PhD. DISSERTATION

<u>THESES</u>

STATISTICAL MODELLING OF MEAN MAXIMUM URBAN HEAT ISLAND INTENSITY IN SZEGED AND DEBRECEN

ZSOLT BOTTYÁN

SUPERVISOR:

DR. JÁNOS UNGER

UNIVERSITY OF SZEGED

Doctoral School of Earth Sciences

2007

1. Precedents and objectives

Since more and more people live in towns, urbanization accelerated and reached enormous magnitude from the second half of the twentieth century. Compared to their surroundings, not only large cities, but also smaller settlements can significantly modify several characteristics of the urban atmospheric environment. The artificial factors create a local climate (so-called urban climate), whose most obvious modification occurs in temperature. Generally, this modification is an excess, which is called as ***urban heat island*** (***UHI***). The intensity of the heat island shows a typical diurnal variation and spatial distribution inside the settlement. These theoretical backgrounds are summarized in Chapter 2 (*Stummer,* 1939; *Duckworth and Sandberg*, 1954; *Oke and Hannell*, 1970; *Oke and Fuggle*, 1972; *Probáld*, 1974; *Yoshino,* 1975; *Probáld*, 1975;; *Oke and Maxwell*, 1975; *Oke,* 1976; *Oke*, 1979; *Landsberg*, 1981; *Barry and Chorley*, 1982; *Oke*, 1982; *Park*, 1987; *Mézes*, 1995; *Oke*, 1997; *Unger*, 1997; *Kuttler*, 1998; *Unger és Sümeghy*, 2002).

In Chapter 3 I give a short foreign (*Sundborg*, 1950, 1951; *Duckworth and Sandberg*, 1954; *Kratzer*, 1956; *Manley,* 1958; *Chandler*, 1960; *Mitchell*, 1961; *Chandler*, 1962, 1967; *Myrup*, 1969; *Bach,* 1970; *Delage and Taylor*, 1970; *Yu*, 1973; *Oke*, 1973; *Oke and Maxwell*, 1975; *Bornstein and Robock*, 1976; *Vukovich et al.*, 1976; *Nkemdirim and Truch*, 1978; *Terjung and O'Rourke*, 1980; *Landsberg*, 1981; *Park*, 1986; *Chow et. al*., 1994; *Moreno-Garcia*, 1994; *Kuttler et al*., 1996; *Bornstein et al.,* 1999; *Thielen and Troude*, 2001; *Morris et al.*, 2001; *Goncalves et al.*, 2003; *Long et al.,* 2003; *Giridharam et al,* 2005; *Masson*, 2006; *Alcoforado and Andrade*, 2007) and Hungarian (*Unger et al.,* 2000; *Unger et al*., 2001; *Bottyán és Unger*, 2001; *Bottyán and Unger*, 2002; *Bottyán and Unger*, 2003; *Bottyán et al*., 2003; *Unger et al*., 2004; *Bottyán et al*., 2004; *Bottyán et. al.,* 2005) overview about urban heat island modelling. These mentioned papers are the precedents of this work from a certain aspect.

The Chapter 4 contains the geographical and climatological attributes of the Hungarian Plain area because physical geographical conditions of the city's environment (e.g. topography, distance from large water bodies) also affects the climate. It is necessary to discuss the environmental conditions of Szeged and Debrecen (*Frisnyák et al.*, 1978; *Péczely*, 1979, 1984; *Mezősi*, 1983; *Keveiné Bárány*, 1988). Both of mentioned cities are located in a flat area with a same configuration of the terrain and their climatic conditions and areal extensions are the similar. On the basis of these facts there is a real possibilitiy to compare and analyse the spatial distribution of urban temperature field over two mentioned cities.

