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# **Thermal stress** in the northern Carpathians and air circulation

**Abstract**
In mountain areas, air circulation plays a major role in the forming of the climate. This paper examines how it influences thermal stress in the northern Carpathians. The Niedźwiedź's classification of air circulation was applied. Thermal stress was assessed by Universal Thermal Climate Index (UTCI). Daily meteorological and circulation data for the period 1986–2015 were used for 20 stations in Poland, Slovakia and Ukraine. Air circulation was found to have a significant impact on thermal stress. The highest UTCI values are observed at Ca+Ka (centre of the high and anticyclonic wedge or ridge of high pressure) and the lowest values at N+NE and W+NW circulation; at the Southward stations, UTCI is higher than in the Northward ones; thermoneutral days are more frequent on the southward than on the northward slopes; during N+NE, E+SE and W+NW circulation and for heat stress days, the greatest thermal privilege of the southward slopes is observed at E+SE, S+SW, Ca+Ka and Cc+Bc (centre of low and through of low pressure) types of circulation.

**Keywords**
Northern Carpathians • thermal stress • UTCI • air circulation



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## Introduction

Thermal stress caused by meteorological conditions can influence different kinds of human activity, for example performance of work outdoors, sport, tourism, preventative healthcare, etc. Mountain regions are areas that are very sensitive to atmospheric factors and climate change (Migała 2005). The general features of the climate and its vertical zonation are very important due to their elevation above sea level (Błażejczyk et al.; 2013, Smith 2015; Rubel et al. 2017; Bokwa et al. 2019). Local weather is also influenced by exposure to predominant winds, depending on regional and local circulation patterns (Niedźwiedź 1983, 2012).

Within the large number of biometeorological indices that have been proposed for assessing bioclimatic conditions (Epstein & Moran 2006; Błażejczyk et al. 2012; de Freitas & Grigorieva 2017) the newly developed Universal Thermal Climate Index (UTCI), which defines thermal stress in humans, is more and more frequently applied in bioclimatic research (Morabito et al 2014; Urban & Kysely 2014; Kolendowicz et al. 2018).

General climate and synoptic classifications are frequently used to explain how different air masses influence meteorological elements (temperature, wind, solar radiation, precipitation, etc.) (e.g. Lityński 1970; Kalkstein & Nicholls 1996; Bissolli & Dittmann 2001; Sheridan 2002; Niedźwiedź 2003; Bower et al. 2007; Huth et al. 2008; Vallorani et al 2017). Within COST Action 733, European researchers have conducted a review and harmonization of different synoptic classifications (e.g. Huth et al. 2008). There is some research dealing with the influence of air circulation on bioclimatic conditions. Ono and Kawamura (1991) assessed heat discomfort in southern Asia in relation to summer and winter monsoons. Kolendowicz et al. (2018) studied distribution of UTCI at southern Baltic and Nowosad et al. (2013) – in eastern Poland (Lublin) in relation to air circulation. The latest research conducted by Owczarek et al. (2019) describes the impacts of Grosswetterlagen weather types on UTCI distribution in northern Poland. Błażejczyk and Skrynyk (2019) applied the Niedźwiedź classification in Chornohora.

In mountain areas, climate features depend both on general regional factors and on vertical zonation of all meteorological variables: temperature, precipitation, cloudiness, insolation, etc. (Trepińska 2002; Migała 2005; Twardosz 1999, 2007; Baranowski 1999, 2003; Niedźwiedź 2003; Żmudzka 2009, 2011; Messeri et al. 2015; Sindosi et al. 2015; Łupikasza & Niedźwiedź 2016; Błażejczyk 2019; Żmudzka & Kulesza 2019). The important factors that have a major effect on the mountain climate are geographical position and orientation of the mountain ridges (Smith 2015). At elevated locations, lower air temperature and higher wind speeds cause that the human body is exposed to greater thermal stress. In addition, in the mountains, atmospheric conditions affecting humans can significantly differ over a relatively short horizontal distance (Błażejczyk et al. 2013; Bokwa et al. 2019). Until now there have not been many papers presenting the biometeorological specificity of mountain areas (Gajić-Čapka & Zaninović 1997; Mateeva & Filipov 2003; Zaninović et al. 2006;

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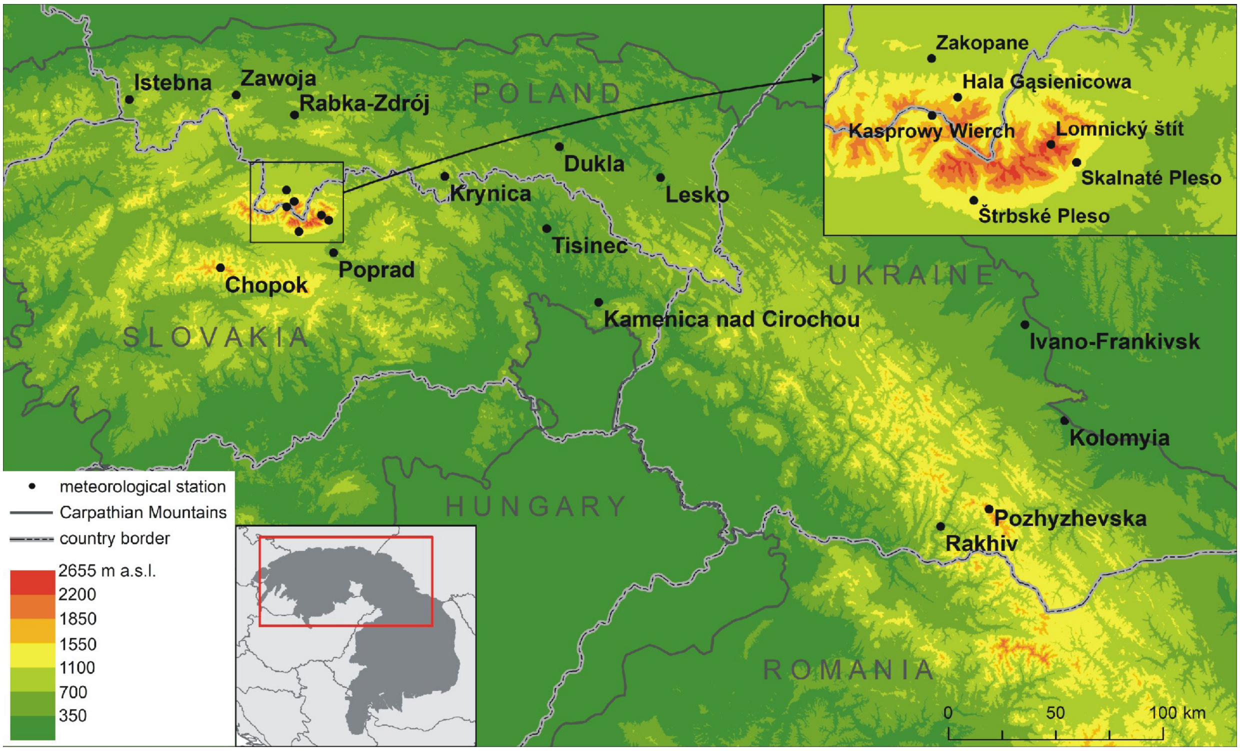


*Figure 1. Northern Carpathians – location of meteorological stations used in research; the extent of the northern Carpathians is marked in the red rectangle. Source: produced by author*

Miszuk 2008; Endler et al. 2010; Milewski 2013; Pecelj et al. 2017; Bokwa et al. 2019).

For the Carpathian region, there are also complex climatic characteristics (Konček 1974; Niedźwiedź 2012; Cheval et al. 2014; Spinoni et al. 2014; Dąbrowska & Guzik eds. 2015). The general features of thermal stress conditions in the northern Carpathians were analysed by Błażejczyk et al. (2020), who concluded that 1) due to the higher altitude, UTCI values became lower, cold stress days are more frequent, and the number of heat stress days is reduced and at sites elevated >1500 m ASL is equal to 0, 2) in eastern areas with sub-mountain, coline relief, cold stress is more evident and heat stress days are more frequent than in the western, montane landscape, 3) on the southward slopes of the Carpathian arc, heat stress is greater and more frequent then in north-facing areas.

