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Intra-urban temperature observations in two Central European cities: a summer study

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Abstract—This paper presents an urban climatological application of the urban monitoring systems – recently implemented in Szeged, Hungary and Novi Sad, Serbia – using the first set of data collected during the summer of 2014. In order to ensure a representative number and placement of stations, the selection of measurement sites was based on Local Climate Zone (LCZ) maps developed for both cities. Present paper concentrates only on the intra-urban temperature pattern characteristics expressed by the thermal reactions of the different LCZ classes in both cities. The daily temperature indices (e.g., summer days) have the highest values in the densely built up LCZs. The diurnal cycle of surplus temperatures by LCZ classes under anticyclonic weather conditions were found to be similar in the two cities with higher absolute values in the case of Novi Sad. During summer, the diurnal variation of conventional heat island intensity confirms the general knowledge that it remains positive with highest values at night, while negative values occur predominantly during the day.

Key-words: urban climate, Local Climate Zones, monitoring networks, intra-urban and inter-urban temperature comparison, summer, Szeged, Novi Sad

1. Introduction

It is well established that urbanization alters the radiative, thermal, moisture, and aerodynamic properties of the environment, which therefore modifies the water and energy balance of the overlaying atmosphere (*Chandler*, 1965; *Oke*, 1982). The importance of urban climate is highlighted by its effects on urban energy and water management (e.g., *Santamouris et al*., 2001; *Kolokotroni et al*., 2006; *Balling* and *Gober*, 2006) as well as on human health (e.g., *Tan et al*., 2010; *Gabriel* and *Endlicher*, 2011). The urban heat island (UHI) effect – the temperature surplus of built-up areas – is one of the most studied characteristics of the city's modified thermal environment (*Oke*, 1987).

In Central Europe, climate change is expected to increase the frequency, duration, and intensity of heat waves (*IPCC*, 2012; *Pongrácz et al.*, 2013), along with thermal stresses experienced by people (*Tomlinson et al*., 2011). With reduced nocturnal cooling, the climate of cities is expected to make these already adverse projections worse, as elevated heat loads are linked to higher morbidity and mortality rates (*Petralli et al*., 2012). Thus, monitoring the spatial and temporal patterns of the elevated urban temperature is an important task that can help both in the mitigation of and in the adaptation to the altered circumstances of the future. Besides monitoring, modeling also plays an important role in this regard. However, modeling requires data obtained from measurements for input and validation.

Air temperature in the city varies according to the properties of the urban environment and the characteristics of the regional climate as modified by hills, water bodies, etc. (*Chandler*, 1965). Urban climatology has traditionally relied on a temperature difference between a pair of stations to describe the climate of cities in reference to its background climate: the 'urban' station is generally located in the inner city (e.g., an old meteorological station of the town), while the 'rural' one, placed outside the city, served as the reference. Through an extensive literature review, *Stewart* (2007) drew attention to the marked difference that exists between station pairs, and which makes inter-urban cross comparisons between different cities almost impossible. For example, in some cases the urban station is located at an airport next to the city, while in other cases it is placed in a paved parking lot or in an urban park. As a consequence, the local climatic differences that exist between measurement sites are the sum of the background climate and urban effects, and the two cannot be separated (*Lowry*, 1977).

In order to investigate the spatial pattern of the air temperature fields in cities, mobile measurements utilizing instrumented vehicles – such as *Bottyán* and *Unger* (2003) – are used. But, they are based on occasional measurements, therefore not suited to monitoring simultaneously both the spatial and temporal development of the urban heat island. However, they are applicable to be the basis of empirical models that are capable of estimating urban temperature patterns based on surface properties (e.g., *Balázs et al.*, 2009).

One way to automate urban measurements is through remote sensing, as done for example by *Bartholy et al.* (2009). However, this method has its limits as well: first, establishing the linkage between the surface temperatures detected by satellites and the actual temperatures within the urban canopy is not straightforward (*Weng*, 2009); second, data can only be obtained during clear-sky conditions.

Another way of measurement automation is offered by the use of automatic weather stations (AWSs). This is a more suitable approach to study the UHI's spatial and temporal resolution, and it can be refined by increasing the density of the stations as far as it is needed (limited by financial sources). They are also applicable for method development and public information as well. The need of operational urban meteorological networks is underpinned for example by *Grimmond et al.* (2010) and *Muller et al.* (2013a). Existing global AWSs networks are primarily utilized for operative tasks, such as to provide input to numerical weather forecast models or for the notification of the public. These networks are, however, not applicable for urban climate investigations. While urban AWS networks are most suited for such analyses, they are rather rare. Despite the fact that the rules for establishing urban weather stations are less strict (*Oke*, 2006) than those for ordinary meteorological stations (*WMO*, 2008), sensor deployment in urban areas presents other challenges (e.g., safety concerns regarding sensor placement, or the increased network density required for the characterization of small-scale phenomena). There are only a few local scale urban heat island monitoring networks in Europe (*Table 1*), whereas they are more prevalent in other parts of the world such as in Oklahoma, USA (*Basara et al.*, 2011), Tokyo, Japan (*Mikami et al.*, 2003), Taipei, Taiwan (*Chang et al.*, 2010), and Hong Kong, China (*Hung* and *Wo*, 2012).

