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Assessment of urban thermal stress by UTCI – experimental and modelling studies: an example from Poland

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Abstract
The paper presents a new approach to the study of the spatial variability of heat stress in urban areas. The Universal Thermal Climate Index UTCI was applied for this purpose. The spatial variability of UTCI at the local scale was studied using examples of urban areas with different sizes and geographical locations. The experimental research on urban heat stress was conducted in Warsaw. The research covers both differences between UTCI in urban to rural areas as well as the variation of heat stress within small residential districts in Warsaw. We found a very large and significant heat stress gradient between downtown Warsaw and rural stations. Spatial variability of UTCI was also observed in microclimate research. A modelling approach was presented based on examples from Warsaw, a city with a population of almost 2 million, as well as examples from several spa towns with populations of up to 40,000 located in various parts of Poland. GIS analysis (ArcGIS for Desktop and IDRISI) was applied for this purpose.

Zusammenfassung
Der Beitrag stellt einen neuen Ansatz zur Untersuchung der räumlichen Differenzierung von Hitzestress in städtischen Gebieten vor, in welchem der Universal Thermal Climate Index UTCI Anwendung findet. Die räumliche Differenzierung des UTCI wurde anhand von Beispielen städtischer Räume unterschiedlicher Größe und Lage auf lokaler Ebene untersucht. Die experimentelle Forschung zum Hitzestress wurde in Warschau durchgeführt. Sie behandelt sowohl Unterschiede im UTCI zwischen städtischen und ländlichen Räumen als auch die unterschiedliche Ausprägung des Hitzestresses innerhalb kleiner Wohngebiete Warschaus. Im Ergebnis zeigt sich beim Hitzestress ein beträchtlicher und signifikanter Gradient zwischen dem inneren Stadtgebiet von Warschau und ländlichen Stationen im Umland. Auch auf kleinräumlicher Ebene konnte eine räumliche Differenzierung beobachtet werden. Dazu wird ein Modellansatz vorgestellt, der sich sowohl auf Beispiele aus Warschau stützt – einer Stadt mit fast 2 Millionen Einwohnern – als auch auf Beispiele aus mehreren Kurorten in verschiedenen Landesteilen Polens mit Bevölkerungszahlen von bis zu 40 000. Zur Anwendung kam dabei eine GIS-gestützte Analyse (ArcGIS for Desktop und IDRISI).

Keywords Urban heat stress, Universal Thermal Climate Index, local bioclimatic variability, Warsaw, Poland

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1. Introduction

During the last century more than 100 indices were developed to assess bioclimatic conditions for human beings (*Epstein* and *Moran* 2006). The majority of these indices were used sporadically, for specific purposes and for particular regions or seasons. Some indices are based on the generalised 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 concentrates on studying direct relationships between the atmosphere and the human organism. Human heat balance models are used for this purpose. They allow the consideration of both the effects of heat exchange with the atmosphere (stress) and the physiological response (strain). Balancing the human heat budget, i.e. the equilibration of heat exchange between the organism and the atmosphere in fluctuating ambient conditions, is controlled by a very efficient autonomous thermoregulatory system (*Havenith* 2001, IUPS 2003, *Parsons* 2003). The crucial factor for humans is to keep the body core temperature within a narrow range around 37°C in order to ensure the correct functioning of the inner organs and the brain. The intensity of physiological adaptation processes to equilibrate the human heat balance in different meteorological conditions is proportional to the intensity of ambient heat stress. Urban areas are "laboratories" for the study of major modifications of meteorological variables (*Oke* 1987, *Erell* et al. 2011). In the light of an increasing urban population and demographic changes, it is very urgent to develop tools for assessing possible changes in heat stress.

Modelling of the human heat balance goes back 70 years. Most experimental research has been accomplished in the area of occupational and military medicine, occupant comfort and indoor climate design in artificial, man-made spaces. However, recently used indices have been adapted to a wide range of bioclimatic research dealing with outdoor climate, e.g. the Outdoor Standard Effective Temperature model, SET (*Gagge* et al. 1986, *Pickup* and *de Dear* 2000), Munich Energy Balance Model of Individuals, MEMI (*Höppe* 1984), Man-Environmental Heat Exchange Model, MENEX (*Błażejczyk* and *Kunert* 2011), and Klima-Michel-Model (*Jendritzky* 1990). 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 heat transfer phenomena both inside the human body and at its surface taking into account the anatomical, thermal and physiological properties of the human body.

The aim of the paper is to present the results of research assessing heat stress in urban areas. Both experimental research carried out at the scale of a whole city and at the micro-scale of residential districts as well as a modelling approach (GIS application) are discussed.

2. Methods and materials

2.1 Principles of UTCI

The UTCI, derived from the Fiala multi-node model, is defined as the air temperature (t) of the reference condition causing the same model response (strain: 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, *Fiala* et al. 2012, *Psikuta* et al. 2012). The offset, i.e. the deviation of UTCI from air temperature depends on the actual values of air temperature (*ta*) and mean radiant temperature (*Tmrt*), wind speed (*v*) and water vapour pressure (*vp*). This may be written in general mathematical terms as:

$$\mathrm{UTCI} = f(ta; Tmrt; v; vp) = ta + \mathrm{Offset}(ta; Tmrt; v; vp)$$

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

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-

Tab. 1 UTCI equivalent temperature categorised in terms of thermal stress

UTCI range (°C)	Stress Category	
Above +46	4	Extreme heat stress
+38 to +46	3	Very strong heat stress
+32 to +38	2	Strong heat stress
+26 to +32	1	Moderate heat stress
+9 to +26	0	No thermal stress *
+9 to 0	-1	Slight cold stress
0 to -13	-2	Moderate cold stress
-13 to -27	-3	Strong cold stress
-27 to -40	-4	Very strong cold stress
Below -40	-5	Extreme cold stress

* UTCI values between 18 and 26°C, based on the average dynamic thermal sensation, fully comply with the definition of the "thermal comfort zone" (IUPS 2003). This is "the range of ambient temperatures … within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period".

segmental, multi-layered representation of the human body with information on the anatomical and physiological properties of the body. 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. The active system of the model predicts the thermoregulatory reactions of the central nervous system: suppression and elevation of the cutaneous blood flow, shivering thermogenesis and sweat secretion (*Fiala* et al. 1999, 2012). The UTCI values are categorised in terms of heat stress and represent the load (i.e. heat or cold stress) caused by the physiological response (strain) of an organism in actual environmental conditions (*Tab. 1*) (*Błażejczyk* et al. 2010, 2012).

2.2 Experimental research

The experimental research on the influence of urban structures on heat stress in man was carried out in Warsaw (Poland). Two spatial scales of UTCI variation were examined. The general scale refers to urban-rural differences in heat stress. For this purpose winter and summer series of meteorological variables (air temperature and humidity, wind speed, global solar radiation) were used for the calculations of UTCI. The urban station (Twarda) is located in downtown Warsaw. The rural station (Borowa Góra) lies 30 km to the north of the city centre. The stations are operated by the Institute of Geography and Spatial Organization of the Polish Academy of Sciences (*Kuchcik* et al. 2008) (*Fig. 1*).

Multiannual hourly data from the period 2005-2010 from two stations, Twarda (an urban station) and Tłuszcz (a rural station), were used for comparison of the frequency of particular UTCI categories of heat stress. In this case Tłuszcz rural station formed part of the air pollution monitoring network administered by the Regional Inspectorate of Environmental Protection.

The microclimatic variation in heat stress was examined within two residential districts in Warsaw: the Koło and Włodarzewska housing estates located to the west of the city centre, both of which are situated near parks. Koło estate was established about 50 years ago. The 4-5 floor buildings are built at low density. Wide spaces between buildings are covered by lawns and high mature deciduous trees. The RBVA (Ratio of Biologically Vital Areas) is 54.3 % and SDC (Settlement Density Coefficient, which is calculated as: SDC = built-up area ≅ total floorspace area / total area of housing estate) is 0.8. The Włodarzewska estate was built about 15 years ago and is surrounded by many open spaces and a park, but arranged in a way which effectively precludes air entry from outside. It is characterised by compact development (the 4-5 floor blocks are very densely built up and are constructed over underground car parks), with only small flowerbeds with coniferous shrubs and lawns between buildings. Only a few young deciduous trees are growing there. RBVA is 40.7 % and SDC is 1.25. Air temperature and humidity, wind speed and global solar radiation were measured twice a day (in early morning and at midday) on 21 and 22 May 2013. The posts were situated in various micro-structures of the housing estates examined (*Fig. 1*). The full regression model (*Błażejczyk* et al. 2010, *Bröde* et al. 2012) was used for the calculations of UTCI. The BioKlima 2.6 software package was used to apply the model.

