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Spatial variation of the Universal Thermal Climate Index in Lublin in specified weather scenarios

Zróżnicowanie przestrzenne wskaźnika UTCI w Lublinie
w określonych scenariuszach pogodowych

Key words: urban bioclimate, sensible climate UTCI urban planning, Lublin
Słowa kluczowe: bioklimat miasta, odczuwalny UTCI, planowanie przestrzenne, Lublin

INTRODUCTION

Due to the diversified land relief and presence of numerous gorge dissections intensively used by man largely for recreational purposes, Lublin is a valuable study area in terms of bioclimatology. The results of modelling of the variation of the bioclimatic conditions of Lublin provide information useful e.g. in the economy and spatial planning. The determined features of the city's bioclimate can be a significant element in the selection of locations for new residential and recreational investments. Knowledge on the spatial variation of biometeorological situations positively and negatively influencing the human organism can also find application in activities concerning the improvement of life quality and health protection, as well as in tourism and recreation. The objective of the paper is to present the spatial variation of biometeorological conditions in Lublin based on the example of specified weather scenarios.

STUDY AREA

The area within which the model of spatial distribution of UTCI values was executed covers the area within the administrational boundaries of Lublin[1], the

[1] The paper does not discuss the southern part of the Zemborzyce Reservoir and the adjacent area located within the city's boundaries due to the lack of complete necessary data for the area.

largest city of Poland located to the east of the Vistula River (Fig. 1). The paper adopted the geomorphological division by H. Maruszczak (1972). According to the division, Lublin includes areas belonging to three geomorphological mesoregions – the Nałęczów Plateau, the Bełżyce Plateau, and the Łuszczów Plateau.

The mean air temperature at the Lublin-Radawiec station (located 13 km SW of the city centre) equals 7.5°C (based on the period 1976–2010). The 24-hour temperature in the centre of Lublin is higher than that in the suburbs by approximately 0.9°C (Filipiuk et al. 1998). Kaszewski et al. (2011) specified days with the 24-hour temperature > 20°C as strenuous for active tourism, and calculated that approximately 20 such days occur annually at the Lublin-Radawiec station, and 33 in the city centre.

The mean annual sunshine duration in the centre of Lublin equals 1542 hours (Gluza 2000). The mean annual cloudiness is 68% (Gluza, Kaszewski 2007).

The area of Lublin subject to the analysis covers 132.41 km^2. Land cover and land use classes were distinguished within the area (Fig. 2). The "fields and wastelandland" class predominates, occupying 36.7% of the area. In this paper, this class also includes allotment gardens. "Urban and industrial areas" (including buildings) and "transportation areas" constitute 34.0% of the area of Lublin analysed. Grassy areas classified as "meadows" cover 16.1% of the study area. The remaining classes distinguished ("lakes and rivers", "forests", "parks", and "orchards") occupy a total of 13.2% of the area described (Fig. 3).

MATERIAL

The paper used digital spatial data including information on the land relief and land cover use of Lublin. The land relief was presented with the application of a digital elevation model (DEM) numerical terrain model with a resolution of 5 x 5 m, generated based on a contour drawing of the topographic map at a scale of 1:10000 PUWG 1992. Information on the type of land cover and land use comes from the Topographic Database (TBD) (*GUGiK*) and topographic maps at a scale of 1:10000. Based on the data the division of land cover and land use classes was made. This division was slighty modified (Fig. 2, Fig. 3) comparing to the K. Błażejczyk (2001) (Tab. 2) division. All of the maps included in the paper were prepared by means of the ArcGIS 10 software.

METHOD

The description of the spatial variation of bioclimatic conditions in Lublin adopted a new bioclimatic index, namely the Universal Thermal Climate Index (UTCI). Its main quality distinguishing the index from the traditional biothermal descriptions indicating so-called thermal sensations is the fact that it is based on

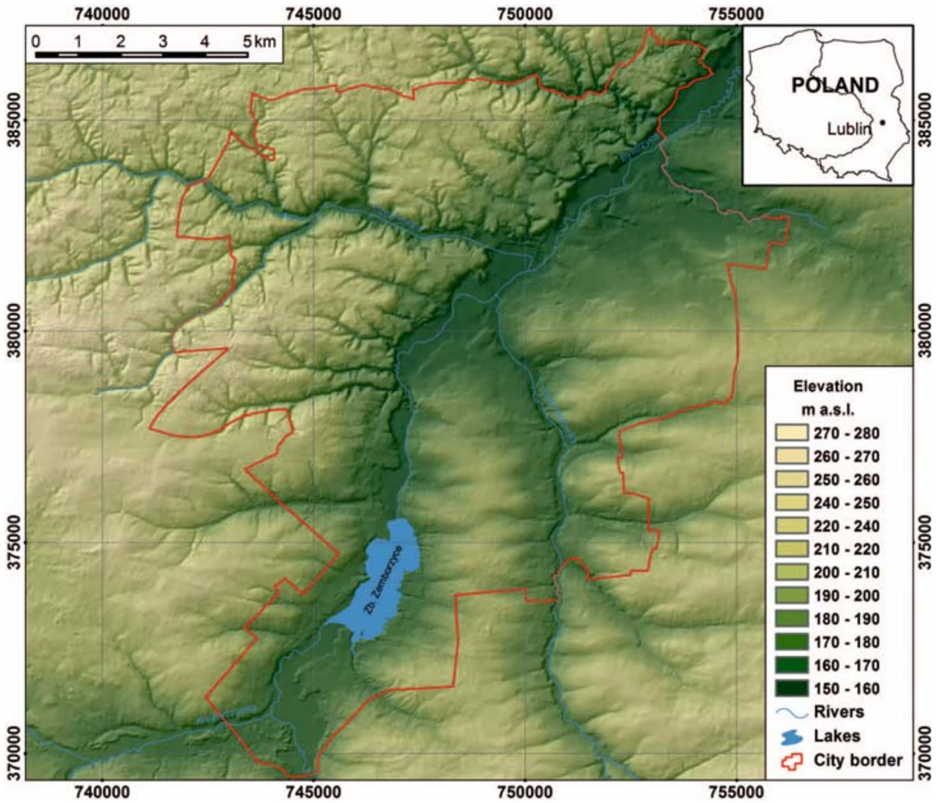


Fig. 1. The relief of Lublin and surrounding areas
Ryc. 1. Rzeźba terenu Lublina i okolic

