC in the discussed period show that the conditions of very strong or extreme cold stress occur primarily in the period from November to March, and only sporadically in April and October. Therefore, further analyses consider only the period from November to March. The highest frequency of occurrence of the discussed conditions in the years 1966/67 to 2018/19 was characteristic of the north-eastern part of Poland, where they constituted 7–9% of

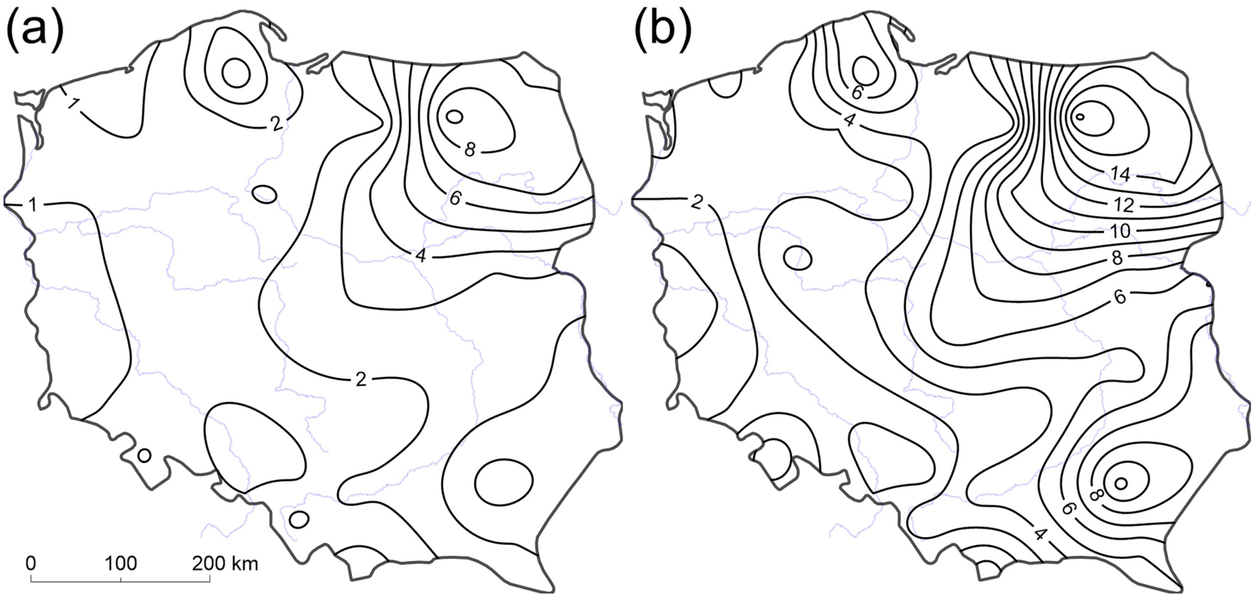

Fig. 2. Mean frequency of occurrence (%) of very strong and extreme cold stress according to the UTCI in Poland in the period November to March (A) and January (B), 1966/67 to 2018/19. UTCI, Universal Thermal Climate Index.

all cases (Fig. 2A), corresponding to even more than 10 days. The lowest frequency of the analysed combined cold stress categories occurred in the west of Poland and on the coast of the Baltic Sea (up to approximately 1% of cases). The biothermal conditions there are subject to the mitigating effect of the waters of the Baltic Sea. Among the analysed months, the greatest frequency of occurrence of the discussed cold stress is recorded for January, and the feature of its variability in that month is an increase from the west to the east, and particularly to the north-east (Fig. 2B) from less than 2% to more than 15% of cases (i.e. even up to 5 days in a month). The effect of increasing thermal continentalism on biothermal conditions is evidently reflected in an increase in distance from the Atlantic Ocean. Out of the period from December to February the greatest frequency of occurrence of the discussed cold stress can observed in Lakelands (in approximately in 3% of days in November as well as in March).

A feature of temporal variability of occurrence of strong cold stress at 12 UTC in Poland in the study period is a multiannual decrease in the number of days with such heat stress. On half of the analysed stations, it has a character of a statistically significant trend. The greatest rate of such changes, by 2–4 days per 10 years, is observed in Lakelands, particularly in Mazurian Lakeland, Suwałki Lakeland (e.g. in Suwałki, Fig. 3A, Table 1) and Białystok Upland, north-eastern Poland. As already mentioned, the area is also characterised by the highest frequency of occurrence of the discussed cold stress. Since 1966/67 (over the period of the analysis), however, the number of days with strong cold stress decreased there by 10 to even more than 20 days. The remaining identified trends on 14 stations point to a decrease in the number of days with strong and very strong cold stress by approximately 1 day per 10 years (e.g. in Warszawa, Fig. 3B, Table 1). On these stations, the number of days with very strong and extreme cold stress decreased over the analysed multiannual period by 12–20 days. On half of the stations, particularly on the coast and in western Poland, no change was observed in the analysed number of days. It should be emphasised, however, that from the beginning of the 1990s, on the majority of the stations, days with the strongest cold stress throughout the season from November to March do not occur, or occur in a maximum of 2 days. In earlier years, several to even dozen such days were recorded. No increasing tendency was recorded on any of the stations. Seasons during which days with very strong and extreme cold stress at 12 UTC occurred throughout the territory of Poland were 1978/79, 1981/82 and 1986/87. On 18 stations, the maximum number of such days among all seasons was recorded in season 1978/79. The

