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ASSESSMENT OF BIOCLIMATIC VARIABILITY ON REGIONAL AND LOCAL SCALES IN CENTRAL EUROPE USING UCTI

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Abstract: The paper presents new approach to study spatial and temporal variability of bioclimatic conditions. The new Universal Thermal Climate Index *UTCI* was applied in this purpose. *UTCI* bases on multi-note human heat balance Fiala model and it represents heat stress in man caused by meteorological conditions. The seasonal and regional variability of bioclimate was assessed on an example of selected European cities: Kołobrzeg, Warsaw, Świeradów, Prague, Budapest, Ljubljana and Milan. Daily meteorological data (air temperature, vapour pressure, wind speed and total cloud cover) for the period 1991-2000 was used in this purpose. Annual course of *UTCI* values and the frequency of *UTCI* categories are discussed. Significant regional differences between studied cities were found. The results confirm frequent occurrence of unfavourable thermal conditions in Mediterranean region in summer months. However, heat stress was frequently observed in summer in all compared stations. Spatial variability in detail local scale was studied on the examples of selected regions of Poland (Mazovia Lowland, Warsaw). The results show that occurrence of strong heat stress depends not only on general meteorological conditions but also on land use. The greatest heat stress is observed mostly in urbanised areas especially in the central parts of cities and inside industrial districts.

Key words: *bioclimatic conditions, Central Europe, Universal Thermal Climate Index, seasonal variability of UTCI, local variability of UTCI*

I. INTRODUCTION

During the last century more than 100 indices were developed to assess bioclimatic conditions for human beings (Epstein, Moran, 2006). The majority of these indices were used sporadically for specific purposes and for particular regions or seasons. Some indices are based on generalized results of measurements (e.g. wind chill, cooling power, wet bulb temperature) and some on empirically observed reactions of the human body to thermal stress (e.g. physiological strain, effective temperature).

Contemporary bioclimatic research focuses on studying direct relationships between the atmosphere and the human organism. In this purpose so called “biothermal conditions” are considered. They comprise both the consideration of the conditions of heat exchange with the atmosphere (stress) and the physiological response (strain). Balancing the human heat budget, i.e. equilibration of thermal state of an organism to fluctuated heat exchange is controlled by a very efficient autonomous thermoregulatory system (Havenith, 2001; Parsons, 2003; *Glossary…* 2003; Błażejczyk, Kunert, 2011). The crucial for the human being is to keep the body core temperature within a narrow range around 37°C in order to ensure functioning of the inner organs and the brain. In contrast the temperature of the skin and extremities can vary widely, depending on the environmental conditions, which is one of the mechanisms to keep heat production and heat loss over a longer period in equilibrium, i.e. to reduce changes in heat content in the body to zero. The indices that are based on human heat balance considerations are referred to as the "rational indices" (Błażejczyk et al., 2012, Epstein, Moran 2006).

Modeling of the human heat balance goes back 70 years. Most of research has been accomplished in the area of occupational medicine, occupant comfort and indoor climate design in artificial, man-made spaces, e.g. Outdoor Standard Effective Temperature model, SET (Gagge et al., 1986; Pickup, de Dear, 2000), Munich Energy Balance Model of Individuals, MEMI (Höppe, 1984), Man-Environmental Heat Exchange Model, MENEX (Błażejczyk, 1994; Błażejczyk, Kunert, 2011, Błażejczyk, Matzarakis, 2007), Klima-Michel-Model (Jendritzky, 1990), and the required sweat rate approach [ISO 7933]. In the past two decades multi-node models of human thermoregulation have been developed (Fiala et al., 1999, 2001, 2003; Huizenga et al., 2001; Tanabe et al., 2002). These models simulate phenomena of heat transfer inside the human body and at its surface taking into account the anatomical, thermal and physiological properties of the human body.

The aims of the paper are: 1) to compare specific seasonal and regional features of *UTCI* in selected Central European cities (i.e. cities located between 45 and 55 parallels North as well as 9 and 23 meridians East) represented various climatic regions, 2) to discuss the applicability of *UTCI* in research of bioclimatic conditions in local scale.