This study is designed to examine how air circulation affects the spatial differentiation of thermal stress in the northern Carpathians. Attention is paid to exposure of meteorological stations to predominant flows of air.

## Materials and methods

To analyse thermal stress in the Carpathians, we have used daily meteorological data from 20 stations of national weather networks of Poland, Ukraine and Slovakia for the period 1986-2015 (Fig. 1). For Poland, data are available at: Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy 2020. Ukrainian and Slovak data were made available by archives of the Ukrainian Hydrometeorological Institute and Slovak Hydrometeorological Institute. In general, Polish stations represent the northward slopes of the Carpathian arc (opened to advections of air from N, NW and NE) and Slovak stations represent the southward slopes (influenced by air advection from S and SE). Ukrainian stations are located both on the north-eastern (exposed to N, NE and E advections) and south-western slopes of the Carpathian arc (open to air flows from W, SW and S).

The Carpathians are a wide, crescent-shaped mountain ridge located in Central and Eastern Europe. They are the third longest mountain system in Europe (after the Urals and Scandinavian Mountains) extending for approximately 1300 km from the Danube gorge near Bratislava to the Iron Gate – the Danube gorge near Orshova. The Carpathians consist of many geologically and orographically distinct mountain ridges (Rączkowska et al. 2012). The highest part of the mountains is the Tatra Massif (characterized by typical alpine relief), which consists of more than 50 peaks with an elevation above 2000 m (the culmination is Gerlachovský štít, 2 655 m ASL). In the Eastern Carpathians, Chornohora is the highest ridge, with six peaks >2000 m (Hoverla 2 061 m ASL).

In the Carpathian Mountains, several vertical climate zones were distinguished by Hess (1965), namely: moderately warm (<700 m ASL), moderately cool (700–1100 m ASL), cool (1100–1550 m ASL), very cool (1550–1850 m ASL), moderately cold (1850–2200 m ASL), and cold (>2200 m ASL). For the Eastern Carpathians, Niedźwiedź (2012) has proposed modified borders of those zones, in respective order for those zones: 850, 850–1200, 1200–1550, 1550–1850 and 1850–2100 m ASL (there is no cold belt).

The Carpathian vertical climate zones correspond to zones observed in the European Alps. Rubel et al (2017) have applied the Koppen-Geiger climate classification to those zones, as follows: <1050 m ASL – Cfb climate (coline belt), 1050-1390 m ASL – Cfc/Dfb climate (montane belt), 1390-1880 m ASL – Dfc climate (subalpine belt), 1880-3250 m ASL – ET climate (alpine belt).

Taking into account orographic, geological, and climatic facts discussed by Błażejczyk et al (2020) and the nomenclature proposed

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*Table 1. Geographical information of studied meteorological stations*

| Name of station (and abbreviation) | Latitude | Longitude | Elevation above sea level (m) | Physiographical type | Location |
|---|---|---|---|---|---|
| **Poland** | | | | | |
| Istebna-Kubalonka (IK) | 49°36'N | 18°54'E | 760 | Montane | Northward |
| Zawoja (ZAW) | 49°37'N | 19°31'E | 720 | Montane | Northward |
| Zakopane (ZAK) | 49°17'N | 19°57'E | 857 | Montane | Northward |
| Hala Gąsienicowa (HG) | 49°14'N | 19°59'E | 1520 | Alpine | Northward |
| Kasprowy Wierch (KW) | 49°13'N | 19°59'E | 1990 | Alpine | Peak |
| Krynica (KRY) | 49°25'N | 20°58'E | 595 | Montane | Northward |
| Rabka (RAB) | 49°37'N | 19°58'E | 510 | Montane | Northward |
| Dukla (DUK) | 49°34'N | 21°41'E | 360 | Coline | Northward |
| Lesko (LES) | 49°27'N | 22°20'E | 420 | Coline | Northward |
| **Ukraine** | | | | | |
| Ivano-Frankivsk (IF) | 48°53'N | 24°41''E | 275 | Coline | Northward |
| Kolomyia (KOL) | 48°32''N | 25°03''E | 298 | Coline | Northward |
| Pozhyzhevska (POZ) | 48˚09''N | 24˚32''E | 1451 | Alpine | Northward |
| Rakhiv (RAK) | 48º02''N | 24º11''E | 431 | Coline | Southward |
| **Slovakia** | | | | | |
| Tisinec (TIS) | 49°13´N | 21°39´E | 216 | Coline | Southward |
| Lomnicky **Štít** (LS) | 49°12´N | 20°13´E | 2635 | Alpine | Peak |
| Skalnaté Pleso (SKP) | 49°11´N | 20°14´E | 1778 | Alpine | Southward |
| **Štrbské** Pleso (STP) | 49°07´N | 20°04´E | 1322 | Montane | Southward |
| Poprad (POP) | 49°04´N | 20°15´E | 694 | Montane | Southward |
| Chopok (CH) | 48°57´N | 19°36´E | 2005 | Alpine | Peak |
| Kamenica nad Cirochou (KC) | 48°56´N | 22°00´E | 176 | Coline | Southward |

*Source: produced by author*

by Rubel et al (2017), in this research meteorological stations were gathered in three groups: 1) Coline, with an elevation of <500 m ASL, located mostly in the Eastern Carpathians, 2) Montane, with an elevation of 500-1400 m ASL, located mostly in the Western Carpathians, 3) Alpine, with an elevation of >1400 m ASL, and alpine relief (Table 1).

For every station, daily data (for the period 1986–2015) on air temperature, relative humidity, total cloud cover, and wind speed at 10 m above ground for 12 UTC were used. The data for midday hours were applied due to their representativeness for any human activity (Jendritzky & de Dear 2008). The Universal Thermal Climate Index (UTCI) was applied as a measure of thermal stress (Błażejczyk et al. 2012). The BioKlima©2.6 software package was used (Instytut Geografii i Przestrzennego Zagospodarowania PAN 2020) to calculate UTCI.

UTCI is defined as air temperature of reference condition causing the same model response (in sweat production, shivering, skin wettedness, skin blood flow, and in rectal, face and mean skin temperatures) as the actual conditions. The UTCI values are categorised according to 10 classes, from extreme cold stress to extreme heat stress (Bröde et al. 2012). In this research, three groups of UTCI categories are considered, namely: thermoneutral (TN, UTCI = 9.1–26.0°C), cold stress (CS, UTCI≤-13°C) and heat stress (HS, UTCI>32°C). The CS category combines UTCI classes of strong, very strong, and extreme cold stress, and the HS category the classes of strong, very strong and extreme heat stress.

To examine the effect of air circulation on thermal stress in the northern Carpathians, the authors used the Niedźwiedź calendar of circulation types (2019). This is a subjective classification based on the synoptic maps of Europe. The type of atmospheric circulation is determined by the direction of air mass advection and the kind of pressure pattern (a – anticyclonic, c – cyclonic). The area for which the calendar has been created extends from 49-51°N to 18–24°E, covering southern Poland as well as part of the Czech Republic, Slovakia and Ukraine. In this paper, eleven circulation types were used, among which eight are advection types, two are non-advection types, and one is used in cases of unclassified situation or baric col (Table 2). The Niedźwiedź classification was applied to analyze the impact of air circulation on different atmospheric phenomenon occurrences, for example fog (Łupikasza & Niedźwiedź 2016), precipitation (Twardosz 1999, 2007; Kholiavchuk & Cebulska 2019) and secular changes in bioclimatic conditions (Błażejczyk et al. 2003).

The STATGRAPHICS Centurion XVI software package was used for statistical analysis. A 95% confidence level was applied for verifying statistical significance of the studied relations.