2.3 Modelling research

The presentation of the spatial distribution of any variables and indices is very important in bioclimatic research on urban areas. In the present research Geographical Information Systems (GIS) were ap-

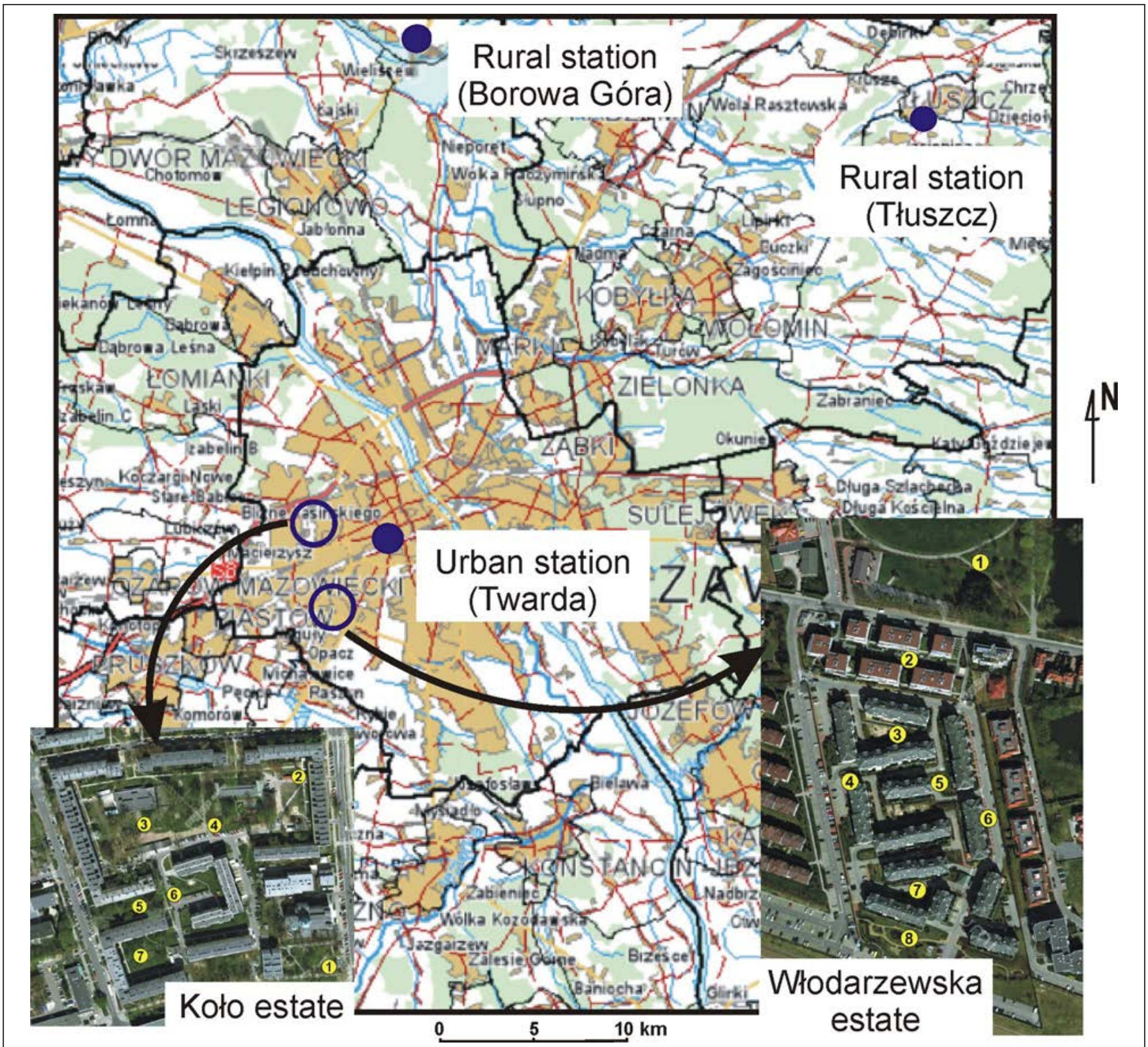

Fig. 1 Locations of the urban and rural stations as well as the measuring posts in the housing estates in Warsaw

plied for the presentation of the spatial variation of meteorological variables (air temperature and relative humidity, wind speed and solar radiation) and UTCI. The GIS used in heat stress studies consists of three groups of layers: basic environmental layers (land use, types of relief, ground moisture), basic topoclimatic layers (global solar radiation, air temperature, wind speed, air humidity) and bioclimatic layers (mean radiant temperature, UTCI). Values of particular meteorological components were calculated by the reclassification of environmental layers using coefficients of changes (*Tab. 2*) in solar radiation, wind speed, air temperature and relative humidity in different types of local landscapes. The coefficients listed in *Table 2* were derived from experimental topoclimatic research carried out in different types of landscape in Poland, 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. Since the experimental research was carried out during the warm seasons, the coefficients of the changes in air temperature are valid within the range of 5-35°C (*Błażejczyk* 2002).

Using such coefficients, the predicted values of basic meteorological elements were determined for various weather scenarios. Next, the meteorological variables modelled were used for the calculation of UTCI for every type of landscape. The following meteorological scenarios were used:

Tab. 2 Coefficients of change in global solar radiation (zr), air temperature (zt), wind speed (zv) and relative humidity (zf) in selected types of landscape

Type of landscape		Coefficients of change			
		zr	***zt***	***zv***	***zf***
Relief features	Plains	1	1	1	1
	Tops and upper parts of hills	1	1	1.4	1
	Valley bottoms (H: valley depth; W: valley width):				
	> 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 (EL: elevation above slope foot):				
	South, EL 20 - 50 m	1.2	1.2	1	0.95
	South, EL > 50 m	1.2	1.2	1	0.95
	North, EL 20 - 50 m	0.8	0.85	1	1.1
	North, EL > 50 m	0.8	0.85	1	1.1
	East/west, EL 20-50 m	1	0.95	1	1
	East/west, EL > 50 m	1	0.95	1	1
Land use	Fields and wetlands	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

– cloudy (and sunny), air temperature: 10°C, relative humidity: 50 %, wind speed: 8 m/s,
– cloudy (and sunny), air temperature: 20°C, relative humidity: 50 %, wind speed: 4 m/s,
– cloudy (and sunny), air temperature: 30°C, relative humidity: 50 %, wind speed: 2 m/s.

Because of operational limitations of the GIS applications the following simplified equation (UTCI*) was used for the presention of the Universal Thermal Climate Index on the maps:

$$UTCI^* = 0.84 \cdot ta + 0.246 \cdot Tmrt - 2.45 \cdot v + 0.204 \cdot vp - 0.01$$

where *ta* is air temperature (°C), *Tmrt* is mean radiant temperature (°C), *v* is wind speed at 10 m above ground ($m \cdot s^{-1}$), *vp* is water vapour pressure (hPa).

The simplified UTCI* equation used was derived from comparative research. The data set consisted of almost 30 000 items of information of: air temperature (within the range of -50.0 to 47.5°C), water vapour pressure (range 0.02-38.35 hPa), wind speed (0.5-22.0 $m \cdot s^{-1}$) and mean radiant temperature (ranging from -67.4 to 76.9°C). The UTCI, calculated using a polynomial function, was compared with the UTCI*. The correlation coefficient between both variable is 0.9955. The