Based on earlier studies, a long research project started in Szeged in 1999. Two one-year-long measurement campaigns were carried out: the first one, which can be considered as a thorough pre-study, took place between March 1999 and February 2000 in Szeged, while the second one between March 2002 and March 2003 in Szeged and Debrecen at the same time. The latter provided the greatest part of the data set used for the presentation of the spatial structure of the maximum UHI. Due to their importance, the methods of the areal investigation of the UHI and the urban built-up parameters are summarised in Chapter 5.

The attributes (spatial distribution and anomalies) of the UHI in two investigated areas are shown in the Chapter 6.

Using a large amount of temperature data are given by two measuring campaigns of 1999/2000 and 2002/2003 we developed two multiple linear statistical model for predicting the UHI in both cities. In Chapter 7 it can be read a short overview about the methods of mathematical modelling of a climatic system. After that in the Chapter 8 can be seen two statistical model: model I. (for Szeged) and model II. (for Szeged and Debrecen) were developed for predicting the mean maximum urban heat island intensity with the help of urfan surface parameters and their aerial extensions.

The investigation of the urban heat island is an important task from several viewpoints, because the UHI influences the comfort sensation of the citizens (at the middle latitudes with different signs according to the seasons), the energy demand of heating and cooling as well as the length of vegetation period and phenological phases. That is why the important and useful to estimate the maximum values of the spatial distribution of the UHI intensities.

2. Investigated areas

The base of mapping and visualising of our results was the 1:10.000 scale maps of the Unified National Mapping System developed for the topographical maps of Hungary. The area of investigation in Szeged and Debrecen had been divided into two sectors and subdivided further into 0.5 km x 0.5 km square cells. The same grid size was employed earlier in several studies of urban climate (e.g. *Jendritzky – Nübler*, 1981; *Park*, 1986), but it is applied in other projects, too (e.g. *Lindberg et al.*, 2003; *Long et al.*, 2003).

Our investigated area in Szeged contains 107 cells (26.78 km^2) covering the urban and suburban parts of the city. The same grid-network was applied to cover the similar parts of Debrecen city (105 cells and 26.25 km^2).

3. Methods, measurements and evaluation

3.1. Temperature measuring

The examination of the maximum UHI intensity, based on mobile measurements, took place in the period of March 2002 - March 2000 at the same time in Szeged and Debrecen. In case of near-surface air UHI measurements, vehicle-based observation is a common process in urban climate research (e.g. *Oke and Fuggle*, 1972; *Moreno-Garcia*, 1994; *Eliasson*, 1996; *Yamashita*, 1996; *Voogt and Oke*, 1997; *Klysik and Fortuniak*, 1999; *Comrie*, 2000; *Santos et al.*, 2003).

Based on the literature (e.g. *Oke*, 1987) and on the experience of our earlier investigations (*Boruzs – Nagy*, 1999; *Unger – Sümeghy*, 2000), measurements along the given routes were taken between 2.5 and 5.5 hours after sunset. This was caused by the fact that the possible time of the maximum UHI (reference time) was 4 hours after sunset.

Temperature readings were obtained using radiation-shielded LogIT HiTemp resistance sensors (resolution of 0.01°C) connected to LogIT DataMeter 1000 data loggers (DCP Microdevelopments and SCC Research) for digital sampling.

Having averaged the temperature values by cells, adjustments to a reference time (4 hours after sunset) were applied. The maximum UHI values, namely maximum temperature difference between the city and its surroundings (ΔT – ºC), can be determined by cells as follows:

$$\Delta T = T_{cell} - T_{cell(R)}$$

where T_{cell} and $T_{cell(R)}$ are the temperatures of a given urban cell and the outer cell regarded as rural in case of both cities.

As it was mentioned earlier, the investigation of the maximum UHI intensity using mobile measurements in Szeged started already in 1999, whereas the first measurement campaign was carried out between March 1999 and February 2000. Ennek területe és módszerei lényegében megegyeztek a fentiekben ismertetettekkel, ezért most csak az eltéréseket vázolom fel.