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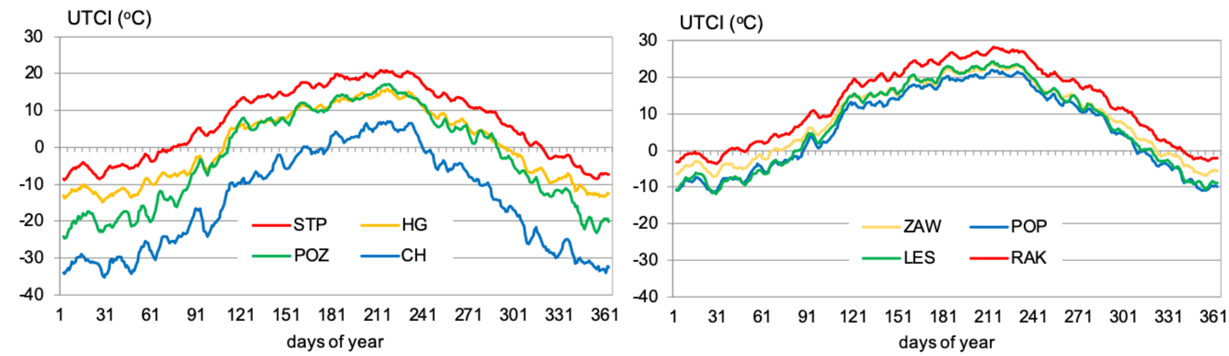


*Figure 2. Average daily UTCI values in course of the year at selected meteorological stations, 1986-2015*
*Source: produced by author*

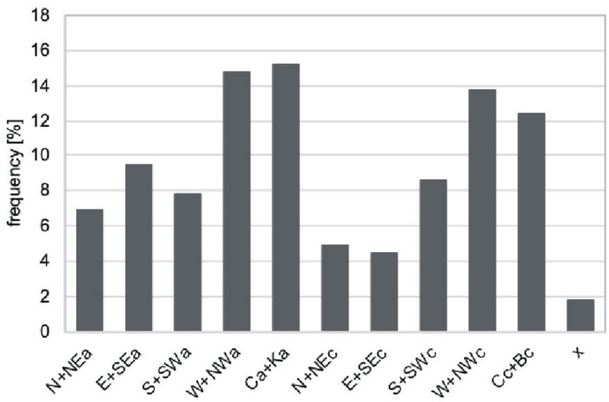


*Figure 3. Annual frequency of circulation types during the period 1986-2015*
*Source: produced by author*

*Table 2. Air circulation types according to Niedźwiedź classification*

| Anticyclonic situations: | Cyclonic situations: |
|---|---|
| N+NEa | N+NEc |
| E+SEa | E+SEc |
| S+SWa | S+SWc |
| W+NWa | W+NWc |
| Ca+Ka - centre of high and anticyclonic wedge or ridge of high pressure | Cc+Bc - centre of low and through of low pressure |
| x — unclassified situation | |

*Source: adapted from Niedźwiedź (2019)*

## Results

### General characteristics of UTCI

When analysing annual UTCI values, most intensive heat stress is found to occur in Rabka (Northward Montane station). There is noted highest mean yearly (+13.5°C), UTCImax >40°C and frequent occurrence of HS conditions (4.6% of days yearly). High UTCI means (above +10°C) are also observed in Istebna and Krynica (Northward Montane stations) as well as in Kamenica and Rakhiv (Southward Coline stations). The absolute maximum UTCI >40°C was mostly registered at stations located in the eastern part of the area (TIS, KAM, IF, RAK, KOL). The lowest UTCI values, both mean (<-11°C) and minimum (<-60°C), are observed at most elevated Alpine stations in the Western Carpathians (KW, CH, LS) as well as at the POZ station in the Eastern Carpathians. At Alpine stations, cold stress days are noted frequently (>45% yearly). However, at stations located >1400 m ASL no days with heat stress are noted. On the contrary, HS days were recorded more frequently (>5% days per year) in stations situated on the southward slopes of the Eastern Carpathians (TIS, KAM, RAK) (Table 3).

Figure 2 presents average yearly UTCI course at selected stations. The first group (left panel) represents four high elevated (>1300 m ASL) locations in the Tatras (CH, HG and STP) and in Chornohora (POZ). The second group (right panel) illustrates Montane (ZAW, POP) and Coline (LES, RAK) stations situated in western and eastern parts of the studied area. In general, the yearly course of UTCI at all stations is the same. Visible UTCI decrease and increase phases occurred in approximately the same periods, and these were a warming phase in the third decade of January, and cooling periods in the first decade of April and between 5 and 13 May. On almost the same days, we also observe the annual maximum UTCI (30 July–3 August). These similarities over the course of a year demonstrate that the whole studied area is influenced by the same air circulation patterns

The lowest UTCI at stations of high elevation is highly evident, especially at Chopok. At stations of similar altitude, the Southward station STP is warmer than the Northward one (HG). At station of most eastern location (POZ), UTCI values in the cold season are significantly lower than in the Tatras. For the Montane and Coline stations, UTCI are similar over the course of the year, and average differences do not exceed 10°C. The highest values are noted at the southernmost station (RAK) and the lowest ones at relatively elevated Poprad and at Northward Lesko located in the eastern part of the studied area.

### Atmospheric circulation

During the period 1986-2015, anticyclonic circulation types were more frequent (54.1% days) than cyclonic ones (44.1% days). This period was characterized by the most frequent advections of air masses from the west and northwest, both anticyclonic (14.7%) and cyclonic (13.7%) as well as non-advection types Ca+Ka (15.2%) and Cc+Bc (12.4%) (Fig. 3). Advection types are prevalent in the cold half-year, while non-advection types are prevalent in the warm half-year. In summer (JJA), the frequency of circulation types is very similar to annual distribution, but with a higher occurrence of non-advection types:

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*Table 3. Minimum (min), mean and maximum (max) annual UTCI values as well as yearly frequency of selected UTCI categories, 1986-2015*

| Station | UTCI values (°C) | | | Frequency of UTCI categories (%) | | |
|---|---|---|---|---|---|---|
| | min | mean | max | CS | TN | HS |
| Northward | | | | | | |
| Coline | | | | | | |
| Dukla | -54.9 | 5.3 | 38.7 | 14.7 | 35.3 | 1.9 |
| Lesko | -45.2 | 6.9 | 38.7 | 10.3 | 38.3 | 1.8 |
| Ivano Frankivsk | -42.7 | 7.8 | 41.8 | 11.3 | 38.8 | 3.1 |
| Kolomyia | -48.2 | 9.1 | 40.8 | 7.9 | 38.8 | 3.9 |
| Montane | | | | | | |
| Istebna | -36.3 | 10.2 | 38.0 | 3.5 | 41.6 | 1.5 |
| Zawoja | -35.3 | 8.5 | 40.1 | 6.6 | 42.1 | 1.5 |
| Zakopane | -28.2 | 8.4 | 37.2 | 3.6 | 43.9 | 0.6 |
| Krynica | -49.9 | 10.3 | 36.9 | 5.0 | 41.5 | 1.9 |
| Rabka | -31.2 | 13.5 | 40.5 | 1.4 | 44.2 | 4.6 |
| Alpine | | | | | | |
| Hala Gąsienicowa | -52.1 | 0.3 | 30.1 | 17.5 | 28.0 | . |
| Pozhyzhevska | -66.0 | -2.7 | 33.7 | 24.1 | 31.8 | . |
| Southward | | | | | | |
| Coline | | | | | | |
| Tisinec | -47.2 | 10.4 | 42.2 | 7.5 | 37.2 | 5.4 |
| Kamenica | -47.4 | 11.3 | 41.3 | 5.0 | 39.5 | 5.1 |
| Rakhiv | -36.4 | 12.5 | 41.6 | 2.2 | 43.6 | **5.6** |
| Montane | | | | | | |
| Štrbské Pleso | -38.2 | 6.6 | 34.1 | 5.8 | 41.7 | 0.2 |
| Poprad | -48.1 | 5.7 | 36.6 | 11.3 | 38.0 | 0.7 |
| Alpine | | | | | | |
| Skalnaté Pleso | -60.3 | -1.3 | 28.2 | 20.7 | 23.6 | . |
| Peaks (Alpine) | | | | | | |
| Chopok | -71.0 | -14.8 | 26.8 | 51.8 | 11.6 | . |
| Lomnicky Štit | -73.5 | -15.7 | 24.2 | 52.2 | 6.4 | . |
| Kasprowy Wierch | -60.8 | -12.1 | 26.8 | 45.7 | 11.4 | . |

*Source: produced by author*

Ca+Ka (18.6%) and Cc+Bc (16.7%). In winter (DJF), circulation types with advection of air masses from the northwest sector W+NWa (21.2%) and W+NWc (15.6%) are dominant. In the transitional seasons, there is no single dominant type, and the frequency is quite even. In spring (MAM), days with non-advection types were more noticeable than other days (altogether 29.2%). Spring is also the season with the highest frequency of circulation types with advection from the east (E+SEa, E+SEc, N+NEa, N+NEc) while in the autumn occurs the highest frequency of types with advection from southwest (S+SWa, S+SWc).

