Geographia Polonica
2015, Volume 88, Issue 3, pp. 439-453
http://dx.doi.org/10.7163/GPol.0027

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

REGIONAL FEATURES OF THE BIOCLIMATE OF CENTRAL AND SOUTHERN EUROPE AGAINST THE BACKGROUND OF THE KÖPPEN-GEIGER CLIMATE CLASSIFICATION

Krzysztof Błażejczyk[1] • **Jarosław Baranowski**[2] • **Gerd Jendritzky**[3]
Anna Błażejczyk[4] • **Peter Bröde**[5] • **Dusan Fiala**[6]

[1] University of Warsaw
Faculty of Geography and Regional Studies
Krakowskie Przedmieście 30, 00-927 Warsaw: Poland
e-mail: kblazejczyk@uw.edu.pl

[2] Institute of Geography and Spatial Organization
Polish Academy of Sciences
Twarda 51/55, 00-818 Warsaw: Poland
e-mail: j.bar@twarda.pan.pl

[3] University of Freiburg
Chair of Meteorology and Climatology
Werthmannstraße 10, 79085 Freiburg: Germany
e-mail: gerd.jendritzky@meteo.uni-freiburg.de

[4] Laboratory of Bioclimatology and Environmental Ergonomics
Łukowska 17/55, 04-133 Warsaw: Poland
e-mail: pracownia@bioklimatologia.pl

[5] Leibniz Research Centre for the Working Environment and Human Factors
Ardeystr. 67, 44139 Dortmund: Germany
e-mail: broede@ifado.de

[6] ErgonSim – Comfort Energy Efficiency
Holderbuschweg 47, 70563 Stuttgart: Germany
e-mail: info@ergonsim.de

Abstract

This paper presents an application of the Universal Thermal Climate Index UTCI to studies of regional variability in human-biometeorological conditions. The variability in question was assessed by reference to selected meteorological stations representing Central and Southern Europe, i.e. Kołobrzeg, Warsaw and Świeradów (in Poland), Prague, Budapest, Ljubljana, Milan, Rome and Athens, with the bioclimatic features characterising these localities being presented against the background of the Köppen-Geiger climate classification. In line with that classification, the first five stations are found to represent the cold climate zones (Dfb, Dfc). The last four stations are in turn located in the temperate climate zones (Cfa, Cfb, Csa). Seasonal changes in UTCI values and the frequency of occurrence of UTCI categories are discussed. Significant regional differences in bioclimatic characteristics were found between the stations representing various types of climate. While the highest summer values for UTCI are very similar at all stations (39-42°C), the frequency of occurrence of days with at least strong heat stress (SHS) varied from 2% at the coastal station of Kołobrzeg in Poland to more than 50% at the Milan, Rome and Athens stations. In winter the lowest UTCI values are much differentiated regionally, from -54°C at the mountain station in Świeradów, Poland, to -22°C in Rome. In the zone of cold climate, the frequency of occurrence of days with at least strong cold stress (SCS) is >40%, while in the temperate climates, strong cold stress is characteristic of less than 2% of winter days.

Key words

human bioclimate • Universal Thermal Climate Index • Köppen-Geiger climate classification • seasonal and regional variability of bioclimate

Introduction

In the last century more than one hundred indices were developed to assess bioclimatic conditions for human beings (Parsons 2003; Epstein & Moran 2006; Błażejczyk et al. 2012). Some of these are based on generalised results of measurements (e.g. of wind chill, cooling power, wet-bulb temperature), while others relate to empirically observed reactions of the human body to thermal stress (e.g. physiological strain effective temperature).

Contemporary bioclimatic research is based on study of the direct relationships between the atmosphere and the human organism. It considers both conditions for heat exchange with the atmosphere (stress) and the physiological response in human beings (strain). The balancing of the human heat budget, i.e. the equilibration of the thermal state of an organism, is controlled by a very efficient autonomous thermoregulatory system (Havenith 2001; IUPS 2003). It is crucial for human beings that body core temperature be kept within a narrow range around 37°C. In contrast, the temperature of the skin and extremities can vary widely, depending on environmental conditions. Variation in skin temperature is one of the mechanisms keeping heat production and heat loss in equilibrium over a longer period, this leading to a reduction in changes in the heat content of the body to zero (Hensel 1981; Clark & Edholm 1985).

First attempts at modelling the human heat balance go back to the end of the 1960s. Almost every such model proposes a specific index of thermal comfort or thermal sensations. These include the Outdoor Standard Effective Temperature and SET index (Gagge et al. 1986; Pickup & de Dear 2000), the Munich Energy Balance Model of Individuals and the PET (Physiologically Equivalent Temperature) index (Höppe 1984), the Man-Environmental Heat Exchange Model and PST (Physiological Subjective Temperature), as well as STI (the Subjective Temperature Index) (Błażejczyk 1994), the Klima-Michel-Model and the PT (Perceived Temperature) index (Jendritzky 1990). In the past two decades multi-node models of human thermoregulation have been developed (Fiala et al. 1999, 2001; Huizenga et al. 2001; Tanabe et al. 2002). These models simulate heat-transport phenomena within the human body and at its surface, taking into account the anatomical, thermal and physiological properties of the human body, as well as physical features of clothing. One measure of heat stress caused by meteorological conditions is the Universal Thermal Climate Index (UTCI) derived from the multi-node dynamic UTCI-Fiala model of human temperature regulation and thermal comfort (Fiala et al. 2012).

The majority of bioclimatic indices have been used more or less frequently for specific purposes, and for particular regions or seasons. One of the first widely-used indices was Effective Temperature (ET), as proposed by Missenard (1933). This was applied in East Germany, Poland and the Soviet Union, etc. Thus, for example, Błażejczyk et al. (1994) and Kozłowska-Szczęsna et al. (2004) used it to validate the bioclimate at different Polish health resorts. They found, not only significant seasonal variability to bioclimate, but also spatial differentiation found to depend on air-mass circulation and local features of the environment. In Hong Kong, Li and Chan (2000) applied Missenard's approach to the forecasting of heat and cold stress risk.

Recent bioclimatic studies have made frequent use of indices derived from human heat balance considerations. As mentioned by Staiger et al. (1997, 2012), Perceived Temperature (PT) is used by the German Weather Service as an indicator of bioclimatic conditions (Jendritzky et al. 2011). The index has also served as a basis for climate-related mortality studies (Laschewski & Jendritzky 2002), and for the bioclimatic mapping of Germany (Jendritzky 1990). The maps present the frequency of occurrence of particular categories of thermal sensation.

Great differences between seasons are reported when using Physiologically Equivalent Temperature (PET) (Mayer & Höppe 1987; Matzarakis et al. 1999). PET has been used to assess bioclimatic conditions in many countries and regions (e.g. Matzarakis & Mayer 1991; Gulyás & Matzarakis 2009; Matzarakis et al. 2012). At all the sites studied the authors found a risk of heat stress in the summer and/or a risk of cold stress in the winter season.

