

Changes in biothermal conditions in the Sudetes Mountains and their foreland in relation to the circulation conditions

Abstract

Progressing climate change is often reflected in changing biometeorological conditions. The Sudetes Mountains, located in the Polish–Czech border area, are concerned by this phenomenon. The goal of this paper is to evaluate the influence of atmospheric circulation on multiannual changes in biothermal conditions using the UTCI index. In the analysis, data for 1991–2020, from both Polish and Czech meteorological stations, was considered, while the circulation factor was evaluated using the Lityński classification. The research indicated a positive tendency of UTCI values for the majority of circulation types, which consequently contributed to a decrease in the frequency of cold stress categories. In the summits, a decline in the number of days with extreme cold stress was the most characteristic feature, especially under anticyclonic and northern circulation. Tendencies of heat stress occurrence were in most cases statistically insignificant, except for cyclonic and transitional circulation.

Keywords

Bioclimate • UTCI • climate change • atmospheric circulation • Sudetes Mountains

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Received: 14 November 2023

Accepted: 26 January 2024

Introduction

Climate change, especially in relation to thermal, humidity, wind and solar conditions, affects numerous social, economic and environmental sectors (Kundzewicz, Hoy & Okruszko 2017). It also concerns aspects of human health and tourism that largely depend on biometeorological conditions. These sectors are important, especially in mountain regions such as the Sudetes Mountains, where numerous health and tourism resorts are located. The influence of weather on the human organism can be described using different biothermal indices. Most of the recent ones that have been developed are based on human heat balance models and consider various aspects of meteorological and physiological factors. Such indices as PET (Physiological Equivalent Temperature) (Höppe 1999) and STI (Subjective Temperature Index) (Błażejczyk 2004) are based on mean radiant temperature, which reflects the intensity of thermal stimuli at skin thermoreceptors. STI also considers the role of central thermoreceptors, which play an important role during heat stress conditions, whereas PET allows for the comparison of the integral effects of complex thermal conditions observed outdoors with the thermal senses experienced indoors (without wind and solar radiation). Currently, one of the most popular and accurate biothermal indices is UTCI (Universal Thermal Climate Index), which takes into consideration a vast spectrum of physiological parameters (Błażejczyk et al. 2013). This index has been widely used, contributing to the evaluation of biothermal conditions throughout the world, including in Central Europe (Nemeth 2011; Matzarakis, Muthers & Rutz 2014; Pecelj et al. 2020). The Czech studies mainly focused on testing the index during various weather conditions (Novak 2013), comparing it to other thermal indices (Urban & Kysely 2014) and implementing it in weather forecasts and models (Geletiĉ et al. 2021; Novak 2021). The Polish analyses for the Sudetes Mountains and their

foreland concerned the assessment of bioclimatic conditions for tourism purposes (Miszuk et al. 2016) and in suburban areas (Bryś & Ojrzyska 2016) and the influence of geographical factors on UTCI values (Milewski 2013). The studies also focused on multiannual changes, based on 12 UTC data, indicating a positive trend for south-west Poland (Głogowski, Bryś & Perona 2021). A similar tendency was noted for other Polish regions (Kuchcik, Błażejczyk & Halaś 2021), which often resulted in the modification of heat load categories, particularly the increase of heat stress frequency (Tomczyk & Owczarek 2019; Dobek, Wereski & Krzyżewska 2020; Krzyżewska, Wereski & Dobek 2021; Błażejczyk & Twardosz 2023).

Some of the studies concerned the relationship between UTCI and atmospheric circulation, particularly the impact of synoptic situations on UTCI values and the frequency of its categories (Pórolniczak, Szyga-Pluta & Kolendowicz 2016; Bartoszek et al. 2017; Rozbicka & Rozbicki 2018; Tomczyk & Owczarek 2019; Błażejczyk et al. 2020; Owczarek & Tomczyk 2022). On the other hand, very few papers referred to the problem of multiannual changes of biothermal conditions depending on the atmospheric circulation. In the discussed region, the only analysis of this type concerned the changes of UTCI in relation to the NAO phases in the area of Kłodzko (Głogowski, Bryś & Bryś 2020). It should be noted that multiannual changes not only concern meteorological variables but also refer to the frequency of weather types in both Poland (Niedźwiedz & Ustrnul 2021) and Czechia (Brázdil et al. 2022).

Taking into account the changes in UTCI and the dependence of UTCI on the circulation factor, it can be assumed that the modification of the structure of circulation conditions can potentially affect the values and categories of this index. Therefore, the main goal of this study is to examine the impact of atmospheric circulation on multiannual changes of UTCI in the

Sudetes Mountains and their northern foreland. This includes a comparison of the UTCI course for the selected circulation types in order to indicate a potential direction of further changes in biothermal conditions that depend on the circulation factor. The study also aims to examine the intensity of UTCI changes in the hypsometric profile of the Sudetes and, consequently, the differences observed between particular zones. The results of the study can be a base for further investigations focusing on the relationship between atmospheric circulation and biometeorological conditions.

