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SEASONAL CASE STUDIES ON THE URBAN TEMPERATURE CROSS-SECTION

Z. SÜMEGHY and J. UNGER

Department of Climatology and Landscape Ecology, University of Szeged, P.O.Box 653, 6701 Szeged, Hungary
E-mail: sumeghy@geo.u-szeged.hu

Összefoglalás – A kutatás a városi hősziget (UHI) éjszakai dinamikájára összpontosít a vizsgált település, Szeged esetében. A munka célja az UHI fel- és leépülésének tanulmányozása egy kiválasztott városi keresztmetszet mentén úgy, hogy minden évszakból bemutat egy-egy jellegzetes esetet, amelynek sajátosságait a meteorológiai és területhasznosítási paraméterek figyelembevételével magyarázza. Az UHI kiformálódása meglehetősen szabályos volt: a legmagasabb értékek a városközpontban, pár órával napnyugta után tűntek föl. Mindazonáltal megfigyelhető néhány asszimetria az izotermákban, mert azok mindig eltolódnak a keresztmetszet keleti széle felé. Ez elsősorban annak tulajdonítható, hogy ez egy sűrűn beépített környék. A nyári éjszaka esetében például a normalizált UHI értékek használata a profilok számos speciális vonását tárta föl. A keleti és a nyugati külvárosokban az UHI nagyságában bekövetkező változásokat a hűvösebb vidéki levegő először ÉNy, majd pedig KÉK felől (a szélirány változásával összhangban) történő beáramlása okozta. Az őszi mérés során észlelt kettős csúcs jelensége csak a szélsebbeségben bekövetkezett átmeneti csökkenéssel magyarázható.

Summary – Investigations concentrated on the temporal dynamics of the urban heat island (UHI) during the night in Szeged, Hungary. Task includes the revelation of building and re-building of the UHI along an urban cross-section studying example cases by seasons and the explanation of their features using land-use and meteorological parameters. The UHI formations were rather perfect with the highest values in the city centre and a few hours after sunset. However, some assimetry occurs in the isotherms because they are always shifted a bit to the eastern edge of the transect. It can be attributed to the influence of the highest built-up density of this neighbourhood. For example in the case of the summer night using normalized UHI values some interesting features in the profiles emerge. Presumably, the changes in the magnitudes of UHI in the western and eastern suburbs are caused by the cooler rural air transport (first from NW then from E-NE) according to the changed wind direction. The phenomena of the two peaks was observed in the course of the fall measurment and it can be explained only by the temporary decrease of the wind speed.

Key words: UHI, urban cross-section, summer and winter cases, 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). In general this intensity has a diurnal cycle with a strongest development of 3-5 hours after sunset.

The purpose of this study is to reveal the temporal dynamics (building and re-building) of the UHI during the night along an urban cross-section investigating some seasonal example cases and to explain their features using land-use and meteorological parameters.

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 (*Unger et al.,* 2001). These environmental circumstances make Szeged a favourable place for studying of an almost undisturbed urban climate.

Within the city's administration district of 281 km^2, the number of inhabitants is 160,000. The region is in Köppen's climatic region Cf which means a temperate warm climate with a fairly uniform annual distribution of precipitation.

Grid network and temperature (maximum UHI intensity)

The area of investigation (inner part of the administration district) was divided into 0.5 km x 0.5 km cells (*Fig. 1*). The original study area consists of 107 cells covering the urban and suburban parts of Szeged. 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 present study we use only 17 cells, which is a cross-section of the urban area consisting each of the typical land-use types of Szeged (*Fig. 1*). It is streching from the rural area (cell 1) across zones used for industry and warehousing (cells 4-7), the densely-built centre (cell 9-11) and large housing estates of tall concrete buildings set in wide green spaces (13-15) to the areas occupied by detached houses (17). The distance between the centerpoints of the first (1) and the last (17) cells along the cross-section is about 8 km. Basically, the orientation of the cross-section is from W to E-NE.

