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Urban heat island development affected by urban surface factors

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Abstract—This study examines the spatial and quantitative influence of urban factors on the surface air temperature field of the medium-sized city of Szeged, Hungary, using of mobile measurements under different weather conditions between March 1999 and February 2000. This city with a population of about 160,000 is situated on a low, flat flood plain. The efforts have been concentrated on investigating the development of the urban heat island (UHI) in its peak development during the diurnal cycle. Tasks include determination of spatial distribution of mean maximum UHI intensity, using of standard kriging procedure and determination of statistical model equations in the one-year study period, as well as in the heating and non-heating seasons. Multiple correlation and regression analyses are used to examine the effects of urban surface parameters (land-use characteristics and distance from the city centre determined in a grid network) on the UHI. Results indicate isotherms increasing in regular concentric shapes from the suburbs toward the inner urban areas with a seasonal variation in the UHI magnitude. In the city centre the mean maximum UHI intensity reaches more than 2.6°C, 3.1°C and 2.1°C, respectively. As the patterns show, there is a clear connection between urban thermal excess and built-up density. As the model equations show, strong relationships exist between urban thermal excess and distance, as well as built-up ratio, but the role of water surface is negligible.

Key-words: UHI, spatial distribution, grid network, built-up ratio, water surface ratio, distance, statistical analysis, regression equations.

1. Introduction

The temperature-increasing effect of cities caused by urbanization (the so-called urban heat island — UHI) is one of the most deeply examined fields of climatology. Features of the UHI are well documented from different cities mainly from the temperate zone (e.g., *Oke*, 1997; *Kuttler*, 1998) and one of the most difficult aspect of this phenomenon is studying of its peak development during the diurnal cycle.

The detection of real factors and physical processes generating the distinguished urban climate is extremely difficult because of the very complicated urban terrain (as regard surface geometry and materials) as well as artificial production of heat and air pollution. The simulation of these factors and processes demands complex expensive instrumentation and sophisticated numerical and physical models. Despite these difficulties, several models have been developed for studying small-scale climate variations within the city, including the ones based on energy balance (*Tapper et al.*, 1981; *Johnson et al.*, 1991; *Myrup et al.*, 1993), radiation (*Voogt* and *Oke*, 1991), heat storage (*Grimmond et al.*, 1991), water balance (*Grimmond* and *Oke*, 1991) and advective (*Oke*, 1976) approaches.

As an other solution of the above mentioned problems, utilisation of statistical models may provide useful tools, which give us quantitative information about the magnitude as well as spatial and temporal features of the UHI intensity (defined as the temperature difference between urban and rural areas) by employing urban and meteorological parameters. Some examples of the modeled variables (surface and near surface air UHI intensity or even the possible maximum UHI intensity) and the employed variable parameters are gathered in *Table 1*.

Table 1. Survey of some statistical models with modeled UHI variables, employed parameters and authors

Modeled variable	**Employed parameters**	**Author(s)**
UHI intensity	wind speed, cloudiness	*Sundborg* (1950)
UHI intensity	population, wind speed	*Oke* (1973)
Max. UHI intensity	population	
UHI intensity	wind speed, wind speed, cloudiness, atmospheric stability, traffic flow, energy consumption, temperature	*Nkemdirim* (1978)
UHI intensity	wind speed, land-use type ratios	*Park* (1986)
Max. UHI intensity	impermeable surface, population	
UHI intensity	cloudiness, wind speed, temperature, humidity mixing ratio	*Goldreich* (1992)
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)

Counting all weather conditions except rain, the main purpose of this study is to investigate the effects and interactions inside the city on the surface air temperature a few hours after sunset, when the UHI effect is most pronounced. To achieve this aim, we construct horizontal isotherm maps to show the average spatial distribution of maximum UHI intensity in the investigated period as a whole and in the distinguished, so-called heating and non-heating, seasons. Then, we intend to reveal some obvious relationships between temperature patterns and urban factors using built-up (covered surface) ratio within the city. Further aim was to determine quantitative influences of the urban surface factors on the patterns of urban-rural temperature.

2. *Study area and methods*

Szeged is located in the south-eastern part of Hungary on the Great Hungarian Plain (46°N, 20°E) at 79 m above sea level (*Fig. 1*). The city and its countryside situate on is a large flat flood plain. The River Tisza passes through the city, otherwise, there are no large water bodies nearby. This geographical situation (no orographic climate influences) makes Szeged a good case for the study of a relatively undisturbed urban climate. Using Köppen's classification, the area belongs to the climatic region *Cf*, which means a temperate warm climate with a rather uniform annual distribution of precipitation (*Table 2*). The regional climate of Szeged has, however, a certain Mediterranean influence. It appears mainly in the annual variation of precipitation, namely in every 10 years approximately 3 years show some Mediterranean (relatively high autumn-winter rainfall) characteristics (*Unger*, 1999).