Study area

The study area covers the region of the Sudetes Mountains and their northern foreland. The main ridge of the mountains stretches from the north-west to the south-east and forms a natural border between Poland and Czechia; the highest altitude is located at the peak of Śnieżka (1603 m asl). The mean annual air temperature in the mountain basins of Kłodzko and Jelenia Góra, in the lower hypsometric zones, is 7–8°C and decreases to about 0.8°C in the summit zone. According to Schmuck (1969), the mean vertical thermal gradient in the Sudetes reaches 0.6°C/100 m. The annual values of wind speed vary from 2.5 m/s, in the basins located lower down, to more than 12 m/s in the summits, whereas relative humidity and cloudiness differ from 79% to 87% and from 68% to 74%, respectively (Szyga-Pluta 2017; Błażejczyk 2019). Climate conditions are modified by terrain relief, exposition and the location in relation to predominant advection of air masses. These factors contribute to the specific climate conditions in the Western Sudetes, namely strong modification of thermal conditions by local relief, significant precipitation totals (especially in the cold season) and very high rates of wind speed and fog frequency in the summits (Błaś & Sobik 2005). The research carried out for this region reported notable changes in some meteorological variables, especially in the Giant Mountains. They indicated a statistically significant increase in air temperature of 0.2–0.8°C per decade (Migala, Urban & Tomczyński 2016; Błażejczyk 2019). A positive tendency (without statistical significance) was also observed for cloudiness, particularly in the lower hypsometric zones (Szyga-Pluta 2017). In terms of circulation conditions, polar maritime air masses are predominant in the region (64%), while the frequency of polar continental, arctic and tropical masses amounts to 30%, 4% and 2%, respectively (Sobik et al. 2013). The western circulation usually prevails, although the directions can be strongly modified by local terrain relief (i.e. in the Kłodzko basin). The western parts of the Sudetes and their northern foreland are also significantly affected by foehn winds that are usually related

to warm, dry and windy weather and which consequently modify thermal, humidity, wind and cloudiness conditions in the northern foothills of the Sudetes (Kwiatkowski & Holdys 1985).

Data and Methods

The analysis is based on meteorological data for 1991–2020, derived from five Polish and three Czech stations, and representing different hypsometric zones of the Sudetes Mountains and the Polish part of their foreland (Fig. 1, Tab. 1). The data included records for 12.00 UTC, which are widely used in biometeorological research because of high human activity during daytime hours and their high significance for both tourism and climate therapy (Błażejczyk 2004). This is a standard observation term used in biometeorology and in multiannual analysis (i.e. Dobek, Wereski & Krzyżewska 2020; Kuchcik, Błażejczyk & Halaś 2021; Błażejczyk & Twardosz 2023). The data concerned the variables necessary for the calculation of UTCI – air temperature, relative humidity, wind speed and cloudiness. In order to examine the radiation factor, information regarding the sun angle for particular days was also considered.

The evaluation of biothermal conditions was carried out using UTCI, which is based on multi-node models, especially Fiala's model (Fiala, Lomas & Stohler 2001), and considers both passive and active heat exchange regulation subsystems. This index is defined as the air temperature of the reference condition that causes the same model response as actual conditions, and depends on air and mean radiant temperature, wind speed and humidity (Błażejczyk et al. 2013). According to UTCI, ten classes of thermal stress categories can be defined, referring to specific human physiological responses to the thermal environment (Tab. 2). Detailed information on this index can be found in papers devoted to its principles (i.e. Jendritzky, de Dear & Havenith 2012; Błażejczyk et al. 2013).

The values of UTCI for 12.00 UTC and the frequency of its categories were calculated using the BioKlima2.6 software package (Institute of Geography and Spatial Organization 2020). Based on the calculations, trends of UTCI values and frequency of thermal stress categories were evaluated, considering statistical significance at the level of 0.05. Using these terms, linear regression analysis was applied, additionally verified using the Mann-Kendall test.

The Lityński classification (Lityński 1969) and its modification (Pianko-Kluczyńska 2007) were the basis of the analysis with regard to circulation conditions. This is an objective method that takes into account both zonal and meridional indices, as well as the vorticity aspect. As a result, each circulation type is classified

Table 1. Meteorological stations in the Sudetes Mountain and their foreland; mean annual values of air temperature (*T*), relative humidity (*U*), wind speed (*v*) and cloudiness (*N*) for 12.00 UTC

Station	Abbr.	Altitude [m asl]	Location	<i>T</i> [°C]	<i>U</i> [%]	<i>v</i> [m/s]	<i>N</i> [%]
Wrocław	WR	120	Lowlands (river valley)	13.0	63	4.1	71
Legnica	LE	122	Lowlands (flatland)	12.9	64	4.5	74
Jelenia Góra	JG	342	Lower mtn. zone (basin)	11.8	64	3.3	75
Kłodzko	KL	356	Lower mtn. zone (basin)	11.3	68	3.8	72
Liberec	LI	398	Lower mtn. zone (basin)	11.2	67	3.9	71
Desna-Souš	D-S	772	Middle mtn. zone (convex form)	8.7	72	3.2	70
Pec pod Sněžkou	PE	819	Middle mtn. zone (slope)	8.6	69	3.1	71
Śnieżka	SN	1603	Summits (convex form)	2.1	86	10.9	79