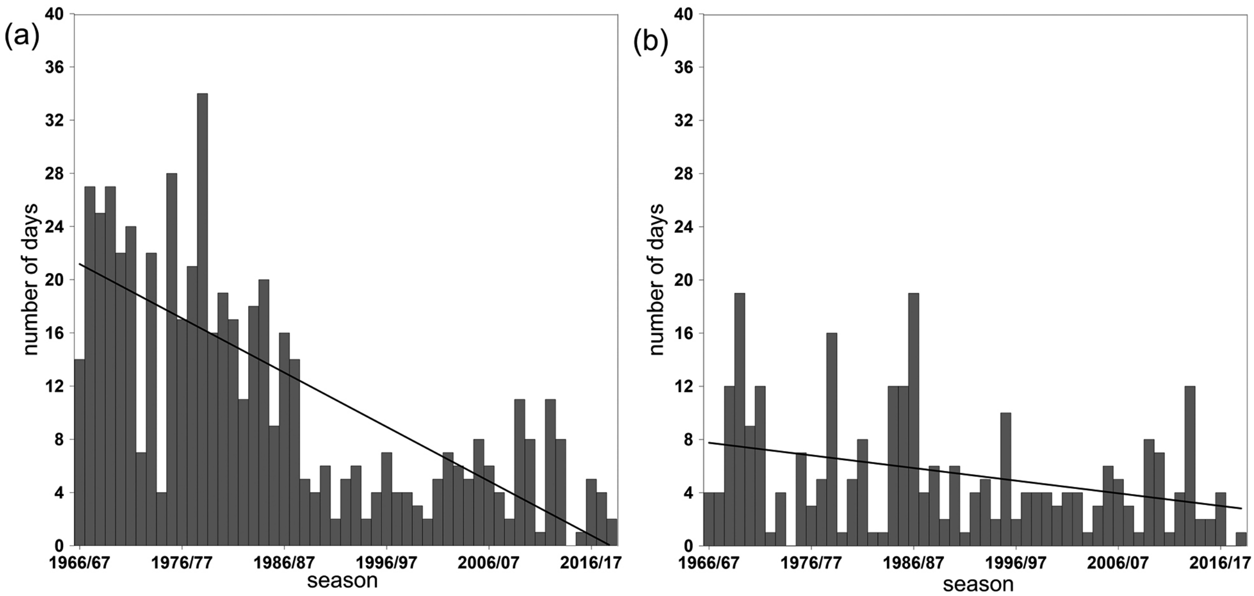

Fig. 3. Multiannual variability of seasonal (November–March) number of days with very strong or extreme cold stress according to UTCI in Suwałki (A) and Warszawa (B), 1966/67 to 2018/19. Solid lines represent respective trends. UTCI, Universal Thermal Climate Index.

recording made at the time indicates findings ranging from 6 such days in the west of Poland to 34 days in the north-east. The season was also the most severe in terms of intensity of cold stress. Conditions of combined very strong and extreme cold stress occurred on 31 stations, including extreme cold stress (UTCI <−40°C) on 26 stations.

Table 1. Selected characteristics of the number of days with very strong and extreme cold stress according to UTCI in Poland, 1966/67 to 2018/19: their maximum number and trend coefficient. Statistically significant (at 0.05 level) trend values are in bold.

Station	Maximum number of days and season of their occurrence	Trend (days · decade^{-1})
Białystok	42 1971/72	**−3.53**
Bielsko-Biała	17 1967/68	**−0.91**
Borucino	48 1969/70	**−2.33**
Chojnice	7 1978/79 1986/87	0.00
Elbląg	19 1969/70	−0.34
Gdańsk	15 1978/79	0.00
Gorzów Wlkp.	13 1978/79	−0.57
Hel	16 1978/79	**−0.29**
Jelenia Góra	10 1975/76	**−0.36**
Kalisz	15 1986/87	0.00
Katowice	6 1978/79	**−0.31**
Kielce	12 1984/85	**−0.24**
Kłodzko	9 1969/70, 1977/78, 1983/84, 1984/85	**−0.34**
Kołobrzeg	8 1978/79	−0.53
Koszalin	9 1978/79	−0.59
Kraków	14 1968/69	0.00
Lesko	15 1978/79	**−1.43**
Lublin	13 1986/87	0.00
Łeba	19 1978/79 1986/87	0.00
Łódź	16 1969/70	**−0.99**
Mikołajki	47 1971/72	**−4.62**
Mława	28 1971/72	**−1.67**
Olsztyn	12 1969/70	0.00
Opole	5 1978/79	−0.31
Poznań	14 1978/79	**−0.49**
Racibórz	10 1986/87	0.00
Rzeszów	21 1968/69	−0.35
Siedlce	17 1986/87	**−0.81**
Słubice	6 1978/79	−0.29
Suwałki	34 1978/79	**−4.00**
Świnoujście	16 1986/87	**−0.53**
Szczecin	11 1978/79	0.00
Terespol	20 1968/69	**−0.59**
Toruń	9 1978/79	−0.53
Ustka	10 2010/11	0.00
Warszawa	19 1969/70, 1986/87	**−0.67**
Włodawa	21 1978/79	−0.48
Wrocław	9 1978/79	**−0.38**
Zakopane	4 1967/68	−0.18
Zielona Góra	9 1978/79	−0.33

