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PhD DISSERTATION

THESES

MODELING OF THE SPATIAL DISTRIBUTION OF THE MEAN URBAN HEAT ISLAND AND THE EXTENSION OF MODEL

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Introduction, objectives

In our days more than 6.6 billion people live in this world and half of them are city dwellers. The urban population of the world is growing faster than the full population, thus on a world-wide scale (in Hungary too) more and more people live in an urban environment.

Urban environments differ significantly from the surrounding natural lands, because they have different surface geometry, material- and air composition, and the anthropogenic heat emission also affects them. This leads to a local-scale alteration of climate: e.g. the formation of the urban heat island (UHI). This is a positive thermal alteration, namely that the town is usually warmer than its surroundings.

The alteration of the climate changes the comfort and health of city dwellers and the phenologic phases of the vegetation. In addition it has economical influence, since in winter less energy is needed for the heating, while in the summer more for the cooling. Thus in our days this phenomenon is a significant issue, which influences the lives of many people. Thus in order to moderate the effects of climate change, the measurement, investigation, within this the modeling and prognosis, as well as the development of architectural processes are very important.

The aim of my study is to create a multiple-parameter model based on easily accessible and producible input data for the approximation of the spatial distribution of the mean heat island using temperature and surface coverage data of Szeged and Debrecen. A further aim is to extend the general model to other, different-sized settlements having similar climatic and geographic conditions but no temperature measurements available.

In order to achieve this, the following steps are needed:

1. To analyze the connection between the surface parameters and UHI.

2. To create parameters which give information about the built-up ratio of an area (or its surroundings) and about its location in the town.

3. To develop a multiple-parameter model for the approximation of the spatial distribution of the mean heat island based on data from Szeged and Debrecen.

4. To examine the reliability of the model and to determine the validity of the model.

5. To validate the model on databases which are independent from the data of Szeged and Debrecen, using data from settlements with similar environmental conditions.

6. To extend the model to different-sized settlements having similar climatic and geographic conditions but no temperature measurements available.

Study Areas

The next towns were examined: Arad, Békéscsaba, Debrecen, Hajdúböszörmény, Hajdúdorog, Hajdúnánás, Hódmezővásárhely, Karcag, Kecskemét, Makó, Orosháza, Szeged and Temesvár. For the creation of the model Szeged and Debrecen are used, for the validation data from Hajdúböszörmény, Hajdúdorog and Hajdúnánás are used while the other cities are needed for the extension of the model.

All the investigated cities are situated on the Alföld (Great Hungarian Plain). The area of the Plain is about 100 000 km^2. According to Trewartha's climate classification, the whole plain belongs to the climatic type D.1 (continental climate with longer warm season).

Debrecen is the second biggest town in Hungary (211 000 inhabitants). 170 000 people live in Szeged. Both cities are important educational, cultural and business centers. The structure of Debrecen is lop-sided, Szeged has one centre and an avenue-boulevard system, and the river Tisza flows across the city.

Hajdúböszörmény, Hajdúnánás and Hajdúdorog are situated near Debrecen, so they have similar topography and climate, but they are smaller than Debrecen (about 30 000, 20 000, 10 000 inhabitants. These towns both have avenue-boulevard systems.

Populations of Arad, Békéscsaba, Hódmezővásárhely, Karcag, Kecskemét, Makó, Orosháza and Temesvár are between 22 000 and 308 000.

The multiple-parameter model and its elements of distribution of UHI intensity

Determination of the dependent variable of model: UHI intensity

The temperature data collection described below was carried out within the scope of a bigger urban climate project, which has been in progress in the Department of Climatology and Landscape Ecology of the University of Szeged for years. I myself had a part in this project.

For the information on the UHI intensity (as a dependent variable) and its pattern, temperature data were collected by mobile measurements in Szeged and Debrecen. The study areas were divided into 500 m x 500 m cells. The study areas consist of 107 (25.75 km^2) and 105 cells (26 km^2) in Szeged and in Debrecen (*Unger et al.*, 1999; *Szegedi and Kircsi*, 2003b), respectively. They cover the inner and suburban parts of the towns. In both towns one rural cell was used as a reference area for the comparison of temperature data (labeled R).

The required data were collected with cars on assigned routes, in two, one-year-long periods in Szeged (March 1999 – February 2000, April 2002 − March 2003) (*Unger et al.*, 2001a; *Sümeghy and Unger*, 2003a) and in a one-year-long period in Debrecen (April 2002 − March 2003) (*Szegedi and Kircsi*, 2003b). In the study areas the representative temperature pattern derives from the measurements, which took place every 10th days. This means the measurements were taken 29 times in Szeged and Debrecen at the same time. The three-hour measurements were carried out under all weather conditions except rain. Based on experiences from previous studies the data collection took place at the expected time of the daily maximum development of the UHI, at 4 hours after sunset (*Boruzs és Nagy*, 1999; *Oke*, 1981). In the hours after sunset the linear change of temperature was applied to the calculation of the measured data (*Oke and Maxwell*, 1975).