Source: own elaboration

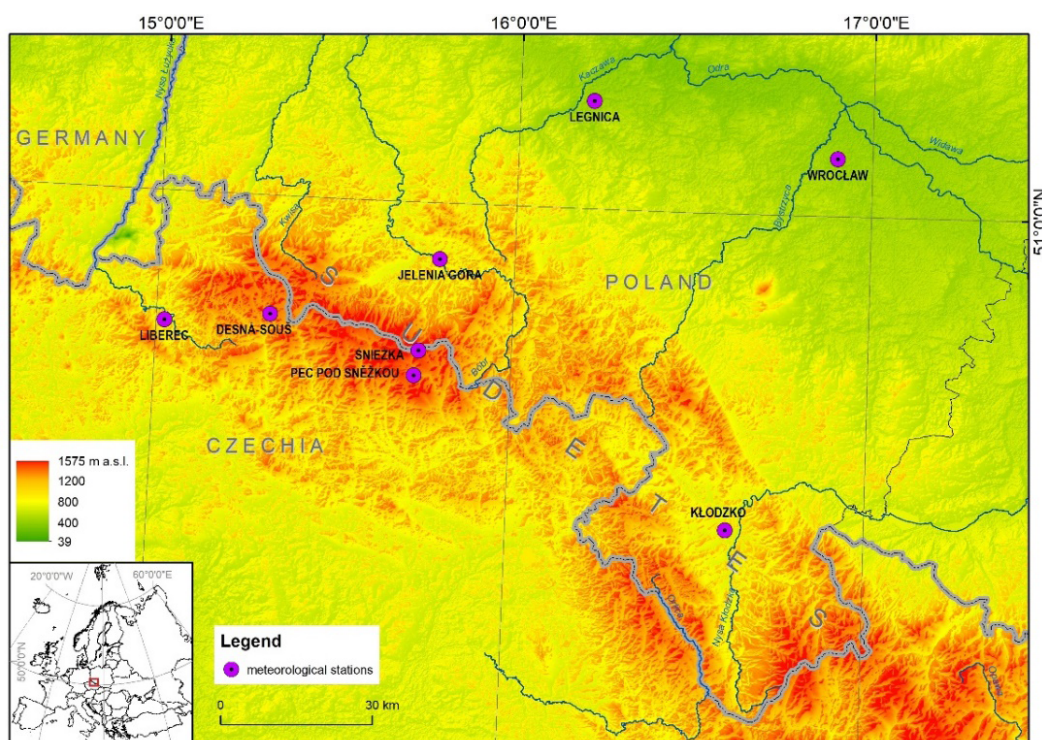


Figure 1. Meteorological stations in the Sudetes Mountains and their foreland
Source: own elaboration

Table 2. Thermal stress categories according to UTCI
(Błażejczyk et al. 2013)

Stress category	Abbreviation	UTCI [°C]
Extreme heat stress	4	above 46
Very strong heat stress	3	38 to 46
Strong heat stress	2	32 to 38
Moderate heat stress	1	26 to 32
No thermal stress	0	9 to 26
Slight cold stress	-1	0 to 9
Moderate cold stress	-2	-13 to 0
Strong cold stress	-3	-27 to -13
Very strong cold stress	-4	-40 to -27
Extreme cold stress	-5	below -40

Source: own elaboration

according to the eight main sectors (N, NE, E, SE, S, SW, NW) or to the indeterminate class (O). In terms of vorticity, anticyclonic (a), cyclonic (c) and transitional (o) types are defined. For the purposes of this paper, the calendar of daily circulation types for 1991–2020, according to the Lityński classification, was used (Pianko-Kluczyńska & Ustrnul 2021). Based on both circulation and UTCI data, changes in the frequency of thermal stress categories were evaluated for the selected circulation types.

Results

Mean values of UTCI in 1991–2020 varied from about 7–8°C, in the lowlands and the lower mountain zones, to -19°C

in the summits (Tab. 3). In terms of thermal stress categories, thermoneutral conditions (no thermal stress) prevailed throughout the region, except for the summits (SN). In the lower zones, the categories of strong and very strong cold stress, as well as moderate and strong heat stress, occurred more rarely, while extreme cold stress, very strong heat stress and extreme heat stress were observed sporadically or did not appear at all. In the summits, extreme cold stress was predominant, due to low air temperature and high rates of wind speed, humidity and cloudiness. Heat stress in this zone hardly ever occurred and was limited to several days with moderate heat stress over the entire period.

According to the calendar of circulation conditions for 1991–2020 (Pianko-Kluczyńska & Ustrnul 2021), anticyclonic weather was predominant (41%), exceeding rates for cyclonic (33%) and transitional (26%) circulation. NW and SW types were the most frequent (13–14%), while E and O types occurred rarely (below 10%). The changes in circulation conditions were generally statistically insignificant, except for the transitional type (increase by more than four days per decade).