According to the experiences of former networks, there are three critical issues to solve: (i) placing the instruments – which is necessarily a compromise between WMO standards, safety, and maintenance criteria and representativity; (ii) data storing and transferring; (iii) power supply. As in this case a relatively dense network is needed (several sensors), it is expected that the instruments should be small, low-cost, and have possibility to transfer data via wireless methods (e.g., *Petralli et al.*, 2011; *Chapman et al.*, 2014). In general, existing networks have two shortcomings from the viewpoint of urban climatology: the placement of measurement sites is either not representative of the built characteristics of the city (as e.g., in Berlin, where only LCZ classes with natural land cover and open built-up characteristics are investigated by *Fenner et al.* (2014)), or the description of the sites' environment does not use any standardized method. These issues are originated from different purposes of the networks (e.g., educational, meso-meteorological) and the lack of communication between research groups. Consequently, it is hard to compare their reported results.

Table 1. Local scale urban temperature monitoring systems in Europe with some characteristics

Country, city	**Number of sensors**	**Area (km^2)**	**Operating**	**Aim, instruments, experiences**
England, Birmingham	111		2013–	– denser network in the downtown area and sparser in the outskirts (*Young et al.*, 2012) – data are transmitted through WiFi – Vaisala WXT-520s, low-cost Aginova sensors (*HiTemp*, 2014; *Chapman et al.*, 2012)
England, London	91	1580	2009–	– educational aim, located at schools – data are transmitted through WiFi (*Davies et al.*, 2011)
Finland, Helsinki	100	150	2005–	– research in mesoscale meteorology –Vaisala WXT-510 – data are transmitted via the mobile phone network (*Dabberdt et al.*, 2005)
Germany, Berlin	10	890	2000–	– different types of sensors and radiation shields – five sites (classified as LCZ A, LCZ A, LCZ B, LCZ 5 and LCZ 6, respectively) – data are transmitted through Ethernet cable (*Muller et al*., 2013a; *Fenner et al.*, 2014)
Italy, Florence	35		2004–	– located randomly in districts characterized by distinct spatial configurations – HOBO PRO Temp/Rh Data Loggers (, 2013)

Urbanized areas can be classified according to their ability to interact with near-surface atmosphere and establish their typical local-scale thermal environments. Classification can either be used for mapping and spatial analysis, or for the characterization of measurement sites based on their induced local climate. Over the past years, the increased need to use well-established and universally applicable system of categories for the description of measurement sites (e.g., *Muller et al.*, 2013b) stimulated efforts to develop an appropriate site classification system. One such approach is the frequently used Local Climate Zones (LCZ) system (*Stewart* and *Oke*, 2012). It is based on a worldwide survey of urban climate studies (*Stewart*, 2007, 2011) and is influenced by earlier concepts (*Auer*, 1978; *Ellefsen*, 1991; *Oke*, 2006). The LCZ system was developed to standardize measurement site description and, therefore, to facilitate intra-urban and inter-urban cross comparisons. The major advantages of LCZ system is that it is a global classification scheme, it contains limited number of classes, and the classes are separated by the main thermal characteristic of the urban surface. The LCZ system does not cover entirely the spatial heterogeneity of the thermal pattern because it is affected by far more and complex processes, but it describes the most important features, thus it can be a good basis for local and regional scale climate models in order to estimate the intra-urban temperature patterns.

The objective of this paper is twofold. First, it introduces the urban climate monitoring and visualization systems recently implemented in two Central European cities. Second, the paper presents the analysis on temperature and partly on humidity data in the first complete summer (2014) period: (1) the validation of the measurement equipment used in the networks; (2) intra-urban and inter-urban comparison of the sites' (representing different LCZs) thermal behavior; and (3) the evaluation of the systems' usefulness.

2. Study areas

Szeged (Hungary) and Novi Sad (Serbia) are located in the Pannonian Plain in Central Europe. They have similar geographical and climatic environments. According to the climate classification system developed by Köppen, both cities belong to the Cfb climate category – temperate warm climate with a rather uniform annual distribution of precipitation (*Kottek et al.*, 2006).

Szeged has 160,000 inhabitants and its terrain is almost completely flat with average height around 79 m a.s.l. While the administrative area of Szeged is 281 km^2, the urbanized area is only about 30 km^2. The avenue-boulevard structure of the city was built to follow the axis of the river Tisza. It is characterized by a densely built up city center, with blocks of flats in the northern part of the city, as well as family homes and warehouses at the outskirts.

Novi Sad consists of two parts. The larger part is located between 80 and 86 m a.s.l. on a plain, whereas the smaller, southern part is situated on the northern slopes of the Fruška Gora hills. With an area of 80 km^2, it is the second largest city of Serbia with a population of 340,000. The River Danube flows through the southern and south-eastern edges of the city. It has a densely built-up central area and an industrial zone at the northern part of the city (*Savić et al.*, 2013).