The Subjective Temperature Index (STI) was used by Błażejczyk (2006) to evaluate seasonal and spatial variability to the bioclimatic conditions in Poland. The work revealed significant regional differences in STI (a relatively mild bioclimate at the Baltic Sea coast, but severe features of bioclimate in north-eastern Poland and in mountain regions). Błażejczyk and Matzarakis (2007) in turn assessed the bioclimatic features of Poland using Physiological Subjective Temperature (PST) and Physiologically Equivalent Temperature (PET) indices. They have detected similar spatial features of bioclimate like those obtained using STI.

UTCI has also been applied in presenting seasonal and spatial differentiation to bioclimatic conditions. Nemeth (2011) studied multiannual variation in UTCI and PET at four Hungarian stations. Nowosad et al. (2013) in turn studied the influence of atmospheric circulation types on UTCI features in two Polish cities, Lublin and Lesko; while Lindner-Cendrowska (2013) and Bröde et al. (2013) used UTCI to assess the bioclimatic conditions of urbanised areas of Warsaw, Madrid, Stockholm and Curitiba. Thus far only a few studies have compared bioclimatic conditions over a wide, regional scale, the work making use of PET (Matzarakis et al. 2007), PT (Jendritzky & Tinz 2009) or UTCI (Błażejczyk et al. 2010; Błażejczyk & Kunert 2010; Idzikowska 2010).

Several classifications have been developed to present the differentiation in global climate. These use various indicators of climate (e.g. air temperature, precipitation, circulation type, vegetation, etc.). Contemporary climate research makes most frequent use of the Köppen-Geiger classification after Köppen (1884) – e.g. in Kottek et al. 2006, Peel et al. 2007, Jylha et al. 2010. This classification produces a quite effective description of the global variability to climate on the basis of thermal and humidity regimes. However, the classification does not offer any characterisation of the human bioclimate, which should therefore be added to the descriptions of climate types. In line with the global nature of the Köppen-Geiger classification, the bioclimatic index should also be valid for all climates around the world – a requirement that is met by the newly-developed Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012).

The aim of the research described here was thus to analyse the principal features of bioclimate in Central and Southern Europe, and to validate those characteristics proving most valuable in bioclimatic indication of the Köppen-Geiger types of climate. To this end, seasonal and regional features of UTCI at selected meteorological stations have been discussed and evaluated with a view to a bioclimatic characterisation of selected types of climate being arrived at.

Materials and Methods

Study areas and data

Meteorological data from the period 1991-2000 were used to study seasonal and regional differentiation to the bioclimatic conditions characterising selected stations in Central and Southern Europe (while the paper presents the first attempt at using UTCI in regional research for validation purposes, the authors have decided to apply available data for a 10-year period, which is accepted by the WMO as the shortest period which can be taken into account by climatic research). Daily data on air temperature, water vapour pressure, wind speed and total cloud cover at midday (12:00 UTC) were used to calculate daily UTCI values. Data for a midday time of observation were used, since this represents the time of the day at which people are most active, with the outdoor climate most influencing the human organism. In bioclimatic research 12:00 UTC is the reference observation time.

The region studied is represented by nine stations: Kołobrzeg, Warsaw, Świeradów, Prague, Budapest, Milan, Ljubljana, Rome and

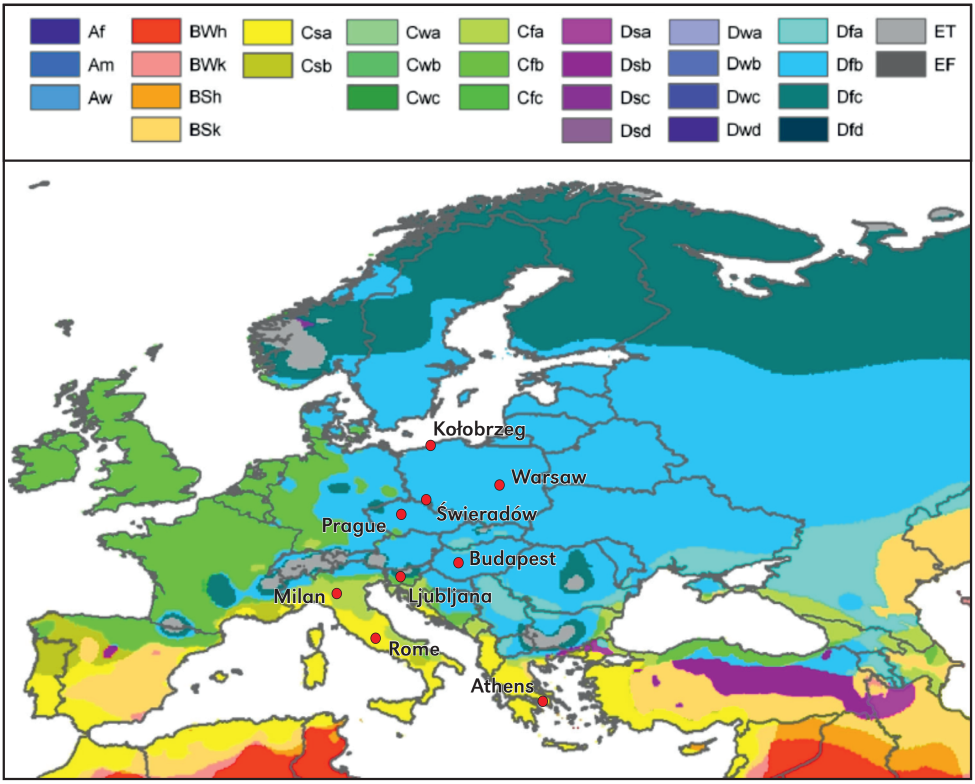


Figure 1. Meteorological stations selected for the research: groups of climate according to the Köppen-Geiger classification: A – tropical, B – arid, C – temperate, D – cold (boreal), E – polar

Source: Peel et al. 2007

Athens (Fig. 1). While the most of the stations meet WMO requirements as regards an airport location, some represent different topographic units: mountain slopes (in the case of Świeradów), the coast (Kołobrzeg) or a wide and deep mountain basin (Ljubljana).

Within different contemporary modifications of the Köppen-Geiger classification, the adaptation proposed by Peel et al. (2007) was taken as a background to the work presented here. The meteorological stations selected represent two groups of climate: cold and temperate. However, secondary features of climate differ from site to site (Tab. 1).