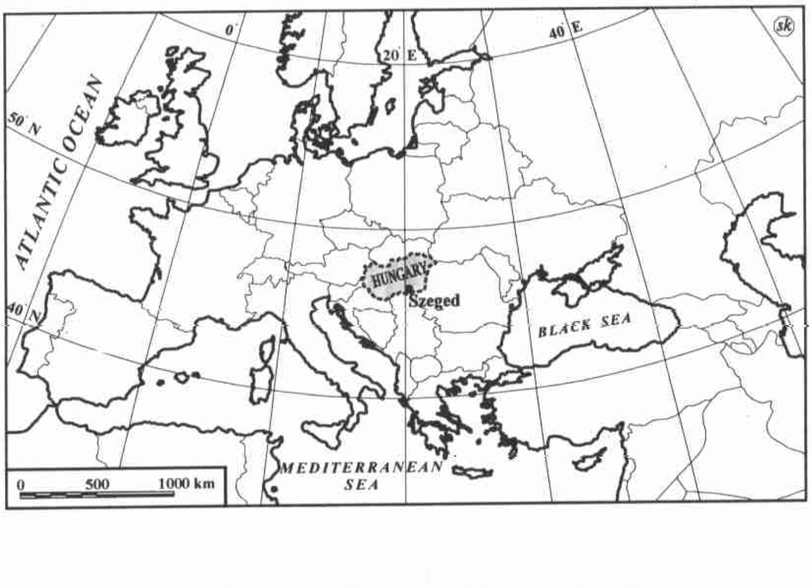

Fig. 1. Location of Hungary and Szeged in Europe.

Table 2. Monthly and annual means or sums of meteorological parameters in the region of Szeged (1961–1990)

Parameter	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature (°C)	-1.8	1.0	5.6	11.1	16.2	19.2	20.8	20.2	16.4	11.0	5.1	0.6	10.4
Precipitation (mm)	29	25	29	40	51	72	50	60	34	26	41	40	497
Sunshine duration (h)	62	87	143	181	235	252	288	267	211	170	82	51	2029
Cloudiness (%)	70	68	63	60	58	54	45	42	45	49	69	76	58
Wind speed (ms^{-1})	3.3	3.4	4.0	3.7	3.2	2.9	2.9	2.7	2.6	3.0	3.0	3.7	3.2
Relative humidity (%)	85	82	73	68	66	67	65	67	70	73	83	87	74
Vapor pressure (hPa)	4.9	6.5	6.8	8.9	12.3	15	16	15.8	13.2	9.8	7.6	5.8	10.1

The city's population of 160,000 (1998) lives within an administration district of 281 km^2. As for the city structure, its basis is a boulevard-avenue road system. Numbers of different land-use types are present including a densely built center with medium wide streets and large housing estates of tall concrete blocks of flats set in wide green spaces. Szeged also contains areas used for industry and warehousing, zones occupied by detached houses and considerable open spaces along the banks of the river, in parks and around the city's outskirts (*Fig. 2*).

As the urban and suburban areas occupy only about 25–30 km^2, our investigation focused only on the inner part of the administration district (Fig. 2). This study area was divided into two sectors and subdivided further into 0.5 km × 0.5 km square grid cells (*Fig. 3*). The same grid size was employed, for example, in a human bioclimatological analysis of Freiburg, Germany, a city of similar size to Szeged (*Jendritzky* and *Nübler*, 1981) and in an other investigation of UHI in Seoul, Korea (*Park*, 1986). *Sailor* (1998) chose a 2 km × 2 km network for his hypothetical city, where he simulated the impacts of vegetative augmentation on the annual heating and cooling degree days. Therefore, our grid network can be regarded as a rather dense one. In the study area there are 107 grid cells totaling 26.75 km^2, covering the urban and suburban parts of Szeged (mainly inside of the circle dike that protects the city from floods caused by the Tisza River). Outlying parts of the city, characterized by village and rural features, are not included in the grid except for four cells at the western side of the area. These cells are needed in order to determine the temperature contrast between urban and rural areas. The grid was established by quartering the 1 km × 1 km square network of the Unified

National Mapping System (EOTR), that can be found on topographical maps of Hungary at the scale of 1:10,000.

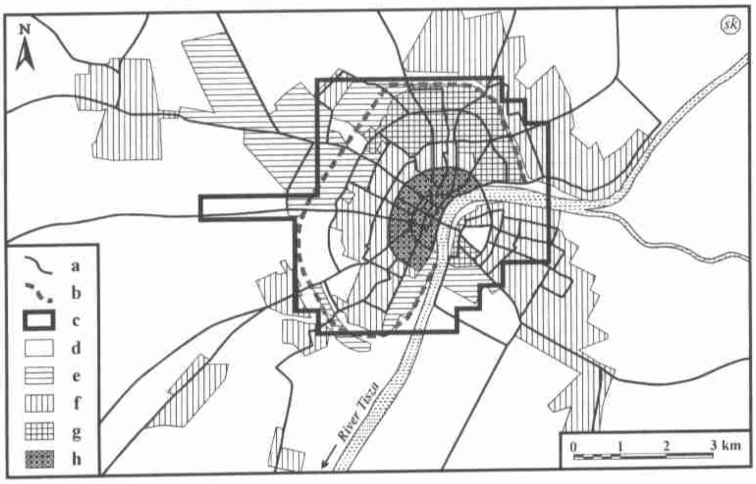

Fig. 2. Characteristic land-use types and road network in Szeged: (**a**) road, (**b**) circle dike, (**c**) border of the study area, (**d**) agricultural and open land, (**e**) industrial area, (**f**) 1–2 storey detached houses, (**g**) 5–11 storey apartment buildings and (**h**) historical city core with 3–5 storey buildings.