The study area and the method were almost the same as the earlier mentioned one. Only one difference between them was that in 1999/2000 the measurements were taken with weekly frequency: altogether 48 measurements took place. The areal extent of the sectors and the lenght of routes were a bit different from the ones in 2002/2003: the northern and southern sectors consist of 59 (14,75 km^2) and 60 (15 km^2) cells, with an overlapping area of 12 cells (3 km^2).

3.2. Determining the built-up ratio and water surface ratio

Built-up ratio values for grid cells were determined by GIS methods combined with remote sensing analysis of SPOT XS images. Normalized Difference Vegetation Index (NDVI) was calculated from the pixel values (*Gallo – Owen*, 1999):

$$NDVI = (IR - R) / (IR + R)$$

where *IR* – pixel value in the near infrared (0.72-1.1 μm) and *R* – pixel value in the visible (0.58-0.68 μm) bands. 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 and their ratios (to total cell area) were determined for each grid square. In case of Debrecen the method of determination of the mentioned parameter was the same but the applied image was given by LANDSAT TM satellite.

3.3. Measuring and calculating of sky view factor

To quantitatively determine of the openness of cell surfaces, we applied the sky view factor (*S*). If the sky completely open the value of *S* parameter is 1 and if the sky is covered by buildings and other objects its value is 0.

Commonly, the *S* is determined by using either analytical or photographic methods (*Szakály*, 1962; *Oke*, 1981; *Bärring*, 1985; *Park*, 1987; *Holmer et al.*, 1992; *Grimmond et al.*, 2001).

In our analytical method, along the measurement route by about 100 meters, we have measured two elevation angles to the top of the buildings (α_1 and α_2) perpendicularly to the axis of streets in both directions, using an 1.5 m high theodolite. From these data, wall view factors can be calculated to the left (WVF_1) and right (WVF_2) sides. The calculation of SVF is based on *Oke's* (1988) results:

$$WVF_1 = (1 - \cos\alpha_1) / 2 \qquad \text{where } \alpha_1 = \tan^{-1}(H_1/W_1)$$

$$WVF_2 = (1 - \cos\alpha_2) / 2 \qquad \text{where } \alpha_2 = \tan^{-1}(H_2/W_2)$$

$$SVF = 1 - (WVF_1 + WVF_2)$$

If there were parks, forests or water surface in a particular direction, we assigned 0 an an angle value because it is difficult to determine S values modified by the vegetation (*Yamashita et al.*, 1986).

3.4. Calculation of building height

As we can see at the S parameter calculation the elevation angles (α_1 and α_2) are available at each points. If we have the distances to the walls from the measiring point (W_1 and W_2), there is a simple formula to calculate wall heigths (H_1 and H_2), taking the instrument height of 1.5 m into account (*Bottyán and Unger*, 2003):

$$H_1 = tan(\alpha_1)\cdot W_1 + 1.5\ m$$
$$H_2 = tan(\alpha_2)\cdot W_2 + 1.5\ m$$

The width of the streets was determined by means of aerial photographs concerning any parts of the street. After digitizing these images, we made an orthophoto of Szeged using the ERDAS IMAGINE GIS software and marked the measuring points on them. These orthopohotos are already suitable to determine distances of the walls (W_1 and W_2) from the measurement points. In the next step we simlple calculated the building heights (H_1 and H_2) in each cells.

3.5. Relationship between the spatial distribution of the mean maximum UHI intensity and urban surface parameters in Szeged and Debrecen

The spatial disribution of the mean maximum UHI intensity generated from the measured values has the following features:

- The highest values of UHI intensitiy can be measured in the highly built-in inner region of cities. The maximum observed values of UHI intensity were 3.1 °C in Szeged (from 1999 to 2000) and 2.5 °C in the case of Debrecen (from 2002 to 2003) during the warmer non-heating season (*Unger et al.*, 2000, *Bottyán et al.*, 2005).
- As a function of structure, geometry and built-in mode of the urban surface we can detect a well-concentric shape of heat island over Szeged on the contrary Debrecen has a two-pole heat island structure (*Bottyán and Unger,* 2003*; Bottyán et al.*, 2005).
- The observed structure of UHI intensity is modified by local anomalies in case of both cities (*Bottyán and Unger,* 2003*; Bottyán et al.*, 2005).
- There were higher UHI intensity values in the non-heting season in case of Szeged and Debrecen alike, but there were not any difference in the spatial distribution of UHI intensity between the two half years.