Effect of atmospheric circulation

The occurrence of days with very strong and extreme cold stress in the analysed period was related to the expansive high-pressure wedge

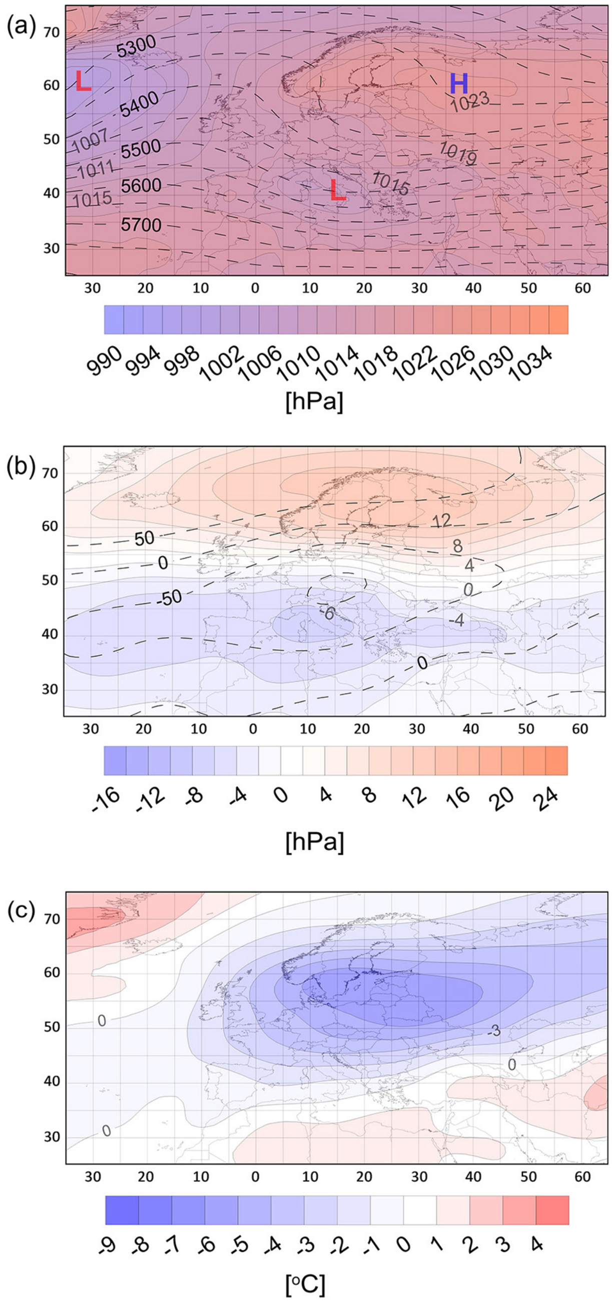

Fig. 4. Mean SLP [in hPa] (colour scale) and z500 hPa [in gpm] (dotted line) (A) anomalies of SLP [in hPa] (colour scale) and z500 hPa [in m] (dotted line) (B) and anomalies of T850 [in °C] (C) for days with very strong and extreme cold stress. SLP, sea level pressure.

extending from eastern Europe, within which a local high developed (>1023 hPa) with a centre over north-western Russia (Fig. 4). Low-pressure centres simultaneously persisted over northern Atlantic (1003 hPa) and the Mediterranean Sea (<1011 hPa). On the analysed days, SLP over the prevalent area of central, northern and eastern Europe was higher than average, and the centre of these anomalies was located over northern Finland and Sweden (>13 hPa). Southern regions of the continent were within the range of negative anomalies with a centre over the Italian Peninsula (<−6 hPa). The described baric conditions generated advection of continental air masses from the north-east. It is confirmed by the course of isoanomalies of T850. Cooler air masses covered a major area of the Euroatlantic sector, and the centre of anomalies also covered the study area (<−5°C). The consequence of the presence of cool air mases was lower height z500 hPa over a majority of the continent. The anomaly field of z500 hPa corresponds to the anomaly field of T850. The greatest deviations of the height of persistence of z500 hPa from average conditions was recorded over central Europe (<−100 m).