The highest annual UTCI was reported for anticyclonic weather, indicating thermoneutral conditions for most of the stations (Tab. 4). In this case, relatively high rates were observed for the mountain basins (JG, KL, LI), where fairly high daytime air temperatures and low wind speeds are often observed during this type of weather. The values noted for the cyclonic and transitional circulation were significantly lower (slight cold stress), while in the summits, they referred to strong cold stress for each vorticity type. It should also be emphasized that the difference in UTCI between anticyclonic and cyclonic circulation in the summits was twice as high as in the lower hypsometric zones and amounted to more than 12°C. Considering the circulation sectors, the highest UTCI was observed for S and O types. This generally resulted from advections of warm air masses (S types) or might have

Table 3. Mean annual values of UTCI and the frequency of thermal stress categories [%] in 1991–2020

Station	UTCI [°C]	-5	-4	-3	-2	-1	0	1	2	3	4
WR	8.0	.	0.2	7.0	24.6	19.2	38.1	8.1	2.5	0.3	.
LE	6.9	.	0.4	9.3	24.0	19.4	37.7	6.9	2.1	0.2	.
JG	8.1	.	0.1	5.9	22.3	22.5	41.3	6.3	1.6	0.0	.
KL	7.1	0.0	0.6	8.6	23.8	19.0	38.9	7.4	1.6	0.0	.
LI	6.7	.	0.6	9.5	24.7	18.8	37.0	7.5	1.8	0.1	.
D-S	6.4	0.1	1.3	7.4	24.6	21.3	38.4	6.3	0.7	.	.
PE	6.0	0.0	0.4	6.3	26.5	22.9	40.1	3.6	0.2	.	.
SN	-19.3	22.1	16.7	19.2	18.9	12.3	10.7	0.0	.	.	.

Source: own elaboration

Table 4. Mean values of UTCI [°C] under selected circulation conditions in 1991–2020

Station	a	c	o	N types (N, NE, NW)	S types (S, SE, SW)	W types (W, NW, SW)	E types (E, NE, SE)	O types
WR	10.2	5.3	8.0	5.9	9.4	8.0	8.2	9.6
LE	9.6	3.7	6.8	4.1	8.9	6.8	7.2	8.8
JG	10.9	4.6	7.8	5.2	10.0	7.8	8.0	10.3
KL	9.9	3.9	6.7	6.0	7.3	6.4	7.7	9.3
LI	9.8	3.2	6.1	5.0	7.0	6.0	7.8	8.7
D-S	9.3	3.1	5.8	3.5	8.0	6.5	6.1	8.8
PE	8.7	3.0	5.3	4.5	6.9	5.4	6.4	7.7
SN	-13.6	-26.0	-20.0	-24.3	-16.7	-21.1	-17.9	-14.6

Source: own elaboration

been caused by the central location of anticyclonic systems over the region and their stationarity (O types). Such systems in the warm season contribute to an increase in air temperature and sunshine duration. High UTCI values in JG under the S types could also be affected by foehn winds, which are often observed in this area under this type of circulation. On the other hand, UTCI in KL (located at a similar altitude) was noticeably lower because of no significant mountain barrier in the south (and the absence of foehn winds) and the possibility of cold air mass advections through the Międzyzleska pass under the anticyclonic circulation in the cold season. The lowest values in the entire region were observed during the N types of circulation.

The anticyclonic circulation was defined by more cases of heat stress and a lower number of days with cold stress, when compared to the other types (Fig. 2). Thermoneutral conditions occurred about 10% more often during the anticyclonic weather than under the cyclonic circulation, while the total fraction of cold stress was 12–20% higher during the cyclonic types. The total frequency of heat stress categories during the anticyclonic weather was three times higher than for the cyclonic circulation.

Regarding the circulation sectors, the N types in the lowlands and lower/middle mountain zones were characterized by the highest frequency of cold stress classes, while the lowest rates were observed for the O types and S types. Simultaneously, these two circulation sectors were responsible for the most intensive heat stress occurrence (5–14%), whereas only 2–7% of days were related to heat stress under the N types. In the summits, the difference in the total frequency of cold stress between N and O types amounted to 9%, reaching the maximum for extreme cold stress (12%).

Mean annual UTCI values in 1991–2020 rose with the intensity ranging from 0.9°C (lowlands) to almost 1.6°C (summits) per decade and were characterized by statistical significance for most of the stations. Furthermore, a decline in the classes of cold stress was reported, in favour of an increase in the frequency

of thermoneutral conditions. In general, no statistically significant trend was found for the heat stress categories.

The trends of UTCI values under particular vorticity types were statistically significant for most of the stations and indicated a more dynamic increase at the higher altitudes for each vorticity type (Tab. 5). In the lowlands (WR, LE) and the lower/middle mountain zones (LI, D-S), the most intensive growth was observed during the anticyclonic weather, while the highest rates in the summits (SN) were reported for the transitional and cyclonic types. Changes in the cold stress classes were usually defined by a negative tendency, especially under the anticyclonic weather for strong and moderate cold stress in the lowlands and lower mountain zones (also accompanied by a major increase in thermoneutral conditions in LI), strong and very strong cold stress in the middle parts and extreme cold stress in the summits. The most distinctive changes in heat stress were observed under the cyclonic circulation and indicated a significant increase in moderate heat stress frequency for most of the stations. Regarding the transitional circulation, positive trends for the classes of moderate cold stress, no thermal stress and heat stress could partially result from the increase in the frequency of this type of circulation. The classes mentioned above were observed relatively often during the transitional type and could rise, along with the increase in the number of days, with this type of circulation. Furthermore, the positive trends for heat stress categories under the cyclonic and transitional circulation was the effect of an intensive, statistically significant and positive trend of air temperature for these types in summer (June–August), whereas the tendency for the anticyclonic weather during this season was statistically irrelevant. This is a crucial aspect, as more than 82% of all heat stress cases were noted in the summer months.