3. Monitoring networks and data

The development of the online urban climate monitoring systems in Szeged, Hungary and Novi Sad, Serbia is funded by the Hungary-Serbia IPA Cross-border Co-operation EU Programme (*URBAN-PATH*, 2015) (*Fig. 1*). The systems record directly measured temperature and relative humidity, along with a calculated human comfort index which is not applied in our study. The systems present the data by maps and graphs, which together with the archived materials are freely available on the project's website (www.urban-path.hu). The development of the monitoring systems is based on the LCZ mapping method (for the details see *Lelovics et al*., 2014). According to *Unger et al*. (2014), there are 24 and 27 stations in the seven and eight LCZ classes occurring in and around Szeged and Novi Sad, respectively (*Fig. 1*).

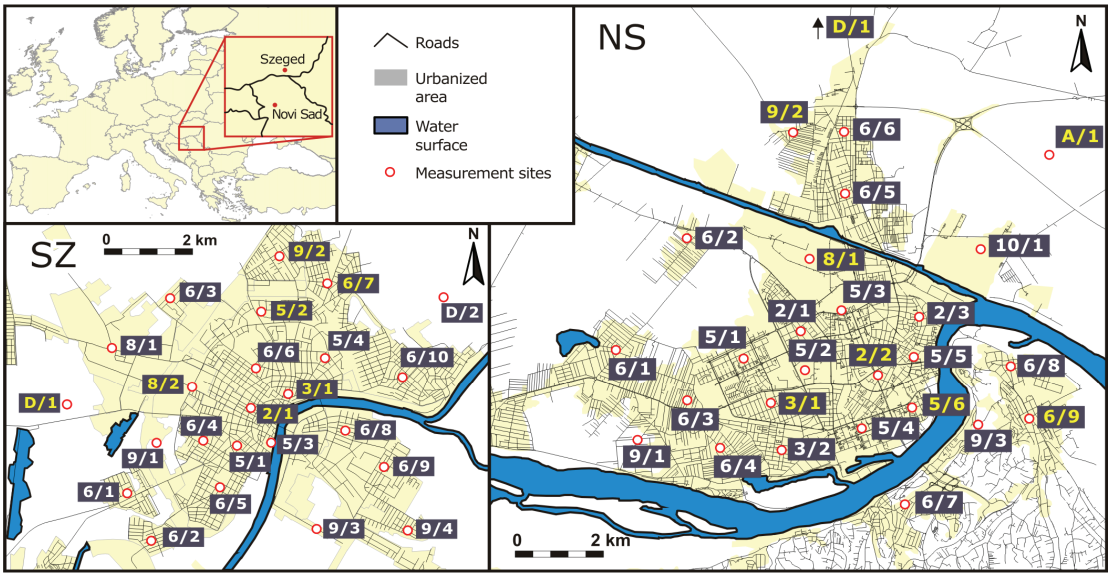

Fig. 1. Maps of the urban monitoring networks in Szeged (SZ), Hungary and Novi Sad (NS), Serbia. In the sites' identification number, the first digit refers to the LCZ class (*Stewart* and *Oke*, 2012) and the second one is an assigned number. Yellow identification numbers are the selected stations for the analysis presented in this paper. The details about the stations and their environs are listed in *Table 2*.

In the case of our networks, the response for the challenges mentioned in Section 1 is (i) to select sites with homogeneous neighborhood and mount them onto lamp posts; (ii) to store data on microSD card and transfer automatically through a 3G network; and (iii) to use batteries charged from the power supply of the city lights. Once the appropriate sites for the stations were selected, the instruments were mounted on lamp posts at 4 m above ground level for security reasons. For further technical details see *Unger et al*. (2015).

In this study, seven and eight measurement sites were selected for the analysis in Szeged and Novi Sad, respectively, representing the LCZ types occurring in the study areas. These sites are in the center of their LCZ areas, and also the surroundings are the most homogenous. The selected sites per LCZ classes and the typical values of surface parameters of their 250 m radius environment are listed in *Table 2*. The aerial photographs in *Fig. 2*. show a set of selected sites as examples with their surroundings.

Table 2. Typical surface properties of the 250 m radius environment around the selected sites. Abbrevations refer to surface properties: ISF – impervious surface factor, BSF – building surface factor, PSF – pervious surface factor, ALB – albedo, SVF – sky view factor, HRE – height of roughness elements. Upper lines refer to Szeged, bottom lines to Novi Sad

