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The influence of atmospheric circulation on bioclimatic conditions in Lublin (Poland)

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Abstract. This study evaluates the relationship between atmospheric circulation conditions and the frequency of heat/cold stress in Lublin in the years 1951–2010 according to the Universal Thermal Climate Index (UTCI). The paper outlines the frequency and conditional probability of heat/cold stress during particular circulation types and analyses the circulation patterns that induce these incidences. Increased wind velocity had a significant effect on creating unfavourable bioclimatic conditions in winter. Meanwhile, in summer, heat stress was observed almost exclusively when a high pressure system from eastern Europe induced a slow inflow of very warm air masses from the east or south.

Key words:
UTCI,
atmospheric circulation,
thermal stress,
Lublin,
Poland

Introduction

People are vulnerable to various types of the physical stimuli (Kozłowska-Szczęsna et al. 2004). The most unfavourable are extreme air temperatures (McMichael et al. 2006). It is presumed that during climate change, positive thermal anomalies will occur more frequently. The evidence that supports this assumption is the increase in the intensity of heat waves in different regions of the world (IPCC 2014; Russo et al. 2015). Particularly stressful bioclimatic conditions will be felt in cities, where currently more than half of the world population resides (Luber and McGeehin 2008).

Lublin is a city in the southeastern (V) bioclimatic region, and has both a large number of days with stressful conditions related to high air temperature (Kozłowska-Szczęsna et al. 1997) and a large number of cold days (Błażejczyk and Kunert 2011). Research on bioclimatic conditions in Lublin was conducted by Kruczko (1962), Mrugała (1992), Kaszewski et al. (2006), Wereski et al. (2010) and Dobek et al. (2015). Furthermore, complex bioclimatic conditions in Lublin (conditions expressed in the UTCI) were studied by Nowosad et al. (2013), Dobek (2013), Dobek et al. (2013), Dobek and Krzyżewska (2015).

Atmospheric circulation can cause extreme values of meteorological elements, thus making it the major factor forming the bioclimates of cities (Bartzokas et al. 2013; Gargol and Jakubowska 2014). The aim of the study is to evaluate the relationship between atmospheric circulation and the frequency of heat/cold stress in humans in Lublin between 1951 and 2010.

Data and methods

The Universal Thermal Climate Index was used to assess heat/cold stress in humans. It is based on a multimode model of the heat balance of a human body (Błażejczyk et al. 2010; Fiala et al. 2012). This is expressed in °C and defined as an equivalent air temperature in which, in referential conditions, the physiological parameters of an organism have the same values as in real conditions.

Index values were calculated with the use of the BioKlima 2.6 software package (Błażejczyk and Błażejczyk 2010) for every single day from October 1951 to December 2010 using the following meteorological data measured at 12 UTC: air temperature, actual vapor pressure, cloud cover and the velocity of the wind reduced to the altitude of 10 m above ground level. Values of the above meteorological elements were obtained from the Meteorological Observatory at Maria Curie-Skłodowska University in the center of Lublin (51°14'N, 22°38'E, 195 m a.s.l.). Each calculated value of UTCI was referred to one of the classes that correspond with the assessment scale of heat/cold stress in humans (Table 1) (Błażejczyk and Kunert 2011). In relation to atmospheric circulation conditions, particular attention was directed to the occurrence of severe heat stress, i.e. to the classes that relate to *strong* and *very strong heat stress* (in the referential period no case of *extreme heat stress* was recorded) as well as to *strong*, *very strong* and *extreme cold stress*.

Firstly, the atmospheric circulation conditions of heat/cold stress in Lublin were presented in an analysis of the relationships between UTCI values on a given day and chosen indicators of atmospheric circulation, i.e. the wind velocity near the surface and relative vorticity, which reflects the intensity of cyclonic (positive values) or anticyclonic circulation (negative values). Moreover, two indicators that describe both zonal and meridional components of geostrophic wind were also used. High positive values of the two indicators correspond with strong air advection from the west and south, while low negative values are linked with strong air flow from the east and north. All circulation indicators were calculated based on equations adapted from Jenkinson and Collison (1977). In this paper, daily gridded fields (5°×5° longitude-latitude) of mean sea-level pressure values were obtained from the Twentieth Century Reanalysis (Compo et al. 2011).