II. METHODS AND MATERIALS

In the Fiala model the human organism is separated into two interacting systems of thermoregulation: (1) the controlling active system, and (2) the controlled passive system. The passive system is a multi-segmental, multi-layered representation of the human body with information on anatomic and physiological body properties. The model represents an average person with a body weight of 73.5 kg, body fat content of 14%, Dubois-area of 1.86 m². Body elements are subdivided into spatial sectors and into individual tissue nodes. The passive system of the UTCI-Fiala model consists of 12 body elements comprising 187 tissue nodes in total. The active system of the model predicts the thermo-regulatory reactions of the central nervous system: suppression and elevation of the cutaneous blood flow, shivering thermo genesis, and sweat excretion (Fiala et al., 2012).

The *UTCI*, derived from Fiala multi-node model, is defined as the air temperature of the reference condition causing the same model response (in sweat production, shivering, skin wettedness and skin blood flow as well as in rectal, mean skin and face temperatures) as the actual conditions (Błażejczyk et al., 2010; Bröde et al., 2012; Psikuta et al., 2012). The model response is indicative for the physiological and thermoregulatory processes which are significant for the human reaction to neutral, moderate and extreme thermal conditions. The offset, i.e. the deviation of *UTCI* from air temperature (*Ta*) depends on the actual values of air and mean radiant temperature (*Tmrt*), wind speed (*va*) and water vapour pressure (*vp*). This may be written in mathematical terms as:

$UTCI = f\,(Ta; Tmrt; va; vp) = Ta + \text{Offset}\,(Ta; Tmrt; va; vp)$

The *UTCI* can be calculated in two different ways. The first method bases on solving Fiala's heat balance model and the second on regression model. As the direct application of Fiala's multi-node model is time consuming an approximating regression function was found. The offsets of *UTCI* to *Ta* (*UTCI-Ta*) were approximated by a polynomial The offsets of *UTCI* to *Ta* (*UTCI-Ta*) were approximated by a polynomial function in *Ta*, *va*, *vp*, *Tmrt-Ta* including all main effect and interaction terms up to 6th order. The least square estimates of the 210 coefficients were found (Błażejczyk, Kunert, 2011; Bröde *et al*., 2012). The root mean squared error was 1.1°C, 50% of all observed errors were within ±0.6°C, 80% within ±1.3°C, 90% within ±1.9°C (Bröde et al., 2012). For operational use *UTCI* can be calculated with the use of BioKlima 2.6 software package (available at http://www.igipz.pan.pl/Bioklima-zgik.html).

The *UTCI* values are categorized in terms of thermal stress. The present approach looks at responses for the reference conditions and deducts load (i.e. heat or cold stress) caused by physiological response of an organism at actual environmental conditions. Table 1 presents the labelled stress categories (Błażejczyk et al., 2012; Fiala et al., 2012).

Table 1. *UTCI* equivalent temperature categorized in terms of thermal stress.

UTCI (°C) range	Stress Category	
above +46.0	4	extreme heat stress
+38.1 to +46.0	3	very strong heat stress
+32.1 to +38.0	2	strong heat stress
+26.1 to +32.0	1	moderate heat stress
+9.1 to +26.0	0	no thermal stress *
0.1 to 9.0	-1	slight cold stress
-13.0 to 0.0	-2	moderate cold stress
-27.0 to -12.9	-3	strong cold stress
-40.0 to -26.9	-4	very strong cold stress
below -40.0	-5	extreme cold stress

* With respect to the averaged dynamic thermal sensation *UTCI* between 18 and 26ºC fully comply with definition of the "thermal comfort zone" (*Glossary*… 2003) as: "The range of ambient temperatures … within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period".

For seasonal and regional research the meteorological data represent the period 1991-2000. Eight synoptic stations were chosen: Kołobrzeg, Warsaw, Świeradów, Prague, Budapest, Milan and Ljubljana (Fig. 1). Daily midday hours data (taken from PHEWE project and gathered by national meteorological services) of air temperature, air vapour pressure, wind speed and cloud cover were used to calculate daily *UTCI* values. Most of stations were located in local airports and only Kołobrzeg and Świeradów stations are located in small coastal and mountain resorts, respectively. BioKlima 2.6 software package was used in this purpose. *UTCI* values were analysed for decadal periods of particular months (monthly decades).

Fig. 1. Meteorological stations chosen for the research.

Local scale research is based on the coefficients of changes (Table 2) of solar radiation, wind speed, air temperature and humidity in different types of local landscapes (Błażejczyk, 2002, Kunert, 2010).