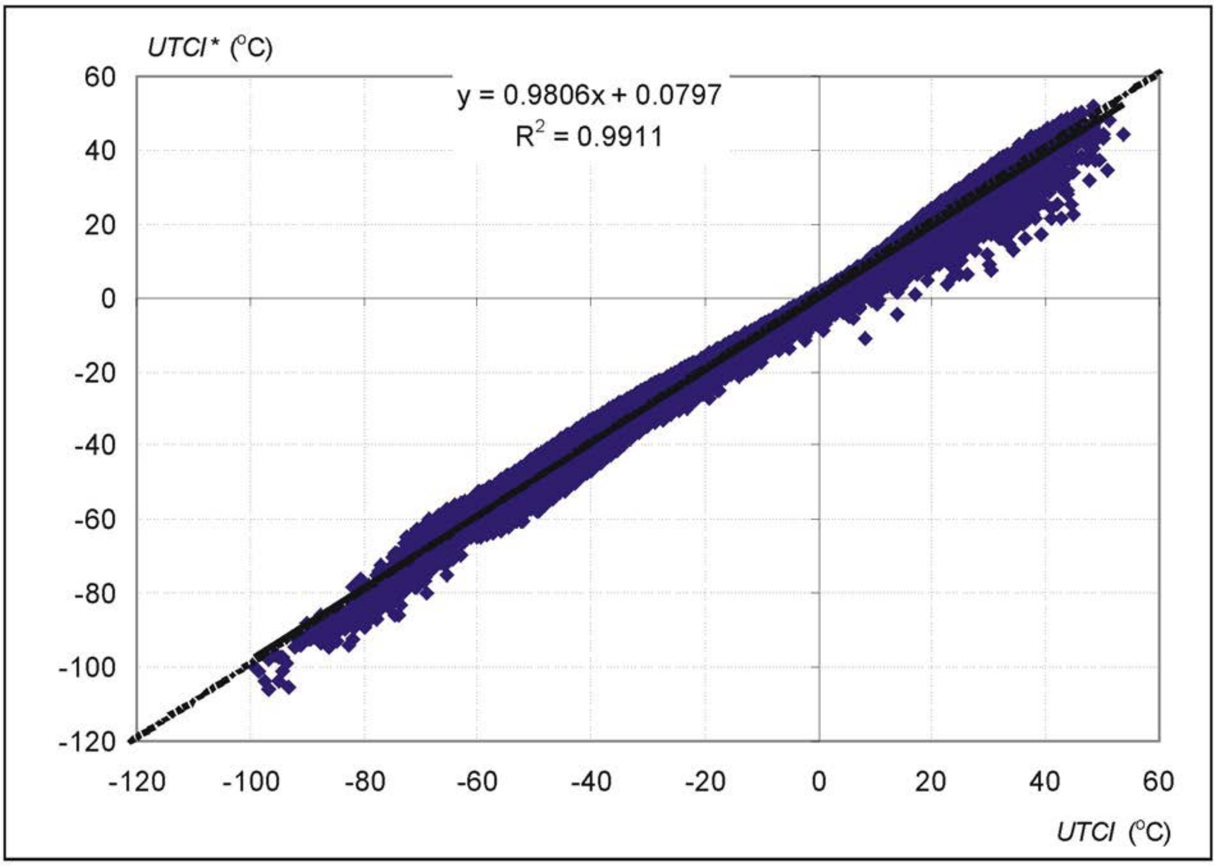

Fig. 2 Correlation between the Universal Thermal Climate Index calculated by polynomial function (UTCI) and by simplified regression model (UTCI), n=29664*

inclination coefficient of the regression line is 0.98 and the regression line is very close to the line of identity (*Fig. 2*). The mean error of the UTCI* is 0.2°C. Only 10 % of UTCI* values differ from UTCI of more then ±5°C. The highest uncertainty of UTCI* occurs at UTCI > 25°C.

The UTCI* distribution was calculated for two city types. The first was the large conurbation of Warsaw with an area of about 517 km^2 and a population of about 1.7 million (in 2012). The second type was a group of five health resorts situated in different regions of Poland. Świnoujście (area of 90 km^2, population about 41,000) is located in the coastal region of the Baltic sea. Gołdap (area 15 km^2, population 15,000) represents the north-east region. Busko (area 12 km^2, population 17,000) is located in an upland region. Konstancin (area 18 km^2, population 17,500) lies next to Warsaw in the central region and Lądek (area 20 km^2, population 6,000) represents the Sudetic region (*Fig. 3*).

Two GIS software programs were used depending on the particular city size. For the whole area of the city of Warsaw IDRISI Tajga was used. The raster size was 250 x 250 m. A comparison of LANDSAT thermal and NDVI images as well as a detailed classification of land-use units with the results of ground meteoro-

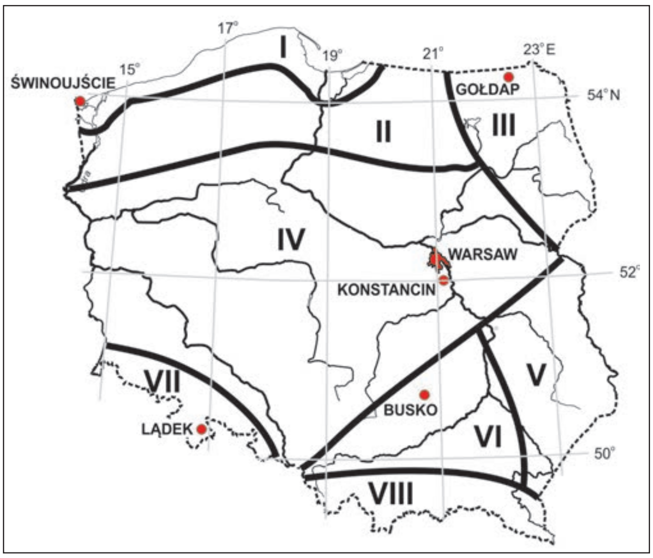

Fig. 3 Bioclimatic regions of Poland with the locations of the cities studied. Regions: I – Coastal, II – Lakeland, III – North-east, IV – Central, V – South-east, VI – Upland, VII – Sudetic, VIII – Carpathian

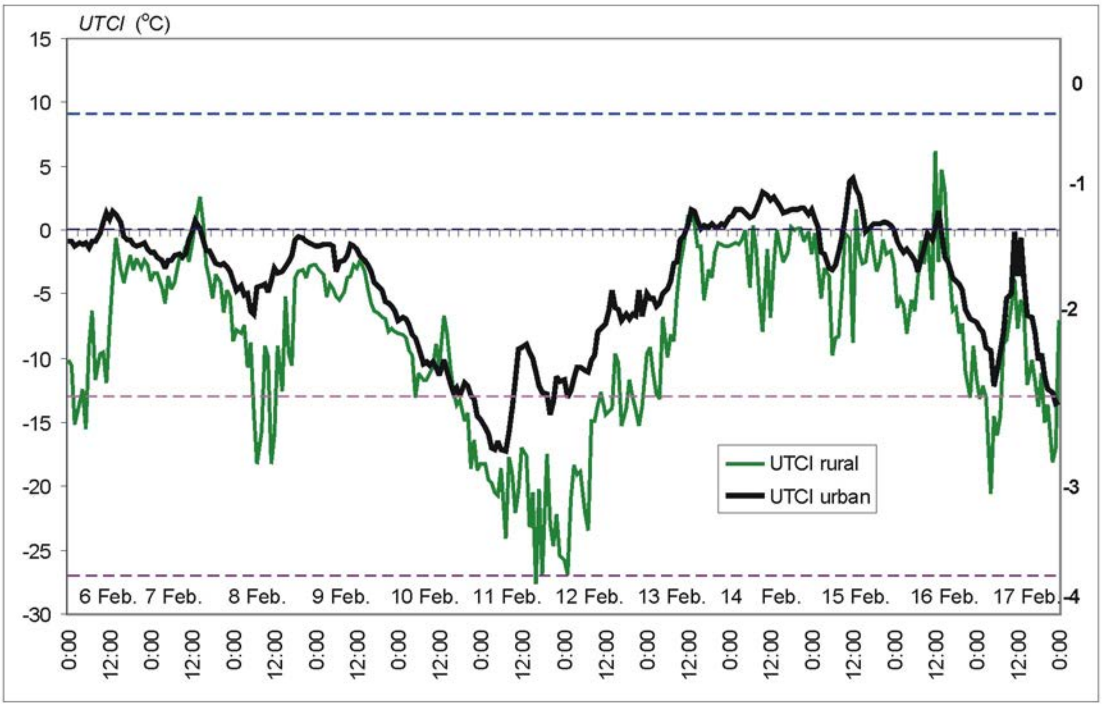

Fig. 4 Daily courses of UTCI in the centre of Warsaw (UTCI urban) and in Borowa Góra (UTCI rural), February 2007; heat stress categories: 0: no thermal stress, -1: slight cold stress, -2: moderate cold stress, -3: strong cold stress, -4: very strong cold stress

logical measurements shows that in the case of Warsaw topoclimatic conditions are an effect of the averaged influences of different urban structures and this size of raster best represents local climate conditions (*Blazejczyk* and *Blazejczyk* 1999). The environmental layers were digitised manually from topographic and thematic maps with a scale of 1:25 000. The spatial distribution of UTCI* in Warsaw was calculated for the weather scenarios mentioned above.

The spatial distribution of UTCI* values in spa towns was also modelled in the raster mode but at a resolution of 100 x 100 m which is optimal for small cities (*Milewski* 2013). For this purpose the ArcGIS for Desktop application (version 10.1) was used. Calculations of UTCI* were made using a database of environmental information created for each town. Such a database includes information about land use, types of relief and ground moisture (*Milewski* 2013). The land-use layer is based on the Corine Land Cover data for 2006 (European Environment Agency 2007). The layer with types of relief was developed using the Digital Terrain Elevation Data (DTED) for level 2 (National Geospatial-Intelligence Agency 2000). Ground moisture was estimated on the basis of information derived from surface geological maps. In each town studies were limited to the area of A and B health resort zones. UTCI* calculations are based on the following types of weather:

A) warm with moderate cloudiness: global solar radiation of 500 $W \cdot m^{-2}$, air temperature of 20°C, air humidity of 70 %, wind speed of 4 $m \cdot s^{-1}$, total cloud cover of 50 %,

B) warm and sunny: global solar radiation of 800 $W \cdot m^{-2}$, air temperature of 25°C, air humidity of 70 %, wind speed of 4 $m \cdot s^{-1}$, total cloud cover of 10 %.