Table 1. UTCI assessment scale of thermal stress in man (Błażejczyk et al. 2010)

UTCI (°C)	Stress category
>+46	Extreme heat stress
+38 - +46	Very strong heat stress
+32 - +38	Strong heat stress
+26 - +32	Moderate heat stress
+9 - +26	Thermoneutral zone
0 - +9	Slight cold stress
-13 - 0	Moderate cold stress
-27 - -13	Strong cold stress
-40 - -27	Very strong cold stress
<-40	Extreme cold stress

The circulation indicators were also the basis of the author's classification of circulation types over Eastern-Central Europe (Bartoszek 2015, 2017). The classification differentiates between 8 directional cyclonic, transitional and anticyclonic types, and three non-directional types: cyclonic, anticyclonic, and undefined. They were grouped by direction and vorticity in order to generalise the obtained results (Table 2). The above classification of circulation types allowed for an evaluation of frequency and conditional probability of the occurrence of heat/cold stress during particular circulation patterns.

Multiple regression analysis was applied to evaluate the relationship between circulation indicators and the UTCI values, whereas the t-Student test was used to assess the statistical significance of Pearson's correlation coefficient. In turn, the non-parametric Mann–Kendall test was applied to evaluate the statistical significance of trends (Kendall 1975). The magnitude of change of UTCI values was determined by Sen's method (Sen 1968).

The large-scale circulation patterns that cause heat/cold stress in Lublin are presented in maps of sea level pressure and anomalies of wind velocity near the surface over the European continent. Application of Ward's hierarchical method (1963) helped to group similar circulation patterns that induce *extreme cold*, *very strong cold* and *strong cold stress* (from December to February) and *strong heat* and *very strong heat stress* (from June to August). This method is based on Euclidean distances, which merges the pair of clusters. After merging, this process provides the minimum of the sum of squares of

Table 2. Grouped circulation types over East-Central Europe applied in the study

Circulation types	Description
N+NEc, E+SEc, S+SWc, W+NWc	Directional cyclonic types (evident advection during cyclonic circulation)
N+NEo, E+SEo, S+SWo, W+NWo	Directional transitional types (evident advection with a contribution of both low and high pressure systems)
N+NEa, E+SEa, S+SWa, W+NWa	Directional anticyclonic types (evident advection during anticyclonic circulation)
C	Cyclonic non-directional type (high positive shear vorticity values over the study area)
A	Anticyclonic non-directional type (high negative shear vorticity values and weak geostrophic wind velocity over the study area)
x	Undefined non-directional type (low shear vorticity values and weak geostrophic wind velocity)

all deviations from the centre of gravity of the new cluster (Tomczyk et al. 2015). Data from NCEP/NCAR Reanalysis was used in drawing up the maps (Kalnay et al. 1996).

Characteristics of the frequency of thermal stress events

The greatest number of days with cold stress (UTCI<0°C) was recorded in 1979 (222 cases) and the least in 1972 (161 cases). Compared to the 1961–1990 period, there was a higher frequency of these events between the late 1970s and the last decade of the 20th century (Fig. 1a). However, the major statistically significant decrease (at $p<0.01$) in the number of days with the cold stress occurred in the years 1977–2006 (9 days/10 years).

The greatest number of heat stress days (UTCI>26°C) was recorded in 1972 (67 cases). In 1971 and 2006, there was also an increased occurrence of heat stress events (56 and 55 cases) (Fig. 1b). In turn, the lower frequency of these bioclimatic conditions occurred in the 1980s and 1990s (the least in 1986 – 8 cases). In the 1981–2010 period there was a significant increase in the number of such days (5 days/10 years; $p<0.05$).