Table 2. Coefficients of changes in solar radiation (*zr*), air temperature (*zt*), wind speed (*zv*) and air humidity (*zf*) in selected types of landscape

Types of landscape		Coefficients of changes			
		zr	*zt*	*zv*	*zf*
Relief features	plains	1	1	1	1
	tops and upper parts of hills	1	1	1.4	1
	correction due to absolute altitude (m)	0.0065·m/100	-	-	-
	Valley's bottoms (H – is valley depth, W – is valley wide):				
	> 20 m H and < 200 m W	0.95	0.85	0.7	1.1
	< 20 m H and < 200 m W	1.05	0.9	0.8	1
	> 20 m H and > 200 m W	1.05	0.95	0.9	1.05
	< 20 m H and > 200 m W	1	1	1	1
	Slopes:				
	sun-faced, elevation 20 - 50 m	1.2	1.2	1	0.95
	sun-faced, elevation > 50 m	1.2	1.2	1	0.95
	sun-backed, elevation 20 - 50 m	0.8	0.85	1	1.1
	sun-backed, elevation > 50 m	0.8	0.85	1	1.1
	east/west, elevation 20-50 m	1	0.95	1	1
	east/west, elevation > 50 m	1	0.95	1	1
	correction due to elevation above valley's bottom (h)	-	t -0.6 ≅h/100	0.0075≅h/50 + 0.6833	-
Land use	fields and westlands	1	1	1	1
	meadows	1	0.95	1	1
	forests	0.3	0.9	0.2	1.1
	ground transportation belts	1	1.05	0.95	0.9
	rural settlement	1	1.1	0.8	1
	intra-forest-settlement	0.6	0.95	0.6	1
	downtown	0.8	1.25	0.6	0.9
	industrial areas	0.8	1.3	0.6	0.9
	water banks and water bodies	1	0.85	1.1	1.2
Ground moisture	dry	1	1	1	1
	humid	1	0.95	1	1.1
	wet	1	0.9	1	1.2

Caution: *zt* coefficients are valid within the air temperature range of 5-35°C (Source: Błażejczyk, 2002, modified by Kunert, 2010)

The coefficients were derived from experimental, topoclimatic research carried out in different types of landscape (mostly in Poland, but also in other Europeans countries as Bulgaria and France) both, natural (forests, meadows, fields, wetlands, slopes, ridges etc.) and anthropogenic (urban, rural, industrial). The variables in particular landscapes were compared with analogical variables observed at the nearest meteorological station. While the experimental research was carried out during warm seasons, the coefficients of the changes in air temperature are valid within the range of 5-35ºC (Błażejczyk 2002).

Using such coefficients the predicted values of basic meteorological elements and mean radiant temperature for various weather scenarios were calculated for standard meteorological station (open, flat area covered by grass, without horizon obstructions) as well as for particular types of land use, geomorphological units and ground moisture. Next, the simulated meteorological variables were used for the calculation of *UTCI* for every type of the landscape. The following meteorological scenarios were considered: cloudy (solar radiation of 200 $W \cdot m^{-2}$), moderately cloudy (solar radiation of 500 $W \cdot m^{-2}$) and sunny (solar radiation of 800 $W \cdot m^{-2}$), air temperature of 10, 20 and 30ºC, relative humidity of air (20, 50 and 80%) and wind speed (2, 4 and 8 $m \cdot s^{-1}$). Such meteorological scenarios are typical for warm half-year in Europe.

In local scale research both, absolute values of *UTCI* and their deviations (d*UTCI*) from standard landscape condition are considered. d*UTCI* represents the difference of index value calculated for standard meteorological station and for particular landscape units.

III. RESULTS

III.1. Seasonal and regional differentiation

As was expected *UTCI* values were differentiated seasonally and regionally. At northern locations average and minimum *UTCI* values were significantly lower then in southern part of studied region. We can also observe lower standard deviations in Milan and Ljubljana in comparison to other cities. This indicates relatively more stable thermal conditions in northern Mediterranean stations then in stations located in central and northern parts of studied region. Summer *UTCI* maximums are very similar each other in all locations and they represent “very strong heat stress” category. However, *UTCI* minimums are significantly differentiated over Central Europe; the lowest ones were noted at mountain station (Świeradów) and in Warsaw, which is exposed to advections of cold polar continental or arctic air. Relatively warm, because of coastal location are winters in Kołobrzeg. The highest minimums are noted in Milan. In contrast, in

Ljubljana, located at the similar latitude as Milan but in the bottom of mountain basin, winter minimums are of 10ºC lower (Table 3).