In order to collect temperature data for every cell during the night, mobile measurements were taken on fixed return routes on an hourly basis along the cross-section between April 2002 and March 2003, altogether 12 times. In case of surface and near-surface air UHI investigations, the moving observation with different vehicles (car, tram, helicopter, airplane, satellite) is a common process (e.g. *Conrads and van der Hage*, 1971; *Oke and Fuggle*, 1972; *Voogt and Oke*, 1997; *Klysik and Fortuniak*, 1999). To get some information on the temporal dynamics (building and re-building) of the UHI during the night, the measurements started at sunset and took about 7-10 hours (depending on the season), which means 7-10 transects (*Table 1*). Return routes were needed to make time-based corrections and one transect took about 50-60 minutes. Readings were obtained using a radiation-shielded resistance sensor connected to a data logger for digital sampling. Data were collected every 10 s, so at a car speed of 20-30 kmh^{-1} the distance between the measuring points was 55-83 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 speed provided adequate ventilation for the sensor to measure the momentary ambient air temperature. The logged values at forced stops were rejected from the data set.

Having averaged the approximately 15-20 measurement values by cells, time adjustments to the reference times (namely integer hours after sunset) were applied assuming linear air temperature change with time. Consequently, we can assign one temperature value to every cell (centerpoint) by transects. ΔT values were determined by cells referring to the temperature of the westernmost cell of the cross-section, which was regarded as a rural cell because of its location outside of the city (*Fig. 1*).

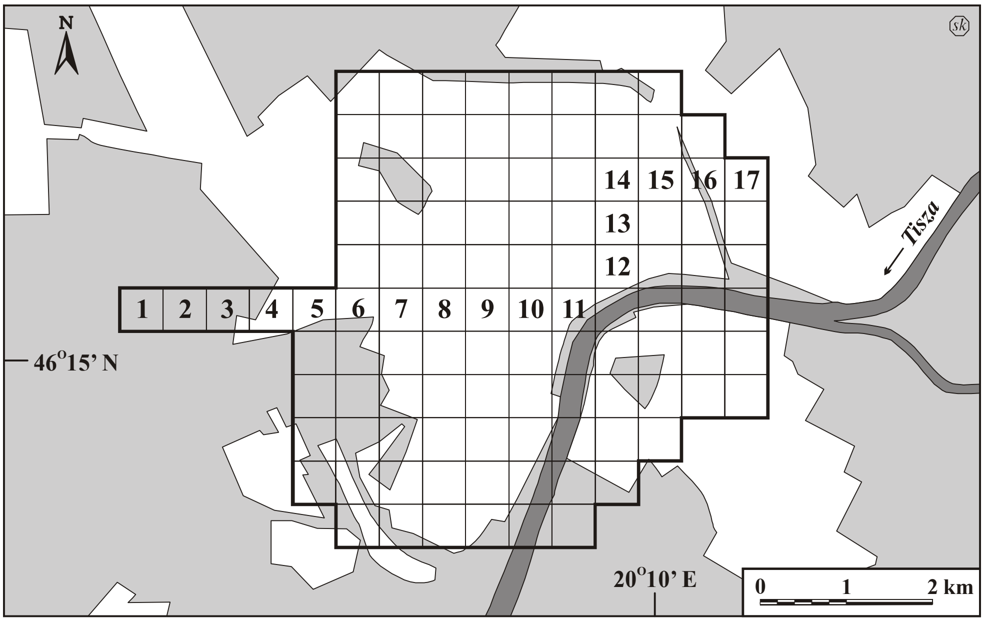

Fig. 1 Division of the original study area into 0.5 km x 0.5 km grid cells. Cells of the urban cross-section are numbered from 1 to 17. The urbanized areas are marked by white.

Table 1 Survey of mobile measurements along the cross-section in Szeged (April 2002 - March 2003)

No.	Date	Time of the sunset (CET)	Number of transects	Reference times
1	16-17. 04. 2002	18.27	10	19.00 – 04.00
2	22-23. 05. 2002	19.13	8	20.00 – 03.00
3	17-18. 06. 2002	19.33	7	21.00 – 03.00
4	10-11. 07. 2002	19.31	7	21.00 – 03.00
5	29-30. 08. 2002	18.24	9	20.00 – 04.00
6	10-11. 09. 2002	18.01	10	19.00 – 04.00
7	17-18. 10. 2002	16.50	10	18.00 – 03.00
8	14-15. 11. 2002	16.08	10	17.00 – 02.00
9	10-11. 12. 2002	15.53	10	17.00 – 02.00
10	15-16. 01. 2003	16.19	10	17.00 – 02.00
11	12-13. 02. 2003	17.00	10	18.00 – 03.00
12	17-18. 03. 2003	17.47	10	19.00 – 04.00