Similarly to Gdańsk, Warsaw and Lesko (Lindner 2011; Nowosad et al. 2013; Nidzgorska-Lencewicz 2015), the most frequent thermal stress events in Lublin were related to the UTCI's *thermoneutral zone* class (142 days per year). It primarily occurred from May to September (on average 21 to 23 days per month), whereas in winter time it was recorded sporadically, i.e. once every few years (Fig. 2). Classes representing *moderate cold stress* or *slight cold stress* occurred slightly less often (87 and 63 days per year, respectively). Harsh bioclimatic conditions (from strong to *extreme cold stress* UTCI classes) occurred from September to May. However, there was only one such day in September (28.09.1959) and 4 cases of strong *cold stress* in May (8.05.1956; 3.05.1978; 1.05.1984; 1.05.2007). The largest number of days with UTCI<-13°C was recorded in January – on average 14 days in a month.

Conditions of *strong* and *very strong heat stress* were recorded in Lublin from May to September. The most frequent occurrence of such cases occurred in July (on average 2 days), whereas in June and August it was observed on average once a month. In the analyzed period, conditions related to *strong heat stress* were recorded in September only five times (5.09.1967; 6/7.09.1972, 9.09.1972 and 1.09.1991).

Relationships between atmospheric circulation and stress events

The highest correlation between atmospheric circulation and bioclimatic conditions in Lublin was related to the September–March period, when circulation indicators explain 19–24% of the UTCI variability (Fig. 3), whereas the weakest linkages between the analyzed variables was in May ($R^2\approx10\%$). These results are in good agreement with the results obtained by Nowosad et al. (2013). Among the circulation indicators, the highest partial correlation

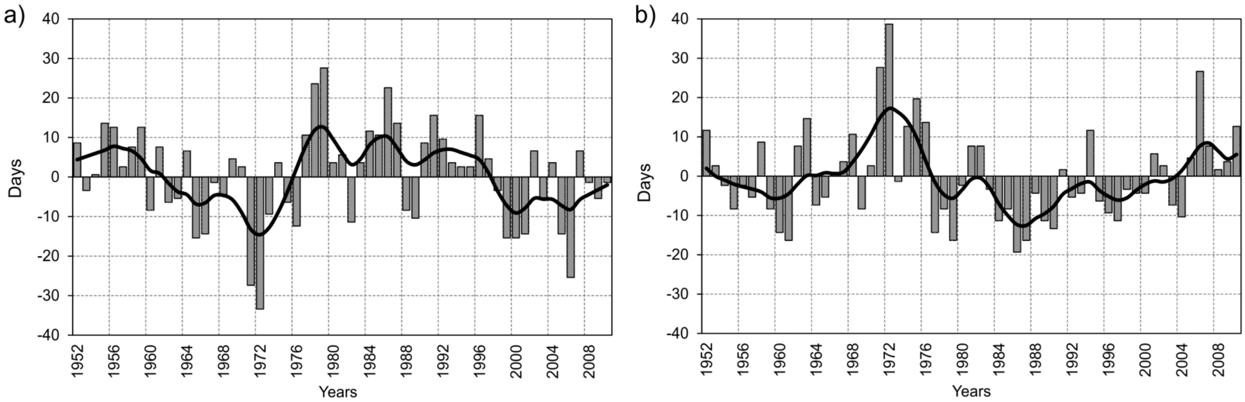

Fig. 1. Anomalies of numbers of days with cold stress (a) and heat stress (b) in Lublin from 1951 to 2010. Values smoothed by 7-element triangular filter