## UTCI and air circulation

When looking for spatially averaged annual UTCI values for different types of circulation, the highest values are observed at Ca+Ka (the average value for all considered stations is 9.1±1.5°C). A high UTCI is also noted at the S+SWa and Cc+Bc circulation types. However, the lowest values are related to the N+NEc (-1.6±2.3°C) and W+NWc (-0.8±2.4°C) circulation types. The highest mean annual UTCI is observed in Rabka (17.8°C) during S+SWa circulation. At this station, the highest annual UTCI values are also noted at almost all types of circulation. Only during N+NEc and Cc+Bc circulation types, the warmest is Rakhiv on the southward slopes of Chornohora and for E+SEc – Kamenica on the southward slopes of Beskid Niski. The lowest annual UTCI is noted at Chopok Mt. (-25.9°C) for the N+NEc circulation type. For other circulation types, the lowest index values are recorded either at the summits of Chopok or Lomnicky Štit (Table 4).

At the Montane and Alpine stations located in the western part of the region, the highest mean annual UTCI values are

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*Table 4. Mean annual UTCI values at different air circulation types, 1986-2015*

| Measure | N+NEa | E+SEa | S+SWa | W+NWa | Ca+Ka | N+NEc | E+SEc | S+SWc | W+NWc | Cc+Bc | x |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 1.9±2.1 | 4.9±1.6 | 7.7±2.0 | 1.1±2.1 | 9.1±1.5 | -1.6±2.3 | 5.0±1.9 | 2.7±2.7 | -0.8±2.4 | 7.2±2.1 | 5.4±1.9 |
| Highest station | 12.0 RAB | 12.5 RAB | 17.8 RAB | 11.1 RAB | 16.8 RAB | 10.2 RAK | 13.7 KAM | 16.3 RAB | 9.5 RAB | 16.7 RAK | 13.7 RAB |
| Lowest station | -20.9 LS | -12.3 LS | -14.6 CH | -21.1 LS | -8.5 LS | -25.9 CH | -14.0 CH | -25.3 CH | -23.9 LS | -12.9 CH | -12.6 LS |

*spatially averaged, the highest and the lowest values for all considered stations*
*Source: produced by author*

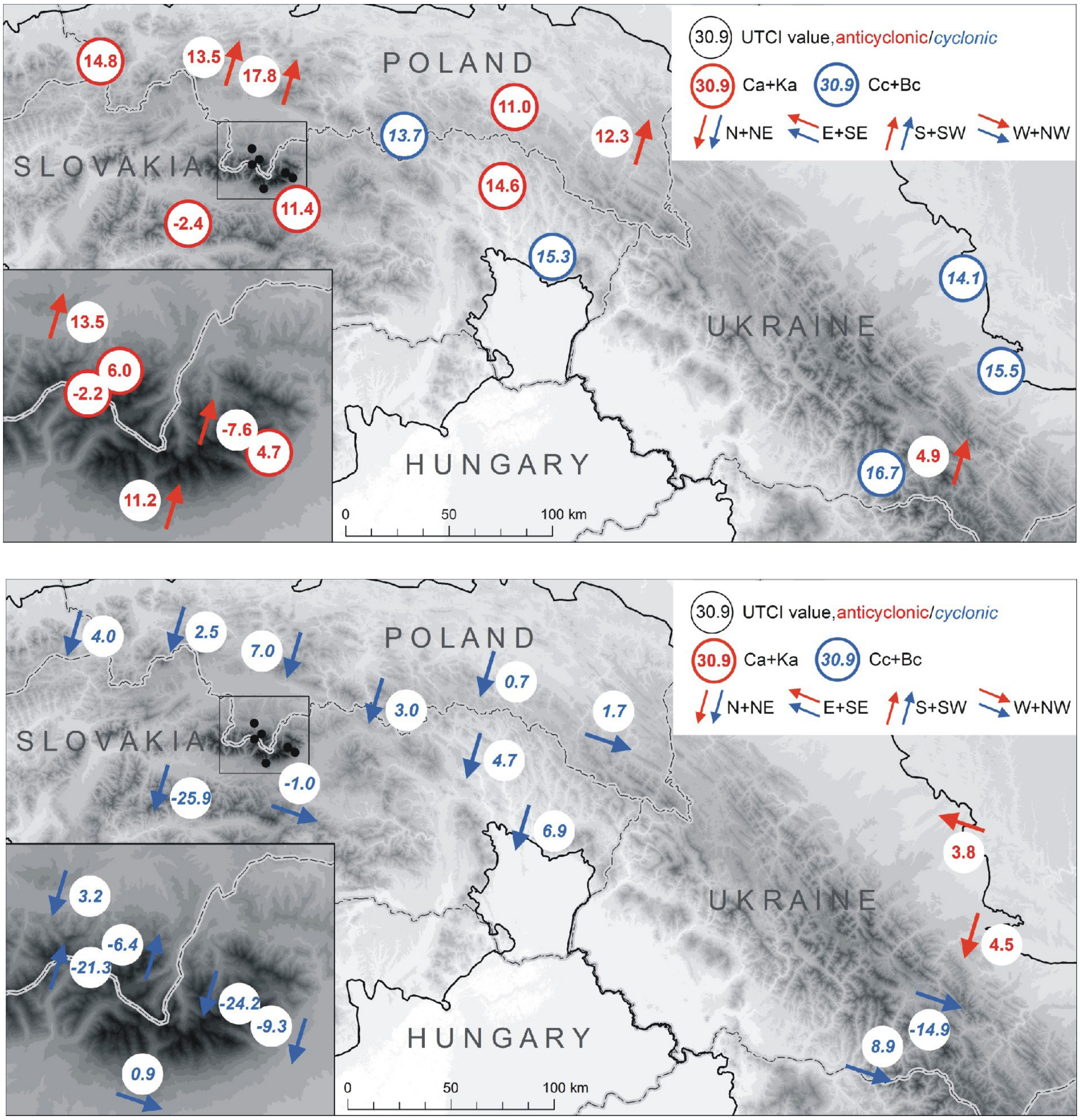


*Figure 4. Highest (upper panel) and lowest (lower panel) mean annual UTCI (°C) in relation to air circulation type*
*Source: produced by author*

mostly related to S+SWa and Ca+Ka air circulation types. However, at the Coline stations, situated mainly in the eastern part of the northern Carpathians, the analogical highest values of the thermal stress index are observed mostly during Cc+Bc and S+SWa types of circulation (Fig. 4).

The lowest mean annual UTCI values are generally related to the N+NEc circulation type. At some stations (POP, STP, LES, RAK, POZ), the lowest means are observed for the W+NWc type. The situation at the HG and KW stations in the Polish Tatras was unusual, when the lowest annual UTCI is related to S+SWc

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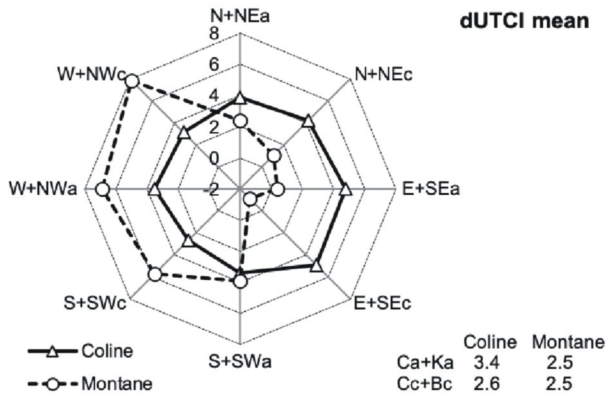


*Figure 5. Differences in UTCI mean yearly values at Coline and Montane stations in relation to particular air circulation types*
*Source: produced by author*

circulation, and at the IF station (NE foot of the Carpathians), where the lowest annual values occur at the E+SEa circulation type. This needs more detailed research in the future.