Seasonal patterns of *UTCI* for northern and southern stations of the studied region show significant differences (Fig. 2). In the north of the region (Warsaw) great amplitudes of decadal *UTCI* values are observed. From the end of December till the middle of February *UTCI* can fall down up to -50ºC which represents extreme cold stress. However, in the same period maximum index values can reach +10ºC (no thermal stress category). In the summer months *UTCI* can vary from -5ºC (moderate cold stress) to about 40ºC (great heat stress). In Milan (south of region) summer *UTCI* values fluctuate from +8ºC (slight cold stress) to 40ºC (great heat stress). In winter bioclimatic conditions are considerably milder then in Warsaw. *UTCI* fluctuates from about -20ºC (strong cold stress) to 25ºC (no thermal stress).

Table 3. Annual average (avg) with standard deviation (SD), maximum (max) and minimum (min) values of *UTCI* in the studied cities, 1991-2000

UTCI (ºC)	Kołobrzeg	Warsaw	Świeradów	Prague	Budapest	Milan	Ljubljana
average	5.7	4.2	6.6	6.0	12.4	18.9	13.8
SD	10.6	13.0	11.0	12.6	11.8	9.8	9.6
maximum	41.5	41.1	38.8	39.4	41.0	42.1	39.1
minimum	-43.8	-51.9	-53.9	-39.3	-31.0	-24.2	-33.6

In bioclimatic research very important is the frequency of particular categories of used index. In case of *UTCI* its value indicates possible heat stress. In all seasons Milan is the city with the greatest frequency of the most sever heat stress in comparison to another cities. In transient seasons (spring and autumn) moderate and strong heat stress in Milan occurs during about 20% of days. In other cities their frequency did not exceed 10% (Fig. 3).

While maximum *UTCI* values in summer are not spatially differentiated the frequencies of particular heat stress categories are in great variety. Again, in Milan all categories of heat stress (moderate, strong and very strong) occur in more then 80% of days. They are very frequent also in Budapest and Ljubljana (almost 60% of days). The less frequent were such biothermal situations in coastal city of Kołobrzeg.

Winter is the season with much differentiated frequency patterns. Warsaw, Prague and Kołobrzeg are the cities where optimal, “no thermal stress” *UTCI* category is very rare. At the same time very strong cold stress can occur at 2-5% of winter days. The milder biothermal conditions can be found in Milan, where “no thermal stress” occurs at almost 40% of days.

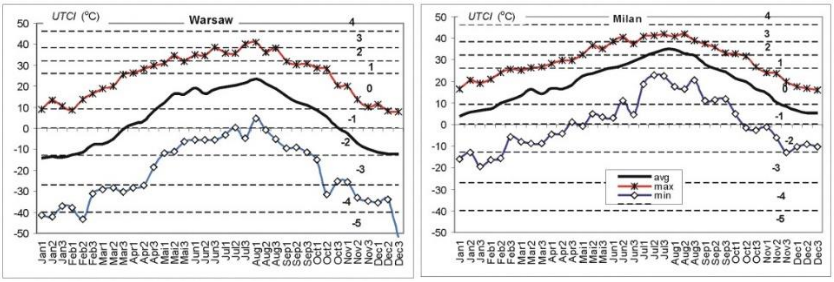

Fig. 2. Seasonal changes of maximum (max), average (avg) and minimum (min) *UTCI* values at selected stations represented North (Warsaw) and South (Milan) of studied region, 1991-2000; -5 to 4 – stress categories (see table 1).

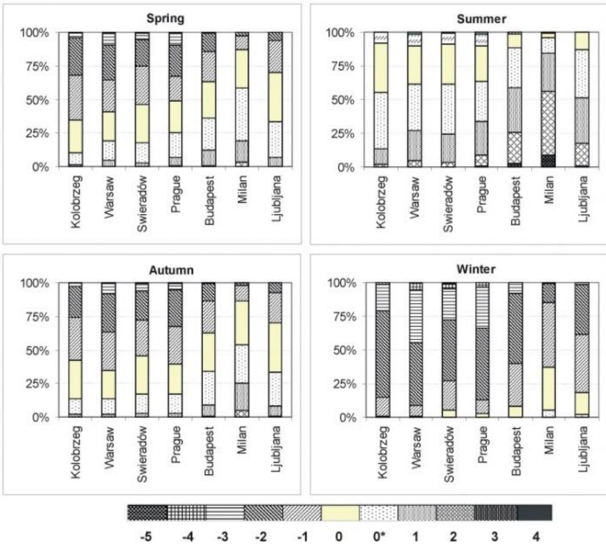

Fig. 3. Frequency of heat stress categories in spring, summer and winter months in the studied cities; -5 to 4 - stress categories (see table 1)