changes of physiological parameters of the human organism induced by the effect of the atmospheric environment (Błażejczyk et al. 2010a 2010b; Błażejczyk, Kunert 2011; P. Bröde et al. 2012). This permits attributing specific heat stress of the organism to the relevant index values (Tab. 1).

UTCI is based on the multi-node model of the human heat balance, the so-called Fiala Model (Fiala et al. 2001; Fiala et al. 2011), considering two parameters of heat exchange regulation between the human organism and the surroundings. The first one, called passive, involves the transport of heat inside the organism and on the body surface. The second one, called active, determines the physiological mechanisms of thermoregulation. The index can take the form of the following function:

UTCI = f (Ta, vp, va, dTmrt)

where:

Ta – air temperature [°C],

vp – water-vapour pressure [hPa],

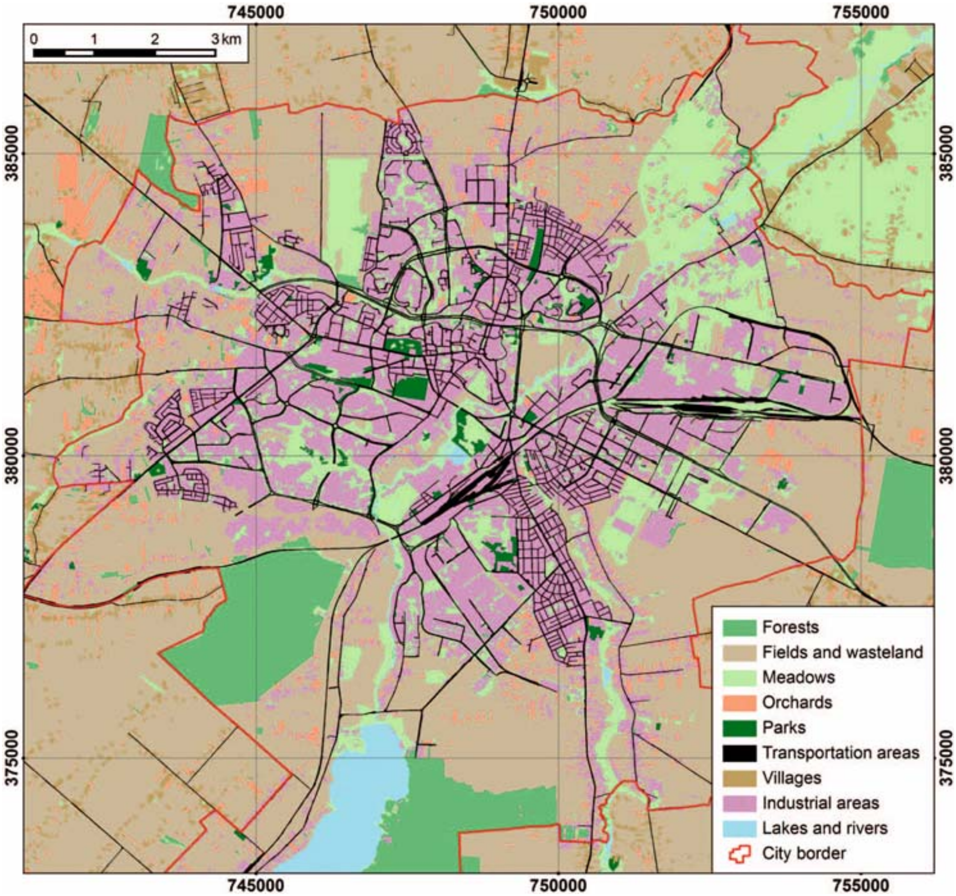


Fig. 2. Land cover and land use classes within the area of Lublin subject to analysis (data source: GUGiK, Topographic Database)

Ryc. 2. Klasy pokrycia i użytkowania terenu w obrębie Lublina (źródła danych: GUGiK, Baza Danych Topograficznych)

va – wind velocity at a height of 10 m above the ground [$m \cdot s^{-1}$],

dTmrt – difference between the mean radiation temperature and air temperature [°C].