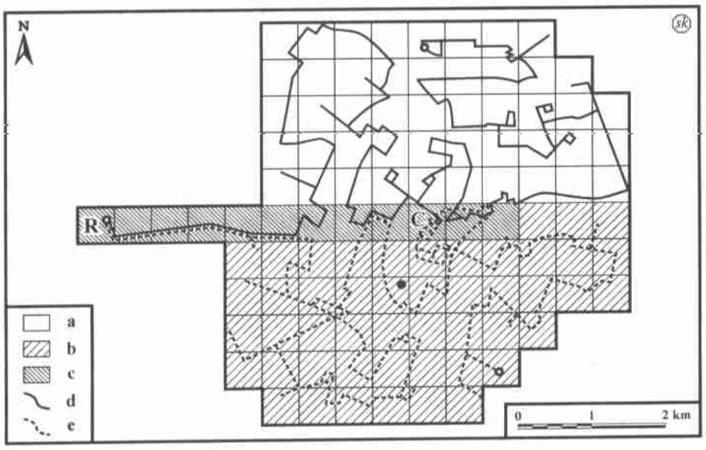

Fig. 3. Division of the study area into 0.5 km × 0.5 km grid cells: (**a**) northern sector, (**b**) southern sector, (**c**) overlap area and (**d, e**) the measurement routes. Rural and central grid cells are indicated by R and C, respectively. The permanent measurement site at the University of Szeged is indicated as •.

The examination of the spatial and temporal distribution of surface air temperature was based on mobile observations during the period of March, 1999–February, 2000. In case of surface UHI and near surface air UHI investigations, the moving observation with different vehicles (car, tram, helicopter, airplane, satellite) is an often used process (e.g., *Johnson*, 1985; *Yamashita*, 1996; *Voogt* and *Oke*, 1997; *Klysik* and *Fortuniak*, 1999; *Tumanov et al.*, 1999).

In order to collect data on maximum UHI intensity (namely the temperature difference between urban and rural areas) at every grid cell, mobile measurements were performed on fixed return routes once a week during the studied period (altogether 48 times) to accomplish an analysis of air temperature over the entire area. This one-week frequency of car traverses secured sufficient information on different weather conditions, except for rain.

Division of the study area into two sectors was needed because of the large number of grid cells. The northern and southern sectors consisted of 59 grid cells (14.75 km^2) and 60 grid cells (15 km^2), respectively, with an overlap of 12 grid cells (3 km^2). The lengths of the fixed return routes were 75 and 68 km in the northern and southern sectors, respectively, and took about 3 hours to traverse (Fig. 3). Such long and return routes were necessary to gather temperature values in every grid cell and to make time-based corrections. Temperature readings were obtained using a radiation-shielded LogIT HiTemp resistance temperature sensor (resolution of 0.01 °C), which was connected to a portable LogIT SL data logger for digital sampling inside the car. Since the data were collected every 16 s at an average car speed of 20–30 km h^{-1} the average distance between measuring points was 89–133 m. The temperature sensor was mounted 0.60 m in front of the car at 1.45 m above ground to avoid engine and exhaust heat. This is similar to the measurement system used by *Ripley et al.* (1996) in Saskatoon, Saskatchewan. The car speed was sufficient to secure adequate ventilation for the sensor to measure the momentary ambient air temperature.

After averaging the measurement values by grid cells, time adjustments to the reference time were applied assuming linear air temperature change with time. This linear change was monitored using the continuous records of the permanent automatic weather station at the University of Szeged (Fig. 3). The linear adjustment appears to be correct for data collected a few hours after sunset in urban areas. However, because of the different time variations of cooling rates, it is only approximately correct for suburban and rural areas (*Oke* and *Maxwell*, 1975). The reference time, namely the likely time of the occurrence of the strongest UHI, was 4 hours after sunset, a value based on earlier measurements in 1998 and 1999 (*Boruzs* and *Nagy*, 1999). Consequently, every grid cell of 59 in the northern sector or every grid cell of 60 in the southern sector can be characterized by one temperature value for every measuring night. These temperature values refer to the center of each cell.

We determined urban-rural air temperature differences (UHI intensity) by cells referring to the temperature value of the grid cell (the most western cell in the investigated area), where the synoptic weather station of the Hungarian Meteorological Service is located. This grid cell (labeled by R) containing this station was regarded as rural (Fig. 3), because the records of this station were used as rural data in the earlier studies on the urban climate of Szeged (e.g., *Unger*, 1996, 1999). The 107 points (the above mentioned grid cell center-points) cover the urban parts of Szeged and they provide an appropriate basis to interpolate isolines. The isolines, therefore, can show detailed descriptions of thermal field within the city at the time of the strongest effects of urban factors. In order to draw the isotherms, a geostatistical gridding method, the standard kriging procedure was used.