3. Results

3.1 Experimentally recorded differences in UTCI

Comparing biothermal conditions in the city centre and in surrounding rural areas we found significant differences in all seasons and in various weather situations as expected. Two periods were chosen as examples, February 6-17, 2007 and June 9-16, 2008. In February the weather was mostly cloudy and frosty with weak and moderate wind speeds (1-4 $m \cdot s^{-1}$). A relatively clear sky was observed on February 16 and 17. The lowest air temperatures (about -15°C) were measured on 11th February. In June clear skies predominated, and only on June 14 and 15 convective clouds were

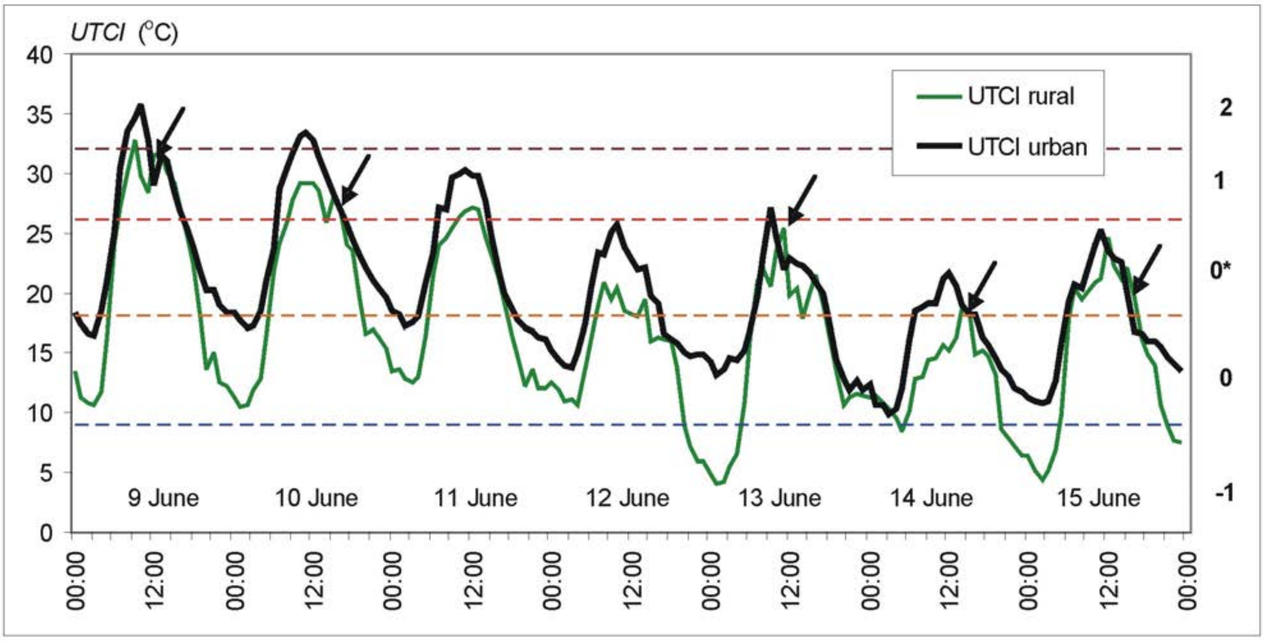

Fig. 5 Daily courses of UTCI in the centre of Warsaw (UTCI urban) and in Borowa Góra (UTCI rural), June 2008; heat stress categories: -1: slight cold stress, 0: no thermal stress (0: thermal comfort zone), 1: moderate heat stress, 2: great heat stress; the arrows indicate periods with milder thermal condition in the city in comparison to the rural area.*

noted during the daytime. Air temperature presented a typical daily rhythm from 6-10°C at night to 25-30°C during the day. Wind was weak (< 2 m · s^{-1}).

In winter the UTCI in the city centre was approximately 4°C higher on average than in the rural areas. The highest UTCI surplus in the urban area was 16.6°C. Only in few cases was the city centre cooler. This occurred at about midday when the street canyon was shaded by buildings and in the rural area clear sky led to relatively intensive insolation. Low winter UTCI values in the rural area were also the effect of a stronger wind speed compared to the city centre (*Fig. 4*).

In summer, UTCI in the downtown area of the city was on average also 4°C higher than in the rural area. The largest differences occurred in the early mornings and they reached 9.4°C. The differences in heat stress index between the sites studied were significantly lower during daytime hours and, due to the shading of street canyons, for a short time at particular hours the city centre was less thermally stressed than rural areas (*Fig. 5*).

Significant differences of UTCI between Warsaw city centre and surrounding rural areas can also be clearly observed when comparing monthly and yearly data (*Fig. 6*). Heat stress in the downtown area occurred on about 19 % of days in the years 2004-2010 while it only occurred on about 4 % of days in the rural areas. It was characteristic that very strong heat stress only appeared in the city centre. Strong heat stress occurred there from May to September (maximum in July with about 30 % of days), while in the rural areas it appeared only in July (about 2 % of days). Cold stress in the city centre was observed on about 39 % of days, mostly as slight and moderate cold stress. There were no days with very strong cold stress in the downtown area. In rural areas cold stress occurred on about 60 % of days. Very strong cold stress was observed on about 2 % days (maximum in January with about 12 % of days).

The variation of heat stress inside residential districts was examined on two sunny days, May 21-22, 2013, in two housing estates, Koło and Włodarzewska, which differ in the provision of green areas as well as in the arrangement of buildings (*Fig. 1*). On these two days the wind was weak (< 2 m · s^{-1}), mornings had clear sky, cumulus clouds were created during the day and a short 10-minute shower occurred on 22nd May. Mean values of global solar radiation in Koło were higher and more differentiated inside the estate than in Włodarzewska. This significantly influenced the calculated UTCI (*Fig. 7*). The air temperatures in the housing estates and in the city centre (Twarda) do not differ significantly and varied between 13-15°C in the mornings and 23-25°C during the middle of the day.