Considering the selected sectors, UTCI values mainly rose under the N types with the highest intensity in the higher zones (D-S and SN). Statistically significant positive trends were also

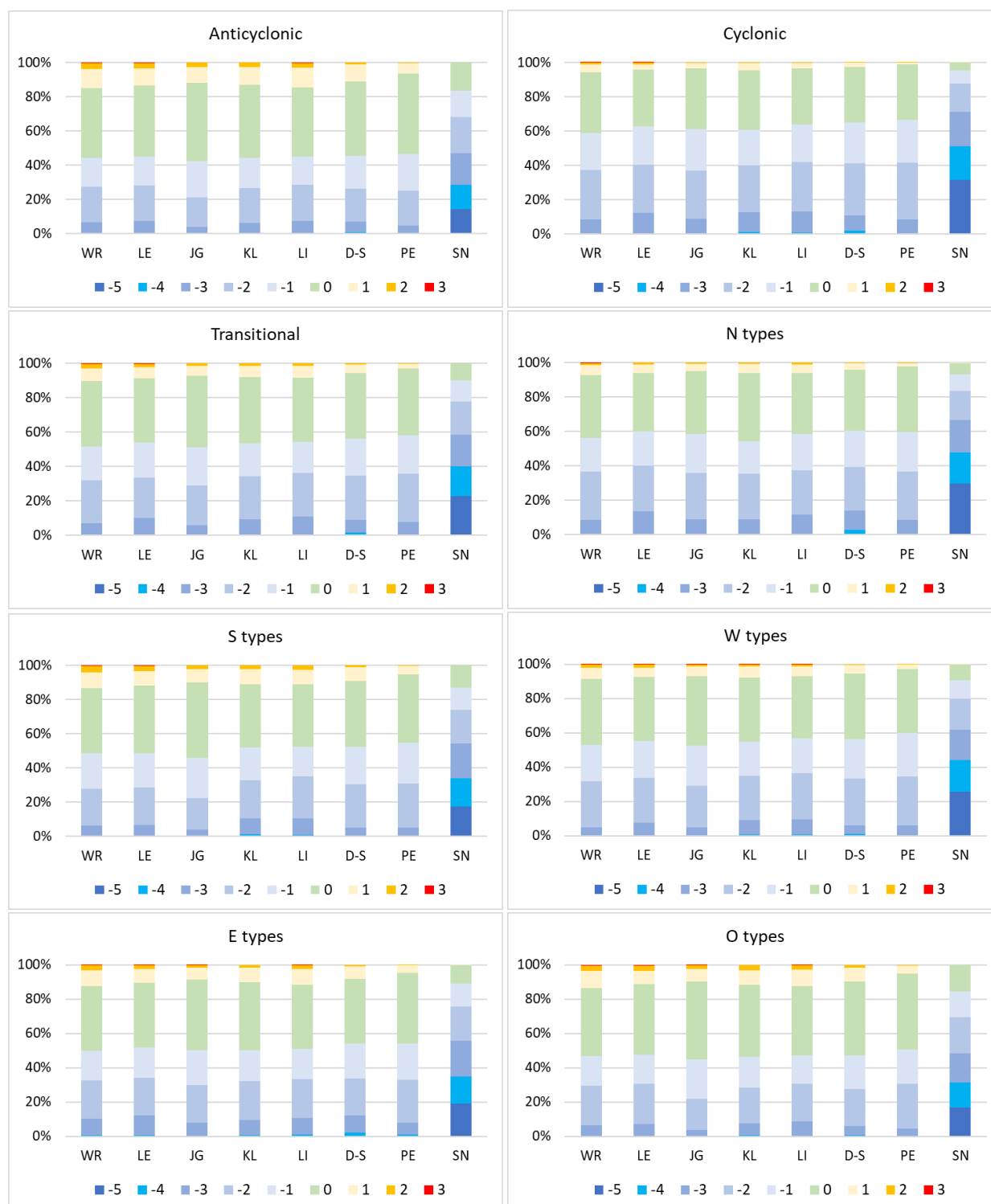


Figure 2. Frequency of the thermal stress classes according to UTCI under various circulation conditions in 1991–2020
Source: own elaboration

Table 5. Changes in UTCI [$^{\circ}\text{C}/\text{decade}$] and the frequency of thermal stress categories [days/decade] in 1991–2020 under anticyclonic (a), cyclonic (c) and transitional (o) circulation; statistically significant trends marked in bold red (positive) or blue (negative)