As mentioned, the location of the station on the southward and northward slopes of the Northern Carpathian ridge affects both values and frequencies of particular UTCI categories. In our research, we considered differences in UTCI values and in the frequencies of UTCI categories between southward slopes and northward slopes stations located in the Coline and Montane physiographical types of area. In general, in the Southward Coline stations dUTCI, the means are 3.65°C higher than in Northward stations. In the Montane stations, such differences are slightly lower (3.16°C). The dUTCI means vary significantly (with $p<0.05$) between particular circulation types. The greatest differences occur at advection from W+NWc, W+NWa and S+SWc (6–8°C at the Montane stations) and E+SEc, E+SEa and N+NEc (4–6°C at the Coline stations) (Fig. 5).

At the majority of stations, the highest UTCI maximum occurred during cyclonic air advection from S+SW as well as for the Cc+Bc circulation type. The SKP station is an exception, where the highest UTCImax was recorded at the N+NWa advection. In general, in stations situated in the eastern part of the region, UTCI max are higher than in stations at the western edge of the Carpathians (Fig. 6).

The lowest UTCImin values occur mostly during N+NE and E+SE advection. However, at some stations (IK, IF and KW), the lowest UTCImin was observed during S+SW (anticyclonic or cyclonic) circulation. There are also differences between western (warmer, with higher UTCImin) and eastern (cooler, lower UTCImin) parts of the studied region (Fig. 6).

In general, dUTCImin values are significantly higher than dUTCImax (respectively 4.95 vs. 2.36°C for the Coline stations and 8.31 vs 0.21°C for the Montane stations). The highest dUTCImax (2-4°C) were found for E+SEc, E+SEa, W+NWa and W+NWc advections for the Coline stations as well as for N+NEa and W+NWa (Montane stations). In the case of dUTCImin, there are significant differences between particular circulation types (from approximately -1 to approximately 15°C). The highest dUTCImin (>7°C) were recorded during S+SWc, S+SWa, N+NWc, E+SEc and E+SEa (Montane stations) as well as S+SWa and W+NWa (Coline stations) air advection (Fig. 7).

Seasonal and regional variability in dUTCI values have been observed. On average, Coline Southward stations represent a higher mean, maximum and minimum UTCI. However, depending on the season, the warming potential of various advection types is different. In spring (MAM), the highest dUTCI is noted during air flow from N+NE, S+SE and W+NW. In summer (JJA), the northward slopes are mostly warmer at E+SE and Cc+Bc advections. During the autumn (SON) and winter (DJF) months, high dUTCImean and dUTCImax values occur mostly at N+NE and S+SE circulation. However, dUTCImin is elevated at S+SW and W+NW advection. In general, in SON and DJF months, the dUTCImean is significantly higher (3.9-4.2°C) than in spring and summer. The highest dUTCImax is noted in autumn and dUTCImin is the highest in winter (Table 5).

At the Montane stations, the highest warming potential of Southward locations is observed for dUTCImin (from 5.5°C in JJA to 10.6°C in MAM) and the highest values reach approximately 21°C (at S+SWc and Cc+Bc circulation). The lowest WP was found for maximum UTCI values. The average dUTCImax varies from 0.1°C in JJA to 1.1°C in MAM. It reached its highest values (8°C) in winter, at W+NWc advection. The average dUTCImean varies between 1.1°C in summer to 5.1°C in winter. In all seasons, mostly elevated dUTCImean are observed at the W+NWc circulation type. During E+SEc advection, southward slopes are cooler than northward slopes when considering the differences in both UTCImean and UTCImax (Table 5).

Single extremely low or extremely high UTCI can be a result of different factors such as season, air circulation, ASL elevation and specific location of a station. Thus to find more general regularities of thermal stress conditions we have considered frequencies of particular UTCI categories. As seen in table 5, annual frequency of cold stress days varied from 2.2% in RAK to 52.3% in LS. Figure 8 shows that on the Northward slope stations, the highest frequency of CS days occurs during N+NEa circulation, and varies from 4.8% in RAB to 22.4% in DUK. At the Southward and Peak stations there are different advections of predominate CS frequency (S+SE, S+SW, N+NW) which varies from 5.9% in RAK to 72.5% in CH. Heat stress was not observed at Alpine stations of high elevation, and their highest annual frequency reached 5.6% in RAK. When considering advection types it was found that at the Polish Northward stations the highest occurrence of HS days (4.1–9.3%) was related to S+SWa. In the eastern part of the studied region, HS days are most frequent (7.5–12.1%) during Cc+Bc circulation.

The annual amount of TN days varied from 6.4% in LS to 44.2% in RAB (Table 5). TN days are most frequent during Cc+Bc or Ca+Ka circulation types, except RAB, SKP, KAM, RAK and POZ stations. The number of days is between 14.5% in LS (at Ca+Ka advection) and 50.5% in RAK (at S+SEc air inflow) (Fig. 9).

When analysing differences in annual frequency of cold stress days (dCS), they are found to be more frequent in the Northward than in the Southward stations. For Montane areas, this difference is on average -7.5% and are highest at N+NE, S+SE and W+NW circulation types. For the Coline stations, the average dCS is -4.9% and the highest values occur at S+SW and W+NW advections. Average dTN and dHS values show that thermoneutral and heat stress days are more frequent on the Southward slope in comparison to the Northward slope stations. For the Coline areas, the greatest dTN occurs at N+NE and dHS – at E+SE and Ca+Ka/Cc+Bc circulation. At the Montane stations, the greatest dTN is observed at W+NW and N+NEa circulation. At the Montane stations, HS days occur sporadically, and there are few dHS (Table 6).

At the Coline stations in the summer months (JJA), no cold stress days were recorded, and the greatest dCS is observed in DJF especially at N+NE circulation. The highest dHS was found for the summer months, mainly during S+SW advection. At the Montane stations, dCS is higher than in the Coline

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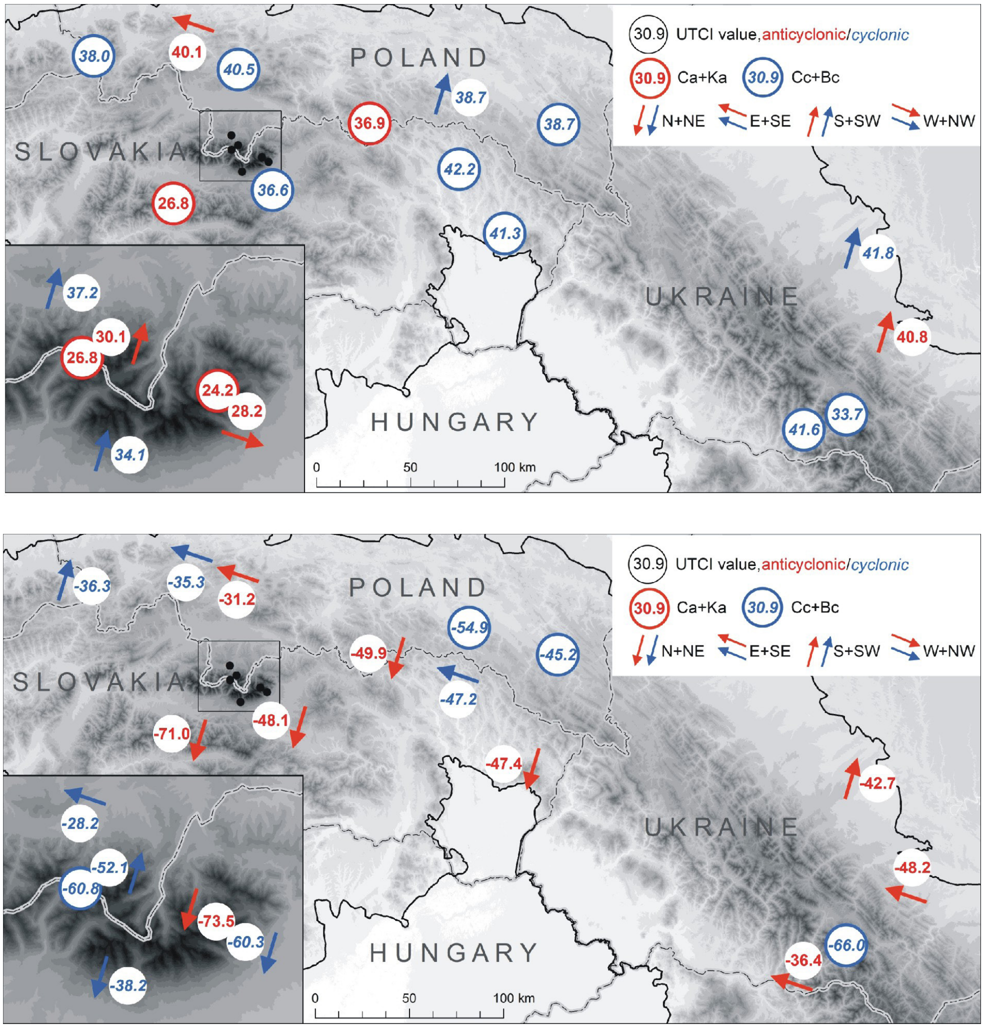