Table 1. Climate features of the stations selected in terms of the Köppen-Geiger climate classification

Station	Symbol of climate	General climate features	Location of station
Cold forest (boreal) climates (T_{hot}>10°C & T_{cold}<0°C) with severe winters and humid (without dry season)			
Kołobrzeg	Dfb	warm summer (up to 4 months with temperature >10°C)	Baltic Sea Coast
Warsaw	Dfb		Central European Lowland
Prague	Dfb		Bohemian Upland
Budapest	Dfb		Pannonian Basin
Świeradów	Dfc	mountainous (short, cool summer)	Sudety Mountains
Temperate rainy climates (T_{hot}>10°C & T_{cold} 0-18°C) with mild winters			
Milan	Cfa	without dry season, long, hot summer (T_{hot}>22°C)	Po valley
Ljubljana	Cfb	without dry season, warm summer (more than 4 months with temperature >10°C)	Ljubljana Basin
Rome	Csa	dry (Ps_{dry}<40 mm) and long, hot (T_{hot}>22°C) summer	Tiber valley
Athens			Attica Basin

T_{hot} – average temperature of the hottest month, T_{cold} – average temperature of the coldest month, Ps_{dry} – precipitation totals for the driest month

Source: Peel et al. 2007

UTCI as an indicator of bioclimate variability

The Universal Thermal Climate Index (UTCI) is derived from the UTCI-Fiala model, in which the human organism is separated into two interacting systems of thermoregulation: the controlling active system, and the controlled passive system. The latter is a multi-segmental, multi-layered representation of the human body with information on anatomical and physiological body properties. The model represents an average person of body weight 73.5 kg, body fat content 14% and Dubois area of 1.86 m^2. Body elements are subdivided into 12 spatial sectors and 187 individual tissue nodes. In turn, the active system predicts the thermo-regulatory reactions of the central nervous system: suppression and elevation of the cutaneous blood flow, shivering thermogenesis and sweat secretion (Fiala et al. 2012).

The UTCI is defined as the air temperature of the reference condition causing the same model response (in terms of sweat production, shivering, skin wettedness and skin blood flow, as well as in rectal, facial and mean skin temperatures) as the actual conditions (Błażejczyk et al. 2010; Bröde et al. 2012; Psikuta et al. 2012). The model response is indicative of the physiological and thermoregulatory processes significant as regards a human being's reaction to neutral, moderate and extreme thermal conditions.

The UTCI can be calculated in two different ways: on the basis of the resolution of Fiala's heat balance model or by reference to a regression model. As the direct application of Fiala's multi-node model is time-consuming, an approximating regression function has been found (Bröde et al. 2012). The offsets of UTCI to Ta (UTCI – Ta) can be approximated using a polynomial function in air temperature (Ta), vapour pressure (vp), wind speed (vp), and Tmrt – Ta, i.e. the difference between mean radiant temperature and air temperature, including all the main effects and interaction terms up to the 6th order. The root mean-squared error of approximation is 1.1°C, while 50% of all observed errors are within ±0.6°C, 80% within ±1.3°C and 90% within ±1.9°C (Bröde et al. 2012). The research described here applied the statistical model of UTCI referred to, the index being calculated using the *BioKlima 2.6* software package (available at http://www.igipz.pan.pl/Bioklima-zgik.html).

While standard meteorological variables were taken directly from observations, the mean radiant temperature was calculated using:

$$Mrt=[(R'+0.5\cdot Lg+0.5\cdot La) / (0.95\cdot 5.667\cdot 10^{-8})]^{0.25}-273$$

where:

$Lg=5.5\cdot 10^{-8}\cdot(273+Tg)^4$

$La=5.5\cdot 10^{-8}\cdot(273+Ta)^4\cdot[0.82-0.25\cdot 10^{(-0.094\cdot 0.75\cdot vp)}]$

Tg is the temperature of the ground surface, approximated as follows:

for cloudiness ≥80% – $Tg=Ta$
for cloudiness <80% and $Ta\geq 0°C$ – $Tg=1.25\cdot Ta$
for cloudiness <80% and $Ta<0°C$ – $Tg=0.9\cdot Ta$

R' is the solar radiation absorbed by the outer layer of clothing in a standing man. It was calculated using the statistical SolAlt model developed on the base of experimental research carried out in various geographical zones, from tropical to sub-polar (Błażejczyk 2004, 2005; Błażejczyk & Matzarakis 2007). The model assesses R' on the basis of information concerning total cloud cover, elevation of the sun and albedo of clothing.

In contrast to other bioclimatic indices (SET, PT, PET, PST and others), the UTCI values are categorised in terms of thermal stress based on the physiological response (strain) rather than on thermal sensations or thermal comfort. The approach uses responses in the reference conditions and deducts load (i.e. heat or cold stress) caused by the physiological response of an organism under actual environmental conditions. Table 2 presents the labelled stress categories and corresponding physiological responses (after Bröde et al. 2012).

Bioclimatic characteristics

The daily values for UTCI were calculated for each day of the studied period (for 12:00 UTC). For the purposes of statistical analysis the year was divided into 10-day periods of each month, i.e. 1-10 Jan, 11-20 Jan, 21-31 Jan, 1-10 Feb … 21-29 Feb … 1-10 Apr … 21-30 Apr, etc. For each 10-day period, mean, highest ($UTCI_{max}$) and lowest ($UTCI_{min}$) registered values of UTCI were calculated. 10-day periods for UTCI were applied to determine the duration of periods with the risk of at least strong heat stress (SHS, UTCI>32°C) and strong cold stress (SCS, UTCI<-13°C). Mean monthly and yearly UTCI values were also calculated, along with the amplitude of the index (dUTCI, i.e. the difference between the highest and lowest UTCI in the studied period). The frequencies of occurrence of particular categories of UTCI were the next measures of bioclimatic conditions.

Statistical analysis involved one-way ANOVA, significance of differences between compared stations being verified by t-Student test applying the *STATISTICA 10* software package.

Results

As expected, UTCI values were differentiated seasonally and regionally. At northern locations (in zones of cold climate), the average UTCI values are significantly lower than in the southern part of the studied region (with temperate climates). In summer, values for $UTCI_{max}$ are very similar at all locations, fall within the 'very strong heat stress' category. However, values for $UTCI_{min}$ are differentiated markedly across the studied area.

Table 2. UTCI equivalent temperature categorized in terms of thermal stress.

UTCI (°C) range	Stress category	Physiological responses
above 46.0	extreme heat stress	Increase in rectal temperature (*Tre*) time gradient. Steep decrease in total net heat loss. Averaged sweat rate >650 g/h, steep increase.
38.1 to 46.0	very strong heat stress	Core to skin temperature gradient <1K (at 30 min). Increase in *Tre* at 30 min.
32.1 to 38.0	strong heat stress	Dynamic Thermal Sensation (DTS) at 120 min >2. Averaged sweat rate >200 g/h. Increase in *Tre*. Instantaneous change in skin temperature >0 K/min.
26.1 to 32.0	moderate heat stress	Moderate increase in sweat rate, *Tre* and skin temperature: mean (*Tskm*), face (*Tskfc*), hand (*Tskhn*). Occurrence of sweating. Steep increase in skin wettedness.
9.1 to 26.0	no thermal stress	DTS between -0.5 and +0.5 (averaged value). Latent heat loss >40 W. Plateau in *Tre* time gradient.
0.1 to 9.0	slight cold stress	DTS <-1. Local minimum of *Tskhn* (use gloves).
-13.0 to 0.0	moderate cold stress	DTS <-2. Vasoconstriction. Averaged *Tskfc* <15°C (pain). Decrease in *Tskhn*. *Tre* time gradient <0 K/h. Face skin temperature <15°C (pain). *Tmsk* time gradient <-1 K/h.
-27.0 to -13.1	strong cold stress	Averaged *Tskfc* <7°C (numbness). *Tre* time gradient <-0.1 K/h. Increase in core-to-skin temperature gradient.
-40.0 to -27.1	very strong cold stress	*Tskfc* <0°C (frostbite). Steeper decrease in *Tre*. *Tskfc* <7°C (numbness). Occurrence of shivering. *Tre* time gradient <-0.2 K/h.
<-40.0	extreme cold stress	*Tre* time gradient <-0.3 K/h. *Tskfc* <0°C (frostbite).