Observed inhomogenities in the spatial distribution of UHI intensity in Szeged, are the following:

- The northeastern and northwestern part of the city has a large housing estates and we can recognize a significant positive UHI intensity anomaly there. On the other hand in the border of mentioned regions the gradient of temperature is very high (*Bottyán and Unger,* 2003).

- As it can be seen the altering effect of Tisza river is well observed at the eastern and southeastern region of Szeged which moderates the urban heat surplus locally.
- Toward the northern direction from the centre of city there is a hardly modified concentric UHI intensity structure by a cooler slightly built-in area.
- At the northern outskirts of the city the temperature decreases very fast towards the rural areas (the temperature gradient is high) which follows the rapid change of the static built-up characteristics.

The local changes of the spatial disribution of mean maximum UHI intensity in Debrecen:

- The northern border of Debrecen has a special surface geometry and rapidly decreasing built-up ratio values thus the UHI intensity is very low there (the value of UHI intensity is 0.2 °C only in the non-heating season) (*Bottyán et al*., 2004; *Bottyán et al*., 2005).
- The western parts of the city have large buildings thus the temperature contrast is locally high in compliance with it the maximum temperature values can be observed a little bit farther from the centre of city.
- The western outskirts of the city has a local positive UHI intensity anomaly because in spite of the decreasing of the built-up ratio, the temperature remains relatively high there.

Szeged has a highly concentric structure of ***built-up ratios***. Its occurent smallest values can be observed on the northern, south-eastern and eastern part of the investigated area. The last mentioned region represents the Tisza river and its riverside. The maximum values of built-up ratio are located in the centre of the city. Thanks to the lakes, some industrial constructions and unbilt areas, the western outskirts of the city has low built-up ratios. From the cell located in the centre of the city towards north-eastern and north-western direction there are two stronger positive UHI intensity anomaly so the isolines strech out in the mentioned directions. The changing of built-up characteristics in the western and south-western part of the investigated area carries the same consequences.

Debrecen has a little irregular, less concentric shape than Szeged but the spatial distribution of the built-up ratio also follows a decreasing from the centre towards the rural areas. It is very important to note this gradient depends on given direction. In this city the maximum temperature values cannot be observed in the central position but rather a little bit_farther in western direction. In the northern direction (towards the Nagyerdő) the built-up ratio decreases rapidly down-to 15-20%, but in the western part of the investigated area there are many large block houses thus the built-up ratio parameter is high there. In the southern region of Debrecen the built-up ratio also very high about between 60 and 80%.

In the case of Szeged the ***water surface ratio*** values are connected with the Tisza river and it has a relative high numbers about 35-40% but in the other areas its values are close to zero.

The ***sky view factor*** is a very important attribute of the urban surface geometry because it represents the limitation of the horizon. The spatial distribution of this parameter has not a concentric-like shape rather it has an island-like structures with locally highest and lowest values. Its low values can be seen in the downtown where there are narrow streets and relative high buildings and farther from the centre in the area of the large housing estates. The outskirts of the investigated area or for example the riverside of the Tisza have high sky view factor values (*Bottyán and Unger*, 2003).

As we can see there are large areas with higher ***buildings height*** values (higher than 10 meters) and on the north-eastern area we can find some huge buildings with height above 20 meters. The building heights values are lower in the eastern region of the investigated area because of the smaller houses and the riverside of the Tisza.

3.6. Methods of mathematical modelling of climatic systems

There are two different approach to mathematical modelling of a climatic system.