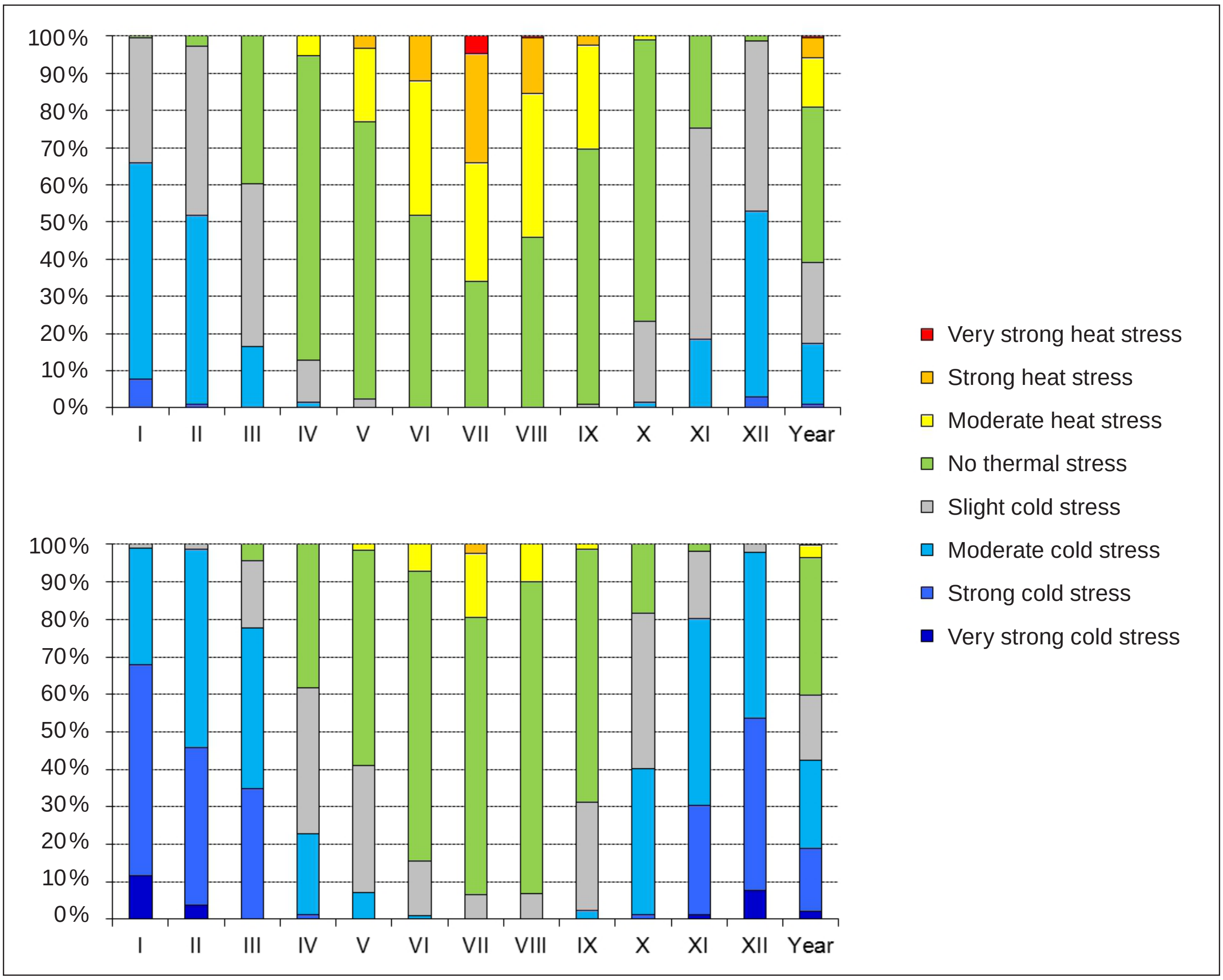

Fig. 6 Yearly courses of UTCI in the centre of Warsaw (upper panel) and in Tłuszcz rural area (lower panel), 12 UTC data, 2004-2010

The differences in air temperature in various microstructures inside both housing estates ranged from 2.5-2.8°C in the early morning to 3.3-3.5°C in the afternoon, reaching higher values in Włodarzewska. In the afternoon, the spatial differences in air temperature increased due to an increase in solar radiation (up to about 600-800 W·m^{-2}). The warmest air was that above artificial surfaces (asphalt, concrete) at well insolated sites and the coldest air was found over natural, shaded surfaces (lawns under trees). The wind tunnel effect was clearly seen at Post 2 (close to the tunnel under the block of flats) and 6 (between

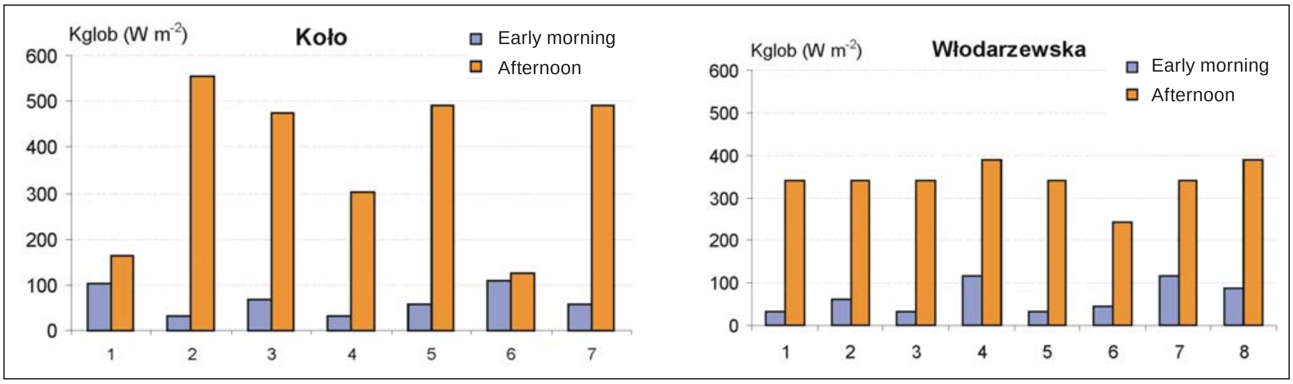

Fig. 7 Mean values of global solar radiation on particular posts in the Koło and Włodarzewska housing estates, May 21-22, 2013

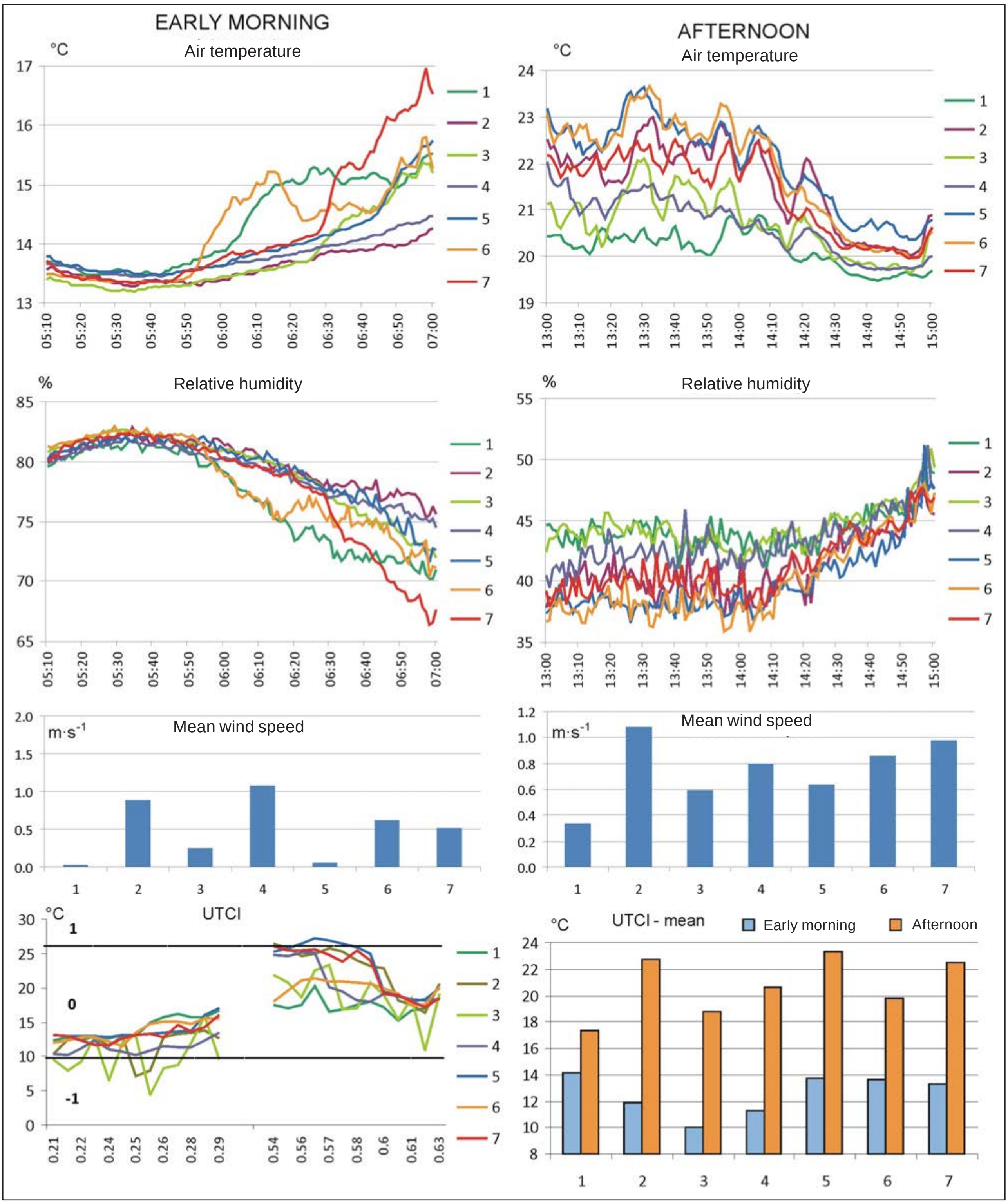

Fig. 8 Meteorological parameters and UTCI courses in Koło housing estate, 21st May 2013; UTCI heat stress categories see Tab. 1, 1-7 – numbers of posts in Fig. 1

two buildings) in Koło, and at Post 6 (on a street along a long block of flats) in Włodarzewska.

