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A STATISTICAL APPROACH FOR ESTIMATING MEAN MAXIMUM URBAN TEMPERATURE EXCESS

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Összefoglalás – Munkánkban a városi hősziget (UHI) maximális napi kifejlődését vizsgáltuk Szegeden, a beépítettségi paraméterek függvényében. A hőmérsékleti adatok valamint a beépítettségi arány, a vízfelszín-arány, az égbolt láthatósági index és az épületmagasság, valamint ezek területi kiterjesztései közötti kapcsolatot statisztikus modellezéssel határoztuk meg. A kapott modell-egyenleteket mindkét félévre (fűtési és nem-fűtési) többváltozós lineáris regresszió segítségével állapítottuk meg. Az eredményekből világosan látszik, hogy szignifikáns kapcsolat mutatható ki a maximális UHI területi eloszlása és a beépítettségi paraméterek között, ami azt jelenti, hogy e tényezők fontos szerepet jatszanak a városi hőmérsékleti többlet területi eloszlásának kialakításában. A városi paraméterek közül az égbolt láthatósági index és az épületmagasság a leginkább meghatározó tényező, ami összhangban van a városi felszín energia-egyenlegével.

Summary – Investigations concentrated on the urban heat island (UHI) in its strongest development during the diurnal cycle in Szeged, Hungary. Task includes development of statistical models in the heating and non-heating seasons using urban surface parameters (built-up and water surface ratios, sky view factor, building height) and their areal extensions. Model equations were determined by means of stepwise multiple linear regression analysis. As the results show, there is a clear connection between the spatial distribution of the UHI and the examined parameters, so these parameters play an important role in the evolution of the UHI intensity field. Among them the sky view factor and the building height are the most determining factors, which are in line with the urban surface energy balance.

Key words: UHI, spatial and seasonal patterns, urban surface factors, statistical model equations, Szeged, Hungary

INTRODUCTION

The climate modification effect of urbanization is most obvious for the temperature (urban heat island – UHI). Its magnitude is the UHI intensity (namely ΔT, the temperature difference between urban and rural areas). Generally, this intensity has a diurnal cycle with a strongest development at 3-5 hours after sunset.

In order to study microclimate alterations within the city, utilization of statistical modeling may provide useful quantitative information about the spatial and temporal features of the urban temperature excess by employing different surface parameters (e.g. *Outcalt*, 1972; *Oke*, 1981, 1988; *Kuttler et al.*, 1996; *Matzarakis et al.*, 1998).

Our objective is to investigate the quantitative effects of the relevant surface factors and their extensions on the UHI patterns. These factors are: built-up ratio, water surface ratio, sky view factor and building height. The selection of these parameters is based on their role in small-scale climate variations (*Oke*, 1987; *Golany*, 1996).

STUDY AREA AND METHODS

General

The studied city, Szeged, is located in the south-eastern part of Hungary (46°N, 20°E) at 79 m above sea level on a flat plain. The River Tisza passes through the city, otherwise, there are no large water bodies nearby. The river is relatively narrow and according to our earlier investigation its influence is negligible (e.g. *Unger et al.*, 2000, 2001b). These circumstances make Szeged a favourable place for studying of an almost undisturbed urban climate.

The city has an administration district of 281 km^2 with the population of 160,000. The base of the street network is a circuit-avenue system. Different land-use types are present including a densely-built centre with medium-wide streets and large housing estates of high concrete buildings set in wide green spaces. There are zones used for industry and warehousing, areas occupied by detached houses, considerable open spaces along the riverbanks, in parks, and around the city's outskirts (*Unger et al.*, 2001a).

The region is in Köppen's climatic region Cf (temperate warm climate with a fairly uniform annual distribution of precipitation). Two half years can be distinguished from the point of view of city dwellers: the non-heating (from April 16^{th} until October 15^{th}) and the heating (from October 16^{th} until April 15^{th}) seasons (*Unger et al.*, 2000).

Grid network and temperature (maximum UHI intensity)

The area of investigation (inner part of the administration district) was divided into two sectors and subdivided further into 0.5 km x 0.5 km cells. The original study area consists of 107 cells covering the urban and suburban parts of Szeged, mainly inside of the circle dike that protects the city from river floods. The same grid size was employed, for example, in an investigation of UHI in Seoul, Korea (*Park*, 1986). The outlying parts of the city, characterized by village and rural features, are not included in the network except for four cells on the western side of the area. These four cells are necessary to determine the temperature contrast between urban and rural areas. In the present investigation the six southern and four western cells of the study area are omitted because of the lack in the data set of one parameter (building height, see chapter *Building height*), so now we employ altogether 97 cells covering an area of 24.25 km^2.