In the first case we solve the differential equations of a system with the help of their initial and/or boundary conditions. If we know the initial conditions and we can formulate the termo- and hydrodinamical laws within the mentioned system then the calculation of temporal variability of condition-changing is the solving an initial-value problem (*Götz*, 1976). This method is called the ***dynamic modelling***.

If we do not know exactly the physical processes within the climatic system we can still apply the observed (measured) data of parameters of these processes to find any relationship among the system parameters. In this case with the using of the observed (measured) values we have to determine a mathematical relationship between the values of predictors and dependent variable. Of course the selection of predictors from the initial set to give the best fit is also a very important procedure.

We can give an estimate for a system parameter using other observed (measured) parameter values from the same system and this method is called ***statistical modelling***.

In this case the given mathematical relationship is not a function because the predictors and their coefficients do not exactly determine the dependent variable. The estimated values are fluctuate around the most probably value (***stochastic relationship***) (*Péczely*, 1979).

4. Results

4.1. Statistical model (model I.) for estimating mean maximum UHI intensity in Szeged

1. In term of Szeged to predict the mean maximum UHI intensity we applied the values of built-up ratio (*B*), water surface ratio (*W*), sky view factor (*S*) and building height (*H*) and their extensions. In case of temperature values we examined the relationship between UHI intensity and above mentioned parameters in two different seasons (heating and non-heating seasons) during the March 1999 to Febr 2000 period in Szeged and during the March 2002 to March 2003 period in Szeged and Debrecen in the same time. Since the temperature of the urban area depends on not only the physical, geometrical characteristics of the near environment thus the extensions of the mentioned static urban parameters had also been applied in the starting set of predictors. The extensions are based on exponential weighting of distance (*Bottyán and Unger, 2003; Bottyán et al.,* 2005).

2. During modelling we had to determine the predictors' coefficients with the special regard to the best estimation of the UHI intensity by mentioned predictors ant their coefficients (*Kőrösi* et al., 1990). In our work we applied the multiple linear regression procedure (MLR) to predict the coefficients of the independent variables (*Dévényi és Gulyás, 1988*). If there are a large number of predictors in our initial predictor set a serious problem is arisen which called ***multicollinearity***. This means the predictors are not independent from each other. The most simple method to eliminate the mentioned collinearity problem deleting those predictors from starting set that are most dependent each other (*Kőrösi* et al., 1990). Using this procedure our predictors' number has decreased to 9 (*Unger* et al., 2004). The applied model is a multiple linear statistical model for estimating the mean maximum UHI intensity with 9 starting predictors (*B, W, H; B1, S1, W1; B2, H2, W2*).

3. The relationship between UHI intensity and urban built-up parameters and their extensions was predicted by multiple linear regression method. The predictors and their coefficients was calculated by FSMLR procedure with the help of SPSS 9 software (*Miller*, 2000). The regression equations were determined by the mentioned procedure are the following in case of Szeged (model I.):

$$\Delta T_{nf} = -4{,}291S1 + 0{,}035H + 0{,}023B1 + 0{,}042W1 + 3{,}824$$

$$\Delta T_{f} = -3{,}242S1 + 0{,}025H + 0{,}014B1 + 0{,}021W1 + 3{,}036$$

where ΔT_{nf} and ΔT_{f} are the UHI intensities (°C) in the non-heating and the heating seasons, respectively. *S1, H, B1, W1* are the known applied predictors. In both seasons the multiple correlation coefficiens has a high value: in the non-heating half year R=0.902, and in the heating period R=0.873. The estimate of the predictors coefficients are significant at 5% probability value (*Bottyán et al.*, 2003).