LCZ class (after 36)	Number of sites	HRE [m]	SVF	BSF	ISF	PSF	ALB	land use: 1: EEA Urban Atlas (*EEA*, 2010) for Szeged 2: Corine Land Cover (*Bossard et al.*, 2000) for Novi Sad
LCZ 2: compact midrise	1	13.5	0.6099	0.4316	0.4454	0.1229	0.1503	60% urban continuous, 20% industrial, 17% roads, 3% green[1]
	3	16.2-20.8	0.4715–0.5892	0.2598–0.3752	0.5930–0.6293	0.0186–0.1472	0.1545–0.1677	100% urban discontinuous[2]
LCZ 3: compact lowrise	1	9.5	0.6746	0.3681	0.4682	0.1637	0.1514	70% urban continuous, 13% roads, 12% industrial, 4% green[1]
	2	12	0.5860–0.6102	0.2168–0.2704	0.6435–0.6621	0.0861–0.1211	0.1676–0.1701	100% urban discontinuous[2]
LCZ 5: open midrise	4	11.7–20.6	0.6909–0.8015	0.1183–0.3338	0.3718–0.5162	0.2526–0.5099	0.1441–0.1453	7–77% urban continuous, 0–43% urban dense, 0–31% urban medium, 4–41% industrial, 10–11% roads, 0–5% urban green, 0–35% water bodies[1]
	6	15.9–25.7	0.6407–0.8840	0.0852–0.3499	0.4553–0.6749	0.0763–0.3314	0.1631–0.1836	60–100% urban discontinuous, 0–40% roads[2]
LCZ 6: open lowrise	10	3.1–5.5	0.8244–0.9562	0.1002–0.2475	0.2829–0.4925	0.2863–0.6101	0.1375–0.1780	0–87% urban continuous, 0–88% urban dense, 0–21% urban medium, 5–14% roads, 0–11% industrial, 0–11% agricultural, 0–7% urban green[1]
	9	12	0.6268–0.9967	0.1837–0.2136	0.6248–0.8632	0.0819–0.3752	0.1594–0.1827	80–100% urban discontinuous, 0–20% urban green, 0–20% roads[2]
LCZ 8: large lowrise	2	4.9	0.9463	0.1545	0.5757	0.2697	0.1347–0.1508	59–81% industrial, 6–9% roads, 0–12% urban continuous, 0–10% water, 0–9% urban dense, 1–7% urban green[1]
	1	12	0.8355	0.3050	0.4676	0.2274	0.1701	100% industrial[2]
LCZ 9: sparsely built	4	2.8	0.9965	0.0062–0.2100	0.0209–0.0500	0.7500–0.9729	0.1351–0.1655	0–64% urban medium, 0–67% agricultural, 0–48% urban green, 0–24% urban low density, 0–23% urban dense, 0–18% water bodies, 0–8% urban very low density, 0–9% roads[1]
	3	12	0.8233	0.0000–0.0950	0.2551–0.5551	0.3499–0.7922	0.1675–0.1855	20–90% agricultural, 10–80% urban discontinuous[2]
LCZ 10: heavy industry	0	–	–	–	–	–	–	
	1	12	0.9617	0.0180	0.5683	0.4137	0.1787	100% industrial[2]
LCZ A: dense trees	0	–	–	–	–	–	–	
	1	0	1.0000	0.0000	0.2078	0.7922	0.1515	100% forest[2]
LCZ D: low plants	2	0	1.0000	0.0000	0.0000–0.1000	0.8000–1.0000	0.1447–0.1563	83–97% agricultural, 3–14% industrial[1]
	1	0	1.0000	0.0000	0.3119	0.6881	0.1240	100% agricultural[2]

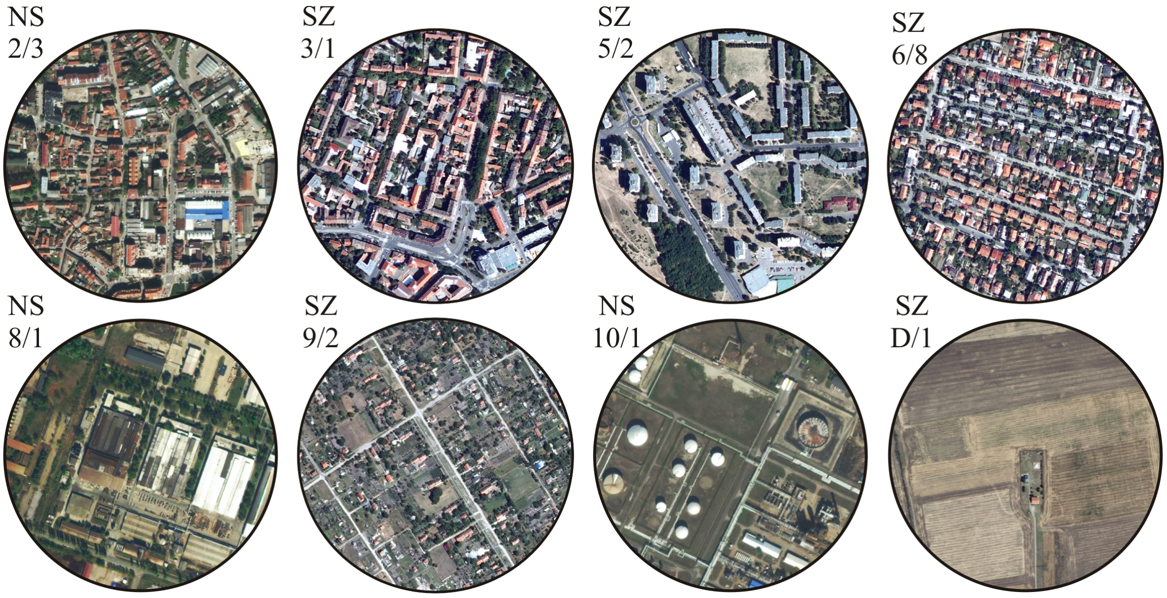

Fig. 2. Aerial photographs illustrating selected measurement sites with their 250 m radius environments (Szeged (SZ), Novi Sad (NS), first number – LCZ class number, second number – station's identity number in the given LCZ class).