Parameters of land-use for the grid cells were determined by GIS (Geographical Information System) methods combined with remote sensing analysis of SPOT XS images (*Mucsi*, 1996). Vector and raster-based GIS databases were produced in the Applied Geoinformatics Laboratory of the University of Szeged. The digital satellite image was rectified to the EOTR using 1:10 000 scale maps. The nearest-neighbour method of resampling was employed, resulting in a root mean square value of less than 1 pixel. Since the geometric resolution of the image was 20 m × 20 m, small urban units could be assessed independently of their official (larger scale) land-use classification. Normalised Vegetation Index (*NDVI*) was calculated from the pixel values, according to the following equation:

$$NDVI = (IR - R) \;/\; (IR + R), \tag{1}$$

where IR is the pixel value in the infrared band and R is the pixel value in the red band. The range of $NDVI$ values is from -1 to $+1$, indicating the effect of green space in the given spatial unit (*Lillesand* and *Kiefer*, 1987). Built-up, water, vegetated and other surfaces were distinguished according to the $NDVI$ value. The spatial distribution of these land-use types of each grid element was calculated using cross-tabulation.

In order to assess the extent of the relationships between the maximum UHI intensity and various urban surface factors, multiple correlation and regression analyses were used. The selection of the parameters was based on their role in determining small-scale climate variations (*Adebayo*, 1987; *Oke*, 1987; *Golany*, 1996).

The selected urban parameters were percentage of built-up area (covered surface-building, street, pavement, parking lot, etc.) and water surface by grid cells, as well as distance to the city centre (grid cell labeled by C, see Fig. 3).

This distance can be considered as an indicator of the location of a cell within the city. These three parameters are constants for the complete (one-year long) measurement period. However, in each cell their values vary from place to place within the city. They are constants temporally but variables spatially. Searching for statistical relationships, we will take into account that our parameters are at once variables and constants.

The ratio of the built-up area to the total area by grid cells in 25% increments is displayed in *Fig. 4.* Fig. 4 shows, that, for example, the location of the River Tisza (low built-up ratio) is clearly recognised with its east-to-south curve in the south-eastern part of the study area (see also Fig. 2).

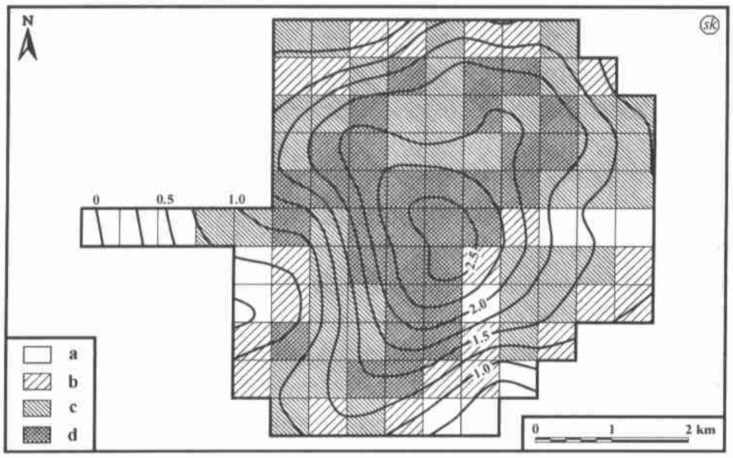

Fig. 4. Spatial distribution of the mean maximum UHI intensity (°C) and the built-up density of the study area by grid cells (ratio of the built-up area to the total cell area) (**a**) 0–25%, (**b**) 25–50%, (**c**) 50–75% and (**d**) 75–100%) during the studied one-year period (March 1999–February 2000) in Szeged.

3. Result and discussion

3.1 Spatial distribution of the maximum UHI

In our investigation not only the one-year period is studied, but within this period we distinguish the so called heating (between October 16 and April 15) and non-heating (between April 16 and October 15) seasons.

It can be seen in *Figs. 4, 5* and *6* that built-up density has a significant influence on the spatial patterns of the mean maximum UHI intensity (4 hours after sunset as supposed). The most obvious common features of these patterns are that the isotherms show almost regular concentric shapes with values increasing from the outskirts toward the inner urban areas. A vigorous deviation from this concentric shape occurs in the north-eastern part of the city, where the isotherms stretch toward the suburbs. This can be explained by the influence of the large housing estates with tall concrete buildings located mainly in the north-eastern part of the city with a built-up ratio higher than 75% (Fig. 2).