In order to collect data on ΔT for every cell, mobile measurements (24 in the northern, and another 24 in the southern sector) were taken on fixed return routes once a week during the period of March 1999 – February 2000. The frequency of car traverses provided sufficient information under different weather conditions, except for rain.

Return routes were needed to make time-based corrections and the measurements took about 3 hours. Readings were obtained using a radiation-shielded resistance sensor connected to a data logger for digital sampling. Data were collected every 16 s, so at an average car speed of 20-30 km h^{-1} the average distance between measuring points was 89-133 m. The sensor was mounted 0.60 m in front of the car at 1.45 m above ground to avoid engine and exhaust heat. The car speed provided adequate ventilation for the sensor to measure the momentary ambient air temperature. The logged values at forced stops (e.g. at traffic lamps) were rejected from the data set.

Having averaged the measurement values by cells, time adjustments to a reference time (namely the likely time of the occurrence of the strongest or maximum UHI in the diurnal course) were applied assuming linear air temperature change with time. It was 4 hours after sunset, a value based on earlier measurements. Consequently, we can assign one temperature value to every cell (centerpoint) in the northern sector or in the southern sector in a given measuring night. ΔT values were determined by cells referring to the temperature of the westernmost cell of the original study area, which was regarded as a rural cell because of its location outside of the city. The 97 points (the above mentioned cell centerpoints) covering the urban parts of Szeged provide an appropriate basis to interpolate isolines (temperature and other parameters) applying the standard Kriging procedure.

Built-up and water surface ratio

The ratios of the built-up (covered surface – building, street, pavement, parking lot, etc.) (B) and water surface (W) by cells were determined by a vector and raster-based GIS database combined with remote sensing analysis of SPOT XS images. The nearest-neighbour method of resampling was employed, resulting in a root mean square value of less than 1 pixel. The geometric resolution of the image was 20 m x 20 m.

Normalized Difference Vegetation Index (NDVI) was calculated from the pixel values, using visible (0.58-0.68 μm) and near infrared (0.72-1.1 μm) bands (*Gallo and Owen*, 1999). They are between -1 to +1 indicating the effect of green space in the given spatial unit. Using these values, built-up, water and vegetated surfaces were distinguished using these values. The ratios of these land-use types for each grid square were determined using cross-tabulation. In the Szeged region the occurrence of bare (non-vegetated) areas is negligible, namely, each non-built-up place is covered by some vegetation (e.g. garden and cultivated plants, trees, grass, bushes, weeds).

Sky view factor

The built-up ratio does not describe completely the characteristics of an artificial urban surface. Streets and buildings create canyons and this 3-D geometry plays an important role in the development of UHI. Namely, heat transport and outgoing long wave radiation decrease because of the moderated turbulence and increased obstruction of the sky.

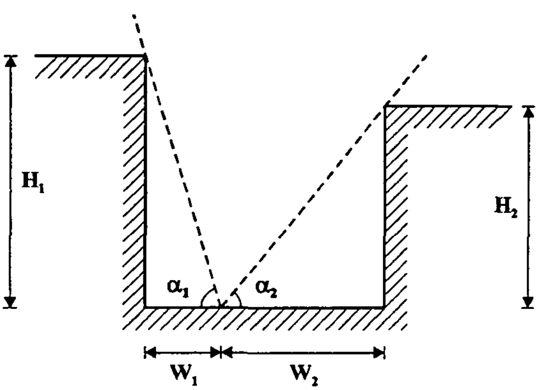

Fig. 1 Geometry of an unsymmetric canyon flanked by buildings with a measuring point not at the centre of the floor (modified after *Oke*, 1988)

To estimate the openness of the cells we applied the sky view factor (SVF, now marked shortly by S) of the degree to which sky is obscured by the surroundings for a given point (*Oke*, 1981, 1988). Commonly, S is determined using either analytical (geometrical) or photographic methods, employing theodolite, digital camera with fish-eye lens, automatic canopy analyzer or available urban morphology database (*Oke*, 1981; *Bärring and Mattsson*, 1985; *Park*, 1987; *Grimmond et al.*, 2001; *Chapman et al.*, 2001).