The spatial variation of biometeorological conditions in Lublin was prepared based on the method proposed by K. Błażejczyk (2001, 2002, 2011). The digital database in the form of a raster with a resolution of 5 x 5 m included information reclassified into categories (Tab. 2) regarding: land relief, land cover and use, and ground moisture. Ground moisture classes were distinguished by means of the saturation model SINMAP. Detailed information about model construction and calculating relative humidity are presented in the paper by R. T. Pack'a et al. (1998) and in the *SINMAP User's Manual.*

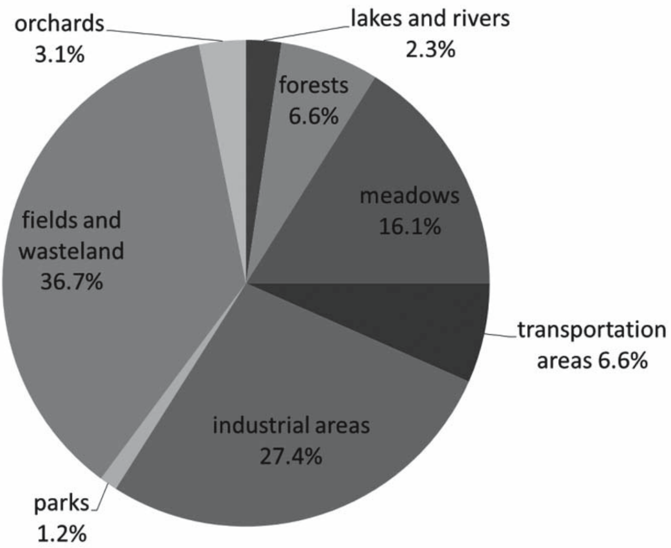


Fig. 3. Land cover and land use classes [%] distinguished within the area of Lublin discussed (data source: GUGiK, Topographic Database)

Ryc. 3. Klasy pokrycia i użytkowania terenu [%] wydzielone w obrębie opisywanej powierzchni Lublina (źródła danych: GUGiK, Baza Danych Topograficznych)

Tab. 1. The scale of the estimation of heat stress of the organism according to UTCI (Błażejczyk, Kunert 2011)

Tab. 1. Skala oceny obciążeń cieplnych organizmu według UTCI (Błażejczyk, Kunert 2011)

UTCI [°C]	Stress category	Recommendations for protection
> 46	extreme heat stress	periodical cooling and drinking > 0.5 $l \cdot h^{-1}$ necessary; stay without activity
38.1 – 46.0	very strong heat stress	periodical use of air conditionor shaded sites and drinking > 0.5 $l \cdot h^{-1}$ necessary; reduce activity
32.1 – 38.0	strong heat stress	drinking 0.25 l/h^{-1} necessary, use shade places and reduce activity
26.1 – 32.0	moderate heat stress	drinking 0.25 $l \cdot h^{-1}$ necessary
9.1 – 26.0	thermoneutral zone	physiological thermoregulation sufficient to keep comfort
0.1 – 9.0	slight cold stress	use gloves and cap
-12.9 – 0.0	moderate cold stress	increase activity, protect extremities and face against cooling
-26.9 – -13.0	strong cold stress	strongly increase activity, protect face and extremities; use better insulated clothing
-39.9 – -27.0	very strong cold stress	strongly increase activity, protect face and extremities; use better insulated clothing; reduce stay outdoor
< -40.0	extreme cold stress	stay indoor or use heavy, wind protected clothing

The change coefficients included in Table 2, specified for the global solar radiation intensity (zr), albedo (za), air temperature (zt), and wind velocity (zv), describe generalised changes of the basic meteorological elements recorded in various types of the geographical environment in relation to conditions at the standard meteorological station (Błażejczyk 2002).

In this paper, the UTCI values were calculated based on the following simplified formula (Błażejczyk, Kunert 2011):

$UTCI = 3.21 + 0.872 \cdot t + 0.2459 \cdot Mrt - 2.5078 \cdot v - 0.0176 \cdot f$

where:

Mrt – mean radiation temperature [°C],

t – air temperature [°C],

f – relative air humidity [%],

v – wind velocity [$m \cdot s^{-1}$].

Mrt values were obtained from the following formula:

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

where:

Lg – ground radiation [$W \cdot m^{-2}$],

La – back atmospheric radiation [$W \cdot m^{-2}$],

R' – radiation absorbed by nude man [$W \cdot m^{-2}$].

Individual Mrt components were calculated by means of the following formulas (Błażejczyk, Kunert 2011):

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

where:

Tg – ground temperature, determined according to the following formulas depending on the degree of cloudiness:

– at cloudiness N > 80% and in forests Tg = t,

– at cloudiness N < 80% and t ≥ 0°C Tg = 1.25 · t,

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

where:

e – current water-vapour pressure [hPa] calculated according to the formula:

$e = 6.112 \cdot 10^{[(7.5 \cdot t) / (273.7 + t)]} \cdot 0.01 \cdot f$

R' was determined for the solar altitude > 12°. The values describing a sunny day were calculated according to the formula:

$R' = 6.160389 \cdot K_{glob}^{0.4861}$,

and respective R' on a cloudy day, according to the formula:

$R' = 0.170223 \cdot K_{glob}^{0.9763}$,

where:

K_{glob} – global solar radiation intensity [$W \cdot m^{-2}$].

The values of the global solar radiation intensity were determined by means

Tab. 2. Coefficients of changes in the global solar radiation intensity (zr), air temperature (zt), and wind velocity (zv) at a height of 2 m above the ground level, as well as the coefficient of albedo changes (za) (Błażejczyk 2001)

Tab. 2. Współczynniki zmian natężenia całkowitego promieniowania słonecznego (zr), temperatury powietrza (zt) i prędkości wiatru (zv) na wysokości 2 m nad gruntem oraz współczynnika zmian albedo (za) (Błażejczyk 2011)