III.2. Local scale differentiation of *UTCI*

The level of *UTCI* depends mostly on actual weather conditions. The table 4 shows *UTCI* calculated for the conditions of standard meteorological station. We can see that depending on insolation, air temperature, wind speed and air humidity *UTCI* varies from -8.7ºC (at cloudy weather with air temperature of 10ºC, wind of 8 $m \cdot s^{-1}$ and air humidity of 20%) to 37.0ºC (at sunny weather with air temperature of 30ºC, slight wind of 2 $m \cdot s^{-1}$ and air humidity of 90%). We can note that *UTCI* values decrease due to: rise of wind speed as well as decrease in air temperature and solar radiation. On the other hand *UTCI* increases according to: rise of air temperature and humidity, increase of solar radiation and decrease of wind speed.

Table 4. *UTCI* values calculated for various weather scenarios for standard meteorological station (plain, open area)

Solar radiation intensity (W·m^{-2})	Relative humidity (%)	Wind speed (m·s^{-1}): 2			4			8		
		Air temperature (ºC)								
		10	20	30	10	20	30	10	20	30
800	20	13.4	22.8	32.4	7.6	19.2	30.5	-0.9	14.3	28.9
	50	15.0	24.3	34.4	9.3	20.7	32.3	1.1	16.1	30.6
	90	16.2	25.9	37.0	10.6	22.3	34.8	2.5	17.7	33.1
500	20	7.8	18.3	29.0	2.1	14.8	27.3	-5.9	10.1	25.8
	50	9.6	20.1	31.3	4.0	16.6	29.3	-4.0	12.1	27.9
	90	10.9	21.9	34.2	5.4	18.3	32.2	-2.5	13.9	30.7
200	20	4.6	15.7	27.1	-0.9	12.3	25.5	-8.7	7.7	24.1
	50	6.4	17.7	29.5	1.0	14.3	27.6	-6.7	9.9	26.3
	90	7.8	19.5	32.6	2.4	16.0	30.7	-5.4	11.7	29.4

In local studies most important is spatial distribution of meteorological and biometeorological variables. At the flat areas local climate and bioclimate are mainly formed by various features of land use. Thermal properties of urbanized areas, both, cities and villages, are seen in regional scale as warm spots. On the other hand, we can also mark out thermal and bio-thermal features of different urban structures as parks, forests and river channels. Deviations of *UTCI* (d*UTCI*) from standard conditions (represented by meteorological station) in different types of land use, depending on weather conditions ranged in warm season from -11.5ºC (during cloudy and windy weather) to +35.5ºC (at sunny and light wind weather). The biggest negative deviations are noted on water bodies and in forests, however the biggest positive deviations are observed at urbanized areas: downtown and industrial zones (Fig. 4).

In forests bioclimatic conditions are modified by weak winds, lower air temperature and also by reduced solar radiation. Thus d*UTCI* can have in forests negative or positive values, from -7.6ºC to 11.7ºC. Positive deviations are observed during cold windy days with low solar radiation. Increased wind speed outside forest is there significantly reduce which lead to the rise of d*UTCI* even of 10ºC.

Negative deviations are noted at soft winds, irrespective of air temperature, except of cloudy and cool weather. The biggest negative d*UTCI* occurs in hot days with low wind speed and high solar radiation (Table 5).

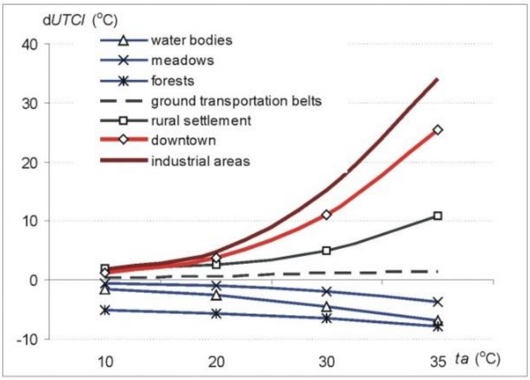

Fig. 4. Deviations of *UTCI* from standard conditions (d*UTCI*) in various types of land use at different air temperature (*ta*) measured on meteorological station (sunny weather with weak wind and great air humidity).