In our analytical method we have measured two elevation angles to the top of buildings (α_1 and α_2) perpendicular to the axis of streets in both directions using a 1.5 m high theodolite. From these data wall view factors can be calculated to the left (WVF_{W1}) and right (WVF_{W2}) sides (*Oke*, 1981). The measuring points are not always coincident with the midpoint of the distance between buildings on both sides (*Fig. 1*). The calculation of S is based on *Oke's* (1988) results (for explanation of symbols see *Fig. 1*):

$$WVF_{W1} = (1-\cos\alpha_1)/2 \qquad \text{where } \alpha_1 = \tan^{-1}(H_1/W_1),$$
$$WVF_{W2} = (1-\cos\alpha_2)/2 \qquad \text{where } \alpha_2 = \tan^{-1}(H_2/W_2),$$
$$S = 1-(WVF_{W1}+WVF_{W2}).$$

In order to determine S values the same long canyons (measuring routes) were used as for temperature sampling. 532 points were surveyed by theodolite, and the S data were also averaged by cells. In line with the temperature sampling, the distance between the points was 125 m on average. Angle measurements taken higher within a canyon (1.5 m) exclude more of the terrain (non-sky) and result in an over-estimate of S after the calculation. This effect is more pronounced in canyons with low H/W ratios (*Grimmond et al.*, 2001). Due to technical difficulties we did not have any measurement points at the intersections of roads, so the calculated S values are probably a bit smaller than the real ones. Furthermore, if there were parks, forests or water surface in a particular direction we have assigned 0° as an angle value, because it is difficult to determine S values modified by the vegetation and the results are not unambiguous (*Yamashita et al.*, 1986).

While earlier investigations were limited to the centre or only one part of the cities and used far smaller numbers of measurements (e.g. *Oke*, 1981, 1988; *Yamashita et al.*, 1986; *Park*, 1987; *Eliasson*, 1996; *Grimmond et al.*, 2001) the obtained data set represents almost the total urban area.

Building height

Since some areas with different land-use features can produce almost equal S data (narrow street with low buildings versus wide sreet with high buildings), S values alone do not describe sufficiently the vertical geometry of cities. It is important to have quantitative information on the vertical size of a canyon because it plays significant role in the energy budget.

To determine the vertical dimension of a canyon, we applied a combined procedure. The above mentioned elevation angles (α_1 and α_2) are available at each point. If we have the distances to the walls from the measuring point (W_1 and W_2, see *Fig. 1*) we can apply a simple formula to calculate wall heights (H_1 and H_2), taking the instrument height of 1.5 m into account:

$$H_1 = \tan\alpha_1 \cdot W_1 + 1.5 \text{ m}$$
$$H_2 = \tan\alpha_2 \cdot W_2 + 1.5 \text{ m}$$

The width of streets can be determined by means of aerial photographs concerning any part of the street. After digitizing these images, we made an orthophoto of Szeged by means of Ortho Base tool of the ERDAS IMAGINE GIS software (*Barsi*, 2000) and marked the measurement points on it. This orthophoto is already suitable to determine distances of the walls (W_1 and W_2) from the measurement points. As the aerial photographs do not cover completely the study area, these distances are not available for six and four cells in the southern and western parts of Szeged, respectively.

Construction of the statistical model

In order to assess the extent of the relationships between the mean maximum UHI intensity (ΔT) and various urban surface factors, multiple correlation and regression analyses were applied. Some examples of the modeled variables and the employed variable parameters of earlier studies are in *Table 1*.

Table 1 Survey of some studies using statistical models for prediction of UHI (extended after *Unger et al.*, 2003)

Predicted variable	Employed parameters	Reference
UHI intensity	wind speed, cloudiness	*Sundborg* (1950)
UHI intensity	population, wind speed	*Oke* (1973)
max. UHI intensity	population	
UHI intensity	wind speed, cloudiness, atmospheric stability, traffic flow, energy consumption, temperature	*Nkemdirim* (1978)
UHI intensity in four different air levels	lapse rate, wind speed, ratio of lapse rate to wind speed	*Nkemdirim* (1980)
max. UHI intensity	sky view factor, height/width ratio	*Oke* (1981)
UHI intensity	wind speed, land-use type ratios	*Park* (1986)
max. UHI intensity	population, impermeable surface	
max. UHI intensity	population, sky view factor, impermeable surface	*Park* (1987)
UHI intensity	wind speed, cloudiness, temperature, humidity mixing ratio	*Goldreich* (1992)
UHI intensity	wind speed, cloudiness, air pressure	*Moreno-Garcia* (1994)
surface UHI intensity	solar radiation, wind speed, cloudiness	*Chow et al.* (1994)
UHI intensity	built-up area, height, wind speed, time, temperature amplitude	*Kuttler et al.* (1996)
UHI intensity for T_{avg}, T_{max}, T_{min}	NDVI, surface temperature (satellite-based)	*Gallo and Owen* (1999)
UHI intensity	distance from the city centre, built-up ratio	*Unger et al.* (2000) *Unger et al.* (2001b)
UHI intensity	wind speed, cloudiness	*Morris et al.* (2001)
max. UHI intensity	max. UHI intensity of the previous day, wind speed, cloudiness, relative humidity	*Kim and Baik* (2002)