Having averaged the temperature values by cells, adjustments to a reference time (4 hours after sunset) were applied. The absolute UHI values, namely maximum temperature difference between the city and its surrounding (ΔT), can be determined by cells as follows (*Unger et al.*, 2001a):

$$\Delta T = T_{cell} - T_{cell\,(R)} \, (^{\circ}C)$$

where T_{cell} = (average) temperature of an urban cell, $T_{cell(R)}$ = (average) temperature of the rural cell. Annual mean ΔTs were determined by averaging the ΔT values of the 29 measurements by cells.

In Szeged the measured annual mean maximum UHI intensity was 3.0 ºC (*Sümeghy and Unger*, 2003a), in Debrecen it was 2.4 ºC (*Szegedi and Kircsi*, 2003b). In Szeged the largest heat island intensity was near 7 ºC (6.8 ºC), in Debrecen about 6 ºC (5.8 ºC). In Szeged the biggest temperature difference between the city and its surroundings was measured in an early spring day (24 March 2003), in Debrecen it was in the middle of summer (15 July 2002).

In Szeged the structure of the heat island is rather concentric, but in Debrecen it is not so regular. The difference derives from the different structures of the two cities.

Determination of the independent variables of model

UHI intensity and its pattern are influenced mostly by the covered surface of the city. A simple, visual description of the urban surface is given by the *built-up ratio* (B or B_0). For a given cell it shows the percentage of the built-up areas (streets, pavements, parking lots, building roofs, etc.) compared to the area of the whole cell. This parameter was determined by the assessment of the Normalized Vegetation Index (NDVI) on LANDSAT satellite images.

It is important to consider the built-up conditions around the cells, because the wider surroundings can influence the temperature of a given cell. In order to take the effect of the surroundings into account, I introduced the *derived variables* B_1, B_2 (concentric areal extensions around the cells) calculated from the built-up ratio B_0.

Furthermore, it is important to know the distance of a given cell from the city boundary. The *distance* can be regarded as a parameter that characterizes the location of an area (or point) inside the city. Comparing areas with the same building structure and design in the suburbs and in the centre, we find a reduced ΔT in the suburbs compared to that in the centre.

Summary of the results in theses

1. I analyzed the distribution of the variables, the data of the ΔT, B_0, B_1, B_2, D variables can be approximated with a normal distribution. The Kolmogorov-Smirnov test accepted the hypothesis concerning normality in all cases at the 95% confidence level. Thus, the connection between the surface parameters and ΔT can be best described as linear. The strength of the linear relationship was supported by the large values of the coefficient of determination.

2. In order to take into account the roles of the distance (D) and the above mentioned surface parameters (B_0 and its areal extensions, B_1, B_2), **I created new combined urban parameters** (B_0', B_1', B_2'), multiplying (or weighing) the surface parameters by the logarithm of distance of each cell.

3. Then I quantified the connection between the combined urban surface parameters and the annual mean UHI intensity. Based on data from Szeged and Debrecen, **I created a general multiple-parameter model** which gives an estimation of the mean ΔT patterns in other settlements situated on a plain with no temperature measurements available. The elements of my multiple-parameter model are the following:

- ΔT, as a variable (°C),
- B_0', B_1', B_2', as invariable parameters ('dimensionless').

According to the results of my investigation the connections between the urban surface parameters and the mean UHI intensity can be described well with linear functions, so linear approach was used by the creation of a model, similarly to *Bottyán and Unger* (2003) and *Bottyán et al.* (2005). I found the following empirical model-equation:

$$\mathbf{\Delta T = 0{,}001032*B_0' + 0{,}002455*B_1' + 0{,}002629*B_2'} \qquad (r^2 = 0{,}97)$$

By the creation of a multiple-parameter model the order of combined urban parameters was examined by stepwise linear regression analysis. The first entrant was the B_1' parameter, which determined the annual mean UHI intensity in 96.3%, the next was the B_2' (96.9%) and the last was the B_0' (97.1%), but both parameters improved the reliability of the model.

4. The reliability of the model: in Szeged and in Debrecen the temperature difference is less than 0.5 °C on most of the anomaly-map of the observed and the modeled annual mean ΔT, which means the model reproduces the original temperature field correctly. The significance levels of the three coefficients are less than 0.001. According to the obtained statistical figures, the three invariable parameters explain 97% of the variation in the magnitude and spatial distribution of the temperature excess in the studied cities, so the reliability of this model-equation is outstanding.

In the course of extension **the validity of the model** is determined by the scope of parameters of Szeged and Debrecen used for the model. When extending the model, reliable results can only be obtained if the values of the investigated area fall within these intervals.

5. **I validated the model** on two independent databases from settlements with similar environmental conditions.

The data of either database were collected in three towns (Hajdúböszörmény, Hajdúdorog and Hajdúnánás) situated on a flat area, between September 2003 and January 2005 (*Szegedi,* 2005). The relationship between the observed and estimated annual mean UHI intensity was determined by 15 pairs of elements in these three towns. The mean absolute deviation of the element pairs was less than 0.09 °C. There is a strong positive relationship between the observed and estimated ΔT values. The strength of the linear relationship is supported by the large value of the coefficient of determination (r^2 = 0.816, n = 15), since at my number of elements (15) the relationship is real at 1% significance level at r^2 = 0.397 (r = 0.63). Thus, the null-hypothesis, that there is no connection between the two parameters, can be clearly rejected; moreover, I can state with 99% certainty that realistic connection exists between the two parameters. Deviation around the regression linear is only 0.11 °C.