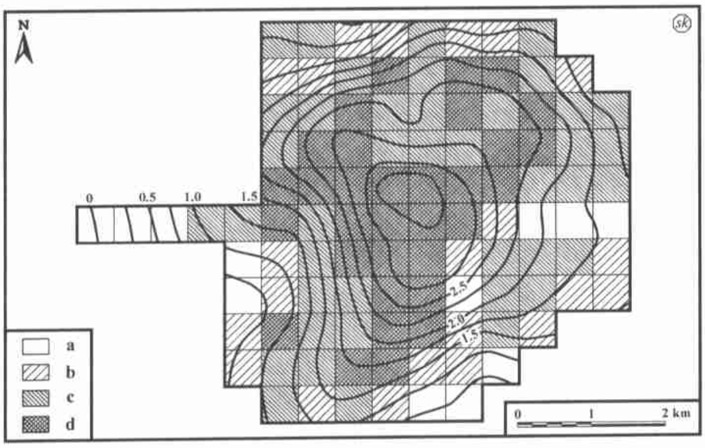

Fig. 5. Spatial distribution of the mean maximum UHI intensity (°C) during the non-heating season (April 16–October 15) in Szeged.

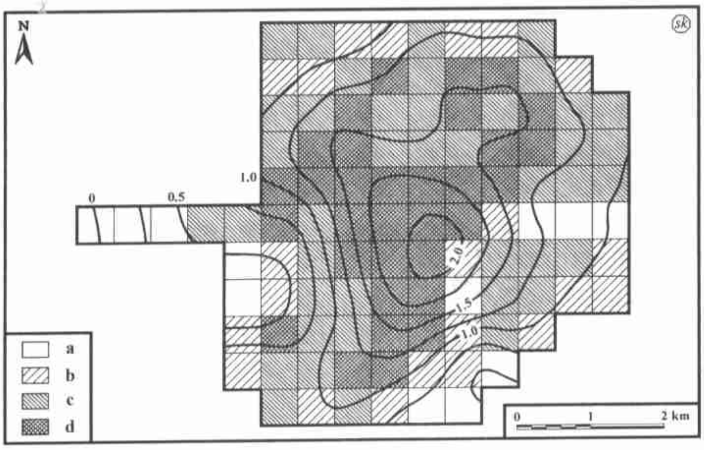

Fig. 6. Spatial distribution of the mean maximum UHI intensity (°C) during the heating season (October 16–April 15) in Szeged.

For the one-year period (Fig. 4), as it was expected, the highest differences (more than 2.5°C) are concentrated mainly in the densely built-up city center (>75%) covered by about 2.5 grid cells (about 0.6 km^2). The strongest intensity (2.60°C) occurs in the central grid cell (C). A mean maximum UHI intensity of higher than 2°C indicates significant thermal modification. In this period in Szeged, the extension of the area, characterized by significant thermal modification, is about 19 grid cells (4.5–5.0 km^2), which is about 18% of the total investigated area.

In the non-heating season, the spreading out of the isolines of 2.25°C and 2.5°C to the north-west of the center, and the isolines of 1.5°C and 1.75°C to the south-west are also caused by the high built-up ratio of more than 75% (Fig. 5). The highest differences (more than 2.75°C) are concentrated in the densely built-up city center (>75%) covered by about 8 grid cells (2 km^2). The greatest intensity (3.18°C) is to the north of the central grid cell (C) in an adjacent cell. The mean maximum UHI intensity of higher than 2°C is relatively large compared to the size of the study area. It covers about 40 grid cells (10 km^2), which is about 37% of the investigated area.

In the heating season, the high built-up ratio of more than 75% also caused the streching out of the isoline of 1.5°C to the north-west, and the isolines of 1°C and 1.25°C to the south-west (Fig. 6). The highest differences (more than 2°C) are concentrated in the city centre (>75%), covered by less than 2 grid cells (0.5 km^2), which is only about 2% of the total area. The strongest intensity (2.12°C) occurs in the central grid cell (C).

The seasonal differences may be formed as a consequence of different weather characteristics in the two seasons rather than as a consequence of heating or non-heating of inhabitants. This explanation is supported by *Klysik* and *Fortuniak* (1999), who found similar differences in the UHI intensities between warm and cold seasons in Łódź, Poland. As in Poland, in Hungary (particularly in the Szeged region) the climate conditions in winter, conducive to the formation of UHI, are less common (Table 1). Thus, in the warmer, therefore non-heating season, the role of appropriate weather conditions (stronger solar radiation income, more frequent clear sky and weak wind) and the reduced latent heat transport because of the more impermeable and guttered urban terrain is more pronounced in the development of UHI than the building heating in urban areas. Consequently, in case of Szeged, the significance of artificial heating in the development of UHI is rather limited.

3.2 Statistical relationships

In order to determine model equations for the maximum value of UHI intensity in the diurnal temperature course (ΔT), we use the earlier mentioned parameters (their labels are in brackets): distance from the central grid cell in km

(D), ratio of built-up surface as a percentage (B) and ratio of water surface as a percentage (W). These parameters are variables spatially, namely by grid cells, but constants temporally.

The bivariate analysis will be accurate if the total period averages of ΔT for each cell are correlated against each of the cell value of D, B and W, thus the time averages of the maximum UHI intensities vary by grid cells (the number of data pairs is $n = 107$).