The profiles of the UHI intensity along the cross-section were investigated by comparison of absolute and normalized values taking land-use and meteorological features into consideration. The normalized value of a given cell in a given hour is the ratio of the absolute values of that cell and the cell where ΔT is the largest at that transect. Since meteorological conditions (first of all wind speed and cloudiness) influence the absolute

UHI intensities (e.g. *Landsberg*, 1981; *Park*, 1986; *Yagüe et al.*, 1991, *Unger*, 1996), the comparison of spatial variation of ΔT is more effective using normalized values. Namely, the normalized UHI intensity profiles are expected to be almost independent of the prevailing weather conditions; nevertheless, they are expected to be dependent mainly on the surface factors (e.g. land-use features, distance from the city centre, etc.).

Present study examines four cases (nights of 16-17 April 2002, 17-18 June 2002, 10-11 September 2002 and 12-13 February 2003) in detail, when the conditions were favourable for relatively strong development of the UHI. The first case represents a pleasant spring night, the second case a warm summer night, the third case a rather warm autumn night and the fourth case a very cold winter night as seasonal example nights.

Built-up surface ratio

Ratios (to total cell area) of the built-up surface by cells were determined by a vector and raster-based GIS database combined with remote sensing analysis of SPOT XS images. 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 (V: 0.58-0.68 μm) and near infrared (IR: 0.72-1.1 μm) bands (*Gallo and Owen*, 1999): NDVI = (IR-V)/(IR+V).

The NDVI values are between -1 to +1 indicating the effect of green space in the given spatial unit. Built-up, water and vegetated surfaces were distinguished using these values. The ratios of these land-use types for each grid element were determined using cross-tabulation.

RESULTS AND DISCUSSION

Table 2 Areal ratios of land-use types by cells along the urban cross-section in Szeged

cell	built-up (%)	open (%)	water (%)
1	0	100	0
2	0	100	0
3	18.9	81.1	0
4	70.4	23.5	6.1
5	54.2	45.3	0.5
6	85.6	11.1	3.3
7	71.7	28.3	0
8	77.8	22.2	0
9	91.4	8.6	0
10	90.5	9.1	0.4
11	77.3	11.3	11.4
12	83.6	16.4	0
13	75.7	24.3	0
14	67.9	32.1	0
15	81.2	18.8	0
16	60.9	39.1	0
17	72.2	27.8	0

Built-up characteristics

Table 2 contains areal ratios (%) of the main land-use types by cells along the cross-section. The largest built-up density (more than 90%) can be found around the centre (cells 9-10, see *Fig. 1*), but the variation from the urban edge to the core is not uniform. The proportion of the water surface is rather negligible except for the cell 11 (River Tisza, see *Fig. 1*). Towards the eastern parts of the city a second high built-up density occurs (cell 15) where the large housing estates are located and the magnitude of the artificial surfaces remained rather significant in the eastern suburbs.

Case 1: the night of 16-17 April 2002

The previous daytime hours were sunny spring hours with a maximum temperature over 20ºC. The sky was almost clear with the highest global radiation flux density of 840 Wm^{-2} and with light wind (1.3-4.6 ms^{-1}). After sunset (6:27 PM) the wind speed remained in this range. The wind direction was N-NW at the whole night. During the night a weak anticyclon centered E from Hungary prevailed in the region with an air pressure over 1013 hPa. The sky remained clear and the temperature dropped under 10ºC.

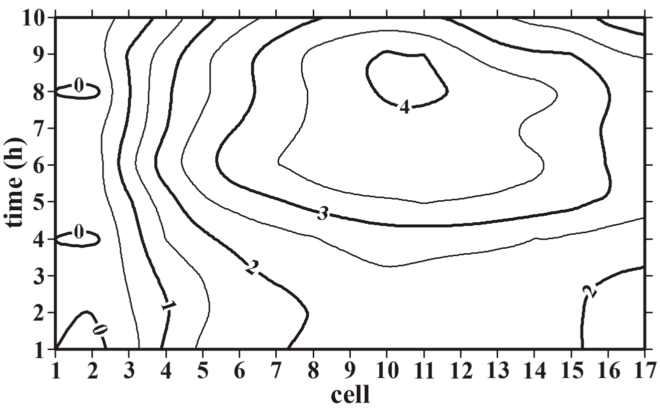

Fig. 2 Isopleths of the UHI intensity (in ºC) along the cross-section during the night of 16-17 April 2002 in Szeged. The unit on the vertical axis is the elapsed time after sunset.