Table 5. Deviations of *UTCI* from standard conditions inside forests at various weather scenarios

Solar radiation intensity (W≅m^{-2})	Relative humidity (%)	Wind speed (m≅s^{-1}): 2			4			8		
		Air temperature (°C)								
		10	20	30	10	20	30	10	20	30
800	20	-5.5	-6.5	-7.6	-0.5	-3.3	-5.8	6.0	0.5	-4.5
	50	-5.2	-6.0	-6.9	-0.3	-2.8	-4.8	6.0	0.7	-3.7
	90	-5.1	-5.7	-6.4	-0.3	-2.5	-4.3	5.9	0.9	-3.3
500	20	-1.0	-2.9	-4.9	3.9	0.2	-3.2	10.0	3.8	-2.1
	50	-0.9	-2.7	-4.4	3.9	0.5	-2.5	10.0	3.9	-1.6
	90	-0.9	-2.5	-4.1	3.9	0.6	-2.2	10.0	3.9	-1.4
200	20	1.1	-1.3	-3.7	5.8	1.8	-2.1	11.7	5.2	-1.2
	50	1.2	-1.1	-3.3	5.8	1.9	-1.5	11.7	5.2	-0.8
	90	1.1	-1.0	-3.2	5.8	2.0	-1.4	11.7	5.3	-0.7

In the mountain areas local climate and bioclimate is mostly depended on relief feature: exposition and elevation of slopes as well as morphometry of valleys (depth, width). Comparing different features of relief we have found great positive deviations of *UTCI* at south oriented slopes, especially their parts elevated over slope foot no more than 50 m. At sunny, hot, wet and calm weather d*UTCI* can reach up to 20ºC. The second important finding deals with valleys and basins. High negative deviations of *UTCI* are observed at the bottoms of deep, narrow valleys. The intensity of such deviations is the biggest at very high air temperature during sunny and calm weather (Fig. 5).

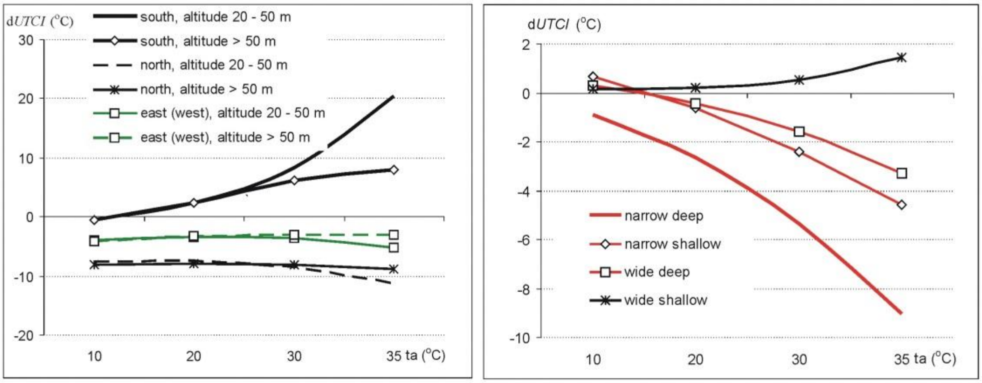

Fig. 5. Deviations of *UTCI* from standard conditions (d*UTCI*) in various types of slopes (northern hemisphere, left panel) and valleys (right panel) at different air temperature (ta) measured on meteorological station (sunny weather with weak wind and great air humidity).

Figure 6 shows two examples of maps presented distribution of modeled *UTCI* values of the central part of Mazovia Lowland for two weather scenarios. The maps were generated in IDRISI Tajga software using raster size of 1x1 km. In spite of relatively large raster size on both maps, in their central parts, the area of Warsaw is well seen with elevated values of *UTCI*, in comparison to surroundings. It is caused by specific topoclimatic conditions of urban area. On both maps the lowest *UTCI* is observed inside forests and along rivers channels.