Table 3 contains the results of the bivariate correlation analyses on ΔT against the urban surface parameters considered in this study. As the table shows, among the examined parameters D has the largest correlation coefficients ($r_{\Delta T,D}$). This fact supports the establisment in Chapter 3.1 on the regular concentric shapes of the UHI isotherms in Szeged. The first two coefficients (D, B) are significant at 0.1% in all the three periods. The strong relationships between ΔT and D as well as B by periods can be seen in the *Figs. 7, 8* and *9*. The ratio of water surface seems not to be important ($r_{\Delta T,W} < 0.06$ always, so it is not significant even at 10% level), for this reason it is not necessary to be used in the multiple regression equations. This statistically insignificant role of water surfaces (mainly connected with the River Tisza) in the development of the maximum heat island in Szeged can be explained by the relatively large size of the grid cells, therefore, water surfaces can be found only in 39 grid cells from the total number of 107 and their ratio is only few percentages in most of the grids.

Table 3. Values of bivariate correlation coefficients between the average of maximum UHI intensity (ΔT) in °C and urban surface parameters (D – distance from the city center in km, B – ratio of built-up area as a percentage and W – ratio of water surface as a percentage) by grid cells in different periods in Szeged ($n = 107$)

Bivariate correlation coefficient (n = 107)	**March 1999–February 2000**		**April 16–October15 (non-heating season)**		**October 16–April 15 (heating season)**	
	Value	**Significance level**	**Value**	**Significance level**	**Value**	**Significance level**
$r_{\Delta T,D}$	-0.837	0.1%	-0.861	0.1%	-0.760	0.1%
$r_{\Delta T,B}$	0.685	0.1%	0.675	0.1%	0.674	0.1%
$r_{\Delta T,W}$	0.044	–	0.056	–	0.020	–

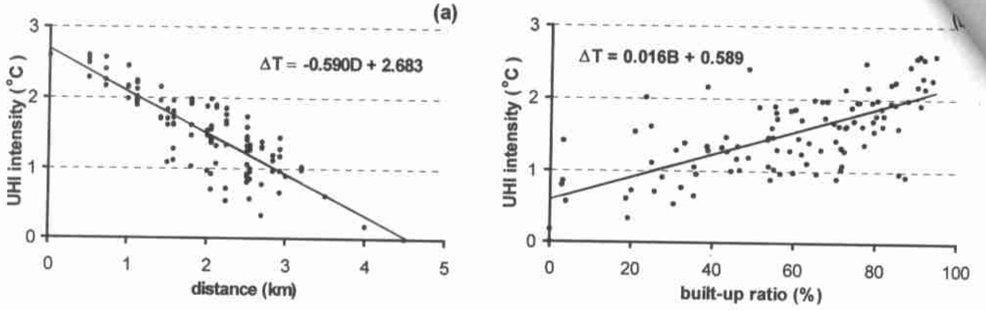

Fig. 7. Maximum UHI intensity (ΔT) as a function of (*a*) the distance from the center (*D*) and (*b*) built-up ratio (*B*) with the best fit regression lines in the one-year period (March 1999–February 2000) in Szeged.

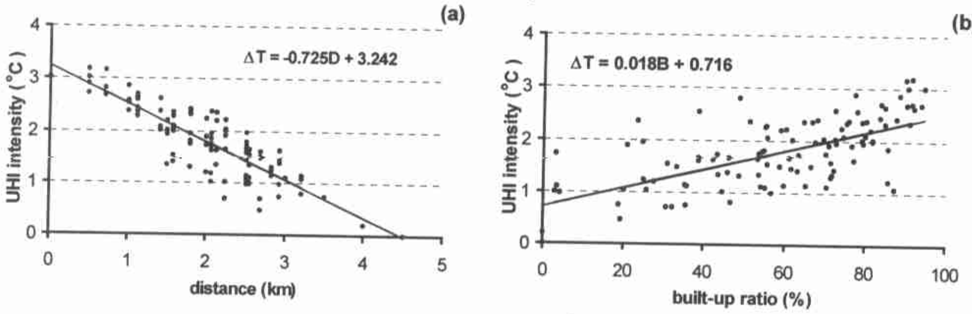

Fig. 8. As *Fig. 7* but in the non-heating season (April 16–October 15).

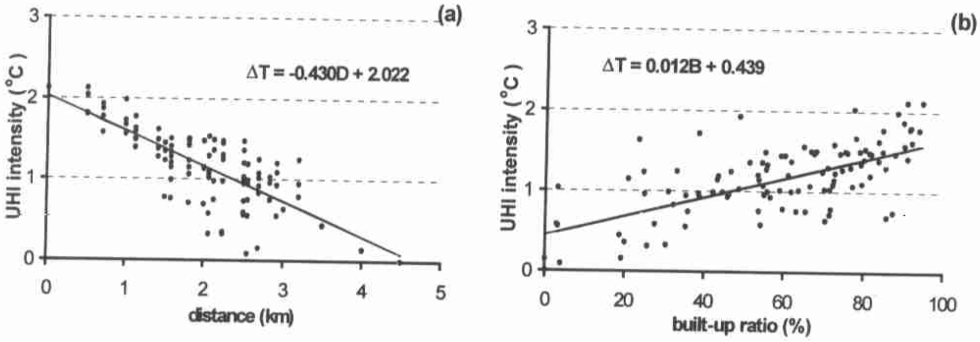

Fig. 9. As *Fig. 7* but in the heating season (October 16–April 15).

sion, was determined with the help of the magnitude of the bivariate correlation coefficients. *Table 4* contains the results of this stepwise regression on ΔT against the urban surface parameters in the three investigated periods. As the results show, the distance from the city center is most pronounced, but the role of the built-up density is also important. The improvements in the explanation caused by entering of B, namely the differences as a percentage in the correlation coefficients in the fourth column of the table (Δr^2) of 6.8%, 5.3% and 15.0% cannot be neglected. The moderate large values of Δr^2 can be explained by the fact that D and B in a city structure are not entirely independent from each other.