*Figure 6. Maximum (upper panel) and minimum (lower panel) UTCI values registered at studied stations and air circulation type they have occurred. 1986-2015*
*Source: produced by author*

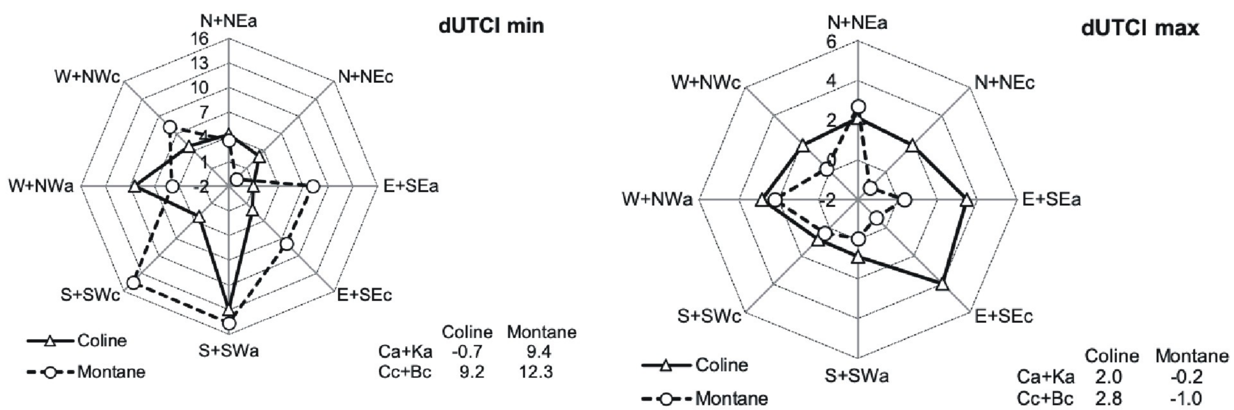


*Figure 7. Differences in extreme yearly values of UTCImax (dUTCImax) and UTCImin (dUTCImin) at Coline and Montane stations in relation to particular air circulation types, 1986-2015*
*Source: produced by author*

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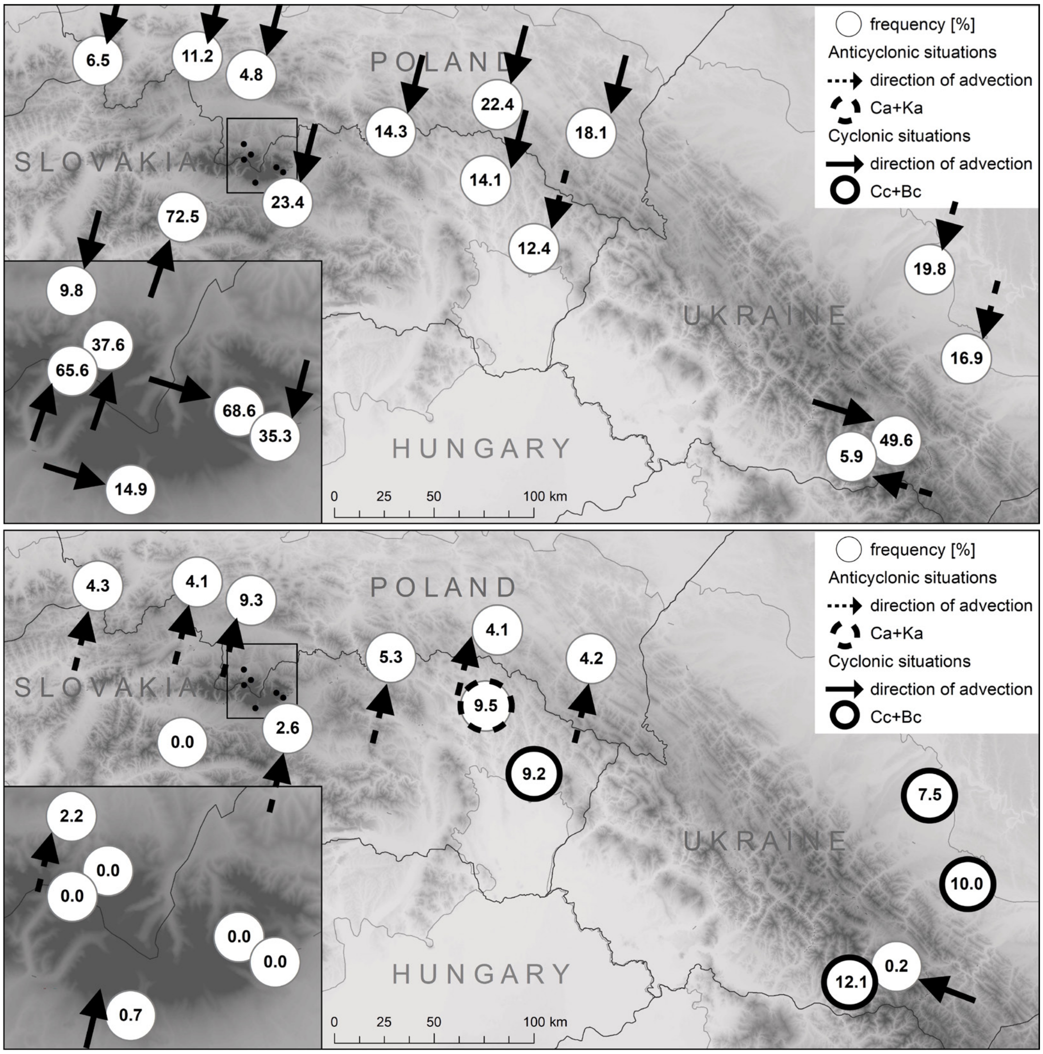


*Figure 8. Highest frequency of cold stress days (upper panel) and hot stress days (lower panel) in relation to air circulation*
*Source: produced by author*