Fig. 2 exhibits the spatial and temporal development of UHI along the cross-section that spring night from the measurements of 10 transects. The UHI formation is rather perfect with the highest (more than 4ºC) values in the city centre (cells 9-12) at 8-9 hours after sunset. In comparison with further cases, there is a time shifting in the highest ΔT values to the late hours of the night, so accordingly the maximum ΔT value of 4.07ºC occurs at 9 hours after sunset (in cell 10). In every hour the UHI becomes stronger from the rural areas towards the city core and after that it weakens reaching the suburbs on the other side. However, some assimetry occurs in the isotherms because they are shifted a bit to the eastern edge of the transect. This can be attributed to the influence of the highest built-up density of this part contrary to the western cells (*Table 2*).

Case 2: the night of 17-18 June 2002

The previous day was a warm summer day with a maximum temperature over 28ºC. The sky was almost clear with the highest global radiation flux density of 860 Wm^{-2} and light wind blew (1.8-3.6 ms^{-1}). After sunset (7:33 PM) the wind weakened and its speed was under 2 ms^{-1} most of the time except for the early morning hours (about 2.5 ms^{-1} in the period of one hour before sunrise). The wind direction was NW in the first hours after sunset (1-2 hours), then it shifted to N (3-4 hours) and in the last part of the night the wind blew from E-NE (5-7 hours). During the night an anticyclon centered over Hungary prevailed in the region with an air pressure over 1020 hPa. The sky remained clear and the temperature sank under 17ºC.

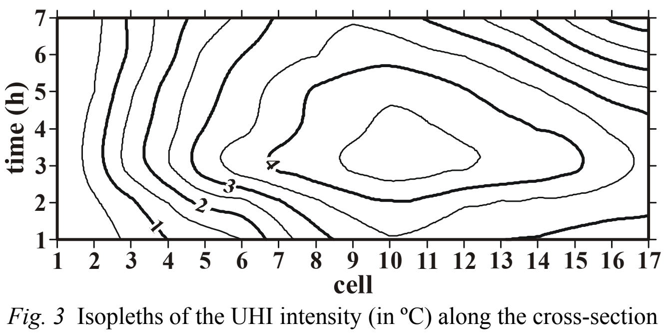

Fig. 3 Isopleths of the UHI intensity (in ºC) along the cross-section during the night of 17-18 June 2002 in Szeged. The unit on the vertical axis is the elapsed time after sunset.

Fig. 3 summarize the spatial and temporal development of UHI along the cross-section that summer night from the measurements of 7 transects.

The UHI formation is rather perfect, too, with the highest (more than 4.5ºC) values in the city centre (cells 9-12) at 3-4 hours after sunset. The maximum ΔT value of 4.84ºC occurs in cell 10 at 3 hours after sunset. In every hour the UHI becomes stronger from the rural areas towards the city core and after that it weakens reaching the suburbs on the other side. However, some assimetry occurs in the isotherms because they are shifted a bit to the eastern edge of the transect. This also can be attributed to the influence of the highest built-up density of this part contrary to the western cells (*Table 2*).

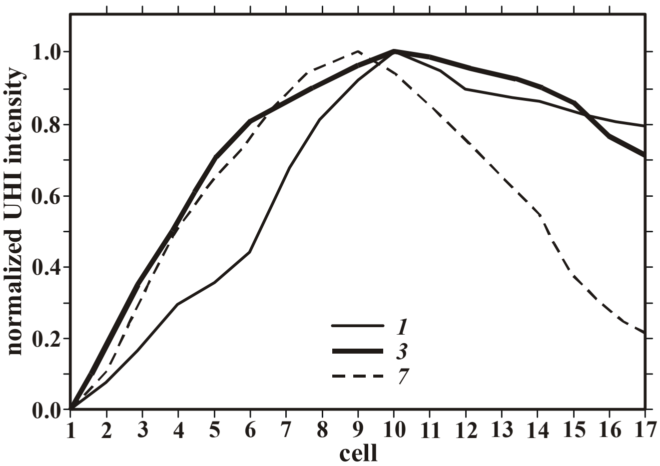

Fig. 4 Selected hourly profiles (1, 3 and 7 hours after sunset) of the normalized UHI intensity during the night of 17-18 June 2002 in Szeged