Components of geographical environment		Modifying coefficients			
		(zr)	(za)	(zt)	(zv)
Relief	uplands	1.00	1.00	1.00	1.00
	valleys	1.05	1.00	0.95	0.90
	hills and peaks	0.95	1.00	0.95*	1.15
	ridges	0.95	1.00	0.95*	1.20
	S slopes	1.20	1.00	1.20*	1.10*
	N slopes	0.80	1.00	0.90*	1.10*
	E/W slopes	1.00	1.00	1.00*	1.15*
Land use	forests	0.30	0.90	0.90	0.20
	forests (allotment gardens)	1.00	1.00	1.00	1.00
	rural areas	1.00	1.20	0.95	1.00
	orchards	0.90	1.00	0.95	0.80
	parks	0.60	0.90	0.95	0.60
	transport areas	1.00	0.80	1.05	0.95
	villages	1.00	0.90	1.10	0.80
	urbanised areas	0.80	1.10	1.25	0.60
	lakes	1.00	0.50	0.85	1.10
Ground moisture	dry	1.00	1.00	1.00	1.00
	wet	1.00	1.00	0.95	1.00
	watered	1.00	1.00	0.90	1.00

* considering varied relief of analyzed area and significant height differences in this paper maximum values of modifying coefficients depended on relative height were used (Błażejczyk 2001)

* uwzględniając zróżnicowaną rzeźbę analizowanego terenu i znaczące różnice wysokości, w artykule posłużono się wartościami maksymalnymi współczynników modyfikujących, zależnie od wysokości względnej (Błażejczyk 2001)

of the RayMan Pro 2.0 software (Matzarakis et al. 2007). The values obtained correlate with the theoretical K_{glob} intensity in Lublin, at 12 a.m. of the local time. Depending on the weather scenario analysed in the paper, values reflecting K_{glob} on 1 April (550 $W{\cdot}m^{-2}$) or 1 July (850 $W{\cdot}m^{-2}$) were used.

Biotopoclimatic maps were prepared for six weather scenarios differing in air temperature values (t), relative air humidity (f), degree of cloudiness (N), and global solar radiation intensity (K_{glob}):

t = 10°C, f = 50%, N = 0%, K_{glob} = 550 $W{\cdot}m^{-2}$,
t = 10°C, f = 50%, N = 100%, K_{glob} = 550 $W{\cdot}m^{-2}$,
t = 20°C, f = 50%, N = 0%, K_{glob} = 850 $W{\cdot}m^{-2}$,
t = 20°C, f = 50%, N = 100%, K_{glob} = 850 $W{\cdot}m^{-2}$,
t = 30°C, f = 80%, N = 0%, K_{glob} = 850 $W{\cdot}m^{-2}$,
t = 30°C, f = 80%, N = 100%, K_{glob} = 850 $W{\cdot}m^{-2}$.

In all of the scenarios, constant wind velocity of 2 $m{\cdot}s^{-1}$ was adopted.

It should be remembered that the occurrence of scenarios 5 and 6 in Lublin is practically impossible. The authors decided to introduce the scenarios for the purpose of demonstrating the possibilities of modelling the biotopoclimate variation in situations strongly straining the human organism. Similar weather scenarios were used among others in papers by A. Kunert (2010) and K. Błażejczyk (2011) for the analysis of the spatial variation of UTCI in the area of the Mazowsze Plain and in Warsaw. However, weather scenarios in other papers are slightly different and it makes comparison of the obtained results difficult.

RESULTS

In the weather scenarios analysed, the mean UTCI values in Lublin are from 11.3°C to 37.0°C (Tab. 3). Considering the variation of the land relief of the area described, the highest mean UTCI values distinguish the southern slopes of gorges and valleys (Fig. 4). Slightly lower mean UTCI values distinguish elevated areas and eastern or western slopes. The lowest mean index values are typical of northern slopes and gorge and valley floors. An example of this is the Bystrzyca River valley and smaller valleys of its tributaries: the Czechówka and Czerniejówka Rivers, where in each of the scenarios described lower heat stress occurs in comparison to the remaining areas of the city. The minimum UTCI values vary from 6.5°C (scenario no. 2) to 27.0°C (scenario no. 5). On the other hand, the maximum UTCI values reach from 17.8°C (scenario no. 2) to 54.1°C (scenario no. 5). The difference between maximum and minimum varies from 11.3°C (scenario no. 2) to 27.2°C (scenario no. 5). This difference increases with increasing temperature (Tab. 3). The highest spatial variation of UTCI values occurs in the western part of Lublin, belonging to the Nałęczów Plateau according to the division by

H. Maruszczak (1972). This region of the city is strongly dissected by dry erosional-denudational valleys the density of which within the Plateau amounts to 2.47 km/km^2 (Rodzoś et al. 2006). The slopes of the valleys, exposed to the south, are distinguished by higher values of the index than the right slopes exposed to the north. In the areas located east of the Bystrzyca River and north of the Czechówka River valley, due to lower land relief variety dominated by weakly dissected plateaus with gentle slopes, substantially lower variation of the index values is observed. Similar features of spatial variation were obtained by analysing the distribution of insolation in Lublin (Dobek, Gawrysiak 2009).

Considering the land use, in each of the weather scenarios discussed, the highest mean UTCI values are obtained for "urban and industrial areas" (Fig. 5, Fig. 6). At this stage of use, in scenario no. 5 (t = 30°C, f = 80%, N = 0%, K_{glob} = 850 W·m^{-2}), heat stress classified as "very strong heat stress" occurs. It is then necessary to periodically use air conditioned facilities or shaded places. In the case of occurrence of such a load of the organism, physical effort should be limited (Błażejczyk et al. 2010a). According to the model, among the natural forms of land use, the highest mean UTCI values in the weather conditions analysed are typical of forests. In the situation of the occurrence of weather conditions described in scenario no. 5, the "strong heat stress" load class should be expected in forests. UTCI values similar to those expected in forest areas are specified by the model also in municipal parks. In forests and parks, as a result of modifications of basic meteorological elements in relation to grassy surfaces on which standard meteorological measurements are conducted, among others the weakening of direct solar radiation in the near-ground layer is observed, as well as a decrease in the air temperature amplitude, higher relative air humidity, and a significant decrease in wind velocity (Jankowiak 1976; Bogucki 1999; Krawczyk, Błażejczyk 1999). It should be remembered that during hot days in these areas, difficulties in transferring heat to the surroundings can occur. This may lead to straining the thermoregulatory system of the organism (Błażejczyk 1993; Krawczyk, Błażejczyk 1999). The highest heat stress in the forecasted conditions occurs in areas located near the rivers and the reservoir. In the scenario assuming conditions favouring the highest heat stress of human organism, the "thermoneutral zone" class should be expected in those parts of Lublin.