The description of the baric situation presented above concerned average conditions occurring during days with very strong and extreme cold stress. The detailed analysis revealed three types of atmospheric circulation favouring the occurrence of the analysed days (Fig. 5). In type 1 (54% of all cases), the baric situation was approximate to average conditions. Over a considerable area of central, northern and eastern Europe, a high-pressure wedge was dominant with a high developed within its range with a centre over the Scandinavian Peninsula (>1030 hPa). Low-pressure systems persisted over the south of Europe and northern Atlantic. The occurrence of days with very strong and extreme cold stress in type 2 (24% of all cases), similar to that in type 1, was related to the anticyclonic situation. The centre of the high persisted over western Russia (>1034 hPa). A low (<992 hPa) simultaneously persisted over the Atlantic, west of the British Isles (<992 hPa). In both types, a bipolar field of SLP anomalies was observed. In type 1, the course of SLP anomalies was of latitudinal character. Positive anomalies were recorded over the northern regions, and negative over the southern ones. In the centre of positive

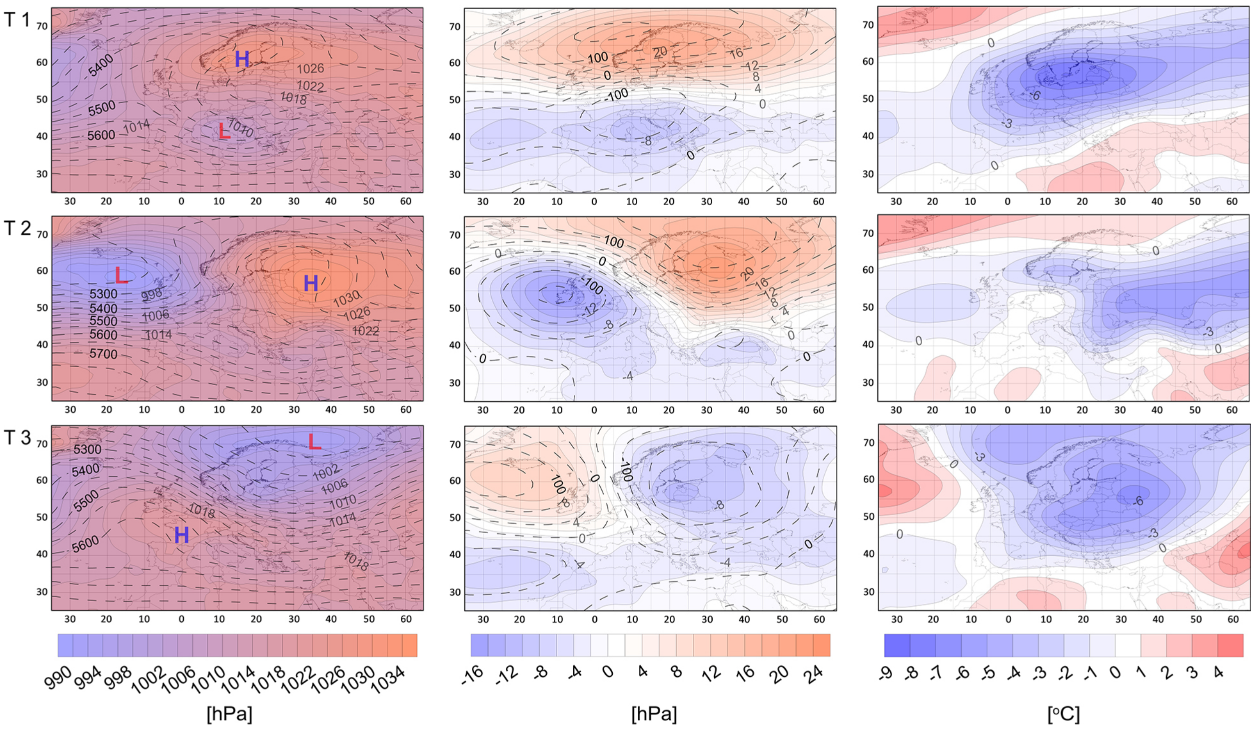

Fig. 5. Mean SLP [in hPa] (colour scale) and z500 hPa [in gpm] (dotted line) (left column); SLP [in hPa] (colour scale) and z500 hPa anomalies [in m] (dotted line) (middle column); and anomalies of T850 [in °C] (right column) for the designated circulation types. SLP, sea level pressure.

anomalies, SLP was higher by more than 20 hPa. In type 2, the course of SLP anomalies was of longitudinal character. Positive anomalies were recorded over the eastern and northern parts of the Euroatlantic sector, and negative over the western and southern ones. In the centre of positive anomalies, SLP was higher by more than 22 hPa. The described situation in type 1 as well as in type 2 caused advection of continental air masses from north to east. T850 anomalies show that inflowing air masses in type 1 were cooler than in type 2, and covered a considerably larger area. A different baric situation occurred in type 3 (22% of all cases). Over a considerable part of the Euroatlantic region, a low-pressure system occurred with a centre over northern Europe (<996 hPa). A high also persisted over the south-western regions (>1020 hPa). The above baric situation generated advection of cool air masses from the northern sector. Cool air masses covered a prevalent area of Europe, reaching the Mediterranean Sea. The presence of cool air masses caused lower height of the isobaric surface of 500 hPa. The greatest negative anomalies over the analysed area were recorded in type 3, when z500 hPa persisted lower than on average by more than 150 m.