Using normalized UHI intensities some more interesting features emerge. Selecting some example profiles from the first part of the night (1 hour after sunset), from the middle (3) and from the last part (7), we can observe alterations in the form of the profiles which can not be explained simply by the land-use variations (*Fig. 4*).

According to the *Fig. 4*, profile 1 shows a moderate increase from a rural level after reaching the densely built-up areas (cell 6, see *Table 2*) and after a sharp increase the largest value (3.46ºC) occurs in the city centre (cell 10). After the summit the ΔT values are decreasing very slowly in the eastern part of the city.

There is a significant increment in the building of UHI intensity in profile 3 already near the urban edge (cell 2) and it is increasing continuously to the centre (cell 10) with the absolute maximum of the UHI intensity at that night (4.84ºC). Then its re-building is very moderate towards the eastern cells.

The variation of the profile 7 is very similar to the profile 3 in the first half of the transect but it reaches its maximum (4.57ºC) already in the cell 9. After that the ΔT values are decreasing very quickly, in contrast with the previous two cases, in the second half of the transect.

In order to explain these pecularities we have to take the weather conditions at this night into consideration. Of course, the land-use features are given for the whole examined period. Therefore, the temporal anomalies in urban temperature are attributed mainly to the differences in weather conditions, particularly to the wind characteristics, because the sky was perfectly cloudiness. As was mentioned previously, the wind speed was low and was ranging in a rather narrow interval during the night, but there was a marked shift (about 120-130º) in the wind direction from NW to E-NE in a couple of hours. Presumably, the changes in the magnitudes of ΔT in the western and eastern suburbs are caused by the air transport, that is cooler rural air streamed to the city first from NW then from E-NE according to the changed wind direction.

After the utilization of the normalized values, we can state that the form of the UHI profiles depend mainly on urban surface factors. Among them the built-up ratio may not be the most important factor, because the steady, but not uniform increment of temperature towards the city core from both directions does not follow exactly the built-up variations by cells (*Table 2*). Another parameter, however, the distance from the city centre, seems to be more dominant in this general increasing tendency of urban temperature. The observed small alterations in the forms can be attributed to the changing weather conditions, especially to the variation in wind direction.

Case 3: the night of 10-11 September 2002

The previous daytime hours were sunny and very warm with a maximum temperature over 30ºC. The sky was almost clear with the highest global radiation flux density of 690 Wm^{-2}. Light wind blew (1.4-3.5 ms^{-1}) and its speed reached the lower values (between 1.4 and 1.9 ms^{-1}) at 4-5 hours after sunset (6:01 PM). That morning the wind direction was E-NE, but afternoon it shifted to N-NE, which remained under the whole measurement. During the night the temperature dropped under 20ºC. An anticyclon centered N from Hungary prevailed in the region with an air pressure over 1015 hPa.

Fig. 5 exhibits the spatial and temporal development of UHI along the cross-section that autumn night from the measurements of 9 transects. The UHI formation is not fully regular because of occuring of two peaks at 3 and 5-6 hours after sunset, respectively. The highest (more than 4ºC) values appear at all times in the city centre (cells 9-12). The maximum ΔT value of 4.37ºC occurs in cell 10 at 3 hours after sunset (in time of the first peak). In every hour the UHI becomes stronger from the rural areas towards the city core and after that it weakens reaching the suburbs at the other side. Some assimetry can be found in the isotherms because they are shifted spatially to the eastern edge of the transect. Of course this can be attributed to the influence of the highest built-up density, but the phenomena of the two peaks can be explained only with temporary decrease of the wind speed.