Source: adapted from Błażejczyk et al. 2010 and Bröde et al. 2012

Their lowest values were noted in Świeradów and Warsaw. In Świeradów this was a reflection of a location in a mountain valley where inversions of temperature are typical. In Warsaw, low UTCI values are the result of advections of cold polar continental or arctic air (Błażejczyk 2006). Topographic modification of UTCI$_{min}$ is also seen in Kołobrzeg and Ljubljana. Notwithstanding its most northerly location, Kołobrzeg has a coastal position that provides for warming of the air in winter, and consequently a relatively high UTCI$_{min}$. However, in Ljubljana, located at a similar latitude to Milan but in the bottom of a mountain basin, UTCI$_{min}$ is lower by 10°C. The highest UTCI$_{min}$ values are in turn noted in Rome (Tab. 3).

While UTCI is strongly differentiated seasonally its annual amplitude (dUTCI) was also seen to vary regionally. Differences in dUTCI at the stations located on flat areas changed from about 62°C in Milan (in the zone of temperate climate) to 93°C in Warsaw (zone of cold climate). A similar geographical trend is to be noted for stations situated in valleys and basins: in Ljubljana (the temperate climate zone) dUTCI is 73°C and in Świeradów (cold climate zone) is 93°C (Tab. 3).

When analysing the annual course of UTCI$_{max}$ values, we found similar seasonal patterns for all stations. In winter months the values for UTCI$_{max}$ varied from about 5 to 10°C at the coastal station in Kołobrzeg to about 10 to 15°C in other locations. In the

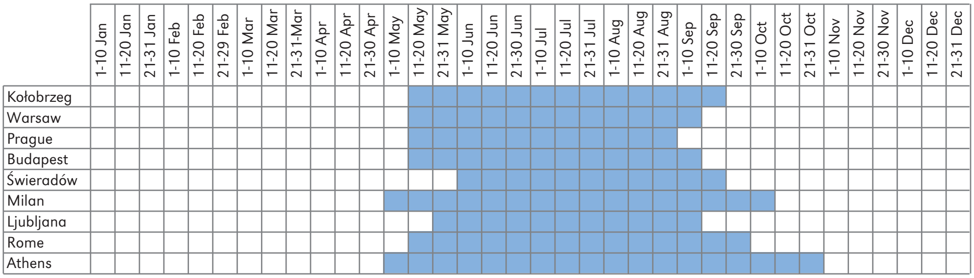
Table 3. Annual mean, highest registered (UTCI$_{max}$), lowest registered (UTCI$_{min}$) daily values and annual amplitudes (dUTCI) for UTCI in the studied cities, 1991-2000

UTCI (°C)	Kołobrzeg	Warsaw	Prague	Budapest	Świeradów	Milan	Ljubljana	Rome	Athens
Mean	5.7	4.2	6.0	12.4	6.6	18.9	13.8	18.9	19.9
UTCI$_{max}$	41.5	41.1	39.4	41.0	38.8	42.1	39.1	41.7	45.0
UTCI$_{min}$	-43.8	-51.9	-39.3	-31.0	-53.9	-24.2	-33.6	-21.9	-31.1
dUTCI	85.3	93.1	78.7	72.0	92.6	61.6	72.8	63.6	76.1

warm season (April to September) the regional variation in values for UTCI$_{max}$ is very small: the differences between the lowest and highest values are of 3 to 6°C (by contrast, in the cold season they reach 12°C). At all stations, the period in which values for UTCI$_{max}$ above 32°C occur is very similar. In most stations, the heat-stress period starts in the second 10-day period of May and lasts until the middle of September. Only in Athens does the period in question extend through to the end of October (Fig. 2).

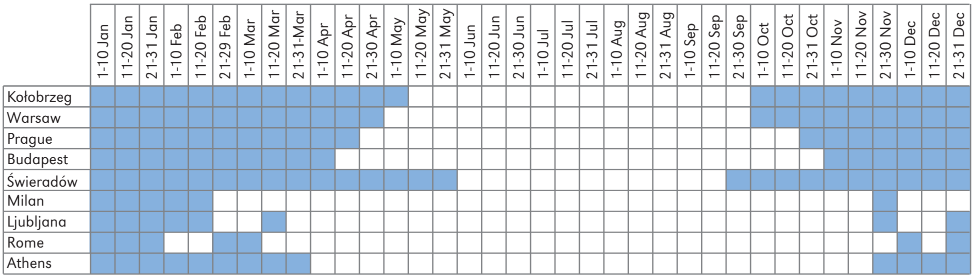
The lowest daily UTCI values vary markedly from station to station. In the summer months the regional variation in UTCI$_{min}$ is of 30 to 40°C (from -8°C in Świeradów to 30°C in Athens). However, in winter the range of UTCI$_{min}$ values reaches almost 50°C (from -54°C in Świeradów to -5°C in Rome). The period with UTCI$_{min}$ below -13°C is also much differentiated regionally. The period with strong cold stress risk varied from station to station. The longest (250 days) occurs at the mountain station Świeradów (Dfc climate type), from the last 10-day period in September through to the last such period in May, while the shortest (of just 50 days' duration) characterises Milan (the Cfa type of climate), extending from the beginning of January through to the end of February. For the stations representing the Dfb climate type the cold risk period extends over 210-220 days of the year in Warsaw and Kołobrzeg and for 160-180 days in Prague and Budapest. In Ljubljana (Cfb climate type), the cold risk period lasts 100 days and in Rome (Csa climate) for 70 days. The exception is Athens (Csa) where cold stress risk is relatively long-lasting (120-130 days a year, Fig. 3).