4.2. Statistical model (model II.) for estimating mean maximum UHI intensity in Szeged and Debrecen

4. Of course we have a similar linear statistical models in connection with both cities applying built-up ratio (*B*) and its areal extensions (*B1, B2, B3*) too. In both seasons there are high multiple correlation coefficients: in the non-heating season R=0.858 and in the heating one R=0.860. The selected 4 predictors determine the UHI intensity very well (variance is 74%). The significance level of R is very high in every cases higher than 0.1% (*Bottyán et al., 2005*). But in Debrecen the selected predictors determine the UHI intensity less than in case of Szeged. In the non-heating season the determining is about 35% and in the heating one it is only about 31%. In spite of it the significance level of multiple correlation coefficients are 0.1% in both seasons. The given seasonal model equations in reference to Debrecen are:

$$\Delta T_{nf} = 2{,}258B1 - 3{,}242B3 + 2{,}056$$

$$\Delta T_{f} = -4{,}240B3 + 1{,}252B1 - 1{,}537B2 + 3{,}281$$

and the same equations in term of Szeged:

$$\Delta T_{nf} = 0{,}082B1 + 0{,}642B - 7{,}340B3 - 3{,}237B2 + 8{,}080$$

$$\Delta T_{f} = -3{,}614B3 + 0{,}743B + 1{,}137B1 + 2{,}789$$

where ΔT_{nf} and ΔT_{f} represent the UHI intensities (°C) int he non-heating and the heating seasons respectively and *B, B1, B2, B3* are the selected predictors.

5. We can see well, applying the extended starting predictor set could obtain for us a large amount of additional information about UHI intensity field without more other measurements. (The estimation is better with 23-24% in Szeged and with 12-16% in Debrecen, if we apply the extended predictors.)

4.3. Comparing the measured and predicted (model I.) UHI intensity fields in Szeged

6. We compared the spatial distribution of the predicted UHI intensity field in the non-heating season with the same distribution and season of observed UHI intensity measured in the period of 2002-2003. The results of comparison are the next:

- The absolute differences are everywhere smaller than 0.5 °C in the whole area of Szeged.
- The estimate of our model gives higher values than measured ones in the larger part of the investigated area (e.g. 57%) and the other part of it the predicted values are smaller.
- The strongest anomalies are located close to the earlier mentioned urban surface (geometrical and structural) inhomogenities for example large housing estates in the nort-eastern part of Szeged (negative anomaly) and western outskirts of the city (positive anomaly) where the difference is higher than 0.4 °C. These areas contain the very small part (4%) of the whole urban area (about 4 cells and 1km^2).
- On the other hand the region that has a smaller anomaly than 0.2 °C means the dominant part of the investigated area with 75% value (73 cells and 18,2 km^2).

4.4. Comparing the measured and predicted (model II.) UHI intensity fields in Szeged and Debrecen

7. It can be stated that the structures of predicted UHI intensity fields essentially fall in with the measured ones but this similarity in Szeged is much better than in the case of Debrecen. Since Debrecen has a two-pole temperature structure our model prediction is a little bit poor but the estimated UHI intensity field gives for us the same structure belongs to measured one. In term of Szeged the UHI intensity field has a concentric shape thus the mentioned prediction has a good agreement with the observed temperature field (*Bottyán et al.*, 2004).

4.5. The reliability and limits of the applied statistical model

8. The further possibilities of the modelling based on statistical approach are the following:

- using other predictors which are describing the urban surface characteristics much better

- applying meteo and climate data sets in the model building procedure
- applying time-dependent temperature values in the models

9. Of course our models have some limitation factors in their using:

- The model equations are determined by the given predictor values intervals. The given model equations can do a valid estimation from the same predictor values range only!
- Our models can only give a correct estimation for the cities have similar geographycal and climatic environment with the special regard to plain relief and low height above sea level (*Bottyán and Unger*, 2003).

Thematic articles published by the author

Articles, not applied in the dissertation are marked with *

Unger, J., Sümeghy, Z., Gulyás, A., Bottyán, Z. and Mucsi, L., 1999*: Modelling of the maximum urban heat island. *Proceed. Int. Congress of Biometeorology and Int. Conf. on Urban Climatology '99, ICUC 10.4,* Sydney, Australia .

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