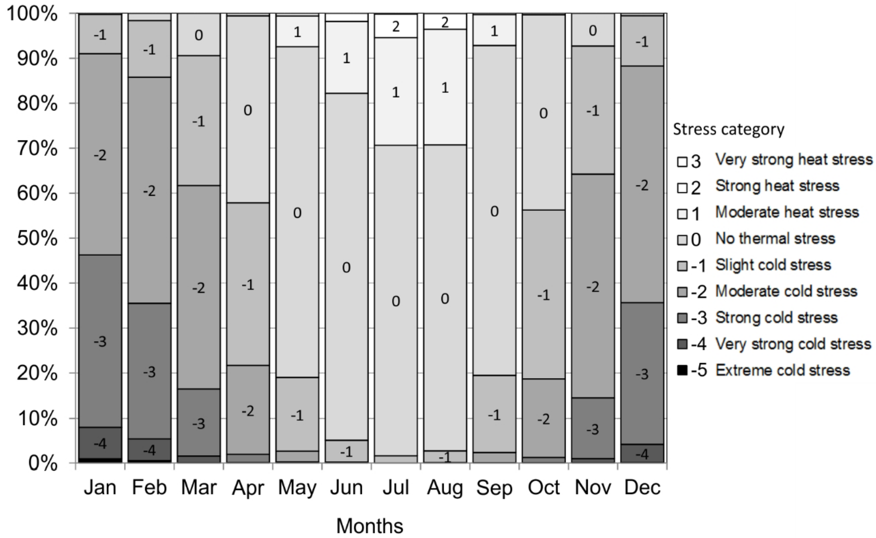

Fig. 2. Frequency of thermal stress categories by UTCI at 12 UTC in Lublin

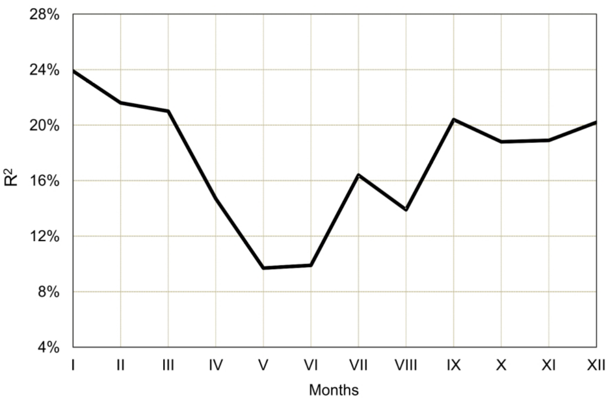

Fig. 3. Monthly coefficients of determination (R^2) between indicators of atmospheric circulation and UTCI values in Lublin at 12 UTC

coefficients in nearly all months (with the exception of July) were for near-surface wind velocity (Table 3). The influence of this circulation indicator on bioclimatic conditions was particularly noticeable in winter (r=–0.41 in February). However, in the other seasons the increased wind velocity also signified the occurrence of lower-than-the-average UTCI values.

Negative correlation coefficients ($p<0.001$) between the zonal circulation index and UTCI values in Lublin were noted from March to September (Table 3). Therefore, in this period, easterly winds caused an increase in UTCI values (in contrast to westerly air flow). A similar relationship, however, was found in all months for the meridional circulation indicator. Positive correlation reflected an increase in UTCI values during air flow from the southern sector and a decrease during northerly circulation (Table 3). Relative vorticity correlation coefficients also varied little within the year. A negative/positive correlation indicated that the higher/lower UTCI values were mostly noticed during anticyclonic/cyclonic circulation over Central and Eastern Europe.

Occurrence of heat/cold stress in circulation types

More detailed information was gained as a result of the analysis of relationships between bioclimatic conditions in Lublin and circulation types over Central Europe. Days with *extreme cold stress*, *very strong cold stress* and *strong cold stress* in winter were mostly accompanied by western and northwestern cyclonic and transitional types (W+NWc and W+NWo) as well as southern and southwestern cyclonic types (S+SWc) (Table 4, Fig. 4a). The occurrence of western zonal circulation corresponds with an increase in wind velocity over Central Europe (Donat et al. 2010). It is commonly associated with a general direction of movement of deep cyclones from the North Atlantic towards Europe (Roberts et al. 2014). In turn, when surface low-pressure gradient patterns located over Poland are recorded, the probability of occurrence of cold stress events is considerably lower.

Similarly to the winter months, strong heat stress from June to August in Lublin can occur in all circulation types (Table 4). Classes representing *very strong* and *strong heat stress* were mostly associated with air flow from the eastern and southern sector during anticyclonic and transitional circulation types (Table 4, Fig. 4b). In contrast, heat stress events were most rare during western and northern air flow. Analogical results were obtained in Cracow by Gargol and Jakubowska (2014).