CONCLUSIONS

The weather scenarios adopted in the paper were used to prepare models presenting the spatial variation of UTCI values in the area of the city. Due to the high variety of landforms, the city is a kind of a mosaic of microclimates. It should be remembered that the images obtained are only a certain theoretical approximation

Tab. 3. Mean, minimum and maximum UTCI [°C] values and heat stress in the area of Lublin in specified weather scenarios

Tab. 3. Średnie, minimalne i maksymalne wartości UTCI [°C] oraz obciążenie cieplne na terenie Lublina w określonych scenariuszach pogodowych

No.	Weather scenario	Mean UTCI Heat load	Minimum UTCI Heat load	Maximum UTCI Heat load
1.	t = 10°C, f = 50%, N = 0%, K_{glob} = 550 W·m^{-2}	13.9 lack of heat stress	9.0 slight cold stress	20.3 thermoneutral zone
2.	t = 10°C, f = 50%, N = 100%, K_{glob} = 550 W·m^{-2}	11.3 lack of heat stress	6.5 slight cold stress	17.7 thermoneutral zone
3.	t = 20°C, f = 50%, N = 0%, K_{glob} = 850 W·m^{-2}	26.3 moderate heat stress	18.8 thermoneutral zone	38.2 strong heat stress
4.	t = 20°C, f = 50%, N = 100%, K_{glob} = 850 W·m^{-2}	24.3 lack of heat stress	16.9 thermoneutral zone	36.0 strong heat stress
5.	t = 30°C, f = 80%, N = 0%, K_{glob} = 850 W·m^{-2}	37.0 strong heat stress	27.0 moderate heat stress	54.1 extreme heat stress
6.	t = 30°C, f = 80%, N = 100%, K_{glob} = 850 W·m^{-2}	34.8 strong heat stress	24.9 thermoneutral zone	51.6 extreme heat stress

of actual conditions. However, they permit the estimation of the effect of the land relief and types of land use on the development of biometeorological conditions.

Considering the variation of land relief of Lublin, in the weather scenarios analysed in the paper, the highest modelled mean UTCI values reflecting “very strong heat stress” distinguish slopes of gorges and valleys exposed to the south. Somewhat lower mean UTCI values are typical of elevated areas and eastern or western slopes. The lowest index values occur on slopes exposed to the north and on gorge and valley floors. The highest variation of UTCI values occurs in the western part of Lublin, within the Nałęczów Plateau. As a result of less varied land relief, the areas of the city located east of the Bystrzyca River valley and north of the Czechówka River valley are distinguished by clearly lower variation of the index values. Considering the land use, the highest modelled UTCI values in each of the weather scenarios discussed are typical of “urban and industrial areas”.

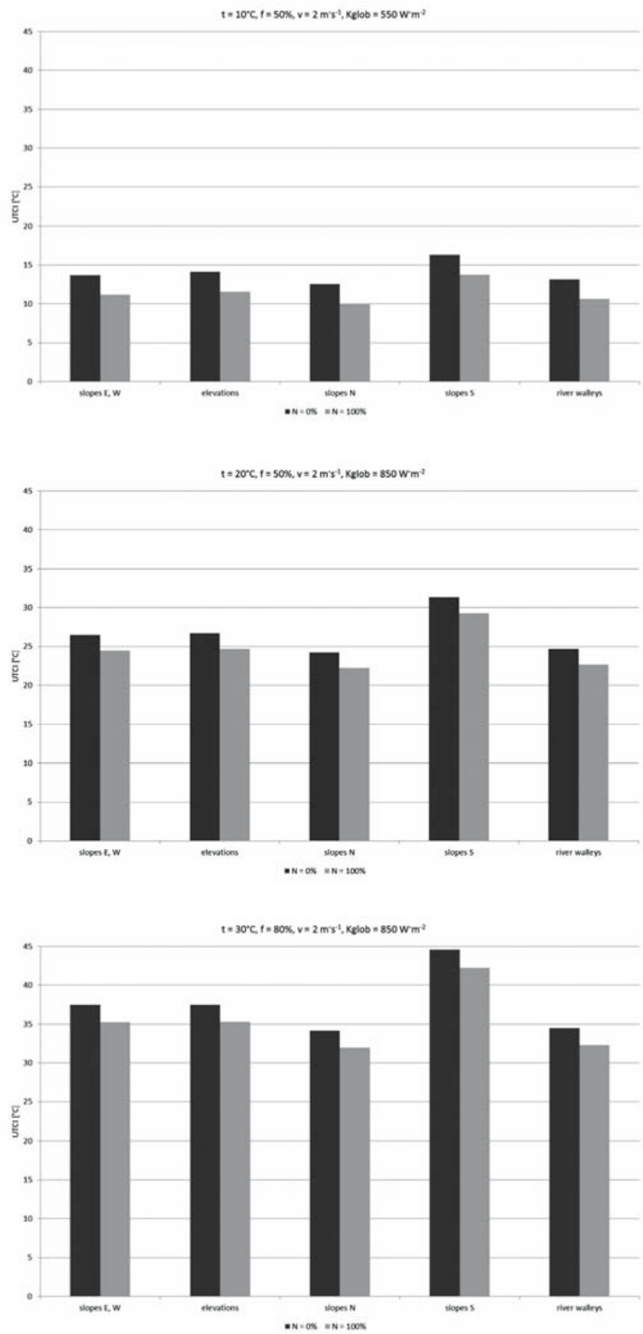


Fig. 4. Mean UTCI values in various landforms in Lublin in specific weather scenarios