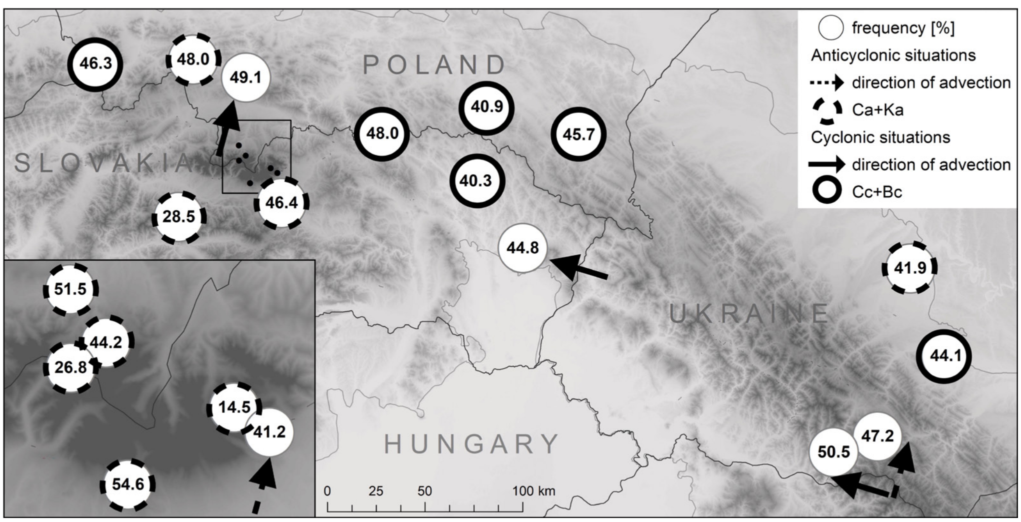


*Figure 9. Highest frequency of thermoneutral days in relation to air circulation*
*Source: produced by author*

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*Table 5. Differences in seasonal values of mean (dUTCImean). Maximum (dUTCImax) and minimum (dUTCImin) of the Universal Thermal Climate Index between Southward and Northward stations at particular air circulation types, 1986-2015*

| Air circulation type | dUTCI mean | | | | dUTCI max | | | | dUTCI min | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAM | JJA | SON | DJF | MAM | JJA | SON | DJF | MAM | JJA | SON | DJF |
| Coline stations | | | | | | | | | | | | |
| N+NEa | 3.6 | 3.8 | 4.0 | 4.5 | 2.2 | 2.4 | 5.0 | 4.2 | 1.5 | 7.3 | 2.7 | 3.8 |
| N+NEc | 4.3 | 2.8 | 5.0 | 6.0 | 2.5 | 1.9 | 0.4 | 4.3 | 7.0 | 0.5 | 5.1 | 1.9 |
| E+Sea | 4.3 | 3.4 | 5.2 | 5.9 | 0.8 | 3.5 | 2.3 | 3.0 | 0.2 | 2.6 | 4.8 | 1.0 |
| E+Sec | 4.6 | 3.5 | 5.1 | 6.2 | 4.0 | 4.0 | 4.7 | 2.3 | 5.3 | 6.0 | 2.6 | 2.5 |
| S+Swa | 2.7 | 2.4 | 3.4 | 4.4 | 1.7 | 0.9 | 0.9 | 1.0 | 4.8 | 2.6 | 6.2 | 13.0 |
| S+SWc | 2.4 | 2.2 | 3.0 | 3.1 | 2.5 | 0.9 | 4.6 | 0.6 | 5.9 | 6.6 | 3.2 | 5.3 |
| W+NWa | 4.0 | 3.8 | 3.4 | 3.0 | 3.1 | 2.8 | 1.4 | 1.9 | 6.7 | 5.9 | 4.1 | 10.9 |
| W+NWc | 3.6 | 3.5 | 2.6 | 3.0 | 1.6 | 1.9 | 3.4 | -1.5 | 1.7 | 4.0 | 8.2 | 4.5 |
| Ca+Ka | 3.3 | 3.0 | 3.9 | 3.6 | 2.0 | 2.0 | 4.5 | 4.7 | 2.9 | 4.0 | 0.6 | -0.7 |
| Cc+Bc | 2.6 | 2.3 | 2.5 | 3.4 | 1.9 | 2.8 | 1.1 | 1.5 | 2.2 | 1.2 | -2.0 | 9.2 |
| X | 3.5 | 3.8 | 4.4 | 2.8 | 1.9 | 3.1 | 3.1 | 2.8 | 5.7 | 0.8 | 9.6 | 2.1 |
| Average | 3.5 | 3.1 | 3.9 | 4.2 | 2.2 | 2.4 | 2.9 | 2.2 | 4.0 | 3.8 | 4.1 | 4.9 |
| Montane stations | | | | | | | | | | | | |
| N+NEa | 2.9 | 1.6 | 3.1 | 2.4 | 2.1 | 1.9 | 3.7 | 1.7 | 4.7 | 1.4 | 4.3 | 3.6 |
| N+NEc | 1.5 | 0.1 | 2.8 | -0.1 | 4.0 | -1.1 | 2.0 | 1.3 | 1.6 | -7.6 | 0.7 | -0.7 |
| E+Sea | 1.3 | 1.4 | 0.2 | -0.9 | 0.9 | 0.3 | -0.2 | 0.0 | 7.1 | -3.8 | -1.3 | 5.4 |
| E+Sec | -0.4 | -0.7 | -1.7 | -1.4 | -0.4 | -0.7 | -2.2 | -0.8 | 2.2 | 4.8 | -1.5 | 7.9 |
| S+Swa | 2.3 | 0.7 | 3.8 | 7.2 | -1.5 | 0.0 | -0.1 | 0.5 | 11.7 | 7.6 | 19.1 | 14.6 |
| S+SWc | 3.5 | 0.1 | 4.4 | 12.8 | 1.7 | 0.4 | 0.6 | 0.1 | 21.2 | 11.3 | 16.5 | 12.1 |
| W+NWa | 7.1 | 2.8 | 6.6 | 9.6 | 1.3 | 2.2 | 2.0 | 2.3 | 10.8 | 15.6 | 10.8 | 3.3 |
| W+NWc | 7.8 | 2.9 | 8.5 | 12.0 | 0.1 | 0.2 | 1.1 | 8.0 | 7.3 | 4.3 | 1.6 | 8.9 |
| Ca+Ka | 3.1 | 1.9 | 1.8 | 3.3 | 1.2 | -0.2 | -2.7 | 1.1 | 15.4 | 8.9 | 7.7 | 9.4 |
| Cc+Bc | 2.8 | 0.0 | 2.6 | 7.1 | 1.9 | -0.6 | 1.3 | -3.1 | 20.5 | 5.2 | 13.1 | 8.6 |
| X | 3.5 | 1.4 | 0.9 | 4.4 | 1.2 | -1.0 | 0.6 | -0.3 | 14.5 | 12.7 | 16.3 | 3.1 |
| Average | 3.2 | 1.1 | 3.0 | 5.1 | 1.1 | 0.1 | 0.5 | 1.0 | 10.6 | 5.5 | 7.9 | 6.9 |

*Source: produced by author*

stations in all seasons and they are greatest during S+SW and W+NW circulation. In the case of thermoneutral days, there are significant seasonal differences. In the summer months, average dTN indicate that on the southward slopes there are less TN days than on the northward ones (of -10.6% at the Coline and -1.4% at the Montane stations). However, during the rest of the year there are more TN days on the southward than on the northward slopes, especially during N+NW (Montane stations) and E+SE/N+NE (Coline stations) circulation (Table 7).

## Discussion

A mountain climate has several specific features. First of all, it is characterised by vertical zonations of essential meteorological elements as reported by Hess (1965) and Rubel et al. (2017). According to the increase of altitude, global solar radiation and insolation rise gradually (Baranowski 2003; Żmudzka & Kulesza 2019). This is caused by two main factors: reduction of the optical mas of the atmoshere at elevated sites, and specific cloud conditions. Very often peaks of mountains are above the clouds covering valleys.