In Szeged, data collection began on March 23, 2014, and in Novi Sad on June 10, 2014. In this study, the examined period is from June 1 to August 31, while in Novi Sad the analyzed interval is somewhat shorter – lasting from June 10 to August 9 – due to technical issues. In order to overcome the issues around daylight saving time in summer and to be in line with meteorological standards (*WMO*, 2008), time is given in UTC both in the database and in the analyses below.

In this region, summer is generally the most critical season from the viewpoint of health and human comfort. Although with 321 mm precipitation recorded in Szeged, this summer was unusually wet compared to the seasonal average of 169 mm measured in the period of 1901–2000 (*HMS*, 2008). As a consequence, the number of days with favorable weather conditions – conducive to the development of micro- and local climates – was lower than usual.

4. Results and discussion

As we utilize a number of widely known methods during the data evaluation, these methods are mentioned at the beginning of the relevant subsections.

4.1. *Sensor performance verification*

The Hungarian Meteorological Service's (HMS) SYNOP station 12982 is located next to the urban network's D/1 station in Szeged (*Fig. 1*). Since the station of the HMS is part of the international surface synoptic network, it meets the requirements of the WMO. HMS utilizes Vaisala HMP-35D and HMP-45D temperature and relative humidity sensors and Vaisala MILOS-500 data loggers and transmitters. It records data with 10 minute resolution. As stations 12982 and D/1 are also mounted on the same platform and their radiation shields are the same, the former can be used as a reference for the validation of the latter. The sensor performance verification compared temperature and relative humidity values from the stations and utilized 25,780 pair of data from April 1 to September 29, 2014 in the process. The scatter plots of these values and their differences are presented in *Fig. 3*. We calculated mean absolute error (MAE), root mean square error (RMSE), standard deviation (STDEV), and mean error (MA).

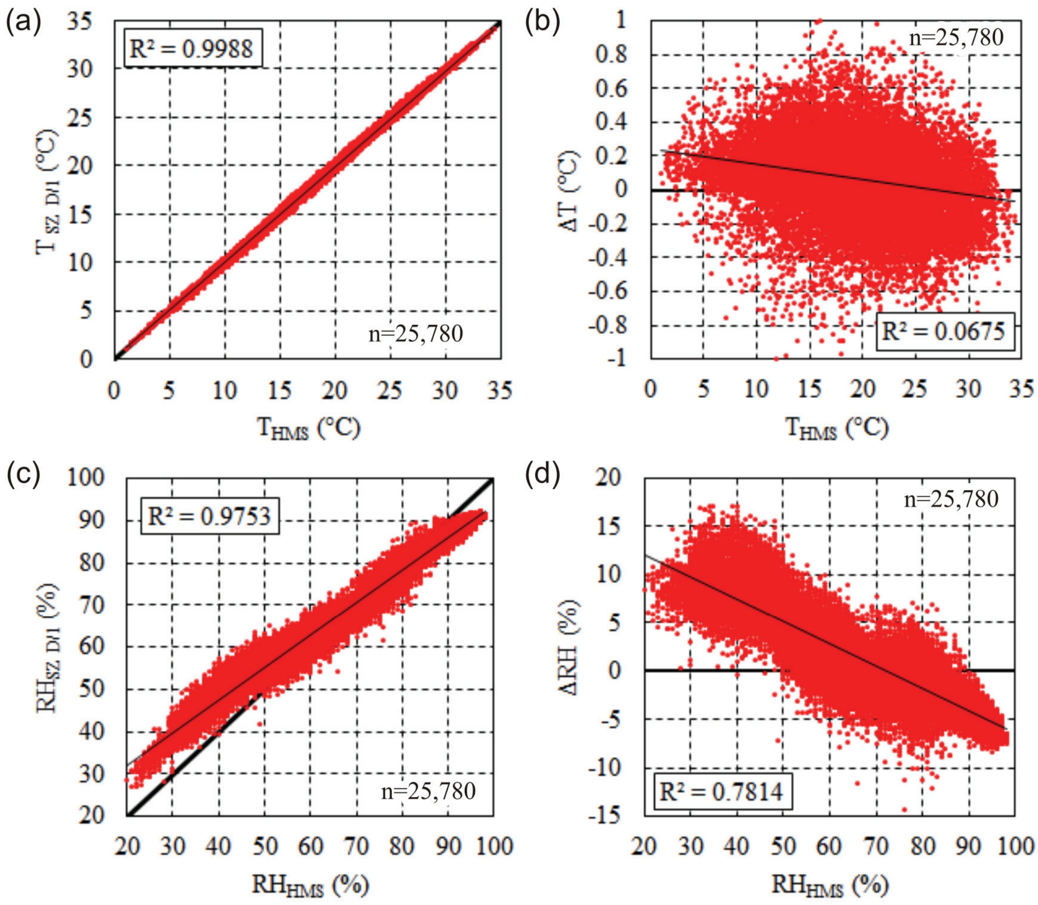

Fig. 3. Scatter plot of temperature (a), relative humidity (c), and their biases (b and d, $\Delta X = X_{SZ\ D/1} - X_{HMS}$) in Szeged.