The spread of UTCI values inside the estates analysed was 3 times greater than that of air temperature (*Fig. 8, 9*), though they mostly fall in one heat stress category, namely "no thermal stress". In Koło estate the differences in UTCI values between posts at individual points in time reached 10.5°C in the morning. The coldest was recorded on a vast lawn in the centre of the estate, surrounded by

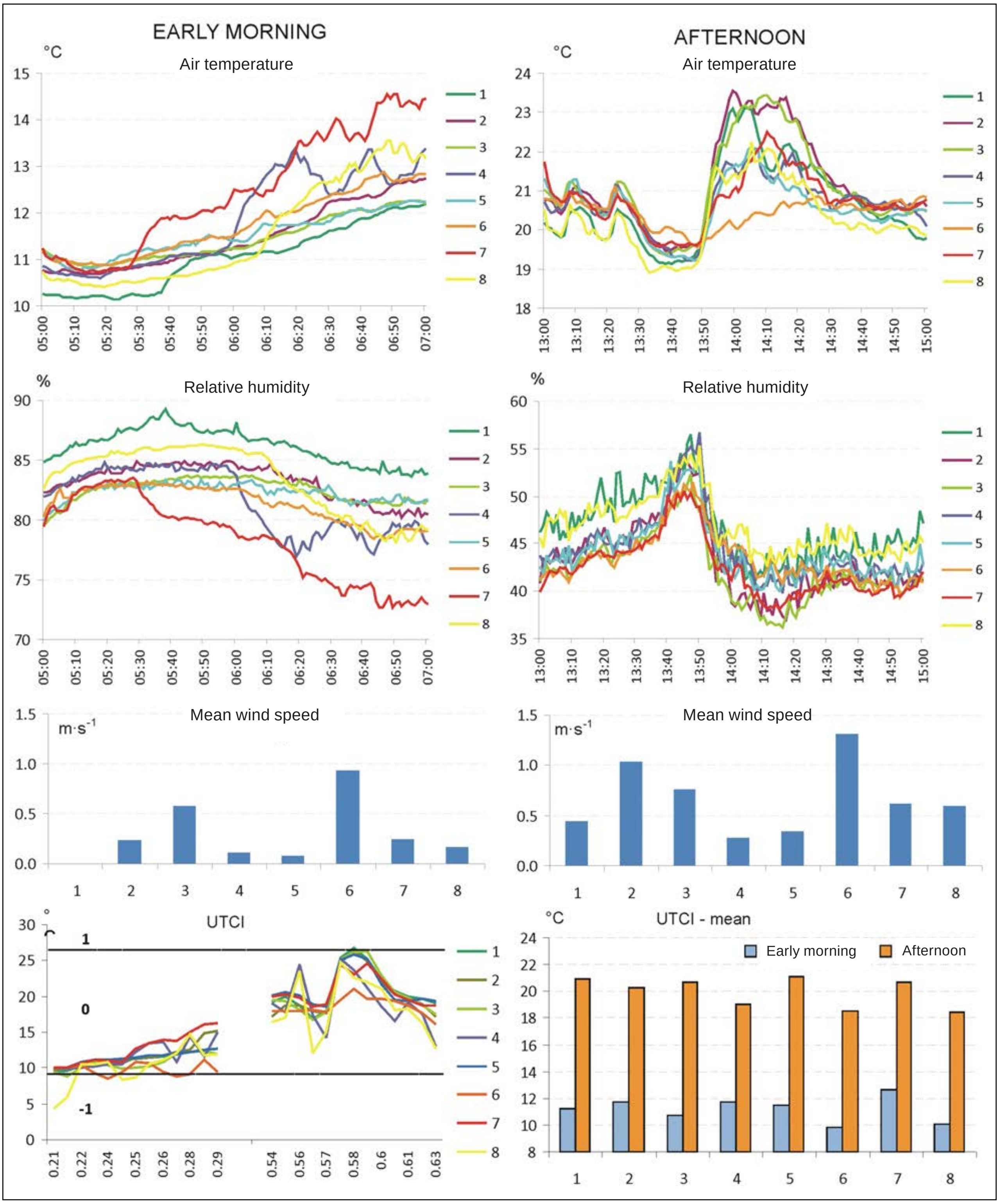

Fig. 9 Meteorological parameters and UTCI courses on Włodarzewska housing estate, 22 May 2013; UTCI heat stress categories see Tab. 1, 1-8 – numbers of posts in Fig. 1

high trees and buildings (Post 3), and the UTCI values indicated "slight cold stress" there. The warmest was a calm site under a canopy of high trees (Post 1). In the afternoon the differences in UTCI there reached 10.4°C. The coldest was a shaded site under the tree canopy (Post 1) and the warmest an asphalt-surfaced parking area (Post 5), where moderate heat stress was noted (*Fig. 8*).

In the Włodarzewska estate the differences in UTCI values were much smaller and they reached only 6.7°C in the morning (*Fig. 9*). The coldest were pavements next to a block of flats, the most windy in the estate (Post 6), and the warmest a calm and sunny square between buildings (Post 7). In the afternoon the spread of UTCI values was up to 6.8°C. The coldest site was the open space outside the estate (Post 8) and the warmest a small lawn with young trees, squeezed between blocks of flats (Post 5). Although the Włodarzewska estate is almost adjacent to a large park (Post 1, the coldest in the morning and with a 10 % higher relative humidity), there are no signs of any influence of the park on the bioclimate of the interior of the estate. This is probably caused by the arrangement of the buildings which provide a 5-floor tall wall that protects the interior of the estate from the inflow of air from the outside, and, unfortunately, precludes amelioration of the climate from this direction.

3.2 Modelled differences in UTCI

Based on topoclimatic information for particular types of landscape (*Tab. 2*) UTCI values were modelled for various weather scenarios. *Table 3* shows how heat stress can differ in urban areas depending on their spatial organisation. UTCI is significantly lower than air temperature during cool weather (taken as 10°C) due to high wind speed. However, some types of land use in the city are relatively warm. While in an open area UTCI can be -4.0°C (in sunny weather and on sunny sites) and -6.7°C in cloudy weather, in forests index values can reach 5-6°C and in downtown and industrial districts 2-5°C. During moderate weather conditions (t=20°C, f=50 %, v=4 m · s^{-1}) the highest UTCI values can be observed in densely built-up areas and the lowest ones inside forests and on the banks of water bodies (rivers, lakes). For hot, humid, calm and sunny weather, UTCI varied from about 28°C (moderate heat stress) inside forests to 42°C in the downtown area and 44°C (very strong heat stress) in industrial areas. Cloudy weather can reduce heat stress in particular parts of urban areas by 1.5°C (*Tab. 3*).

The properties of the thermal environment in urban areas are clearly seen when comparing mean deviations of UTCI (dUTCI) from standard conditions (represented by a meteorological station) calculated for midday hours. In different types of land use, depending on weather conditions, such deviations ranged in the warm season from -11.5°C (during cloudy and windy weather) to +35.5°C (during sunny weather with light winds). The biggest negative deviations are

Tab. 3 Modelled UTCI values in selected types of urban land use in cloudy and sunny conditions during various weather scenarios

Types of land use	**Sunny**	**Cloudy**	**Sunny**	**Cloudy**	**Sunny**	**Cloudy**
	ta=10°C, *RH*=50%, *v*=8 m·s^{-1}		*ta*=20°C, *RH*=50%, *v*= 4 m·s^{-1}		*ta*=30°C, *RH*=50%, *v*=2 m·s^{-1}	
Plains (standard meteorological station)	-4.0	-6.7	20.7	14.3	34.4	29.5
Fields and wetlands	-4.0	-6.7	20.7	14.3	34.4	29.5
Meadows	-4.8	-7.6	19.6	12.9	32.8	27.6
Forests	6.0	5.0	18.0	16.2	27.6	26.2
Ground transportation belts	-2.8	-5.6	21.9	15.6	35.8	31.0
Rural settlement	0.2	-2.6	24.2	18.1	38.2	33.5
Intra-forest settlement	-0.6	-2.5	18.2	15.1	30.1	27.7
Downtown	4.2	1.9	26.3	22.3	41.7	38.7
Industrial areas	4.9	2.6	27.4	23.5	43.7	40.7
Water banks	-7.1	-9.9	17.1	10.2	30.0	24.5

Stress categories:	*UTCI* (°C)
Moderate cold stress	-13.0 – 0.0
Slight cold stress	0.1 – 9.0
No thermal stress	9.1 – 18.0
	18.1 – 26.0
Moderate heat stress	26.1 – 32.0
Strong heat stress	32.1 – 38.0
Very strong heat stress	38.1 – 46.0

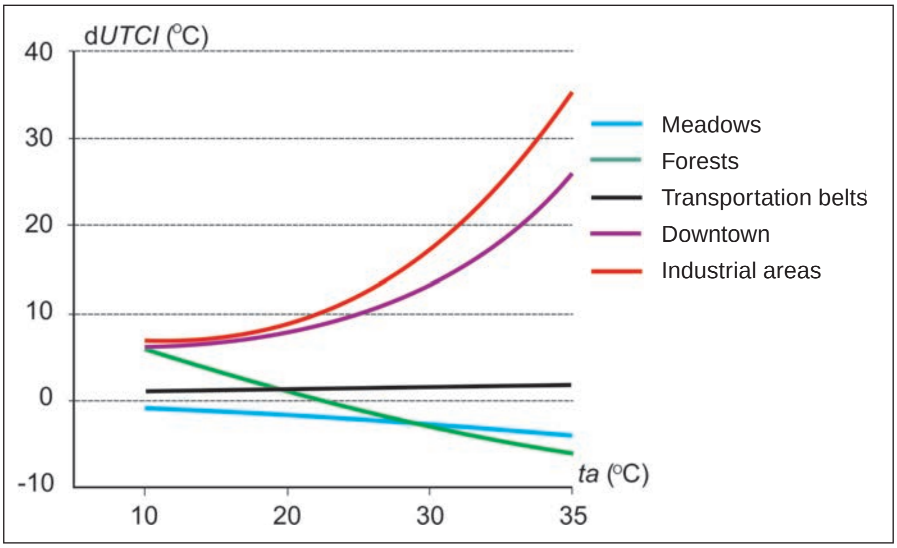

Fig. 10 Average midday hours deviations of UTCI from standard, open rural area conditions (dUTCI) in various types of land use at different air temperatures (ta) measured by meteorological station (sunny weather with weak wind and high humidity); source: Kunert 2010

noted on water bodies and in forests, however the biggest positive deviations are observed in urban areas in the downtown area and in industrial zones (*Fig. 10*).