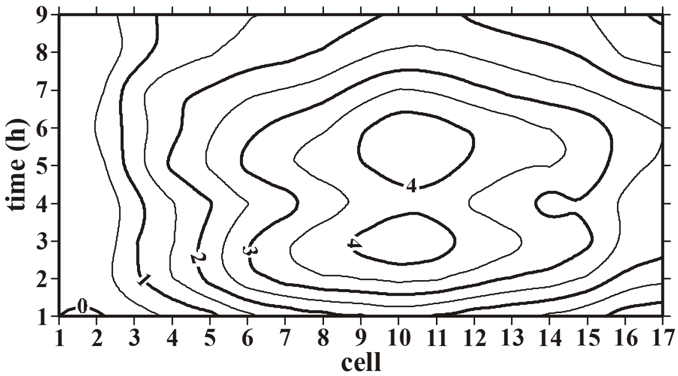

Fig. 5 Isopleths of the UHI intensity (in ºC) along the cross-section during the night of 10-11 September 2002 in Szeged. The unit on the vertical axis is the elapsed time after sunset.

Case 4: the night of 12-13 February 2003

The previous day was a cold winter day with a maximum temperature of -3ºC and with an almost clear sky. After sunset (5.00 PM) the sky remained perfectly clear. During the night the temperature sank under -18ºC, the wind was very light with a velocity of about 1 ms^{-1} and with a direction of NW. An anticyclon centered N from Hungary prevailed in the region with an air pressure between 1030 and 1035 hPa. The surrounding rural areas was covered with compact icy snow, while some parts of the city (mainly the streets and parking lots) were cleared and the remaining snow was soiled and partly piled.

Fig. 6 summarize the spatial and temporal development of UHI along the cross-section that winter night from the measurements of 10 transects. The UHI formation is rather regular with the highest (more than 7.5ºC) values in the broader city centre (cells 10-14) at 6-8 hours after sunset. The maximum ΔT value of 7.97ºC, which represents a very significant urban modification effect on temperature, occurs in cell 12 at 7 hours after sunset. In every hour the UHI becomes stronger from the rural areas towards the city core and after that it weakens reaching the suburbs at the other side. However, some assimetry can be found in the isotherms because they are shifted spatially to the eastern edge of the transect more than at the earliaer cases. Moreover, there is a time shifting in the highest ΔT values to the late hours of the night, too, similar to the spring night. Generally, both the areal and temporal extensions of the strong UHI became larger.

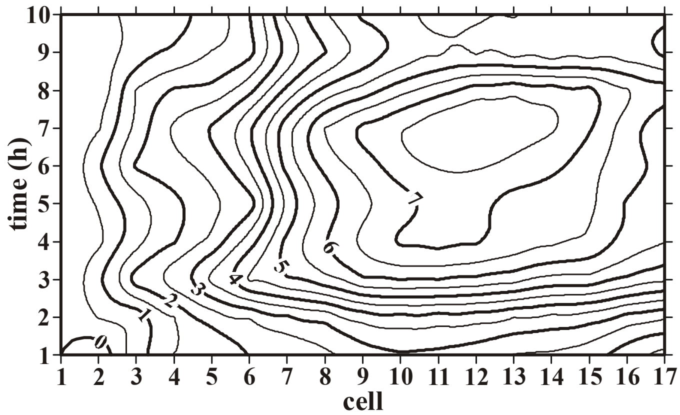

Fig. 6 Isopleths of the UHI intensity (in ºC) along the cross-section during the night of 12-13 February 2003 in Szeged. The unit on the vertical axis is the elapsed time after sunset.

CONCLUSIONS

The following conclusions are reached from the analysis presented on the seasonal example nights:

(i) The UHI formations were rather perfect with the highest values in the city centre and a few hours after sunset in both cases. However, some assimetry occurs in the isotherms because they are shifted a bit to the eastern edge of the transect. It is obviously the influence of the highest built-up density of this neighbourhood contrary to the western cells.

(ii) Using normalized UHI values some irregularities in the profiles emerge. In autumn the phenomena of the two peaks can be explained only with temporary decrease of the wind speed. In winter the changes in the magnitudes of UHI in the western and eastern suburbs are presumably caused by the cooler rural air transport (first from NW then from E-NE) according to the changed wind direction.

(iii) The usefulness of the normalized values in the investigaton of the cross-section temperature distribution in the urban area is proved. It came to light that the shape of the hourly UHI profile is determined by the surface factors in a high rank but it is sensitive to the momentary weather conditions, especially to the wind direction.

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