Synoptic situations that cause heat/cold stress occurrence in Lublin

In this paper, five different pressure patterns over Europe were found to cause days of *extreme cold*, *very strong cold* and *strong cold stress* in Lublin between December and February. The synoptic type 1 is characterised by a low pressure centre over the Baltic countries, which results in air flow from

Table 3. The correlation coefficients between UTCI values in Lublin at 12 UTC and atmospheric circulation indicators

Circulation indicators	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
W	-0.05	-0.02	<u>-0.07</u>	<u>-0.16</u>	<u>-0.18</u>	<u>-0.18</u>	**<u>-0.24</u>**	<u>-0.19</u>	<u>-0.11</u>	-0.02	-0.04	-0.03
S	<u>0.13</u>	<u>0.17</u>	<u>0.20</u>	<u>0.18</u>	<u>0.17</u>	<u>0.17</u>	<u>0.21</u>	<u>0.14</u>	<u>0.26</u>	<u>0.18</u>	<u>0.17</u>	<u>0.12</u>
V	**<u>-0.39</u>**	**<u>-0.41</u>**	**<u>-0.39</u>**	**<u>-0.29</u>**	**<u>-0.20</u>**	**<u>-0.20</u>**	<u>-0.22</u>	**<u>-0.27</u>**	**<u>-0.32</u>**	**<u>-0.36</u>**	**<u>-0.36</u>**	**<u>-0.38</u>**
Z	<u>-0.23</u>	<u>-0.15</u>	<u>-0.13</u>	<u>-0.13</u>	<u>-0.14</u>	<u>-0.08</u>	<u>-0.14</u>	<u>-0.14</u>	<u>-0.17</u>	<u>-0.16</u>	<u>-0.15</u>	<u>-0.17</u>

W – zonal circulation index; *S* – meridional circulation index; *V* – wind velocity near the surface; *Z* – relative vorticity. Underline values – significant correlation at the $p<0.001$ level. Bold values – the highest partial correlation coefficient among analyzed circulation indicators in a given month.

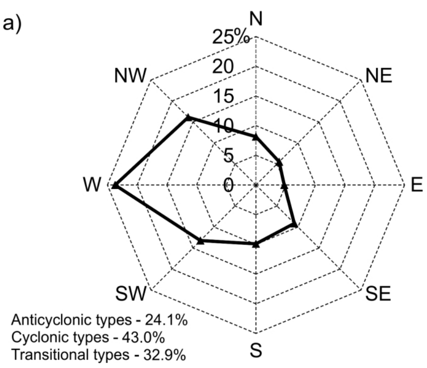

Fig. 4. Frequency (%) of air flow directions during days with a) *extreme cold stress*, *very strong cold stress* and *strong cold stress* as well as b) *very strong heat stress* and *strong heat stress* in Lublin

Table 4. Occurrence of heat/cold stress events in Lublin during circulation types

Extreme cold, very strong cold and strong cold stress (December–February)			**Very strong and strong heat stress (June-August)**		
Circulation types	Frequency (%)	Conditional probability (%)	Circulation types	Frequency (%)	Conditional probability (%)
W+NWc	17.8	63.5	A	17.3	6.5
$W+NW_0$	14.9	49.0	E+SEa	14.3	6.9
S+SWc	11.9	44.7	$S+SW_0$	12.2	7.8
W+NWa	7.1	31.0	S+SWc	7.7	4.3
$S+SW_0$	6.8	31.2	$E+SE_0$	7.1	4.2
C	6.5	41.1	$N+NE_0$	6.6	2.9
E+SEa	5.8	33.8	S+SWa	6.6	7.8
$N+NE_0$	5.5	42.8	N+NEa	5.6	2.4
$E+SE_0$	5.2	34.5	E+SEc	3.6	2.9
S+SWa	4.4	29.8	W+NWc	3.6	1.3
N+NEa	4.2	38.3	C	3.6	2.5
N+NEc	4.0	56.1	x	3.6	3.2
E+SEc	3.0	36.5	$W+NW_0$	3.1	1.2
A	2.7	12.5	N+NEc	2.6	1.4
x	0.2	11.2	W+NWa	2.6	1.9