To determine model equations we used ΔT as predictant (dependent variable) in both seasons and the afore mentioned parameters as predictors: ratios of built-up surface (B) and water surface (W) as a percentage, mean sky view factor (S), mean building height (H) in m by cells. Searching for statistical relationships, we have to take into account that our parameters are at once variables (spatially) and constants (temporally). Since these parameters change rapidly with the increasing distance from the city centre, we applied the exponentially distance-weighted spatial means of the mentioned land-use parameters for our model. The distance scale of the weight should be derived from the transport scale of heat in the urban canopy. Our statistical model have determined this scale from the measured parameter values. A set of predictors concerning all four basic were originated as areal extensions and grouped them urban parameters in the following way:

Group 1: parameter values (S, H, B, W) in the cell with $\Delta i^2 + \Delta j^2 = 0$.
Group 2: mean parameter values (S1, H1, B1, W1) of all cells with $0 < \Delta i^2 + \Delta j^2 < 2^2$.
Group 3: mean parameter values (S2, H2, B2, W2) of all cells with $2^2 \leq \Delta i^2 + \Delta j^2 < 4^2$.

Here i and j are cell indices in the two dimensions, and Δi and Δj are the differences of cell indices with respect to a given cell. These zones cover the entire model area.

With these areal extensions we have 12 predictors to construct the linear statistical model. However, there could be some multi-colinearity among these parameters. In order to eliminate these multi-colinearities the set of parameters have to be selected. Using the cross-correlation matrix of these predictors we can find the highest correlation coefficients, which mean strong connections among them. To avoid the unreasonable reduction of the number of predictors, only that parameter is taken out by groups, which has the maximum absolute mean of his correlation coefficients in the group.

The method for the construction of model equations is the stepwise multiple linear regression. The applied implementation of this procedure is part of the SPSS 9 computer statistics software (*Miller,* 2002). Predictors were entered or removed from the model depending on the significance of the F value of 0.01 and 0.05, respectively. Since there is a well noticeable difference between the magnitudes of ΔT fields in the investigated seasons, under these conditions two linear statistical model equations were determined: one for the heating and one for the non-heating season.

Table 2 Cross-correlation matrix of the parameters and absolute means of the correlation coefficients by lines. The absolute means of the parameters taken out from the models are marked with bold setting.

Param.	B	S	W	H	B1	S1	W1	H1	B2	S2	H2	W2	Abs. mean
B	-	-0.50	-0.48	0.52	0.62	-0.50	-0.24	0.45	0.11	-0.12	0.01	-0.12	0.33
S	-0.50	-	0.13	-0.72	-0.52	0.64	0.09	-0.55	-0.05	0.41	-0.33	0.02	**0.36**
W	-0.48	0.13	-	-0.16	-0.13	0.02	0.29	-0.10	0.04	-0.22	0.18	0.16	0.17
H	0.52	-0.72	-0.16	-	0.43	-0.50	-0.16	0.57	-0.01	-0.42	0.23	-0.11	0.34
B1	0.62	-0.52	-0.13	0.43	-	-0.64	-0.49	0.57	0.15	-0.14	0.06	-0.21	0.36
S1	-0.50	0.64	0.02	-0.50	-0.64	-	0.04	-0.84	-0.04	0.56	-0.49	0.08	0.39
W1	-0.24	0.09	0.29	-0.16	-0.49	-0.04	-	-0.14	-0.08	-0.27	0.17	0.24	0.20
H1	0.45	-0.55	-0.10	0.57	0.57	-0.84	-0.14	-	-0.03	-0.63	0.48	-0.08	**0.40**
B2	0.11	-0.05	0.04	-0.01	0.15	-0.04	-0.08	-0.03	-	-0.10	0.21	0.02	0.08
S2	-0.12	0.41	-0.22	-0.42	-0.14	0.56	-0.27	-0.63	-0.10	-	-0.85	-0.10	**0.35**
H2	0.01	-0.33	0.18	0.23	0.06	-0.49	0.17	0.48	0.21	-0.85	-	0.13	0.28
W2	-0.12	0.02	0.16	0.23	-0.21	0.08	0.24	-0.08	0.02	-0.10	0.13	-	0.12