Type 1 dominated throughout the multiannual period. Nonetheless, the analysis of particular decades shows that it accounted for a range from 41% days in the analysed thermal stress categories in the years 1966–1975 to 65% in the years 1986–1995. Type 2 was second in terms of frequency of occurrence. It accounted for days with strong and very strong cold stress to the greatest degree in the period 1966–1975 (40% of all days recorded in the period) and from 2006 (38% of all days recorded in the period). The share was lower in the years 1986–1995 (only 9% days). The last type, the periods 1976–1985 and 1986–1995, respectively, accounted for 28% and 27% of recorded days in the analysed thermal stress categories in the designated periods. The share was the smallest from 2006.

Selected case studies

On more than 200 days in the analysed multiannual period, very strong and extreme cold stress occurred simultaneously on at least 10 stations. In 42 cases, they were days with particularly dangerous conditions of cold stress, during which very strong and extreme cold stress occurred on at least half of all the analysed stations, including at least one station with extreme cold stress. The greatest spatial range of very strong and extreme cold stress occurred on 12 January 1987, when it was recorded on 38 stations. In several cases, extreme cold stress occurred on a dozen stations simultaneously. A special case was 31 December 1978, when extreme cold stress occurred on 26 stations,

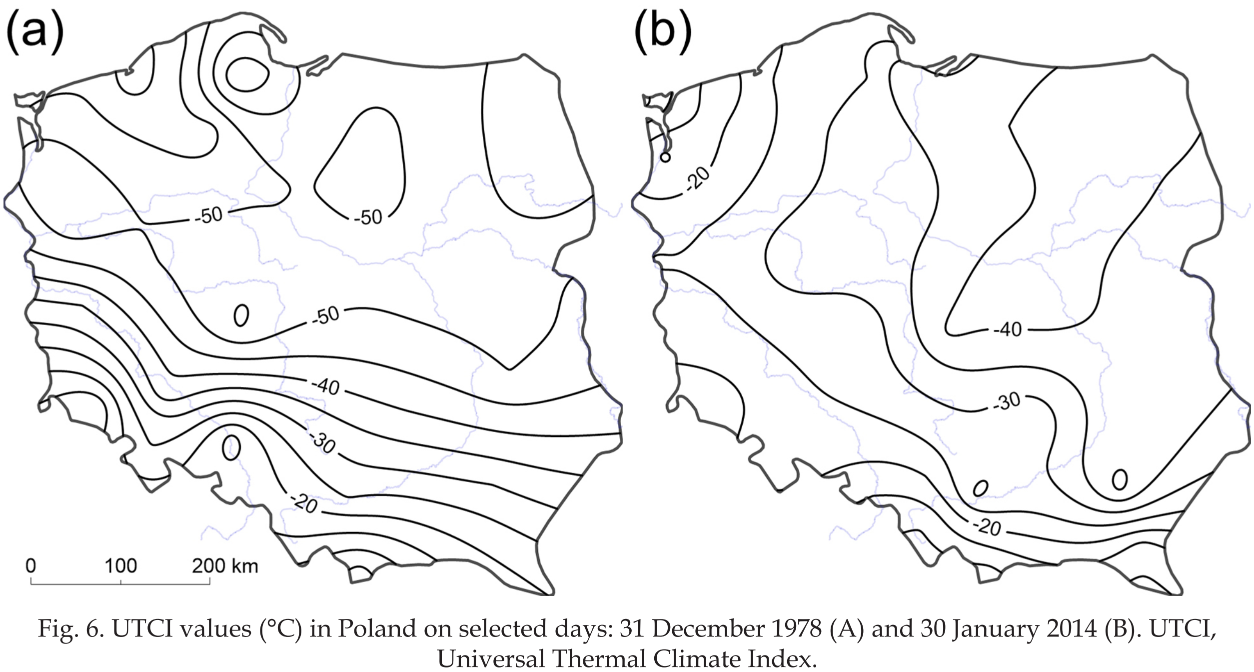

Fig. 6. UTCI values (°C) in Poland on selected days: 31 December 1978 (A) and 30 January 2014 (B). UTCI, Universal Thermal Climate Index.

covering almost the entire territory of Poland, except for its southern part (Fig. 6A). The lowest index values below −50°C occurred in the north of the country. Locally, in the eastern part of the Pomeranian Lakeland, a minimum of UTCI values occurred, with dropping to −64.2°C. Minimum UTCI values occurred on the coast at 12 UTC throughout the analysed multiannual period: from approximately −51 to −59.3°C. Next to very low air temperature, the considerable intensification of cold stress was also caused by strong wind that occurred on that day in the north of Poland. The applied data show that wind speed of even more than 11 m $\cdot$ s^{-1} was