In bioclimatic research importance is attached to both the possible range of extremes and the frequency of occurrence of particular categories of the index. In all seasons, Milan (Cfa) as well as Rome and Athens (Csa), are the cities with the greatest frequency of strong and very strong heat stress. In spring, conditions of moderate and



	1-10 Jan	11-20 Jan	21-31 Jan	1-10 Feb	11-20 Feb	21-29 Feb	1-10 Mar	11-20 Mar	21-31-Mar	1-10 Apr	11-20 Apr	21-30 Apr	1-10 May	11-20 May	21-31 May	1-10 Jun	11-20 Jun	21-30 Jun	1-10 Jul	11-20 Jul	21-31 Jul	1-10 Aug	11-20 Aug	21-31 Aug	1-10 Sep	11-20 Sep	21-30 Sep	1-10 Oct	11-20 Oct	21-31 Oct	1-10 Nov	11-20 Nov	21-30 Nov	1-10 Dec	11-20 Dec	21-31 Dec
Kołobrzeg														■	■	■	■	■	■	■	■	■	■	■	■	■										
Warsaw														■	■	■	■	■	■	■	■	■	■	■	■											
Prague														■	■	■	■	■	■	■	■	■	■	■												
Budapest														■	■	■	■	■	■	■	■	■	■	■	■											
Świeradów																■	■	■	■	■	■	■	■	■	■	■										
Milan													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Ljubljana															■	■	■	■	■	■	■	■	■	■	■											
Rome														■	■	■	■	■	■	■	■	■	■	■	■	■	■									
Athens													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						

Figure 2. 10-day monthly periods (marked in blue) in which the occurrence of UTCI >32°C (days with at least strong heat stress) is possible, 1991-2000



	1-10 Jan	11-20 Jan	21-31 Jan	1-10 Feb	11-20 Feb	21-29 Feb	1-10 Mar	11-20 Mar	21-31-Mar	1-10 Apr	11-20 Apr	21-30 Apr	1-10 May	11-20 May	21-31 May	1-10 Jun	11-20 Jun	21-30 Jun	1-10 Jul	11-20 Jul	21-31 Jul	1-10 Aug	11-20 Aug	21-31 Aug	1-10 Sep	11-20 Sep	21-30 Sep	1-10 Oct	11-20 Oct	21-31 Oct	1-10 Nov	11-20 Nov	21-30 Nov	1-10 Dec	11-20 Dec	21-31 Dec
Kołobrzeg	■	■	■	■	■	■	■	■	■	■	■	■	■															■	■	■	■	■	■	■	■	■
Warsaw	■	■	■	■	■	■	■	■	■	■	■	■																■	■	■	■	■	■	■	■	■
Prague	■	■	■	■	■	■	■	■	■	■	■																			■	■	■	■	■	■	■
Budapest	■	■	■	■	■	■	■	■	■	■																					■	■	■	■	■	■
Świeradów	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												■	■	■	■	■	■	■	■	■	■
Milan	■	■	■	■	■																												■			
Ljubljana	■	■	■	■	■			■																									■			■
Rome	■	■	■			■	■																											■		■
Athens	■	■	■	■	■	■	■	■	■																								■	■	■	■

Figure 3. Monthly 10-day periods (marked in blue) in which the occurrence of UTCI <-13°C (days with at least strong cold stress) is possible, 1991-2000

strong heat stress arise in Milan, Rome and Athens on approximately 15-20% of all days. In other cities the corresponding frequency does not exceed 10%. By contrast, in autumn these categories of heat stress are present 25-50% of the time. While UTCI$_{max}$ values in summer are not differentiated spatially across the region studied, the frequencies of occurrence of particular heat-stress categories varies greatly. Again, it is in Milan and Rome that all categories of heat stress (moderate, strong and very strong) are present on more than 80% of all days. In Athens such conditions occur almost every day (97.5% of the time). They are also very frequent in Budapest and Ljubljana (on 50-60% of days). Such biothermal conditions are far less frequent in the coastal city of Kołobrzeg (occurring just 13% of the time). Winter is the season with the most differentiated UTCI frequency patterns. The optimal 'no thermal stress' UTCI category only arises very rarely in Warsaw, Prague and Kołobrzeg (Dfb). At the same time, very strong cold stress can occur on 2-5% of all winter days. Significantly milder biothermal conditions characterise Milan, Athens and Rome in which there is 'no thermal stress' present on some 40-55% of days (Fig. 4).

Significant regional differences in bioclimate are also well seen when mean monthly values for UTCI are analysed. At all stations,

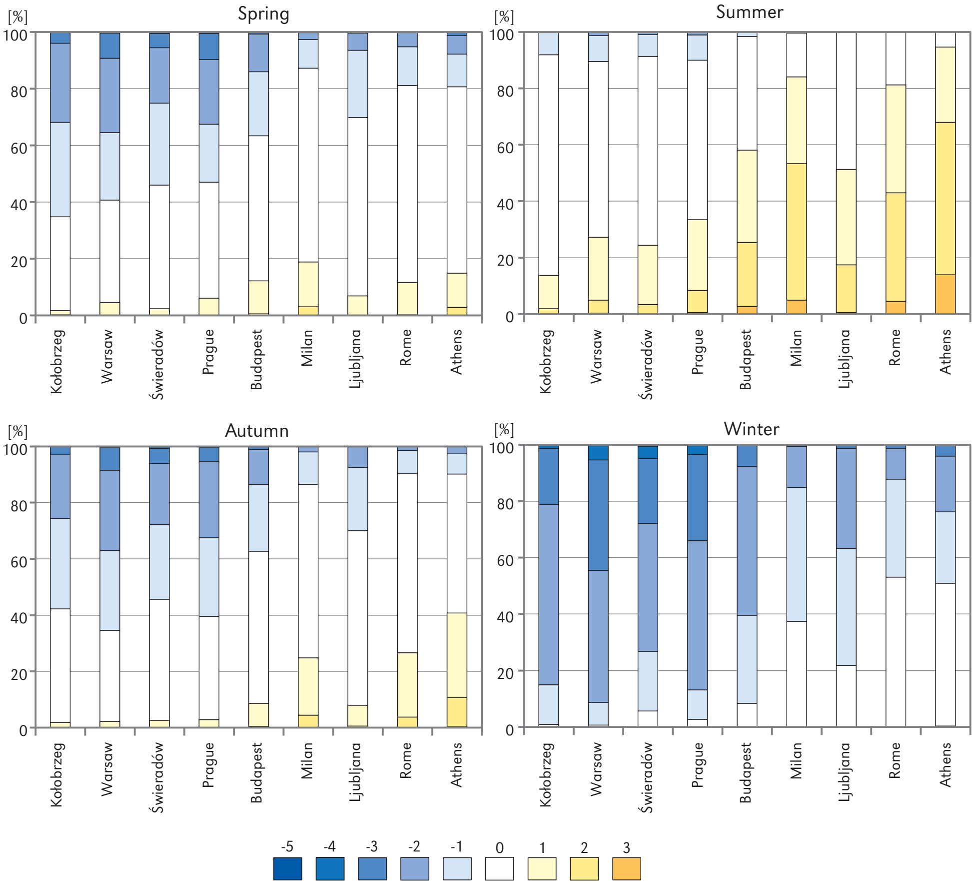


Figure 4. Frequency of occurrence of UTCI heat stress categories in different seasons in the studied cities; -5 to 4 – thermal stress categories (see Tab. 1)

August is the hottest month. In the group of cold climates (Dfb, Dfc) mean monthly UTCI is of 20-29°C. The highest August UTCI value was registered in Budapest (because of its latitude) and the lowest in Kołobrzeg (because of its location on the Baltic Sea coast). Relatively low UTCI means were also found in Warsaw (due to frequent advection of Arctic air masses) and in Świeradów (because of its mountain location). At the stations representing a temperate climate the mean UTCI values for the hottest month (August) were much higher than in the cold zone, reaching about 35°C in Athens. The exception is Ljubljana, located at the bottom of a deep mountain basin, where the mean UTCI for August is of only about 27°C.