Ryc. 4. Średnie wartości UTCI w różnych formach rzeźby terenu w Lublinie w określonych scenariuszach pogodowych

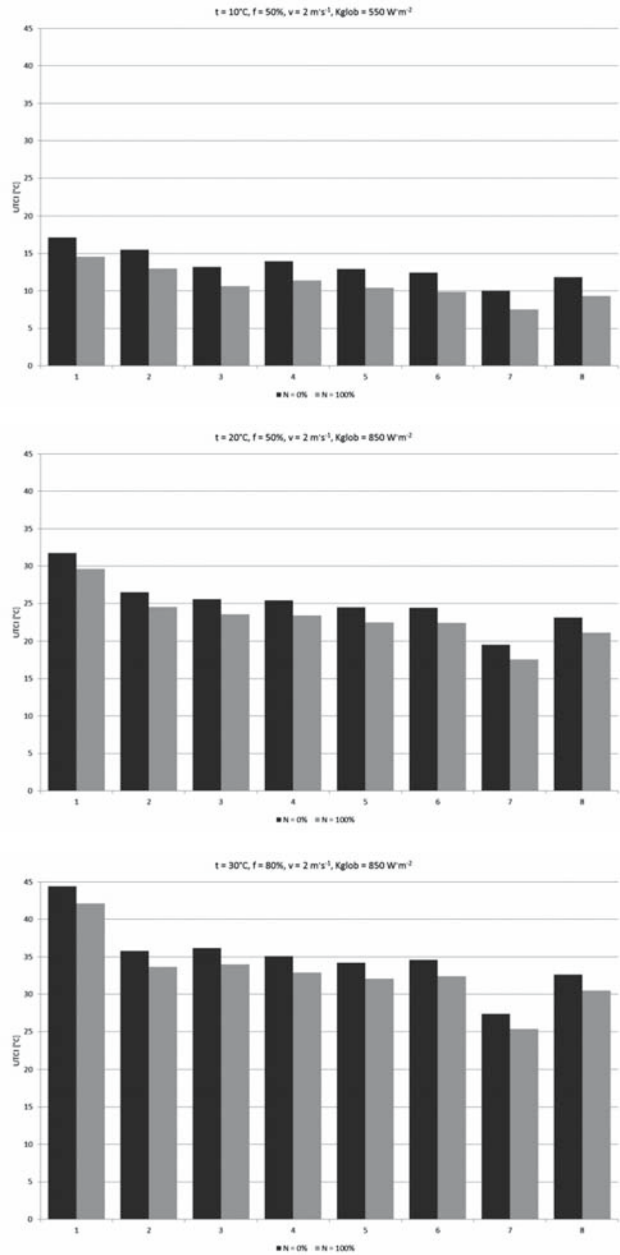
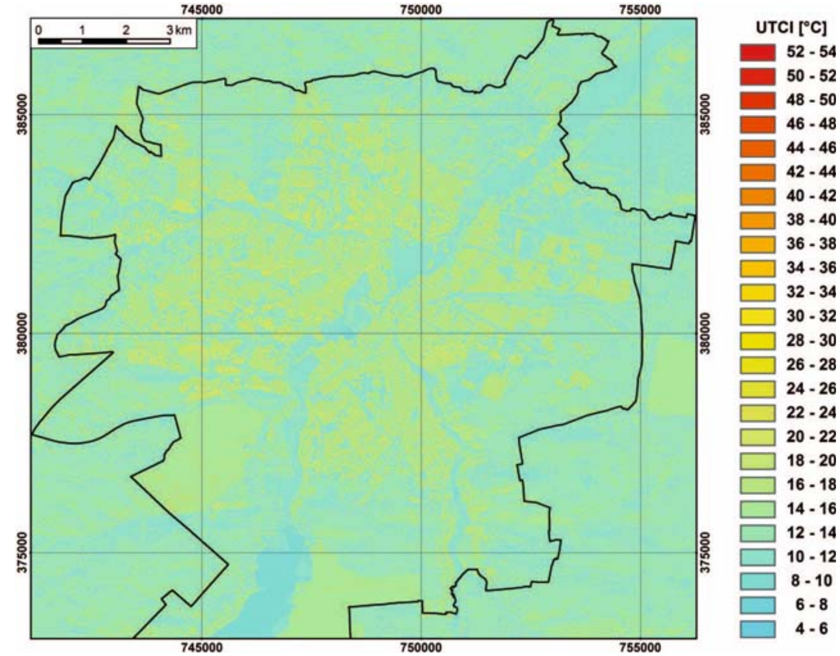
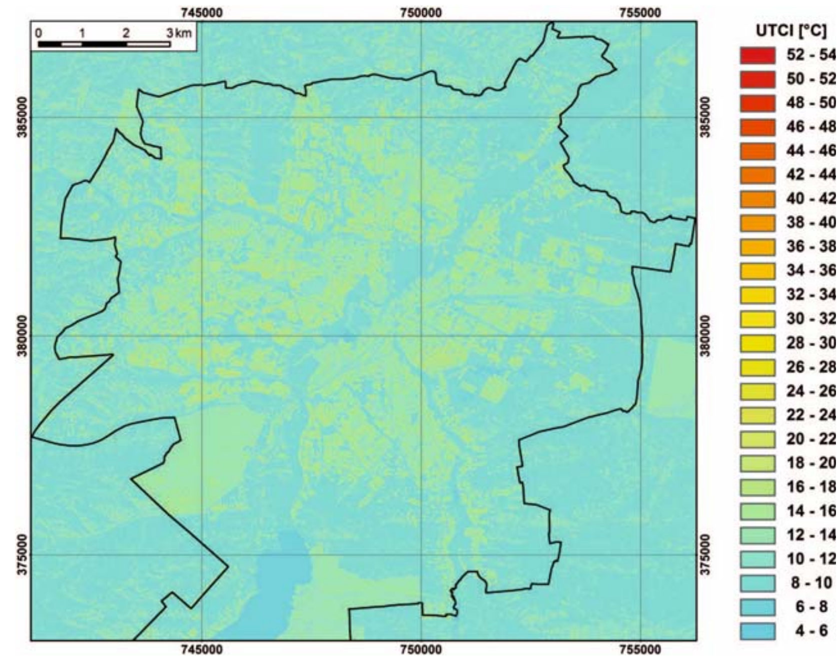