RESULTS AND DISCUSSION

Table 2 contains the cross-correlation matrix of the predictors and maximum absolute means of the correlation coefficients by lines. As a result of the selection procedure to reduce the multi-colinearities three parameters (S, H1 and S2) were chosen from the original parameter-set. Thus, for the construction of the model equations remained nine predictors.

In both seasons the order of significance of the applied parameters is the same but in the heating season the role of them is more pronounced than in the non-heating season. The model equation has four predictors, among them the S1 predictor is the most important one, but H and B1 factors also play important role in both seasons (*Table 3*).

Table 3 Values of the stepwise correlation of mean maximum UHI intensity (ΔT) and urban surface parameters and their significance levels in the studied periods in Szeged (n = 97)

Period	Parameter entered	Multiple |r|	Multiple r^2	Δr^2	Sign. level
April 16 – October 15 (non-heating season)	S1	0.806	0.649	0.000	0.1%
	S1, H	0.845	0.714	0.065	0.1%
	S1, H, B1	0.863	0.744	0.030	0.1%
	S1, H, B1, W1	0.902	0.814	0.070	0.1%
October 16 – April 15 (heating season)	S1	0.791	0.626	0.000	0.1%
	S1, H	0.834	0.696	0.070	0.1%
	S1, H, B1	0.852	0.726	0.030	0.1%
	S1, H, B1, W1	0.873	0.762	0.036	0.1%

Table 4 Values of significance, coefficients and standard errors of the applied urban surface parameters of the models in the studied periods in Szeged (n = 97)

Period	Param.	Signif.	Coeff.	Std. Error
April 16 – October 15 (non-heating season)	S1	0.000	-4.291	0.787
	H	0.000	0.035	0.006
	B1	0.000	0.023	0.003
	W1	0.000	0.042	0.007
	Const.	0.000	3.824	0.897
October 16 – April 15 (heating season)	S1	0.000	-3.242	0.631
	H	0.017	-0.025	0.005
	B1	0.006	0.014	0.003
	W1	0.022	0.021	0.006
	Const.	0.000	3.036	0.718

The four-variable models for the non-heating (nh) and heating (h) seasons, indicate strong linear connections between the UHI intensity and the applied land-use parameters (*Table 3*). The model equations for ΔT_{nh} and ΔT_h (in °C) are the next (*Table 4*):

$$\Delta T_{nh} = -4.291S1 + 0.035H + 0.023B1 + \\ + 0.042W1 + 3.824$$

$$\Delta T_h = -3.242S1 + 0.025H + 0.014B1 + \\ + 0.021W1 + 3.036$$

The absolute values of the multiple correlation coefficients (r) between ΔT and the studied parameters are 0.902 and 0.873 in the non-heating and heating seasons; both are significant at 0.1% level. This means that with these four parameters we are able to explain 81.4% and 76.2% of the above mentioned relationships in the studied periods. The standard errors of the estimates are 0.272 and 0.218 in the non-heating and heating half year, respectively.

We have used these two model equations to determine the spatial distribution of ΔT patterns in the studied area (*Fig. 2*).