Table 4. Values of the stepwise correlation of maximum UHI intensity (ΔT) and urban surface parameters by grid cells in different periods in Szeged (n = 107)

Period	**Parameter entered**	**Multiple $\lvert r \rvert$**	**Multiple r^2**	Δr^2
March 1999– February 2000	D	0.837	0.701	0.000
	B	0.877	0.769	0.068
April 16–October 15 (non-heating season)	D	0.861	0.742	0.000
	B	0.892	0.795	0.053
October 16–April 15 (heating season)	D	0.760	0.577	0.000
	B	0.816	0.666	0.150

Table 5. Best fit model equations for the average of maximum UHI intensity (ΔT) using urban surface parameters in different periods in Szeged (n = 107)

Period	**Parameters**	**Multiple linear regression equations**	**Significance level**
March 1999– February 2000	D	$\Delta T = -0.590D + 2.683$	0.1%
	D, B	$\Delta T = -0.466D + 0.007B + 2.016$	0.1%
April 16– October 15	D	$\Delta T = -0.725D + 3.242$	0.1%
	D, B	$\Delta T = -0.593D + 0.008B + 2.533$	0.1%
October 16– April 15	D	$\Delta T = -0.430D + 2.022$	0.1%
	D, B	$\Delta T = -0.315D + 0.007B + 1.406$	0.1%

Referring to the investigated periods, *Table 5* contains the model equations which describe ΔT in the best way. The absolute values of the multiple correlation coefficients (r) between the maximum UHI intensity and the parameters are 0.837 and 0.877 for the one-year period, 0.861 and 0.892 for the non-heating season and 0.760 and 0.861 for the heating season (they are all significant at 0.1% level) (*Tables 4* and *5*). The corresponding squares of these multiple correlation coefficients (r^2) provide explanations of 70.1% and 76.9%, of 74.2% and 79.5 and of 57.7% and 66.6% of the variance, respectively.

4. Conclusions

The seasonal spatial distribution of the maximum urban heat island and its quantitative relationships with urban surface parameters are investigated in the present study. The results indicate that:

- The spatial patterns of the maximum UHI intensity have regular concentric shapes and the isotherms increase from the outskirts towards the central urban areas in all the three studied periods.
- The anomalies in the regularity are caused by the alterations in the built-up density.
- There are significant differences in the magnitudes of the seasonal (heating and non-heating) patterns. The area of the mean maximum UHI intensity of higher than 2°C — indicates significant thermal modification caused by urbanisation — is 18 times larger in the non-heating than in the heating season (2% and 37%, respectively).
- As the correlation coefficients of the parameters show, a short distance from the city center and a high built-up ratio, which prevail mostly in the inner parts of the city, play important roles in the increment of the urban temperature.

Consequently, our preliminary results prove that the statistical approach which determines the behaviour of the UHI intensity in Szeged is promising and this fact urges us to make more detailed investigations. We are planning to extend this project by modeling urban thermal patterns as they are affected by weather conditions with a time lag. We intend to employ the same parameters used in this study, as well as additional urban and meteorological parameters, to predict the magnitude and spatial distribution of the maximum UHI intensity on the days characterised by any kind of weather conditions (apart from the ones with precipitation) at any time of the year without recourse to extra mobile measurements. These tasks require longer-term data sets, so we intend to gather data for a period of more than one year.

The results will be of practical use in predicting the pattern of energy consumption inside the city. They can be used to forecast and plan the energy demand, particularly in cold and warm periods of the year, when energy consumption of heating and cooling, respectively, is highest.

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References

Adebayo, Y.R., 1987: Land-use approach to the spatial analysis of the urban 'heat island' in Ibadan. *Weather 42*, 272-280.

Boruzs, T. and *Nagy, T.*, 1999: *Urban Influence on the Climatological Parameters* (in Hungarian). MSc thesis, University of Szeged, Szeged, 81 pp.

Chow, S.D., *Zheng, J.* and *Wu, L.*, 1994: Solar radiation and surface temperature in Shangai City and their relation to urban heat island intensity. *Atmos. Environ. 28*, 2119-2127.

Golany, G.S., 1996: Urban design morphology and thermal performance. *Atmos. Environ. 30*, 455-465.

Goldreich, Y., 1992: Urban climate studies in Johannesburg, a sub-tropical city located on a ridge - A review. *Atmos. Environ. 26B*, 407-420.