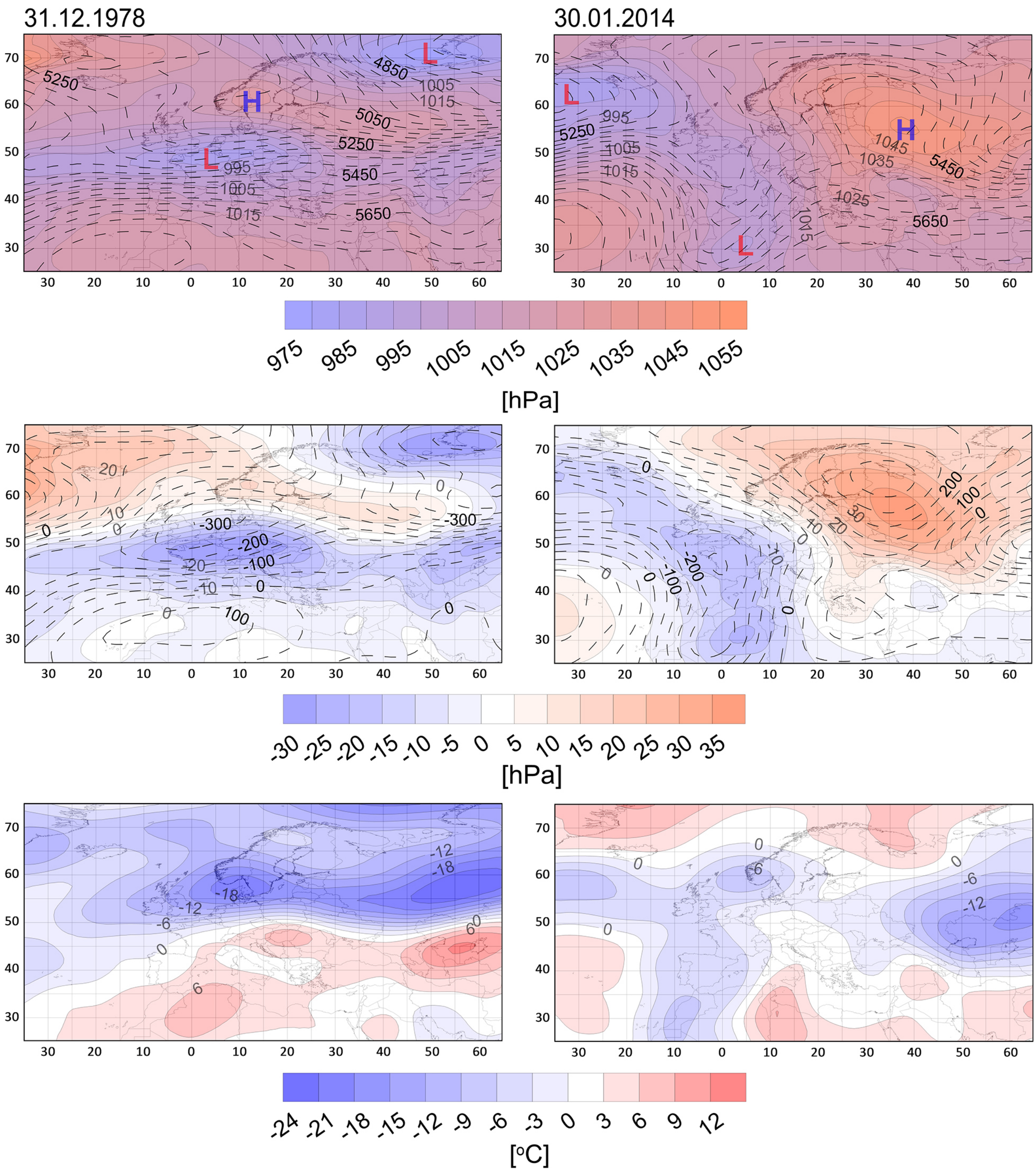

Fig. 7. Mean SLP [in hPa] (colour scale) and z500 hPa [in gpm] (dotted line) (top row); SLP [in hPa] (colour scale) and z500 hPa anomalies [in m] (dotted line) (middle row); and anomalies of T850 [in °C] (bottom row) for the selected days. SLP, sea level pressure.

recorded on meteorological stations. It should be emphasised that a major part of days with extreme cold stress with a considerable spatial range occurred in the period until January 1987. From the 1990s, extreme cold stress occurred simultaneously on at most five stations (in Warszawa, Rzeszów and in the north-east), and UTCI index lower than −50°C occurred only once on one station (Rzeszów) in January 2003. The last case in which very strong and extreme cold stress occurred on the majority of stations was 30 January 2014 (Fig. 6B). It did not cover western or southern Poland. The lowest UTCI values varied from −44.6 to −40.7°C, and occurred in the north-east and in the eastern part of central Poland.

The occurrence of the aforementioned days was related to various baric situations (Fig. 7). On the first day (31 December 1978), a low-pressure system (<990 hPa) persisted over the major area of western and central Europe. A high-pressure wedge simultaneously extended from northern Europe to the eastern regions of the continent. On the analysed days, SLP over the study area was lower than average, and the centre of the anomalies extended from western France to the Czech Republic (<−20 hPa). On the second of the analysed days (30 January 2014), a major part of the continent remained within the range of a high-pressure system with a centre over eastern Europe (>1050 hPa). During the same time, western and south-western regions were under the influence of a trough related to the Icelandic Low. On the analysed day, SLP over the study area was higher than average, and the centre of the anomalies was located over western Russia (>35 hPa). The described baric conditions generated advection of cool continental air masses from the east, and in the case of the second day, from the east and south-east. On the first day, advection of cooler air masses occurred to a greater extent in comparison to the second day. It is evident in maps of T850 anomalies as well as in UTCI values. The range of cool air masses in the case of the analysed days primarily covered northern and eastern regions of Poland. The presence of cooler air masses on the first day is also confirmed by higher negative anomalies of z500 hPa, persisting over a prevalent area of the continent more than 200 m lower.