Fig. 5. Mean UTCI values in various types of land use in Lublin in specific weather scenarios. The markings on the plots: 1. urban areas, 2. forests, 3. transportation areas, 4. parks, 5. orchards, 6. fields and wasteland, 7. lakes and rivers, 8. meadows

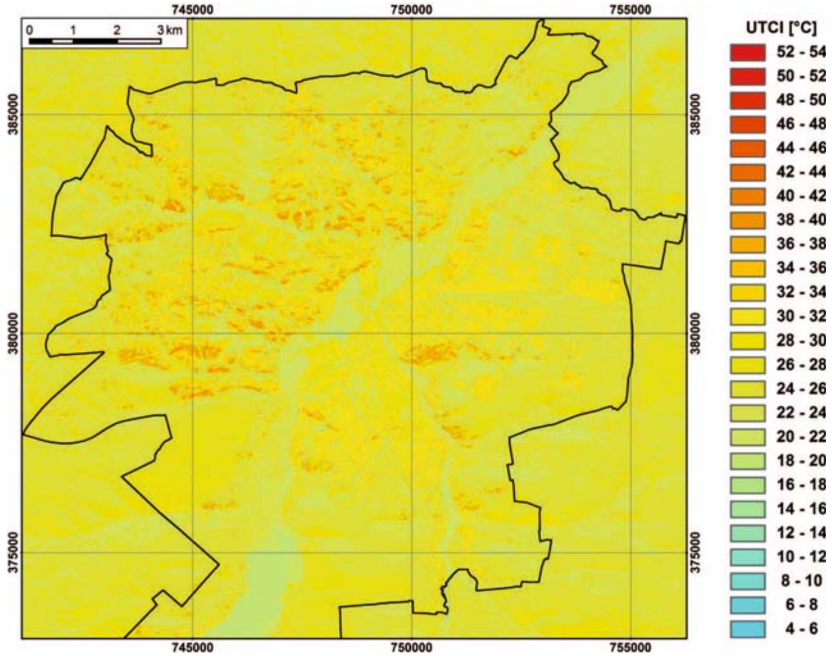
Ryc. 5. Średnie wartości UTCI w różnych typach użytkowania terenu w Lublinie w określonych scenariuszach pogodowych. Oznaczenia na wykresach: 1. tereny zurbanizowane, 2. lasy, 3. obszary komunikacyjne, 4. parki, 5. sady, 6. pola i nieużytki, 7. jeziora i rzeki, 8. łąki



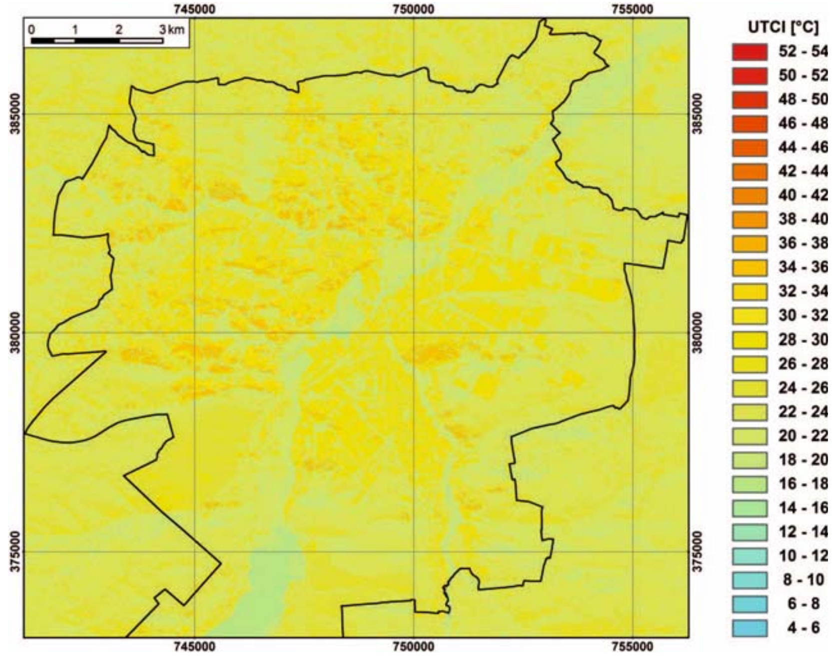
1. t = 10°C, f = 50%, N = 0%, K_{glob} = 550 W·m^{-2}