The performance of the temperature sensor is adequate (*Fig. 3a*). As illustrated in *Fig. 3b*, the errors are small (MAE=0.1745 °C, RMSE=0.2194, while $STDEV_{D/1}$=5.78 °C and $STDEV_{HMS}$=5.83 °C) and almost balanced with a slight overestimation (ME=0.0769 °C). The relative humidity sensor underperforms (ME=0.6044%, MAE=4.2054%, RMSE=5.2277, $STDEV_{D/1}$=15.43%, $STDEV_{HMS}$=19.83%). Although the results shown in *Fig. 3c* do not meet the WMO standards (*WMO*, 2008) – requiring 1% accuracy for high and 5% accuracy for mid-range relative humidity levels –, the sensor was nevertheless deemed adequate for the purpose of the project, as 1–2% difference in RH has little effect on people's thermal comfort sensation in summer (e.g., *Oliveira* and *Andrade*, 2007). In contrast to the temperature sensor where bias is almost independent from its value (*Fig. 3b*), the relative humidity sensor systematically overestimates at lower values and underestimates at higher ones (*Fig. 3d*).

4.2. Intra-urban and inter-urban comparisons

4.2.1. Daily temperature indices

Two temperature indices were determined utilizing daily minimum (T_{min}) and maximum (T_{max}) temperature values: summer days, defined as days with T_{max}>25 °C; and tropical nights, where daily T_{min}>20 °C (*Karl et al.*, 1999). These indices were selected because of their acceptance as reliable indicators of heat stress (e.g., *Gabriel* and *Endlicher*, 2007; *Petralli et al.*, 2011). It was recognized that applying daily minima and maxima causes a kind of time asynchronity, but from the viewpoint of human health and heat stress, these time differences are not significant.

In order to make the daily temperature indices comparable between the two cities, days without data gaps in both locations were selected. The analysis used 48 days that met the criterion. The relative frequencies of these indices for each LCZ class are presented in *Fig. 4*.

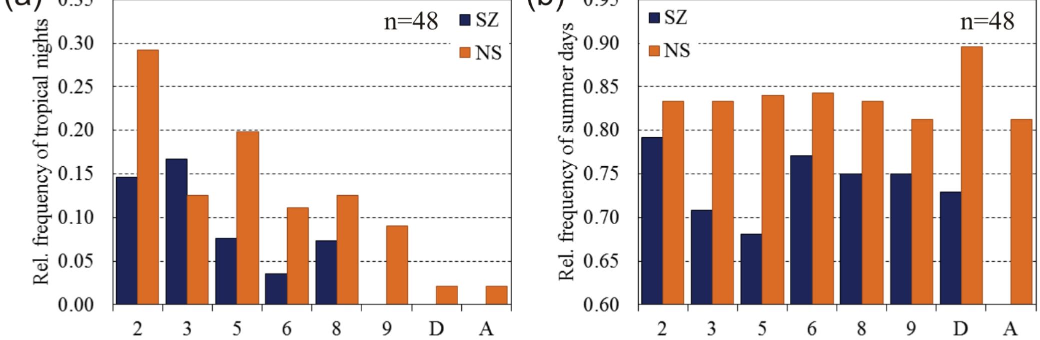

Fig. 4. Relative frequency of tropical nights (a) and summer days (b) by LCZ classes in Szeged and Novi Sad calculated for the selected common set of days.

In the case of tropical nights (Fig. *4a*), the differences between LCZ classes are relatively large, their number varies between 0 (LCZ D and LCZ 9) and 8 days (LCZ 3) in Szeged, while this range is between 1 (LCZ D and LCZ A sites) and 17 (LCZ 2) days in Novi Sad. It is important to note that the highest frequencies of tropical nights occur in the most densely built LCZs (2, 3, and 5). In contrast to tropical nights, the distribution of summer days is relatively even among the different LCZs (*Fig. 4b*). In the case of Novi Sad, LCZ D is an outlier, as it lacks shading from both buildings and taller plants. The cooling effect from shading is the reason behind the lower values recorded at LCZ 3 and 5 in Szeged. In the case of the latter site, the evapotranspiration from the higher amount of vegetation also contributes to this effect.

4.2.2. Diurnal variation of temperature under anticyclonic conditions

For the analysis of the thermal effect of the different LCZs, ideal weather conditions should be examined, because in these conditions the effect of the urban surface for the temperature are undisturbed. In order to eliminate the effects of unfavorable weather conditions and thus to bring forth the characteristic diurnal temperature cycles of various LCZ classes, we applied the average weather factor, Φ_w (*Oke*, 1998) calculated for 3-hour intervals using the data from the HMS SYNOP station 12982. Finally, we selected two time periods with prevailing anticyclonic conditions when Φ_w was greater than 0.7. They run from July 3 to 5, 2014 and from July 19 to 20, 2014 and lasted 72 and 48 hours in length, respectively. *Figs. 5* and *6* present the diurnal variation of absolute and relative temperatures – expressed relative to LCZ D as $T_{LCZ\,X} - T_{LCZ\,D}$.