Specific features of local climate in urban areas produce significant spatial differences in heat stress in cities. In the Warsaw area the smallest differences of heat stress are observed at moderate temperature (20°C), 50 % relative humidity and a wind speed of 4 $m \cdot s^{-1}$. In such conditions moderate heat stress (UTCI of 26-32°C) can only be found inside industrial and very densely built up areas. During extreme weather conditions complicated city structures create great spatial differences in heat stress. In cloudy, cool and windy weather, UTCI in downtown areas can fall to the moderate cold stress range. On the other hand during sunny, hot, humid and calm weather, several hot spells with extreme heat stress were found in the city centre and industrial areas (*Fig. 11*).

The modelling of UTCI* values for spa towns helps to identify the most suitable areas and weather conditions for climate therapy. During "warm with moderate cloudiness" type weather (at the meteorological station in each spa), strong heat stress does not occur anywhere. Moderate heat stress only occurs in a small part of Gołdap and Konstancin (*Fig. 12*). When global solar radiation and air temperature increase slightly, ("warm and sunny" type weather), large areas with moderate and strong heat stress appear in each health resort (*Fig. 13*). Average UTCI* values fall in the range from 24.9°C in Gołdap to 27.9°C in Busko during this type of weather. The minimum (18.1°C) and maximum (36.9°C) values of UTCI* are observed in Gołdap due to the great diversity of the environment in this town. The range of UTCI* values found there in "B" type weather reaches 18.8°C. Gołdap is also the town where the relative area of occurrence of heat stress is the smallest (25 %). The largest relative area under the influence of moderate and strong heat stress was found in Konstancin (over 50 %).

4. Discussion

Bioclimatic research on heat stress in urban areas has been carried out over the last 40 years. Authors have used both simple biometeorological indices (*Clarke* and *Bach* 1971, *Givoni* 1976) as well as indices derived from human heat balance considerations (*Terjung* 1970, *Morgan* and *Baskett* 1974, *Tuller* 1975, *Jendritzky* and *Nübler* 1981, *Burt* et al. 1982, *Terjung* and *O'Rourke* 1983, *Mayer* and *Höppe* 1987). The MENEX models were applied in different Polish towns describing the spatial distribution of thermal stress factors (*Błażejczyk* 2002, *Błażejczyk* and *Błażejczyk* 1999, *Kuchcik* 2003). Although the early human energy models were still relative simple, all the authors found urban areas, and especially their downtown districts, more thermally stressed than rural surroundings.

One of the most significant problems in studying heat stress in urban areas is the validation of radiation fluxes. They are usually expressed by mean radiant

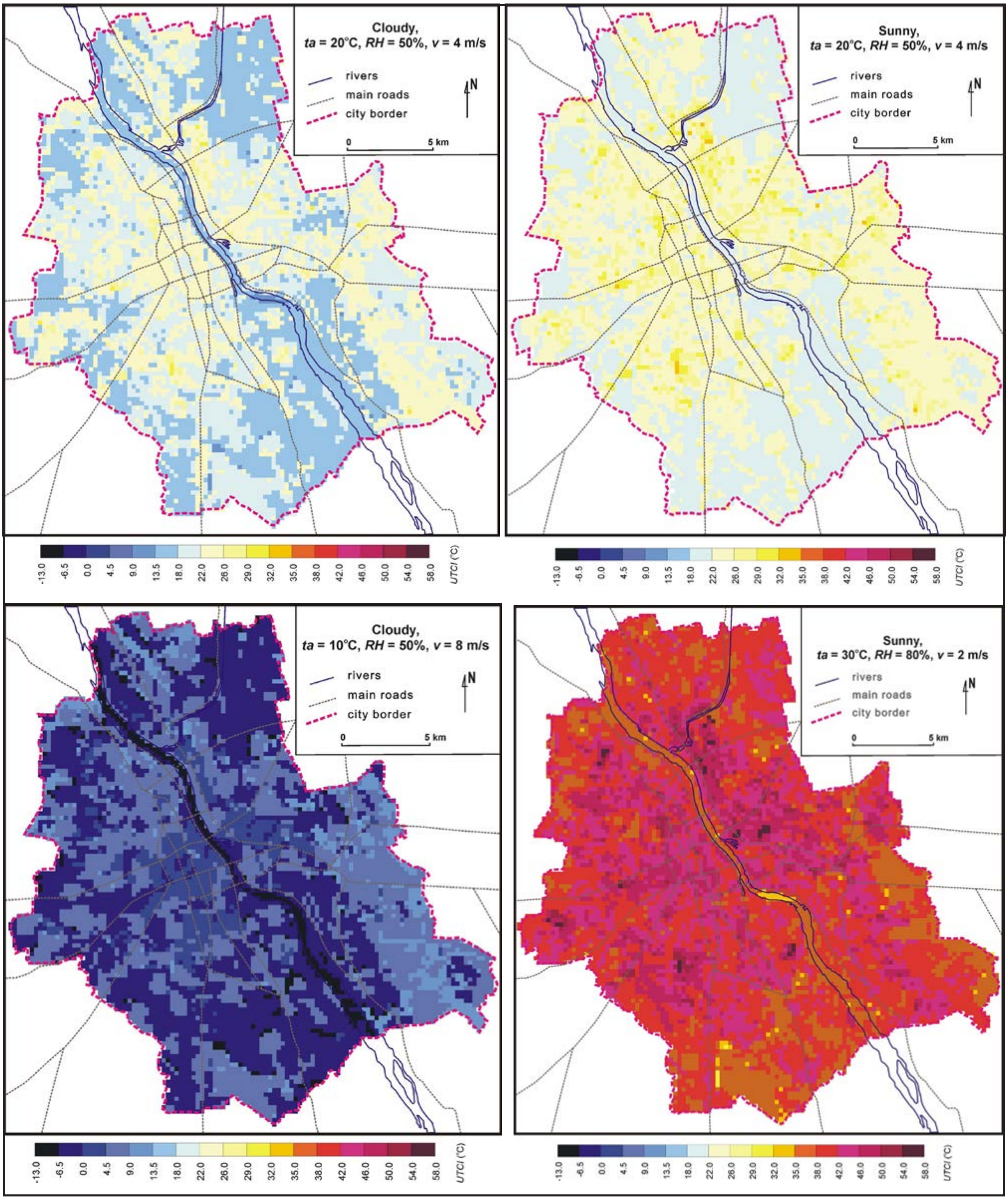

Fig. 11 Spatial distribution of UTCI in Warsaw in selected weather scenarios; source: Błażejczyk 2013*

temperature (*Mrt*). In the present research this variable was calculated through the use of the MENEX model (*Błażejczyk* and *Kunert* 2011). The model calculates *Mrt* from the value of absorbed solar radiation and long-wave radiation fluxes. A similar approach for the calculation of *Mrt* was used by *Jendritzky* (1992), *Matzarakis* et al. (2007, 2010), *Thorsson* et al. (2007) and *Weihe* et al. (2012). While the methods of calculation differ slightly, the resultant values of *Mrt* indicate similar tendencies and dependence on urban structures.