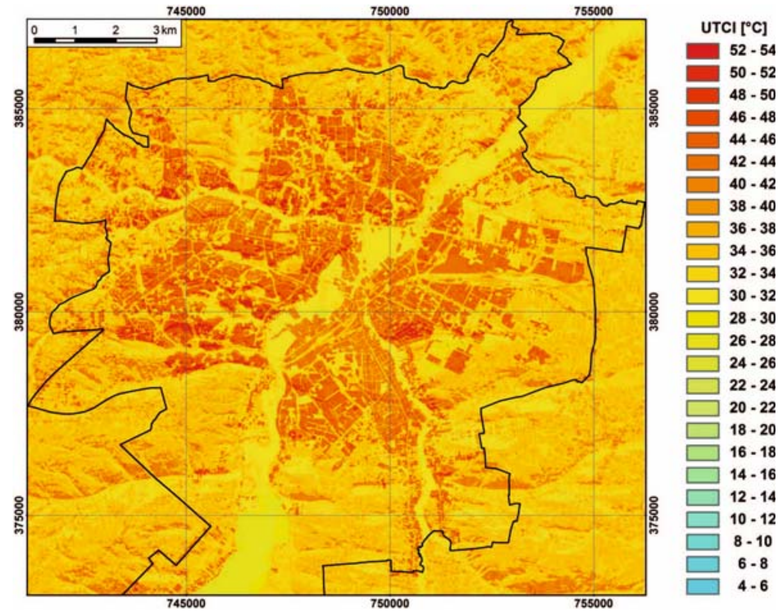
t = 10°C, f = 50%, N = 100%, K_{glob} = 550 W·m^{-2}



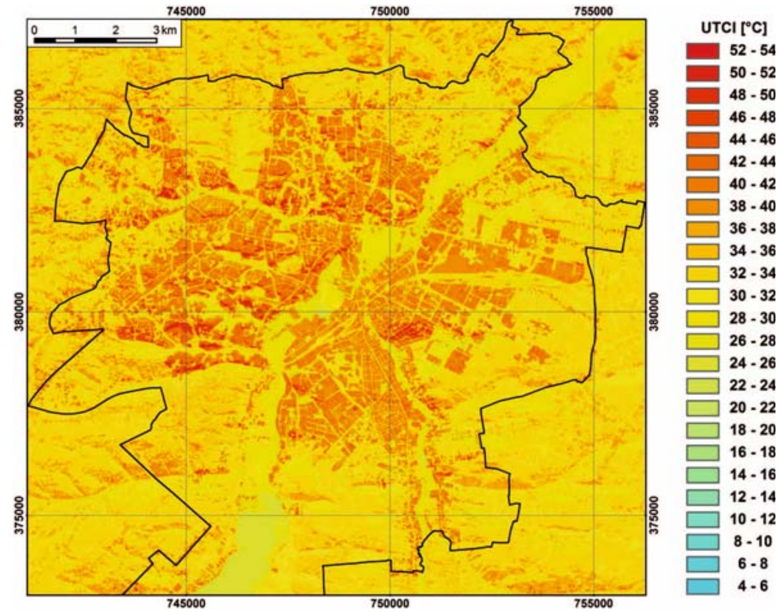
t = 20°C, f = 50%, N = 0%, K_{glob} = 850 W·m^{-2}



t = 20°C, f = 50%, N = 100%, K_{glob} = 850 W·m^{-2}



t = 30°C, f = 80%, N = 0%, K_{glob} = 850 W·m^{-2}



t = 30°C, f = 80%, N = 100%, K_{glob} = 850 W·m^{-2}

Fig. 6. Spatial variation of UTCI values in Lublin in specified weather scenarios

Ryc. 6. Zróżnicowanie przestrzenne wartości UTCI w Lublinie w określonych scenariuszach pogodowych

The description of bioclimatic conditions in Lublin obtained by means of modelling can find extensive application in urban space management. The results obtained constitute a valuable supplementation of information considered in planning residential estates and recreational areas (e.g. cycle paths, green areas).

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STRESZCZENIE

Lublin jest dla bio- i topoklimatologii cennym obszarem badawczym, gdyż ze względu na urozmaiconą rzeźbę terenu oraz obecność licznych rozcięć wąwozowych wykorzystywanych przez człowieka charakteryzuje się dużym zróżnicowaniem mikroklimatu. W pracy przedstawiono zróżnicowanie przestrzenne warunków bioklimatycznych na obszarze miasta, wykorzystując w tym celu nowy wskaźnik bioklimatyczny Universal Thermal Climate Index (UTCI). Otrzymane mapy biotopoklimatyczne opracowane zostały w odniesieniu do sześciu określonych scenariuszy pogodowych. Uzyskane obrazy, będące teoretycznym przybliżeniem warunków rzeczywistych, pozwalają ocenić wpływ rzeźby oraz typów użytkowania terenu na kształtowanie warunków biometeorologicznych obszarów zurbanizowanych. W analizowanych scenariuszach pogodowych i przy uwzględnieniu rzeźby Lublina najwyższe modelowane wartości UTCI charakteryzują zbocza wąwozów oraz dolin o południowej ekspozycji. W obszarach tych prognozowane są warunki biometeorologiczne, odzwierciedlające obciążenia cieplne „bardzo silny stres ciepła”.