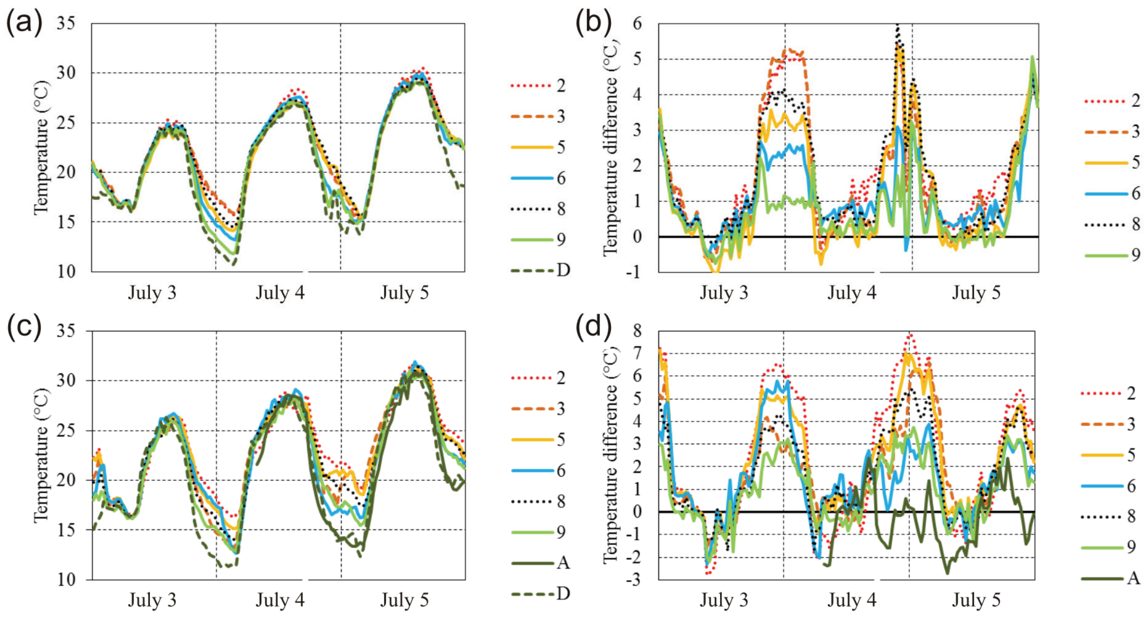

Fig. 5. Absolute and relative (difference from LCZ D) temperature variations at selected sites in Szeged (a, b) and Novi Sad (c, d) (July 3 to 5, 2014).

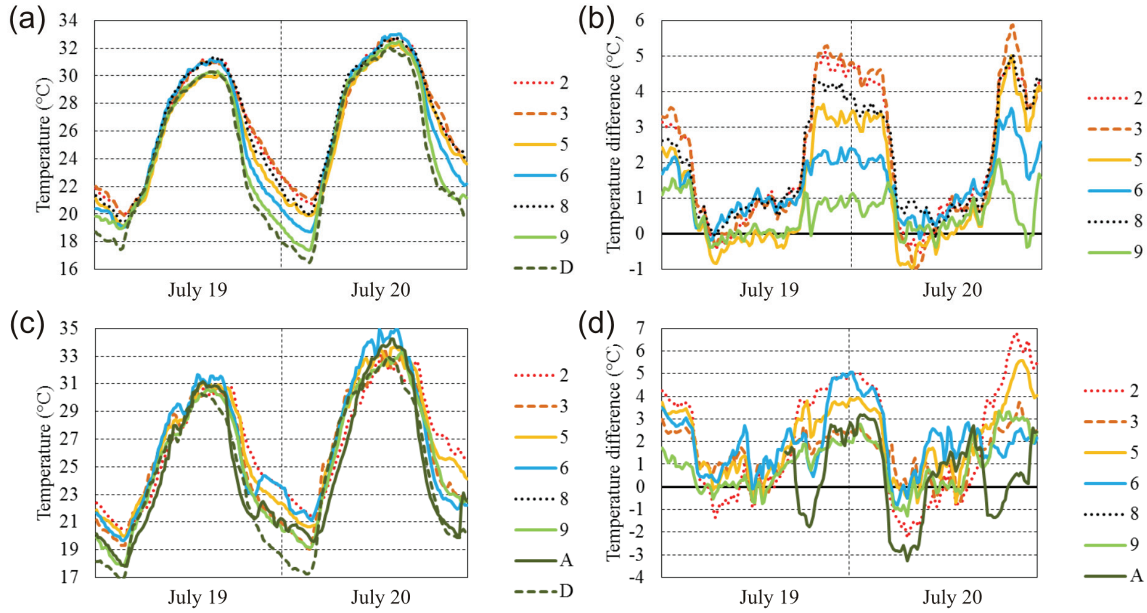

Fig. 6. Absolute and relative (difference from LCZ D) temperature variations at selected sites in Szeged (a, b) and Novi Sad (c, d) (July 19 to 20, 2014).