the northwest over eastern Poland (Fig. 5a). That air mass forms over the region of the Scandinavian Peninsula, and thus the mean minimum temperature value in Lublin was then 1.5°C lower than average. Considerably lower UTCI values were also noted on days with strong westerly air flow over Central Europe (Fig. 5b). Hence, in synoptic type 2, wind velocity (as opposed to air temperature) had the dominant influence on creating unfavourable bioclimatic conditions (*strong*, *very strong* and *extreme cold stress*) in Lublin (anomalies over Poland exceeded 3 ms^{-1}). The third synoptic pattern was also characterised by high wind velocity over Central Europe (Fig. 5c). However, in this case, the co-occurrence of the Azores High and cyclonic pressure systems over Scandinavia caused advection of cold air from higher latitudes towards Poland. In synoptic type 4, cold stress events in Lublin were recorded when a deep low-pressure system over Iceland caused strong southwesterly air flow over the greater part of Europe (Fig. 5d). The last of the synoptic types is characterised by a stable high pressure system over eastern Europe and cyclones over the west of the continent (Fig. 5e). Such a pressure pattern caused a strong inflow of very cold air of continental origin from the south-east through Poland. Under these conditions, negative anomalies of minimum temperature in Lublin were the highest of all discussed synoptic types (on average by 3.2°C).

The occurrence of days with *very strong heat stress* and *strong heat stress* in Lublin (from June to August) was related to only two synoptic types. In type 1, an anticyclone centre formed over south-eastern Europe (Fig. 6a). Such a pressure pattern caused southern inflow of very warm tropical air masses over Poland. In type 2, a slight horizontal pressure gradient existed over Central Europe and an anticyclone centre shifted northward (Fig. 6b). Hence, a slow inflow of warm and dry air from the east was recorded. In both types, high positive anomalies of maximum temperature in Lublin were recorded (on average of 5.1 and 4.1°C, respectively). Similar pressure patterns over Central Europe are also found by Gargol and Jakubowska (2014) to determined stressful bioclimatic conditions.

Conclusions

Atmospheric circulation is an important factor influencing the occurrence of the cold/heat stress events in Lublin. It is particularly evident in the cold part of the year when days with *strong cold*