	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
a	WR	1.08	-	-0.46	-2.40	-3.96	-0.31	3.17	-1.04	-0.04	0.15
	LE	1.26	-	-0.31	-4.05	-3.25	0.45	2.94	-0.79	0.11	-0.01
	JG	0.24	-	-0.11	-1.14	-0.66	-2.38	1.54	-1.45	-0.70	-
	KL	0.08	-	-0.06	-0.64	-1.84	-2.03	2.92	-2.96	-0.32	-
	LI	1.32	-	-0.24	-3.93	-3.61	-0.13	4.49	-1.85	0.44	-
	D-S	1.33	-	-1.10	-2.56	-1.29	-1.92	0.91	0.75	0.53	-
	PE	0.37	-	-0.30	-0.74	-1.17	-2.01	-0.59	0.08	-0.17	-
	SN	1.56	-6.07	-0.76	-0.17	1.48	1.74	-1.02	-	-	-
c	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	0.68	-	-	-1.05	0.02	-0.94	0.31	1.38	0.71	-
	LE	1.07	-	-0.37	-1.25	-0.45	-0.33	0.72	1.69	0.51	-
	JG	-0.09	-	-0.04	0.02	1.54	-1.16	-0.74	0.77	-0.05	-
	KL	-0.49	-	0.25	0.69	0.45	0.47	-2.25	0.70	-0.02	-
	LI	1.02	-	-0.51	-1.55	0.50	-1.09	1.42	1.66	-0.09	-
	D-S	1.26	-	-1.20	-2.25	2.30	-1.38	1.90	0.96	-	-
	PE	0.12	-	0.01	-1.13	1.99	-0.89	-0.10	0.51	-	-
o	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	0.77	-	-	-0.76	0.71	-0.41	2.78	1.13	1.04	-
	LE	1.00	-	-	-0.92	-0.16	1.61	2.07	1.42	0.70	-
	JG	0.22	-	-	-0.08	1.32	1.36	1.00	0.82	0.10	-
	KL	-0.14	-	0.20	-0.39	2.18	0.75	1.76	0.06	-0.02	-
	LI	1.17	-	-0.09	-1.90	1.45	0.18	2.76	1.82	0.40	-
	D-S	1.17	-	-1.07	-0.69	2.20	-0.41	3.35	1.14	0.12	-
	PE	0.41	-	-0.34	-0.46	2.15	-0.16	2.82	0.64	-	-
	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	1.70	-2.29	0.93	0.92	2.45	0.90	1.59	-	-	-

Source: own elaboration

reported for four stations under the W and O types (Tab. 6). Changes in the thermal stress categories in the lower hypsometric zones were mainly defined by a dynamic decrease in strong cold stress occurrence (N and W types), as well as a significant growth of thermoneutral conditions (N types). Furthermore, a decline in the frequency of very cold stress category in various hypsometric zones should also be noted, especially under the N, W and E types. In the case of the S types, a positive tendency for moderate cold stress (especially in JG and PE) resulted from the statistically significant increase in the occurrence of S types in winter, which could consequently contribute to the higher frequency of this category.

Unlike most of the vorticity types, no statistically significant trends were reported for heat stress for the selected sectors, except for moderate heat stress in JG (O types) and strong heat stress in LE (S types). In the summits, a noticeable decline in the number of days with extreme cold stress was the most characteristic feature, particularly for the N types, which were accompanied by an intensive increase in air temperature in the cold season.

Discussion and conclusions

The presented results concerning the changes in UTCI in 1991–2020 indicated an increase in its values, confirming the outcomes carried out for other regions and periods. The intensity of the UTCI growth in the Sudetes Mountains and their foreland was usually higher than 1°C per decade, exceeding the rates noted for 12.00 UTC in various Polish regions in 1951–2018 (Kuchcik, Błażejczyk & Halaś 2021). The dynamics were also

comparable to the changes observed for the Lublin region (Dobek, Wereski & Krzyżewska 2020), Kraków (Błażejczyk & Twardosz 2023) and the Baltic coast (Pórolniczak, Szyga-Pluta & Kolendowicz 2016), as well as for north-western and north-eastern Poland (Tomczyk & Bednorz 2022). It should also be emphasized that changes in UTCI in south-west Poland were more intensive in the last two decades, when compared to the previous periods (Głogowski, Bryś & Perona 2021). Unlike some other regions (Pórolniczak, Szyga-Pluta & Kolendowicz 2016; Kuchcik 2020; Tomczyk & Owczarek 2019; Krzyżewska, Wereski & Dobek 2021), no statistically significant trends for heat stress were noted for 1991–2020, except during cyclonic and transitional circulation. On the other hand, an increase in the frequency of thermoneutral conditions and a decline in cold stress occurrences were observed for most of the hypsometric zones, which corresponds to the situation observed on the Polish coast (Pórolniczak, Szyga-Pluta & Kolendowicz 2016), in Warsaw (Kuchcik 2020) and in north-eastern Poland (Owczarek & Tomczyk 2022).