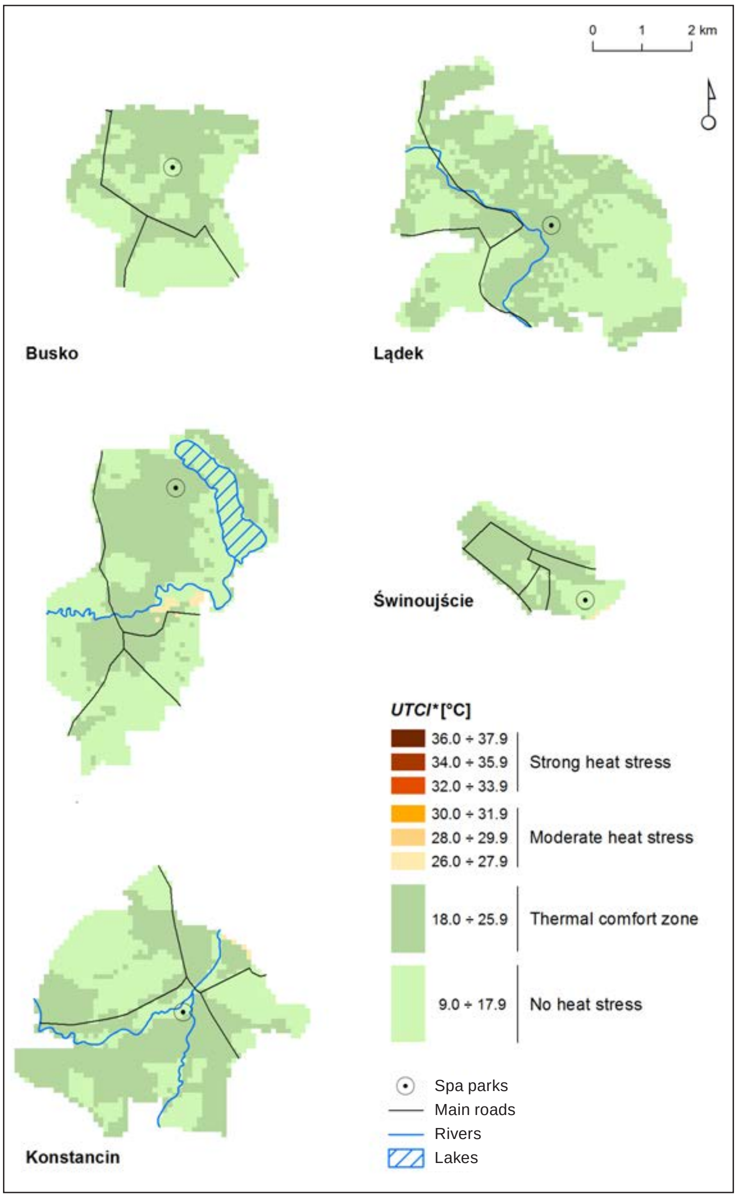

Fig. 12 Spatial distribution of the UTCI in spa towns in "warm with moderate cloudiness" type weather*

Green areas, including both lawns and trees, play an important role in creating urban heat stress. The results of experimental research presented in this paper revealed a bigger variation of UTCI inside a housing estate with a higher ratio of biologically vital areas and a lower coefficient of settlement density. The Koło estate, with a large RBVA ratio, has UTCI values that are on average up to 5.4°C lower than in the centre of the city. In the coolest place these differences are even greater and reach about 9°C in the middle of the day. In the Włodarzewska estate, with low RBVA, UTCI values do not differ significantly from the city centre. The average difference is about -1°C. At the coolest sites the difference is about -3°C (*Tab. 4*). The results are very close to the conclusions drawn by *Matzarakis* (2001) and *Lin* et al. (2010).

UTCI has been published comprehensively in 2012 in a special issue of the International Journal of Biometeorology (vol. 56, 3) and therefore so far there are only a few research studies that use UTCI to assess heat stress in urban areas. *Błażejczyk* and *Kunert* (2010) compared heat stress in 15 European cities in the summer and winter months. They found significantly increased heat stress in larger conurbations. Similar results were obtained by *Mąkosza* (2013) and *Nowosad* et al. (2013) for Polish towns.

Detailed experimental research on heat stress as defined by UTCI and its perception in the city has very rarely been carried out. *Bröde* et al. (2013) compared heat stress in different urban structures in Curitiba (Brazil). They found street canyons more stressful in comparison to open spaces. However, *Lindner-Cendrowska* (2013) documented the application of UTCI in research dealing with thermal perception in cities.

Until now only three papers have reported the use of UTCI to present the spatial variability of heat stress in urban areas. *Kunert* (2010) found a great influence from both meteorological conditions and urban structures on UTCI values. The greatest heat stress was observed in downtown and industrial districts. On the other hand, water bodies and urban green (parks, forests) mitigate heat stress. Cartographic presentations of the UTCI distribution were made by *Błażejczyk* (2011) for Warsaw as well as by *Milewski* (2013) for the mountain region of Ziemia Kłodzka in the Polish Sudety Mountains. The last paper gives valuable results regarding the applicability of UTCI and GIS tools in bioclimatic research in contrasting mountain landscapes.

5. Conclusions

The results of both experimental and modelling research carried out in urban areas show the great applicability of the Universal Thermal Climate Index in studies of heat stress caused by different structures in cities.

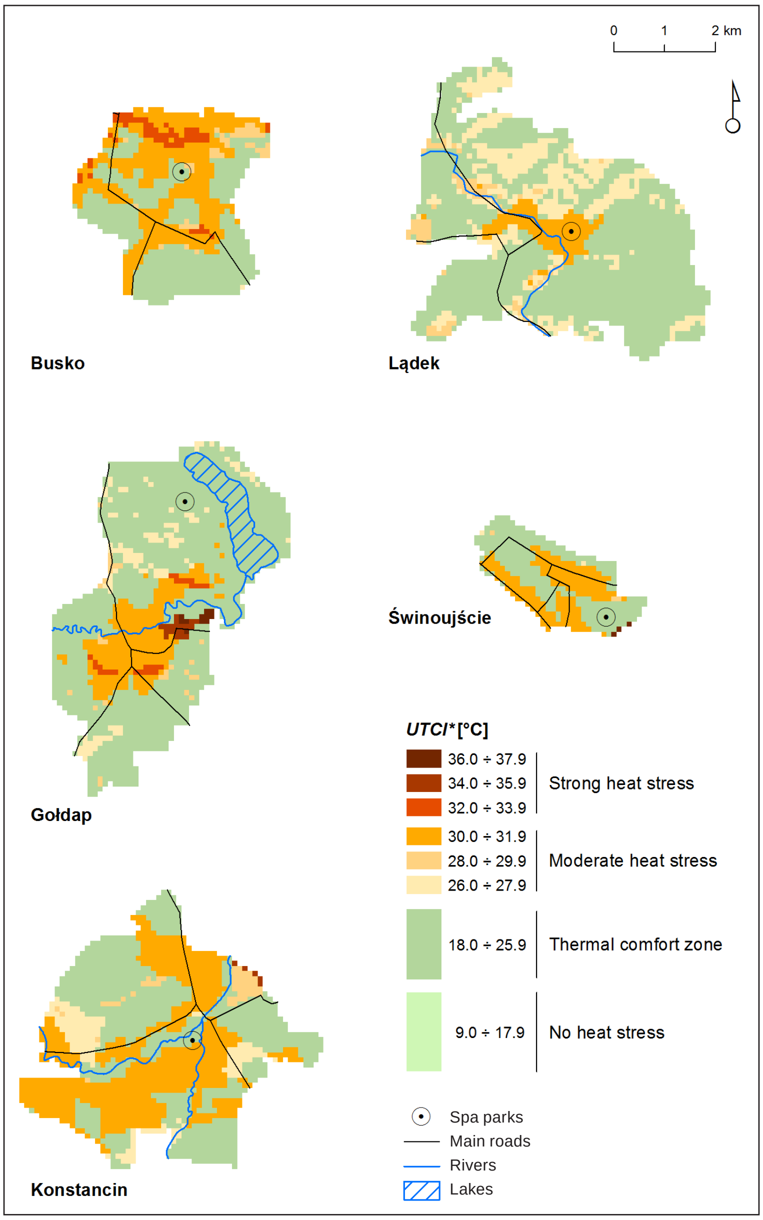

Fig. 13 Spatial distribution of the UTCI in spa towns in "warm and sunny" type weather*

The UTCI very clearly indicates the general features of the urban bioclimate both in comparison to rural areas and in relation to its annual cycles. We have found that intensive heat stress is more frequently observed inside the city than in rural areas. Such urban heat surplus occurs over complete days in both winter and summer seasons.

The UTCI is very sensitive to even small changes in the meteorological variables induced by different urban structures at a very detailed scale. Comparison of two housing estates with different structures shows that low density settlements with a large proportion of biologically vital surfaces and trees can create relatively mild biothermal conditions.

UTCI applied through GIS tools can give a very clear presentation of the spatial differentiation of heat stress caused by urban structures both in large conurbations and in small towns. City centres and industrial districts are clearly seen as the areas with the greatest heat stress.

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Tab. 4 Differences in UTCI values (°C) between the housing estates examined and the city centre

Estate	Time of day	Average	Hottest site inside estate	Coolest site inside estate
Koło (RBVA 54%, SDC 0.8)	Morning	-1.7	-0.1	-4.3
	Midday	-5.4	-2.8	-8.8
Włodarzewska (RBVA 41%, SDC 1.25)	Morning	-0.9	0.6	-2.3
	Midday	-1.3	-0.2	-2.9

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