January is usually the coldest month in the studied region. Again, stations representing the cold climate zone are characterised by significantly lower winter UTCI values than stations from the temperate zone. In the cold zones the lowest UTCI means are below zero (from -3 to -14°C), while in the temperate zone the index values are above zero (2-7°C) (Tab. 4).

In summary, the work described here provides a characterisation of the general features of bioclimate in relation to the considered Köppen-Geiger types of climate. As indicated below, the main types of climate differ in terms of the range of UTCI values in the coldest and hottest months. The frequencies of occurrence of extreme UTCI categories (strong heat stress and strong cold stress), as well as the numbers of days a year characterised by the risk of heat stress (SHS) or cold stress (SCS) also differ noticeably.

The bioclimate in the circumstances of the Dfb type of climate is characterised by UTCI mean (UTCI_{hot}) values in the hottest month of 20-25°C. The frequency of SHS days in the summer is <10%. In the coldest month, average UTCI (UTCI_{cold}) values are below zero. The frequency of occurrence of strong cold stress reaches 40% of all days in winter. The period of strong heat stress risk lasts 160-180 days a year, while the period of strong cold stress risk is of between 160 and 220 days' duration. In particular locations (mountain valleys, the coast, deep basins), some bioclimatic characteristics can differ slightly from those listed above. Along the coast of the Baltic Sea the frequency of occurrence of summer SHS is <2%, while in winter the frequency of occurrence of SCS is at about 20%. In the Pannonian Basin, in turn, in the hottest month has UTCI values reaching some 29°C, while the frequency of occurrence of SHS in summer is around 25%.

The bioclimate associated with the Dfc type of climate was studied observed in Poland's Sudety Mountains. In the hottest month the UTCI_{hot} value is of about 21°C. The frequency of occurrence of SHS in summer is <5%, while the period of heat stress risk lasts 100 days per year. In the coldest month, UTCI falls to -9°C (while the absolute UTCI_{min}

Table 4. Mean monthly values for UTCI at the studied stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kołobrzeg	-8.7	-5.7	-1.7	4.3	12.1	16.7	19.1	20.3	14.5	7.8	-2.5	-7.6
Warsaw	-13.7	-10.6	-4.2	4.7	15.0	18.2	20.6	21.3	13.0	4.8	-6.4	-11.8
Prague	-11.0	-7.6	-3.7	7.1	16.7	18.7	21.1	23.1	14.7	6.0	-3.5	-9.7
Budapest	-3.0	0.1	4.2	12.5	21.3	24.5	26.9	28.7	19.7	14.5	2.9	-3.6
Świeradów	-8.9	-4.3	-0.1	6.5	14.4	17.9	20.8	21.2	14.6	7.9	-3.0	-8.1
Milan	5.2	9.6	14.7	17.2	23.9	27.7	33.1	33.3	26.1	19.2	11.1	5.7
Ljubljana	1.6	4.9	8.2	12.7	19.7	23.5	26.6	27.2	21.0	14.4	5.8	0.5
Rome	7.9	10.0	12.2	13.7	22.6	27.4	31.3	33.1	26.4	20.7	13.3	8.6
Athens	7.2	7.6	9.4	16.3	23.1	31.1	34.9	35.3	29.2	22.4	13.4	8.5

is almost -54°C). The frequency of occurrence of SCS in the winter months increases to 28%, while the period of cold stress risk lasts 250 days a year.

In the Cfa climate zone (Milan) the hottest month has mean UTCI values reaching 30-35°C, with a summer frequency of occurrence of SHS equal to 53%. The period of heat stress risk lasts about 150 days a year. In the coldest month, UTCI is at ~5°C and the winter frequency of occurrence of SCS is <1%. The period of cold stress risk lasts approximately 50 days a year.

The bioclimate of a basin area within the Cfb climate zone in the hottest month is characterised by UTCI of 25-30°C, with a summer frequency of occurrence of SHS equal to about 20%. The period of heat stress risk lasts 100 days a year. In the coldest month, UTCI is at 0-1°C, while the winter frequency of occurrence of SCS is <2%. The period of cold stress risk lasts 50-60 days a year.

For the Csa climate zone the hottest month is characterised by mean UTCI of 30-35°C and a summer frequency of occurrence of SHS of approximately 50-70%. The period of heat stress risk lasts about 150 days a year. In the coldest month, UTCI is equal to 8-10°C, while the winter frequency of occurrence of SCS is 1-4%. The period of cold stress risk lasts 50 days a year on average.

Discussion

The general features to the seasonal cycle of human bioclimate presented in this paper as based on the UTCI are quite similar to the results obtained when using previous generations of thermal indices (e.g. Cegnar & Matzarakis 2004; Kozłowska-Szczęsna et al. 2004; Zaninovic & Matzarakis 2004; Nemeth 2011).

Similarities to the various indices can also be found in spatial distributions for the ET, PT, PET and UTCI indices. Jendritzky and Tinz (2009) have generated maps of PT characteristics (frequency of occurrence of particular PT categories) on the global scale, even with a view to predicting future bioclimate. They found differences in PT between areas in line with their longitude. Matzarakis et al. (2007) presented maps of monthly PET values for January and July over Europe. The visual analysis of maps shows regional differences between northern and southern parts of the continent. Błażejczyk et al. (2010) used UTCI to characterise bioclimatic features of winter and summer months in fifteen European cities representative of the whole continent. They found great summer-to-winter differences in heat and cold stress frequencies between southern and northern, as well as western and eastern, stations. The same stations were used by Błażejczyk and Kunert (2010). The authors have found statistically significant geographical gradients (both latitudinal and zonal) for UTCI values in Europe.

While the general features of the annual cycles of bioclimatic conditions are similar when either the previous generation of indices or UTCI are used, the greatest advantage of the latter is the way in which it indicates the actual physiological responses of an organism to climate stimuli in the most realistic way. UTCI can also explain why particular seasons and regions can be hazardous for human beings from the point of view of physiological responses to ambient stimuli. In Southern Europe the most hazardous period is July and August, when a high frequency of occurrence (>50%) of days with a strong or very strong heat stress risk is characteristic. In Central Europe, in turn, it is January and February that are most hazardous, thanks to the high (>40%) frequency of occurrence of days characterised by a strong or very strong cold stress risk.