The relationship between the atmospheric circulation and the UTCI values/categories was reflected in a high frequency of thermoneutral conditions and heat stress under the anticyclonic, S and O types. Similar results were obtained for the northern Carpathians, where the highest values of UTCI were observed during the anticyclonic circulation related to the southern advections and wedges or ridges of high-pressure systems (Błażejczyk et al. 2020). In the lowlands and lower/middle mountain zones, cold stress was predominant, especially under the cyclonic, N and W types. These types were also responsible for cold stress occurring in south-eastern Poland (Bartoszek et al. 2017). In the summits, cold stress prevailed regardless of the circulation and its

Table 6. Changes in UTCI [°C/decade] and frequency of thermal stress categories [days/decade] in 1991–2020 for various circulation sectors; statistically significant trends marked in bold red (positive) or blue (negative)

N types	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	1.34	-	-	-3.14	-1.63	-1.28	3.68	0.49	0.25	-
	LE	1.46	-	-0.33	-4.26	0.13	-0.99	3.60	0.22	0.16	-
	JG	0.46	-	-0.08	-1.48	-0.03	-0.88	1.37	-0.20	-0.23	-
	KL	0.20	-	-0.10	-0.41	-0.95	0.44	0.59	-1.02	-0.08	-
	LI	1.70	-	-0.60	-4.43	-0.97	0.17	4.62	-0.11	-0.17	-
	D-S	1.86	-	-2.45	-2.81	0.22	-0.18	3.54	0.47	-	-
	PE	0.67	-	-0.32	-1.70	-0.81	-0.66	1.98	0.14	-	-
	SN	1.82	-5.17	-0.84	1.14	1.63	2.50	-0.70	-	-	-
S types	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	0.28	-	-0.19	-0.15	0.29	-0.31	-1.08	1.15	1.02	-0.26
	LE	0.66	-	-0.26	-0.71	-1.67	2.14	-1.30	1.54	1.03	-0.28
	JG	-0.33	-	-0.13	0.02	2.58	-0.36	-1.86	0.18	0.14	-
	KL	-0.61	-	0.29	0.19	1.52	0.48	-1.89	-0.23	0.06	-
	LI	0.53	-	-0.09	-1.28	0.34	-0.19	-0.17	1.45	0.43	-
	D-S	0.59	-	-0.19	-1.80	3.07	-2.07	-0.73	1.77	0.47	-
	PE	-0.22	-	-0.11	-0.31	4.78	-3.30	-0.99	0.36	0.03	-
	SN	1.19	-3.22	1.19	-0.82	1.53	0.21	1.60	-	-	-
W types	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	0.70	-	-	-1.07	-1.58	-0.36	2.23	1.20	-0.02	-0.04
	LE	1.08	-	-0.19	-2.68	-1.56	1.07	3.12	0.65	0.03	-
	JG	0.08	-	-0.06	-0.35	1.10	-0.57	0.88	-0.03	-0.65	-
	KL	-0.30	-	0.16	-0.63	1.36	0.23	0.89	-0.98	-0.68	-
	LI	1.01	-	-0.33	-3.14	0.03	0.08	3.49	0.65	-0.43	-
	D-S	1.21	-	-1.06	-3.03	1.95	-1.83	3.97	0.33	0.05	-
	PE	0.16	-	-0.11	-1.49	1.37	0.11	0.70	-0.12	-	-
	SN	1.83	-6.12	1.03	0.16	2.91	2.28	0.18	-	-	-
E types	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	0.53	-	-0.25	-0.92	-0.37	-1.00	2.49	-0.86	1.04	-
	LE	0.74	-	-0.40	-1.42	-0.52	0.32	1.38	0.17	0.60	-
	JG	-0.36	-	-0.05	0.26	0.55	-0.34	0.43	-0.89	0.18	-
	KL	-0.60	-	0.04	0.11	0.60	-0.01	0.20	-1.15	0.23	-
	LI	0.73	-	-0.26	-1.57	-0.57	-0.34	2.46	-0.38	0.85	-
	D-S	0.98	-	-1.45	-0.81	1.46	-0.99	0.53	1.31	0.27	-
	PE	-0.06	-	-0.41	0.08	1.46	-1.68	0.34	0.46	-	-
	SN	1.12	-3.33	-0.06	1.89	1.37	-0.06	0.26	-	-	-
O types	Station	UTCI	-5	-4	-3	-2	-1	0	1	2	3
	WR	1.44	-	-	-0.63	-0.12	0.29	1.25	0.24	0.06	-
	LE	1.53	-	-	-0.46	-0.24	0.40	0.91	0.61	0.03	-
	JG	0.55	-	-	-0.01	0.67	-0.98	0.85	0.75	-0.17	-
	KL	0.36	-	-	-0.01	0.32	-1.08	2.23	-0.35	0.05	-
	LI	1.67	-	-	-0.49	-0.26	-0.05	1.33	0.50	0.27	-
	D-S	1.42	-	-	-0.51	0.32	-0.05	0.80	0.56	0.29	-
	PE	0.69	-	-	-0.40	0.23	0.27	0.72	0.47	-	-
	SN	1.21	-0.08	-0.36	-0.08	0.88	0.36	0.47	-	-	-

Source: own elaboration

total frequency sometimes exceeded the rate observed for some alpine regions (Błażejczyk et al. 2021). Heat stress mainly occurred during the anticyclonic, S and O types, which is comparable to the results carried out for Warsaw (Rozbicka & Rozbicki 2018).