Discussion and summary

The spatial variability of the frequency of occurrence of the analysed cold stress categories evidenced in the paper refers to the spatial variability of biothermal conditions in Poland. The occurrence of cold stress is determined by latitude and distance from the Atlantic Ocean. Mean and minimum UTCI values in Europe generally show an increase from the north to the south, and from the west to the east (Błażejczyk, Błażejczyk 2014, Błażejczyk et al. 2015). In Poland, the mitigating effect of the thermal regime of Baltic Sea waters is observed, while on the other hand, the effect of height above sea level and land relief favouring the occurrence of thermal inversions in submountain areas is observed to contribute to the intensification of cold stress. Earlier papers also showed that the most strenuous conditions in winter occur in the north-east of Poland, and the mildest ones on the coast (Błażejczyk, Kunert 2011). The frequency of occurrence of very strong cold stress category during winter seasons from 2001 to 2018 in Poland varied from 0.1% in Zakopane to approximately 7% in the south-east (Wereski et al. 2020). In January in the years 1971–1990, the frequency of occurrence of very strong and extreme cold stress at 12 UTC was approximately 10% in the north-eastern region, while it was approximately 6% in Warszawa and 3% at the coast. In Prague, the frequency was approximately 3% (Błażejczyk, Błażejczyk 2014, Błażejczyk et al. 2015). In Budapest and Paris, over a period of 10 years from 1991, only several days with very strong cold stress were recorded. Considering the broader time-scale covered by this study, the evidenced frequency of occurrence of very strong and extreme cold stress in Poland is approximately 1% lower than that evidenced in the previous studies. Monthly mean frequency of the occurrence of very strong and extreme cold stress in Poland in the years 1951–2010 (Owczarek 2021) is significantly higher. Unfortunately, overestimated values of wind speed were used there and that is why these differences occurred. The occurrence of the discussed cold stress in Poland corresponds with the variability of thermal conditions. Apart from high mountains, north-eastern Poland is the coolest region. The number of days with maximum temperature not exceeding

−10°C in the region is on average 4–5 days in a year, and 1–3 days over the remaining area (Owczarek, Filipiak 2016). The average number of days with very strong and extreme cold stress evidenced in this paper is even twice higher in particular regions, evidencing the effect of other factors, such as wind speed and air humidity, potentially considerably intensifying cold stress during periods with low air temperature.

The analysed cold stress at 12 UTC primarily occurred as a single case, although in many cases it was related to the occurrence of cold waves. The lowest UTCI values and greatest spatial range of strong and extreme cold stress were related to the occurrence of strong cold waves, described in previous papers (Wibig et al. 2009, Krzyżewska, Wereski 2014, Twardosz, Kossowska-Cezak 2016, Tomczyk et al. 2019). They frequently covered a considerable area of central Europe (e.g. Lhotka, Kysely 2015, Tomczyk et al. 2019). Moreover, cold waves were characterised by low maximum temperature, even in the western part of the coast (Tomczyk et al. 2019). This evidenced the persistence of low temperature throughout the day, and additionally intensification of cold stress experienced by the organism to a time around noon. The case of occurrence of the lowest value of the index described in the paper also occurred during one of the most intensive cold waves in Poland (Tomczyk et al. 2019).

The analysis of temporal variability of occurrence of very strong and extreme cold stress showed a statistically significant decrease by 1–4 days per decade on half of the analysed stations. Also, no changes towards the intensification of cold stress were recorded. Changes in the occurrence of cold stress in Poland, evidenced earlier, generally confirm its mitigation, although they did not refer to the entire territory of Poland, and concerned different study periods. A decrease in the number of days with all categories of cold stress by even 9 days per decade was recorded in south-eastern Poland in the years 1977–2006 (Bartoszek et al. 2017). Mitigation of cold stress was also evidenced at the coast in the years 1981–2010, where the frequency of days with strong cold stress decreased by 2 days per decade (Półrolniczak et al. 2016). In the 1950s, very strong cold stress in Poland occurred approximately twice as frequently as in the 1990s (Okoniewska, Więcław 2013). The average number of days with at least strong cold stress from approximately a dozen cities in Poland from the mid-1970s decreased by 17 (Kuchcik 2017). The changes revealed in this paper are also in accordance with the observed mitigation of cold stress in Europe. According to estimates in the scope of The Copernicus Programme (2020), the number of days with extreme cold stress according to UTCI based on ERA5 dataset in northern Europe in winter decreased by approximately 4% in the early 1980s to approximately 2% in the season 2018/2019. Current papers emphasise the fact of mitigation of thermal conditions in Poland in the coldest months of the year (Wibig, Głowicki 2002, Owczarek, Filipiak 2016). With the exception of single cases, however, no statistically significant decrease was recorded in the number of days with maximum temperature below −10°C (Wibig et al. 2009, Owczarek, Filipiak 2016, Kuchcik 2017, Twardosz et al. 2021). In the context of occurrence of the analysed cold stress, the greatest importance is assigned to the case of a decrease in the frequency of occurrence of cold waves, and reduction of their duration. In the period 1966–2015, over the prevalent area of Poland, the highest number of strong cold waves was observed until 1986 (Tomczyk et al. 2019). In the years 1951–2015, in the territory of Poland, with the exception of its north-eastern margin, a statistically significant decrease occurred in the annual number of cold waves, and their total duration over the period decreased by 13–40 days (Owczarek, Filipiak 2016). The highest rate of the decrease was determined in central Poland and at the coast. An analogical direction of changes in the occurrence and intensity of cold waves was determined in reference to central Europe, reaching western Ukraine and Romania (Lhotka, Kysely 2015, Spinoni et al. 2015).