Thus far no author has attempted to discuss how analysed bioclimatic indices match the Köppen-Geiger classification of climates. The results of the present study propose several features of bioclimate as supplementary information to the Köppen-Geiger classification. From the bioclimatic point of view the most important are:

1) Mean values of UTCI in the hottest and coldest months; for cold climates $UTCI_{hot}$

is 20-30°C and UTCI_{cold} <0°C, for temperate climates UTCI_{hot} is >30°C and UTCI_{cold} 0-10°C;

2) The frequency of occurrence of SHS days in the summer season and SCS days in the winter season; in particular climate zones SHS is characteristic 5-30% of the time in the case of Dfb, 5-10% for Dfc, 50-55% for Cfa, 20% for Cfb and 50-70% for Csa, however SCS varied from 10-40% for Dfb, 30% for Dfc, and less than 5% for the Cfa, Cfb and Csa climates);

3) The durations of the periods during which a risk of strong heat stress and strong cold stress may arise; the period of strong cold stress risk lasts 160-220 days a year in Dfb climates, 250 days in Dfc and about 50 days a year in the Cfa, Cfb and Csa climates; the period of strong heat stress risk in turn lasts 160-180 days a year in the case of Dfb climates, 100 days for Dfc and 100-150 days a year for the Cfa, Cfb and Csa climates.

Bioclimatic characteristics differ, not only on the main level of the Köppen-Geiger classification, but also within its secondary levels. It seems that bioclimatic conditions are shaped, not only by general features of climate considered in terms of the discussed classification, but also by regional and even local factors. The findings of the present research encourage the undertaking of further studies of bioclimatic features for a wider representation of climate regions, in order that the Köppen-Geiger classification may be further supplemented. In future research, data from stations representative of a wider spectrum of types of climate should be applied.

Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors' on the basis of their own research.

References

Błażejczyk K., 1994. *New climatological-and--physiological model of the human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales*. Zeszyty IGiPZ PAN, vol. 28, pp. 27-58.

Błażejczyk K., 2004. *Radiation balance in man in various meteorological and geographical conditions*. Geographia Polonica, vol. 77, no. 1, pp. 63-76.

Błażejczyk K., 2005. *Radiation balance of different segments of the human body*. DWD, Annalen der Meteorologie, vol. 41, no. 1, pp. 313-316.

Błażejczyk K., 2006. *Climate and bioclimate of Poland* [in:] M. Degórski (ed.), Natural and human environment of Poland. A geographical overview, Warsaw: Polish Academy of Sciences Institute of Geography and Spatial Organization, Polish Geographical Society, pp. 31-48.

Błażejczyk K., Bröde P., Fiala D., Havenith G., Holmér I., Jendritzky G., Kampmann B., Kunert A., 2010. *Principles of the new Universal Thermal Climate Index (UTCI) and its application to bioclimatic research in European scale*. Miscellanea Geographica, vol. 14, pp. 91-102.

Błażejczyk K., Epstein Y., Jendritzky G., Staiger H., Tinz B., 2012. *Comparison of UTCI to selected thermal indices*. International Journal of Biometeorology, vol. 56, no. 3, pp. 515-535.

Błażejczyk K., Kozłowska-Szczęsna T., Krawczyk B., 1994. *Recent bioclimatological studies in Poland*. Geographia Polonica, vol. 63, pp. 37-49.

Błażejczyk K., Matzarakis A., 2007. *Assessment of bioclimatic differentiation of Poland based on the human heat balance*. Geographia Polonica, vol. 80, no. 1, pp. 63-82.

Błażejczyk K., Kunert A., 2010. *Warunki bioklimatyczne wybranych aglomeracji Europy i Polski* [in:] E. Bednorz, L. Kolendowicz (eds.), Klimat Polski na tle klimatu Europy. Zmiany i ich konsekwencje, Poznań: Bogucki Wyd. Naukowe, pp. 93-106.

Bröde P., Fiala D., Błażejczyk K., Holmér I., Jendritzky G., Kampmann B., Tinz B., Havenith G., 2012. *Deriving the operational procedure for the Universal Thermal Climate Index (UTCI)*.

International Journal of Biometeorology, vol. 56, no. 3, pp. 481-494.

Bröde P., Krüger E.L., Fiala D., 2013. *UTCI: validation and the practical application to the assessment of urban outdoor thermal comfort*. Geographia Polonica, vol. 86, no. 1, pp. 11-20.

Cegnar T., Matzarakis A., 2004. *Trends of thermal bioclimate and their application for tourism in Slovenia* [in]: A. Matzarakis, C.R. de Freitas, D. Scott (eds.), Advances in Tourism Climatology, vol. 12, Freiburg: Berichte des Meteorologischen Institutes der Universität Freiburg, pp. 66-73.

Clark R.P., Edholm O.G., 1985. *Man and his thermal environment*. London: E. Arnold Ltd.

Epstein Y., Moran D.S., 2006. *Thermal comfort and heat stress indices*. Industrial Health, vol. 44, no. 3, pp. 388-398.

Fiala D., Havenith G., Bröde P., Kampmann B., Jendritzky G., 2012. *UTCI-Fiala multi-node model of human heat transfer and temperature regulation*. International Journal of Biometeorology, vol. 56, no. 3, pp. 429-441.

Fiala D., Lomas K.J., Stohrer M., 1999. *A computer model of human thermoregulation for a wide range of environmental conditions: The passive system.* Journal of Applied Physiology, vol. 87, no. 5, pp. 1957-1972.

Fiala D., Lomas K.J., Stohrer M., 2001. *Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions*. International Journal of Biometeorology, vol. 45, no. 3, pp. 143-159.

Gagge A.P., Fobelets A.P., Berglund P.E., 1986. *A standard predictive index of human response to the thermal environment*. ASHRAE Transactions, vol. 92, no. 1, pp. 709-731.

Gulyás A., Matzarakis A., 2009. *Seasonal and spatial distribution of physiologically equivalent temperature (PET) index in Hungary*. IDŐJÁRÁS, vol. 113, no. 3, pp. 221-231.

Havenith G., 2001. *An individual model of human thermoregulation for the simulation of heat stress response*. Journal of Applied Physiology, vol. 90, no. 5, pp. 1943-1954.

Hensel H., 1981. *Thermoreception and temperature regulation*. London: Academic Press.

Höppe P., 1984. *Die Energiebilanz des Menschen*. München: Meteorologische Institut München, Universität, Wissenschaftliche Mitteilungen.

Huizenga C., Zhang H., Arens E., 2001. *A model of human physiology and comfort for assessing complex thermal environments*. Building and Environment, vol. 36, no. 6, pp. 691-699.

Idzikowska D., 2010. *Differences in bioclimatic conditions in four European cities: Budapest, Paris, Rome and Warsaw* [in:] A. Matzarakis, H. Mayer, F.-M. Chmielewski (eds.), Proceedings of the 7th Conference on Biometeorology, Albert-Ludwigs-University of Freiburg, Germany, 12-14 April 2010, Berichte des Meteorologischen Institutes der Universität Freiburg, vol. 20, pp. 201-206.