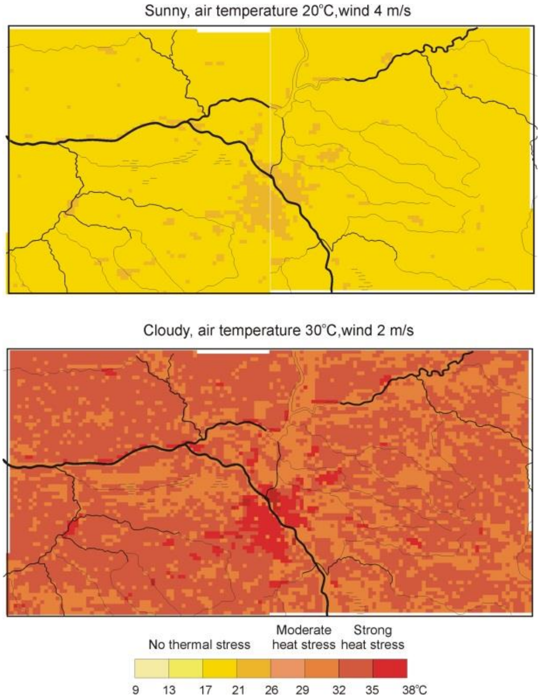

Fig. 6. Distribution of modeled *UTCI* values in the central part of Mazovia Lowland in two weather scenarios

IV. DISCUSSION

In the past various biothermal indices derived from the human heat balance are used to present sensible climate in different seasons and types of landscape. Jendritzky (1990) has assessed urban bioclimate using Perceived Temperature. However, Höppe (1984) and Matzarakis et al. (2010) prefer Physiological Equivalent Temperature (*PET*). Physiological Subjective Temperature (*PST*) was applied by Błażejczyk and Błażejczyk (1999) as well as by Błażejczyk and Kunert (2006) to assess urban bioclimate. Błażejczyk and Matzarakis (2007) have used both, *PET* and *PST* to present bioclimatic differentiation of whole Poland. Till now *UTCI* was applied several times to present seasonal and spatial differentiation of bioclimatic conditions. Nemeth (2011) studied multiannual variations of *UTCI* and *PET* in four Hungarian stations. Nowosad *et al*. (2013) studied the influence of atmospheric circulation types on *UTCI* features in two Polish cities, Lublin and Lesko. Lindner-Cendrowska (2013) and Bröde et al. (2013) used *UTCI* to assess bioclimatic conditions of urbanised areas of Warsaw, Madrid, Stockholm and Curitiba. Błażejczyk (2011) has firstly used it for urban area of Warsaw and

Milewski (2013) – for Sudety Mts. Both, *UTCI* and other biothermal indices indicated similar types of landscape as favourable or stressful for humans. However, the greatest advantage of *UTCI* is indication in the most realistic way actual physiological responses of an organism when staying in particular locations.

The same advantage of *UTCI* is observed in the studies of seasonal features of bioclimate in different European cities (Błażejczyk, Kunert 2010). All indices indicate great seasonality and regional variability of bioclimate in Europe. And again, only *UTCI* can explain in details why particular seasons and regions can be hazardous for man from the point of view of his physiological responses to ambient stimuli.

V. GENERAL CONCLUSIONS

The use of Universal Thermal Climate Index brings valuable input in our knowledge of bioclimatic conditions both, in general, regional assessments as well as in local climate research. In the regional scale the results confirm frequent occurrence of unfavourable thermal conditions in Mediterranean region in summer months. However, heat stress was frequently observed in summer in all compared stations. The results of local scale research show that occurrence of strong heat stress depends not only on general meteorological conditions but also on land use. The greatest heat stress is observed mostly in urbanised areas especially in the central parts of cities and inside industrial districts.

Firstly, while the general features for annual cycles of bioclimatic conditions are similar when using previous generation of indices and *UTCI*, the greatest advantage of *UTCI* is that it indicates the actual physiological responses of an organism to climate stimuli in the most realistic way.

The second advantage of *UTCI* is its universal assessment scale which does not indicate thermal sensations but heat stress in man. While thermal sensations are depended on population features, level of acclimatization and individual characteristics of any subject (e.g. age, body mass, health status etc.), the heat stress depends mostly on ambient conditions and individual factors do not play important role. It makes that *UTCI* can be applied in all climates and the results obtained in different areas are fully comparable.

Acknowledgments

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