The data of the other database were collected in Szeged in a one-year period between March 1999 and February 2000 (*Unger et al.*, 2001b). The relationship between the observed (1999–2000) and the estimated heat island was examined by 103 pairs of elements. There is a strong positive relationship between the observed and estimated ΔT values. The value of the coefficient of determination is large (0.651), since at my number of elements (103) the relationship is real at 1% significance level at r^2 = 0.063. Thus, the null-hypothesis, that there is no connection between the two parameters, can be clearly rejected. Deviation around the regression linear is just 0.31 °C.

When the measured data examined together (118 pairs of elements) from three towns (Hajdúböszörmény, Hajdúdorog and Hajdúnánás) and from Szeged (1999–2000), then a stronger relationship was detected with the data of the estimated UHI. The strength of the linear relationship is supported by the large value of the coefficient of determination (r^2 = 0.781, n = 118), since at my number of elements (118) the relationship is real at 1% significance level at r^2 = 0.063. Thus, the null-hypothesis, that there is no connection between the two parameters, can be clearly rejected; moreover, I can state with 99% certainty that realistic connection exists between the two parameters. Here the deviation around the regression linear is only 0.29 °C.

<u>6.</u> I extended the general model to other, different-sized settlements having similar geographical conditions (topography and climate) for simulating the magnitude and pattern of mean heat islands. As mentioned earlier, only certain Landsat satellite images of the settlements were necessary, from which the built-up ratio and its areal extensions (weighting with the log-distance from the city border) were determined as independent variables for this purpose.

Hereafter, settlements are showed in order of population size (Karcag, Makó, Orosháza, Hódmezővásárhely, Békéscsaba, Kecskemét, Arad, Temesvár), where the given model-equation was used.

In the smallest city, Karcag, the simulated UHI form is slightly stretched out in a S-N direction. The UHI maximum is 0.96 °C, which develops above the most densely built-up cell (45.5%). In the whole city low B values are typical, it alludes to the village-like diffuse built-up.

The structure of UHI is really regular in Makó. The heat island is the largest (1.60 °C) above the city centre, where the most densely built-up cell (53%) can be found. The city is relatively evenly built-up 30-50% B_0 values are typical in most parts.

The largest simulated intensity value (1.69 °C) develops above the centre in Orosháza (B_0 = 69%), but highly built-up industrial parks elongate the isotherms in the direction of N-E. Its size of population is equivalent to the number of inhabitants in Hajdúböszörmény (30 500 people), even so in Orosháza the value of modeled maximum ΔT is much higher than in Hajdúböszörmény. It is explicable with the different character of cities, because in Hajdúböszörmény big gardens and green surfaces are typical, while in Orosháza there are considerable industrial areas.

According to the approximation in Hódmezővásárhely the biggest ΔT value evolves above the centre, however the most densely built-up cell (77%) is in the areas of industrial parks and hypermarkets in the eastern part of the city. On the south-eastern confines of the city there is a gross factory, which pulls the isotherms.

Also in Békéscsaba the modeled heat island is the largest above the centre (1.90 °C), here is the most densely built-up cell (72.5%). On the confines of the city there are big industrial parks and hypermarkets, which modify the form of isotherms.

Kecskemét has a rather regular UHI development with a centre in the historical city core (reaching 78% built-up ratio) and with a largest ΔT of about 2.7°C. In the southern part of the city there are great industrial parks and hypermarkets with big covered surface, so here the UHI reaches 2–2.25 °C.

Arad is of similar size as Szeged and Debrecen. Its modeled heat island has more centers, the Maros river flows across the southern part of the city, so it affects the temperature of its surroundings. The maximum ΔT value is 2.95 °C (similarly to Szeged). The cell with the highest built-up value is in the south-western part of the city (85%).

The investigated area of Temesvár is almost 50 km^2. In the case of this city the model has a bit of extrapolation. The maximum value of the modeled UHI is the same as in Szeged (2.97 °C). In the settlement there are two intensity tops, which both reach the historical core but do not cover it, because in the centre there are relatively big green surfaces. Thus the densest cell is not here, it is in an industrial park in the eastern part of the city (84.7%). The highest ΔT values belong to industrial areas.

Conclusion

The results may have great practical significance, since the temperature difference between the city centre and the rural areas reaches 6-7 °C, on average 2–3 °C in a big city like Szeged. The presented empirical model can be regarded as a useful tool for estimating the mean heat island patterns for cities situated on a plain and in the same climate type. The knowledge of the estimated structure of mean UHI may provide useful basic information for the development projects of neighborhoods or cities. It is useful to consider the climate-modifying effect of buildings in the planning period. The enlargement of green surfaces and the suitable partition of buildings may decrease the injurious effect of heat excess.

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