The impact of circulation was also noted in the case of high differences in the UTCI values between anticyclonic and cyclonic conditions, especially in the summits. Significantly higher UTCI under anticyclonic conditions resulted from frequent thermal inversions and air subsidence, typical for this type of weather.

In this case, an important role is played by free (anticyclonic) foehn winds that occur relatively often in the summits (Kwiatkowski 1979). They do not reach the lower mountain zones and are characterized by high air temperature, low rates of humidity and cloudiness, as well as relatively low wind speed (Kwiatkowski 1979), which consequently increase the values of UTCI. In the lower mountain zones of the Western Sudetes, landform and dynamic foehn winds are significant factors affecting biothermal conditions. The dynamic types of foehn winds increase mean air temperature

in the Jelenia Góra basin by 0.9°C (Kwiatkowski & Holdys 1985), while the concave terrain form, despite foehn winds, limits wind speed when compared to the other stations. As a result, UTCI values are comparable or even higher than in the lowlands, where wind is noticeably stronger. Simultaneously, in spite of the location in a similar landform and altitude, the rates in Jelenia Góra are higher than in Kłodzko because of the lower significance of foehn winds and the presence of the Międzyleska pass in the Kłodzko basin, which modifies local circulation conditions. Nevertheless, due to lower wind speed in this basin region, UTCI values in Kłodzko are usually higher than in the part of the lowlands represented by Legnica.

The most noticeable changes in the UTCI categories, in relation to the circulation factor, were noted for the anticyclonic and N types. They mainly referred to the decrease in the frequency of cold stress and the growth for thermoneutral conditions. This especially concerned the summits, where a major decline in the extreme cold stress occurrence was observed for these types. In the case of the remaining circulation sectors, negative trends were usually observed for the cold stress classes, except for the increase in moderate cold stress under the S types, due to significant changes of this circulation in winter. It should also be noted that UTCI values in the Sudetes Mountains can noticeably differ (8–9°C) depending on various NAO phases, especially at the turn of winter and spring (Glogowski, Bryś & Bryś 2020). The magnitude of changes in UTCI values usually rose with increasing altitudes for most circulation types, except for some of the mountain basins (Jelenia Góra and Kłodzko), where no statistically significant trends were reported for any type. On the other hand, the intensity of statistically significant changes in particular thermal stress categories, mainly related to cold stress and thermoneutral conditions, usually did not indicate major differences between particular hypsometric zones, except for the summits. The distinctive ones were reported for the anticyclonic circulation and concerned the changes in moderate and strong cold stress in the lowlands/lower mountain zones, strong and very strong cold stress in the middle parts and extreme cold stress in the summits. The middle parts of the mountains were also characterized by a more intensive decline in the frequency of very strong cold stress for most of the circulation types, when compared to the stations located lower down. The increase in heat stress conditions concerned the lowlands and the lower mountain zones, whereas the cases of statistically significant trends for strong heat stress were only reported in the lowlands.

Based on the aspects mentioned above, the following conclusions can be expressed:

- The main factor affecting UTCI is altitude. However, the index is also strongly modified by landform and local

circulation, especially in the lower mountain zones. This concerns the Jelenia Góra basin in particular, where terrain relief and foehn winds significantly affect thermal and wind conditions, making the values of UTCI comparable to those observed in the lowlands.

- The observed changes in biothermal conditions are usually related to the cold stress classes, with the most intensive decrease noted for extreme cold stress in the summits. This category is observed very often in this zone due to extreme thermal, humidity, wind and cloudiness conditions. Thus, considering the progressing changes in UTCI, this class is vulnerable to a significant decrease in its frequency. This especially concerns the N types, which are responsible for the highest number of extreme cold stress cases and are defined by more intensive increases in air temperatures in the cold season than in the warm period.
- Strong, positive trends for UTCI values and thermoneutral conditions, as well as a decreasing frequency for cold stress under the N types, show that the changes in biothermal conditions mainly refer to cold types of weather. If such trends continue, further mitigation in the thermal sense may be observed in the future, related to the additional decrease in the cold stress categories and growth in thermoneutral conditions. In the summits, a further decline in extreme cold stress could result in a higher frequency of slight or moderate cold stress classes.
- A positive trend for the frequency of heat stress classes under cyclonic and transitional conditions indicates that a potential further increase in these categories may not be solely related to anticyclonic weather. Such a tendency results from a notable increase in air temperature for cyclonic and transitional weather in the summertime, along with insignificant trends for thermal conditions during the anticyclonic circulation. This is also the effect of changes in the frequency of circulation types, characterized by positive or neutral trends of cyclonic and transitional circulation and a negative one (statistically insignificant) for the anticyclonic type.
- Changes in the UTCI values and categories can be seriously affected by the modifications of the circulation occurrence, such as an increase in frequency of transitional circulation. Therefore, an examination of the frequency of the percentages of the UTCI categories under particular circulation types should be the next step in the investigation.

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