The occurrence of very strong and extreme cold stress is related to various circulation types. In this study, three circulation types favouring the occurrence of the discussed phenomenon in Poland were designated. In two of the types, Poland is located at the edge of a high-pressure system with a centre over the Scandinavian Peninsula or the north-eastern region of Poland. A high together with low-pressure systems over the North Atlantic or also in the area of the Mediterranean Sea favours the occurrence of intensive eastern and north-eastern inflow. The distribution of negative T850 anomalies suggests advection of continental air, in the analysed year characterised by very low temperature. The presence of cold air over the study area confirms the persistence of isobaric surface of 500 hPa at a height lower than on average. Circulation type 1, however, contributed to considerably stronger cold stress, as suggested by even twice higher values of anomalies than in type 2. The occurrence of the analysed cold stress was also manifested due to the presence of the low-pressure system over northern Europe, whereas western and southern Europe were within the range of a high. Such a situation favours advection of cool polar or arctic air from northern directions, and intensification of cold stress throughout Poland. The variability of circulation conditions of the occurrence of cold stress was also revealed in earlier studies concerning smaller areas.

The occurrence of very strong cold stress at the southern coast of the Baltic Sea was associated with both zonal and meridional air flow (Półrolniczak et al. 2016, Kolendowicz et al. 2018). Circulation types favouring advection of cold air from the east or north-east were designated. In terms of location of baric centres and distribution of anomalies, they were similar to types 1 and 2 designated in this paper. The same study also identified circulation types related to the presence of a low with a centre over the Baltic or north-east of Polish borders that favoured inflow of cold air from northern directions. They differed from type 3 designated here in the location of the low, and the determined directions of advection were similar. The occurrence of cold stress categories from strong to extreme in south-eastern Poland was associated with five circulation types (Bartoszek et al. 2017). Two of them are similar to those designated in this paper, and present a pressure field favouring advection of polar continental or arctic air. The authors also interpreted the cause of the occurrence of very strong cold stress during evident longitudinal air flow from the west to be the intensification of cold stress that has been observed to arise concomitant with the occurrence of wind with considerable speed. A similar situation, with simultaneous considerably lower height of the isobaric surface of 500 hPa, was also determined in reference to the coast (Kolendowicz et al. 2018). No such circulation type was identified in this study. Research with the application of circulation classification evidenced the occurrence of extreme stress in different regions of Poland primarily due to anticyclonic situations with advection from eastern directions (Piotrowski 2008, Bryś, Ojrzyńska 2016) and cyclonic and transitional situations with advection from the west and north-west (Bartoszek et al. 2017).

Circulation types designated in this paper show similarities with the circulation conditions of cold waves. Average circulation conditions of the occurrence of cold waves in Poland, similar to the average conditions of occurrence of the analysed categories of cold stress presented in this paper, favour advection of cold air from the east (Tomczyk et al. 2019). Long cold waves are related to the inflow of cold air from the east or north-east, similar to that in types 1 and 2 designated in this paper. The occurrence of cold waves in more than half of the cases caused by the presence of stable systems blocking zonal circulation, particularly located west of central Europe, was confirmed by Porębska and Zdunek (2013). Such situations, similar to that in type 3 in this paper, favour flow from northern directions and persistence of cold air over central Europe. Similar circulation patterns have been determined to favour the occurrence of extremely low air temperature in Europe (Domonkos et al. 2003, Cattiaux et al. 2010).

Results of this study particularly confirm the change of bioclimatic conditions in Poland towards mitigating cold stress, and the important role of atmospheric circulation in shaping conditions causing cold stress. Despite the progressing climate warming, the risk of occurrence of very strong and extreme cold stress still exists, and therefore a threat to human health and life exists in the study area.

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Author's contribution

Conceptualisation and design: MO, AMT; Acquisition of data: AMT, MO; Data analysis and interpretation: MO, AMT; Manuscript writing and revision: AMT, MO.

Data availability statement

The obtained data can be made available on request of interested parties under the condition of approval of the request by the authors of the article.

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