Grimmond, C.S.B., *Cleugh, H.A.* and *Oke, T.R.*, 1991: An objective urban heat storage model and its comparison with other schemes. *Atmos. Environ. 25B*, 311-326.

Grimmond, C.S.B. and *Oke, T.R.*, 1991: An evapotranspiration-interception model for urban areas. *Water Resources Res. 27*, 1739-1755.

Jendritzky, G. and *Nübler, W.*, 1981: A model analysing the urban thermal environment in physiologically significant terms. *Arch. Met. Geoph. Biol. Ser.B. 29*, 313-326.

Johnson, D.B., 1985: Urban modification of diurnal temperature cycles in Birmingham. *J. Climatology 5*, 221-225.

Johnson, G.T., *Oke, T.R.*, *Lyons, T.J.*, *Steyn, D.G.*, *Watson, I.D.* and *Voogt, J.A.*, 1991: Simulation of surface urban heat islands under 'ideal' conditions at night, I: Theory and tests against field data. *Boundary Layer Met. 56*, 275-294.

Klysik, K. and *Fortuniak, K.*, 1999: Temporal and spatial characteristics of the urban heat island of Łódź, Poland. *Atmos. Environ. 33*, 3885-3895.

Kuttler, W., 1998: *Stadtklima.* In *Stadtökologie* (eds.: *Sukopp, H.* und *Wittig, R.*). *Gustav Fischer, Stuttgart-Jena-Lübeck-Ulm*, 125-167.

Kuttler, W., *Barlag, A-B.* and *Roßmann, F.*, 1996: Study of the thermal structure of a town in a narrow valley. *Atmos. Environ. 30*, 365-378.

Lillesand, T.M. and *Kiefer, R.W.*, 1987: *Remote Sensing and Image Interpretation.* J. Wiley & Sons, New York, 705 pp.

Mucsi, L., 1996: Urban land use investigation with GIS and RS methods. *Acta Geographica Univ. Szeged 25*, 111-119.

Myrup, L.O., *McGinn, C.E.* and *Flocchini, R.G.*, 1993: An analysis of microclimatic variation in a suburban environment. *Atmos. Environ. 27B*, 129-156.

Nkemdirim, L.C., 1978: Variability of temperature fields in Calgary, Alberta. *Atm. Environment 12*, 809-822.

Oke, T.R., 1973: City size and the urban heat island. *Atmos. Environ. 7*, 769-779.

Oke, T.R., 1976: The distinction between canopy and boundary layer urban heat islands. *Atmosphere 14*, 268-277.

Oke, T.R., 1987: *Boundary Layer Climates.* Routledge, London and New York, 405 pp.

Oke, T.R., 1997: *Urban climates and global environmental change.* In *Applied Climatology* (eds.: *R.D Thompson.* and *A Perry*). Routledge, London-New York, 273-287.

Oke, T.R. and *Maxwell, G.B.*, 1975: Urban heat island dinamics in Montreal and Vancouver. *Atmos. Environ. 9*, 191-200.

Park, H-S., 1986: Features of the heat island in Seoul and its surrounding cities. *Atmos. Environ. 20*, 1859-1866.

Ripley, E.A., *Archibold, O.W.* and *Bretell, D.L.*, 1996: Temporal and spatial temperature patterns in Saskatoon. *Weather 51*, 398-405.

Sailor, D.J., 1998: Simulations of annual degree day impacts of urban vegetative augmentation. *Atmos. Environ. 32*, 43-52.

Sundborg, A., 1950: Local climatological studies of the temperature conditions in an urban area. *Tellus 2*, 222-232.

Tapper, P.D., *Tyson, P.D.*, *Owens, I.F.* and *Hastie, W.J.*, 1981: Modeling the winter urban heat island over Christchurch. *J. Appl. Meteorology 20*, 365-367.

Tumanov, S., *Stan-Sion, A.*, *Lupu, A.*, *Soci, C.* and *Oprea, C.*, 1999: Influences of the city of Bucharest on weather and climate parameters. *Atmos. Environ. 33*, 4173-4183.

Unger, J., 1996: Heat island intensity with different meteorological conditions in a medium-sized town: Szeged, Hungary. *Theor. Applied Climatology 54*, 147-151.

Unger, J., 1999: Urban-rural air humidity diferences in Szeged, Hungary. *Int. J. Climatology 19*, 1509-1515.

Unger, J., *Sümeghy, Z.*, *Gulyás, Á.*, *Bottyán, Zs.* and *Mucsi, L.*, 1999: Modeling the maximum urban heat island. *Proceed. ICB-ICUC'99*, Sydney, Australia, ICUC10.4.

Voogt, J.A. and *Oke, T.R.*, *1991*: Validation of an urban canyon radiation model for nocturnal long-wave radiative fluxes. *Boundary Layer Met. 54*, 347-361.

Voogt, J.A. and *Oke, T.R.*, 1997: Complete urban surface temperatures. *J. Appl. Meteorology 36*, 1117-1132.

Yamashita, S., 1996: Detailed structure of heat island phenomena from moving observations from electric tram-cars in metropolitan Tokyo. *Atmos. Environ. 30*, 429-435.