IUPS, 2003. *Glossary of terms for thermal physiology, 3rd edition revised by the Commission for Thermal Physiology of the International Union of Physiological Sciences*. Journal of Thermal Biology, vol. 28, no. 1, pp. 75-106.

Jendritzky G., 1990. *Bioklimatische Bewertungsgrundlage der Räume am Beispiel von mesoskaligen Bioklimakarten* [in:] H. Schirmer (ed.), Methodik zur räumlichen Bewertung der thermischen Komponente im Bioklima des Menschen, vol. 114, Hannover: Akademie für Raumforschung und Landesplanung, pp. 7-69.

Jendritzky G., de Dear R., Havenith G., 2012. *UTCI – Why another thermal index?* International Journal of Biometeorology, vol. 56, no. 3, pp. 421-428.

Jendritzky G., Staiger H., Bucher K., Graetz A., Laschewski G., 2011. *The Perceived Temperature: The Method of the Deutscher Wetterdienst for the Assessment of Cold Stress and Heat Load for the Human Body*. Deutscher Wetterdienst, http://www.utci.org/isb/documents/perceived_temperature.pdf [5 January 2015].

Jendritzky G., Tinz B., 2009. *The thermal environment of the human being on the global scale*. Global Health Action, vol. 2, 10.3402/gha.v2i0.2005.

Jylha K., Tuomenvirta H., Ruosteenoja K., Niemi-Hugaerts H., Keisu K., Karhu J.A., 2010. *Observed and projected future shifts of climatic zones in Europe and their use to visualize climate change information*. Weather, Climate and Society, vol. 2, no. 2, pp. 148-167.

Köppen W., 1884. *Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet*. Meteorolische Zeitschrift, vol. 1, pp. 215-226, translated and edited by E. Volken, S. Brönnimann, 2011, The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world, Meteorolische Zeitschrift, vol. 20, no. 3, pp. 351-360.

Kottek M., Grieser J., Beck C., Rudolf B., Rubel F., 2006. *World Map of the Köppen-Geiger climate classification updated*. Meteorolische Zeitschrift, vol. 15, no. 3, pp. 259-263.

Kozłowska-Szczęsna T., Krawczyk B., Błażejczyk K., 2004. *The main features of bioclimatic conditions at Polish health resorts*. Geographia Polonica, vol. 77, no. 1, pp. 45-61.

Laschewski G., Jendritzky G., 2002. *Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany*. Climate Research, vol. 21, no. 1, pp. 91-103.

Li P.W., Chan S.T., 2000. *Application of a weather stress index for alerting the public to stressful weather in Hong Kong*. Meteorological Applications, vol. 7, no. 4, pp. 369-375.

Lindner-Cendrowska K., 2013. *Assessment of bioclimatic conditions in the cities for tourism and recreational purposes (a Warsaw case study)*. Geographia Polonica, vol. 86, no. 1, pp. 55-66.

Matzarakis A., Georgiadis T., Rossi F., 2007. *Thermal bioclimate analysis for Europe and Italy*. Il Nuovo Cimento. C, vol. 30, no. 6, pp. 623-632.

Matzarakis A., Hämmerle M., Koch E., Rudel E., 2012. *The climate tourism potential of Alpine destinations using the example of Sonnblick, Rauris and Salzburg*. Theoretical and Applied Climatology, vol. 110, no. 4, pp. 645-658.

Matzarakis A., Mayer H., Iziomon M.G., 1999. *Applications of a universal thermal index: physiological equivalent temperature*. International Journal of Biometeorology, vol. 43, no. 2, pp. 76-84.

Matzarakis A., Mayer H., 1991. *The Extreme Heat Wave in Athens in July 1987 from the Point of View of Human Biometeorology*. Atmospheric Environment. Part B. Urban Atmosphere, vol. 25, pp. 203-211.

Mayer H., Höppe P., 1987. *Thermal comfort of man in different urban environments*. Theoretical and Applied Climatology, vol. 38, no. 1, pp. 43-49.

Missenard F.A., 1933, *Température effective d'une atmosphere. Généralisation température résultante d'un milieu* [in:] Encyclopédie Industrielle et Commerciale, Etude physiologique et technique de la ventilation, Paris: Librerie de l'Enseignement Technique, pp. 131-185.

Nemeth A., 2011. *Changing thermal bioclimate in some Hungarian cities*. Acta Climatologica et Chorologica Universitatis Szegediensis, vol. 44-45, pp. 93-101.

Nowosad M., Rodzik B., Wereski S., Dobek M., 2013. *The UTCI index in Lesko and Lublin and its circulation determinants*. Geographia Polonica, vol. 86, no. 1, pp. 29-36.

Parsons K.C., 2003. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance*. London, New York: Taylor & Francis.

Peel M.C., Finlayson B.L., McMahon T.A., 2007. *Updated world map of the Köppen-Geiger climate classification.* Hydrology and Earth System Sciences, vol. 11, no. 5, pp. 1633-1644.

Pickup J., de Dear R., 2000. *An Outdoor Thermal Comfort Index (OUT_SET*) - Part I - The Model and its Assumptions* [in:] R. de Dear, J. Kalma, T. Oke, A. Auliciems (eds.), Biometeorology and Urban Climatology at the Turn of the Millenium, WCASP-50: WMO/TD No. 1026, Geneva: WMO, pp. 279-283.

Psikuta A., Fiala D., Laschewski G., Jendritzky G., Richards M., Błażejczyk K., Mekjavič I., Rintamäki H., de Dear R., Havenith G., 2012. *Evaluation of the Fiala multi-node thermophysiological model for UTCI application*. International Journal of Biometeorology, vol. 56, no. 3, pp. 443-460.

Staiger H., Bucher K., Jendritzky G., 1997. *Gefühlte Temperatur. Die physiologisch gerechte Bewertung von Wärmebelastung und Kältestress beim Aufenthalt im Freien in der Maßzahl Grad Celsius*. DWD Annalen der Meteorologie, vol. 33, pp. 100-107.

Staiger H., Laschewski G., Grätz A., 2012. *The perceived temperature – a versatile index for the assessment of the human thermal environment. Part A: scientific basics*. International Journal of Biometeorology, vol. 56, no. 1, pp. 165-176.

Tanabe S.I., Kobayashi K., Nakano J., Ozeki Y., Konishi M., 2002. *Evaluation of thermal comfort using combined multi-node thermoregula-*

tion (65MN) and radiation models and computational fluid dynamics (CFD). Energy and Buildings, vol. 34, no. 6, pp. 637-646.

ZANINOVIC K., MATZARAKIS A., 2004. *Variation and trends of thermal comfort at the Adriatic coast* [in:] A. Matzarakis, C.R. de Freitas, D. Scott (eds.), Advances in Tourism Climatology, vol. 12, Freiburg: Berichte des Meteorologischen Institutes der Universität Freiburg, pp. 74-81.

Article first received • September 2013
Article accepted • April 2014