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*Table 6. Differences in annual frequency of cold stress (dCS), thermoneutral (dTN) and heat stress days (dHS) between Southward and Northward stations*

| Air circulation type | dCS | | dTN | | dHS | |
|---|---|---|---|---|---|---|
| | Coline | Montane | Coline | Montane | Coline | Montane |
| N+NEa | -5.9 | -3.7 | 2.6 | 7.1 | 1.4 | . |
| N+NEc | -7.9 | -2.5 | 7.3 | 2.7 | 0.2 | . |
| E+SEa | -6.0 | 1.3 | 0.8 | 0.9 | 3.6 | 0.0 |
| E+SEc | -5.4 | 1.6 | 5.6 | -2.1 | 4.7 | -0.1 |
| S+SWa | -4.5 | -10.0 | 0.9 | 1.0 | 4.1 | 0.3 |
| S+SWc | -4.6 | -18.1 | 1.2 | 1.8 | 2.7 | 0.4 |
| W+NWa | -7.1 | -15.0 | 1.5 | 9.1 | 0.9 | 0.0 |
| W+NWc | -5.4 | -18.7 | 1.7 | 6.5 | 0.9 | 0.0 |
| Ca+Ka | -3.2 | -3.8 | -3.0 | 3.7 | 4.7 | 0.0 |
| Cc+Bc | -1.7 | -6.9 | -0.9 | 0.5 | 4.4 | 0.0 |
| X | -2.4 | -7.4 | -0.1 | -0.6 | 3.2 | . |
| average | -4.9 | -7.5 | 1.6 | 2.8 | 2.8 | 0.1 |

*Source: Produced by author*

The second feature of a mountain climate is decreasing air temperature due to increase in elevation (Trepińska 2002; Migała 2005; Smith 2015; Błażejczyk 2019), and this has a strong impact on sensible climate conditions. Many authors report a gradual orographical decrease in values of thermal sensation indices and other bioclimatic indicators in different mountain regions around Europe (Zaninović et al 2006; Endler et al. 2010; Bokwa et al. 2019).

The sensible climate is formed by several meteorological factors such as solar radiation, air temperature, air humidity and wind (Jendritzky & de Dear 2008). In mountain areas, a significant increase in wind speed has been observed in comparison to sub-mountain valleys (Baranowski 1999; Osadchyi et al. 2015; Błażejczyk 2019). Increased frequency of cold stress observed on mountain ridges (Błażejczyk et al. 2020) is caused by both low air temperature and high wind speed as reported for the Tatras by Błażejczyk et al. (2013) and for Chornohora by Błażejczyk & Skrynyk (2019).

Air circulation plays an important role in creation of climatic and bioclimatic conditions. The Carpathians are a barrier for air masses. This significantly modifies the air temperature. In the northern Carpathians, the southward slopes are warmer than the northward ones (Hess 1965). In the Eastern and Southern Carpathians, there are thermal differences, which change according to season between the westward and eastward slopes (Cheval et al. 2014; Spinoni et al. 2014). Bioclimatic differences between the northward and southward slopes were reported by Błażejczyk et al. (2020).

In this research air circulation was found to have a significant impact on thermal stress in the northern Carpathians. Research of this kind has not been conducted frequently. However, in research conducted by Nowosad et al. (2013) and Owczarek et al. (2019) significant differences were reported in bioclimatic indices in particular air circulation types.

## Conclusions

1) In general, the highest UTCI values (9.1°C) are observed at Ca+Ka circulation types. A slightly lower UTCI (>7°C) is also noted at S+SWa and Cc+Bc types. However, the lowest values are related to N+NEc (-1.6°C) and W+NWc (-0.8°C) circulation.

2) In the Southward Coline stations, UTCI means are of 3.6°C higher than in the Northward Coline stations. In the Montane stations, such differences are slightly lower (3.2°C). The greatest differences occur at advection from W+NWc, W+NWa and S+SWc (6–8°C at the Montane stations) and E+SEc, E+SEa and N+NEc (4–6°C at the Coline stations).

3) In the western part of the Northward stations, the highest occurrence of heat stress days (4.1–9.3%) is related to S+SWa. However, in the eastern part of the northern Carparthians, HS days are most frequent (7.5–12.1%) during Cc+Bc circulation.

4) Thermoneutral and heat stress days are more frequent on the southward slopes in comparison to the Northward stations. The greatest differences in TN days occur during N+NE (a and c), E+SEc, and W+NW (a and c) circulation. For HS days, the greatest thermal privilege of the southward slopes is observed at E+SE (a, c), S+SWa, Ca+Ka and Cc+Bc types of circulation.

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*Table 7. Differences in seasonal frequency of cold stress (dCS), thermoneutral (dTN) and heat stress days (dHS) between Southward and Northward stations*

| Air circulation type | dCS | | | | dTN | | | | dHS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAM | JJA | SON | DJF | MAM | JJA | SON | DJF | MAM | JJA | SON | DJF |
| Coline stations | | | | | | | | | | | | |
| N+NEa | -5.9 | . | -5.6 | -17.9 | 9.8 | -5.6 | 6.5 | -0.2 | . | 3.9 | 0.5 | . |
| N+NEc | -7.9 | . | -9.8 | -25.1 | 10.2 | 5.4 | 13.1 | 0.2 | 0.6 | -0.1 | . | . |
| E+Sea | -6.0 | . | -3.8 | -15.9 | 5.3 | -16.5 | 4.4 | 3.7 | 0.4 | 19.0 | 0.7 | . |
| E+Sec | -5.4 | . | -2.4 | -17.3 | 9.8 | -12.2 | 18.9 | 4.8 | 2.8 | 15.7 | 0.7 | . |
| S+Swa | -4.5 | . | -1.8 | -13.8 | -1.1 | -11.6 | 4.5 | 4.3 | 1.4 | 22.0 | 0.4 | . |
| S+SWc | -4.6 | . | -2.5 | -11.8 | 7.0 | -11.7 | 5.9 | -1.6 | 0.6 | 15.5 | 0.3 | . |
| W+NWa | -7.1 | . | -3.7 | -14.6 | 10.9 | -11.2 | 10.6 | -1.5 | . | 3.9 | 0.0 | . |
| W+NWc | -5.4 | . | -2.8 | -13.3 | 8.4 | -4.5 | 6.5 | -1.5 | . | 3.5 | 0.1 | . |
| Ca+Ka | -3.2 | . | -1.3 | -10.5 | 1.6 | -17.8 | 4.5 | 4.3 | 0.9 | 14.1 | 0.7 | . |
| Cc+Bc | -1.7 | . | -0.4 | -8.2 | 4.1 | -10.3 | 6.6 | 0.7 | 0.7 | 11.9 | 0.9 | . |
| X | -2.4 | . | -1.5 | -8.1 | 4.8 | -19.1 | 9.5 | 3.0 | 0.7 | 13.1 | . | . |
| Average | -4.9 | . | -3.2 | -14.2 | 6.5 | -10.5 | 8.3 | 1.5 | 1.0 | 11.1 | 0.5 | . |
| Montane stations | | | | | | | | | | | | |
| N+NEa | -5.1 | 0.4 | -1.5 | -11.2 | 12.0 | 4.3 | 9.4 | . | . | . | . | . |
| N+NEc | -2.6 | . | -2.7 | 0.5 | 3.0 | 5.4 | 1.7 | -1.2 | . | . | . | . |
| E+Sea | -2.3 | -0.3 | 2.0 | 1.8 | 8.7 | -9.0 | 0.3 | 0.0 | . | 0.3 | . | . |
| E+Sec | -3.1 | 0.9 | 0.1 | 1.7 | 0.0 | -4.5 | -1.8 | -0.5 | . | -0.5 | . | . |
| S+Swa | -14.0 | . | -5.9 | -26.1 | 2.1 | -15.3 | 7.9 | 0.2 | . | 1.7 | . | . |
| S+SWc | -20.8 | -0.3 | -12.8 | -43.5 | 4.6 | -7.8 | 5.6 | 1.1 | . | 2.3 | . | . |
| W+NWa | -15.9 | -0.3 | -13.6 | -24.8 | 14.9 | 10.0 | 12.7 | 3.5 | . | 0.1 | . | . |
| W+NWc | -19.6 | -1.3 | -22.4 | -29.7 | 6.9 | 11.5 | 7.6 | 0.4 | . | 0.1 | . | . |
| Ca+Ka | -8.5 | -0.4 | -1.8 | -10.8 | 11.1 | -1.4 | 4.4 | 1.4 | . | 0.1 | . | . |
| Cc+Bc | -11.3 | 0.3 | -6.8 | -26.0 | 3.5 | -2.8 | 2.2 | -1.0 | . | 0.1 | . | . |
| X | -10.6 | -1.2 | -3.2 | -15.0 | 5.9 | -5.1 | -5.1 | -0.2 | . | . | . | . |
| Average | -10.3 | -0.2 | -6.2 | -16.7 | 6.6 | -1.4 | 4.1 | 0.4 | . | 0.5 | . | . |

*Source: produced by author*

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