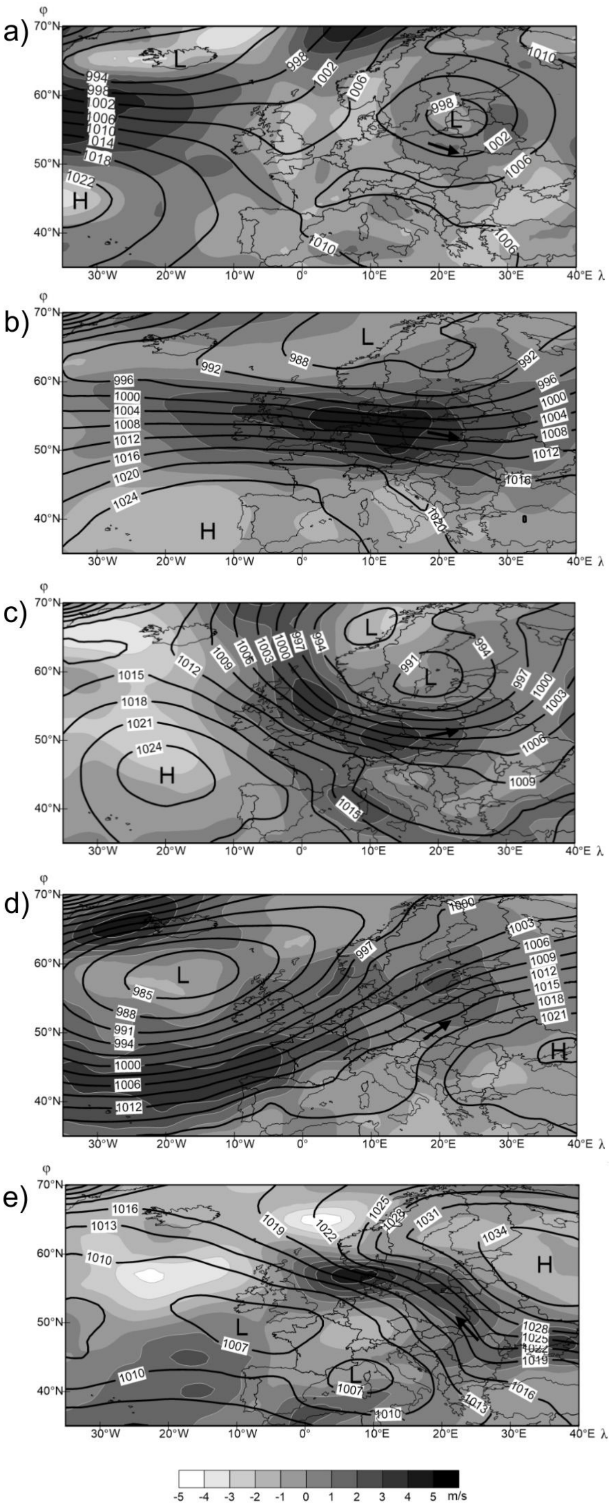

Fig. 5. Mean sea level pressure in hPa (black line) and near-surface wind velocity anomalies (shaded) in different synoptic types during days with *extreme cold stress*, *very strong cold stress* and *strong cold stress* in Lublin

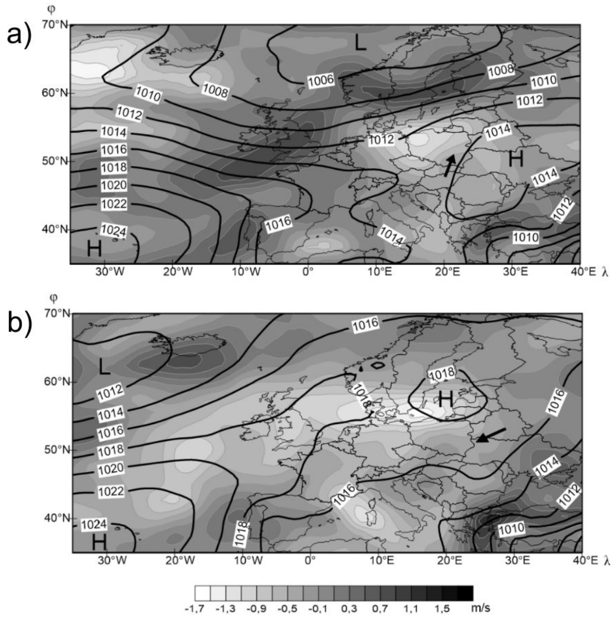

Fig. 6. Mean sea level pressure in hPa (black line) and near-surface wind velocity anomalies (shaded) in different synoptic types during days with *very strong heat stress* and *strong heat stress* in Lublin

stress, *very strong cold stress* and *extreme cold stress* occur. In turn, the weakest relationship between atmospheric circulation and bioclimatic conditions is found at the turn of spring and summer.

Wind velocity has a dominant impact on bioclimatic conditions in Lublin among all analyzed circulation indicators. The effect of air flow on cold stress events was particularly noticeable in winter when horizontal pressure gradients over Central Europe are strongest. In turn, low wind velocity in summer usually accompanied the occurrence of days with *strong heat stress* and *very strong heat stress*.

In the summer months, zonal and meridional circulation indicators correlated more highly with the occurrence of unfavourable thermal conditions than they did in other months. Increases in UTCI values in Lublin were usually recorded during air flow from the southern and eastern sectors – and decreases during westerly and northerly circulation.

Cold stress events in winter are related to various pressure patterns over Europe. In summer, in turn, unfavourable thermal conditions occur especially on days with the presence of a high pressure system east of Poland as well as a slight horizontal pressure gradient over Central Europe.

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