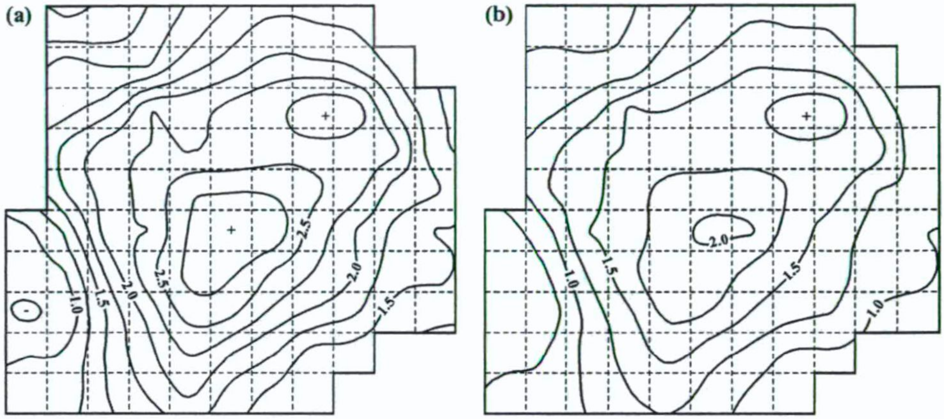

Fig. 2 Spatial distribution of the predicted mean max. UHI intensity (°C) during the (a) non-heating season and (b) the heating season in Szeged

We compared the results of the model to an independent UHI intensity data set which was measured during the non-heating half year in 2002. The study area and the mobile sampling method were the same as in the earlier cases, except that we used two cars to take temperature measurements at the same time in the two sectors, altogether 18 times (*Fig. 3b*). Then we calculated the spatial distribution of the difference between the measured (independent) UHI intensities and the predicted ones by our model (*Fig. 3b*).

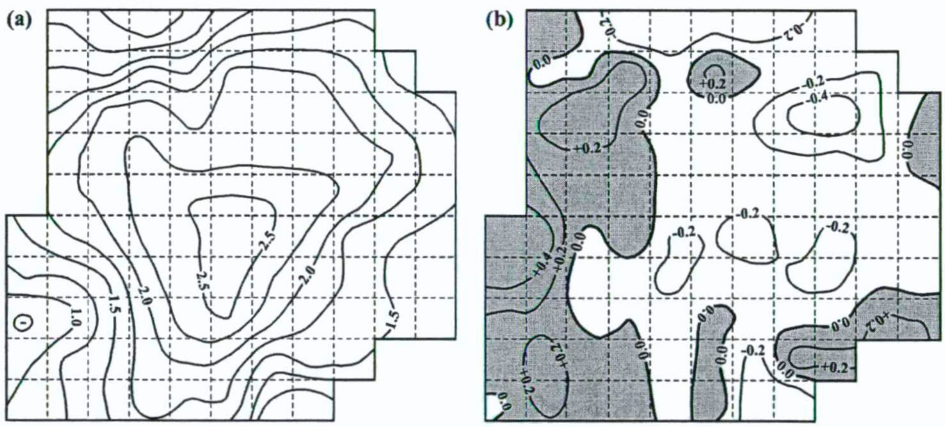

Fig. 3 (a) Spatial distribution of the measured mean max. UHI intensity (°C) during the independent non-heating season in 2002 and (b) spatial distribution of the difference of measured and predicted mean max. UHI intensity (°C) during the same season in Szeged

There is also a similarity between the measured and the predicted ΔT fields but we can find two small areas where the absolute UHI intensity anomaly is between 0.4°C and 0.6°C. In the north-eastern part of the city the predicted values are lower than the measured ones (negative anomaly). At the western border of the investigated area the predicted values are higher than the measured ones (positive anomaly). However, these areas occupy only a minor part of the study area (about 3.9 cells, 1 km^2, 4% of the total area). The areas characterized by the differences lower than 0.2°C are significantly larger, covering altogether 73 cells (about 18,2 km^2, 75%).

It can be stated that our model described the spatial distribution of the real UHI intensity field in the investigated area rather correctly. On the basis of our results, we may apply this model-construction procedure to predict the ΔT for other cities of different size and even non-concentric shape.

CONCLUSIONS

In this paper a statistical estimation of the spatial distribution of mean maximum UHI intensity with the help of surface parameters was presented in Szeged, Hungary. The following conclusions are reached from the analysis:

(i) On the basis of the statistical procedure there is a strong linear relationship between the mean UHI intensity and the studied urban parameters such as sky view factor, building height, built-up ratio, water surface ratio and their areal extensions in both season.

(ii) Generally, our model have described the spatial distribution of the real UHI intensity field in the study area rather correctly, because the areas characterized by the differences lower than 0.2°C cover the larger parts of the city (75 %). Nevertheless, there are small differences between the predicted and measured UHI fields which are caused by some possible errors in the temperature samplings, the low number of studied parameters and the considerable irregularities of the surface geometry.

(iii) This procedure, used to predict the UHI intensity, may be applicable for other cities of different size and even non-concentric shape, but for the true validation it is necessary to have complete databases of measured intensities for those cities.

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