The measurement sites belonging to various LCZs have distinct daily temperature cycles. The differences between the classes are most pronounced in the case of Szeged, where LCZ 2 and LCZ 3 have an over 5°C temperature surplus at 00:00 UTC, July 4 (*Figs. 5a* and *b*) and at 00:00 UTC, July 20 (*Figs. 6a* and *b*). In the case of LCZ 8, LCZ 5, LCZ 6 and LCZ 9 the largest surplus values are 4 °C, 3.5 °C, 2.5 °C and 1 °C, respectively. In Novi Sad, the temperatures are slightly higher, but the classes differ less. The greatest temperature surpluses occur in LCZ 2 and LCZ 6 (between 5–7 °C), while LCZ 5, LCZ 3. and LCZ 8 remain somewhat cooler. The cycles of LCZ A and LCZ D are similar. The temperature difference between the two types remains within the ±3 °C interval, with the largest values occurring around 00:00 UTC.

Fig. 7 shows the examined sites' characteristic daily temperature cycles, calculated from the selected 'ideal' days as hourly averages relative to the average non-urban reference site (LCZ D). While differences are smaller in Szeged – as it is a smaller city with half the population of Novi Sad –, the diurnal cycle of LCZ's in the two cities indicate similar trends. During daytime, when the insolation is high and convective mixing prevails, temperature differences are below ±1 °C. The only exception is LCZ A in Novi Sad during the morning hours, which is the result of lush vegetation that delays warming through shading and evapotranspiration. During the night, when radiative cooling dominates, the differences are larger and mostly positive. The differences between the LCZ classes are most pronounced during this period due to the unique radiative and thermal properties of the sites. In the case of Szeged, the diurnal cycles of classes are more discernible.

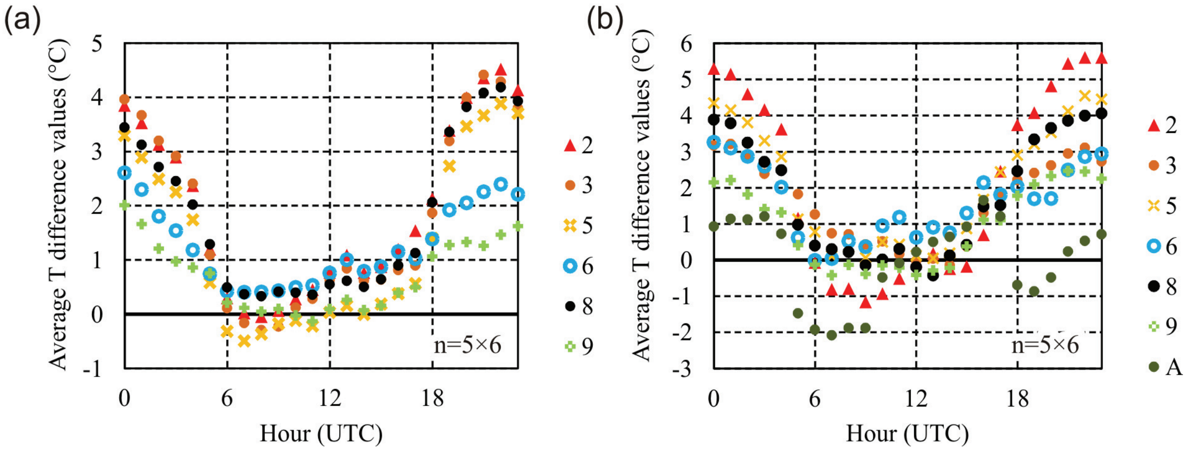

Fig. 7. Average hourly temperature values at selected sites calculated for the five selected days and expressed relative to average LCZ D in Szeged (a) and Novi Sad (b).

4.2.3. Diurnal variation of UHI during summer

This analysis is concerned with the diurnal development of the UHI intensity in the most densely built LCZ areas of Szeged and Novi Sad. Similarly to the conventional heat island studies, the UHI intensity is expressed as the urban conditions relative to non-urban ones. In our case, it was calculated as an average temperature difference between LCZ 2 (urban) and LCZ D (non-urban) sites for half-hour intervals in both cities (*Fig 8*). As noted in Section 3, the investigated period was shorter in Novi Sad due to technical issues.

The shape of isopleths in *Fig. 8* are in line with the general understanding of the thermal behavior of dense urban areas: for the most time, the UHI intensity remains positive with highest values at night, while negative values occur predominantly during the day (urban cool island). The dividing line between these two periods is around 6 UTC and 12 UTC in both cities – see the thick isotherms of 0 °C in *Fig. 8*. The range of UHI intensity is between –1.48 °C and 5.22 °C in Szeged, and between –3.70 °C and 6.85 °C in Novi Sad.

Urban cool island occurs in both cities during the day. It is typically around –1 °C in Szeged and –2 °C in Novi Sad. An exception around 18:00 UTC on July 27 in Szeged (shown in *Fig. 8a*) is caused by the cooling effect of a convective precipitation – 36.4 mm precipitation was measured at the outskirts and 83.0 mm in the inner city. It resulted in large temperature differences between different parts of the city, and produced an outflow with 8.3 ms^{-1} wind speed at the outskirts and 9.3 ms^{-1} in the center. As a consequence, the cooling was much faster in the central area and produced the mentioned anomaly.

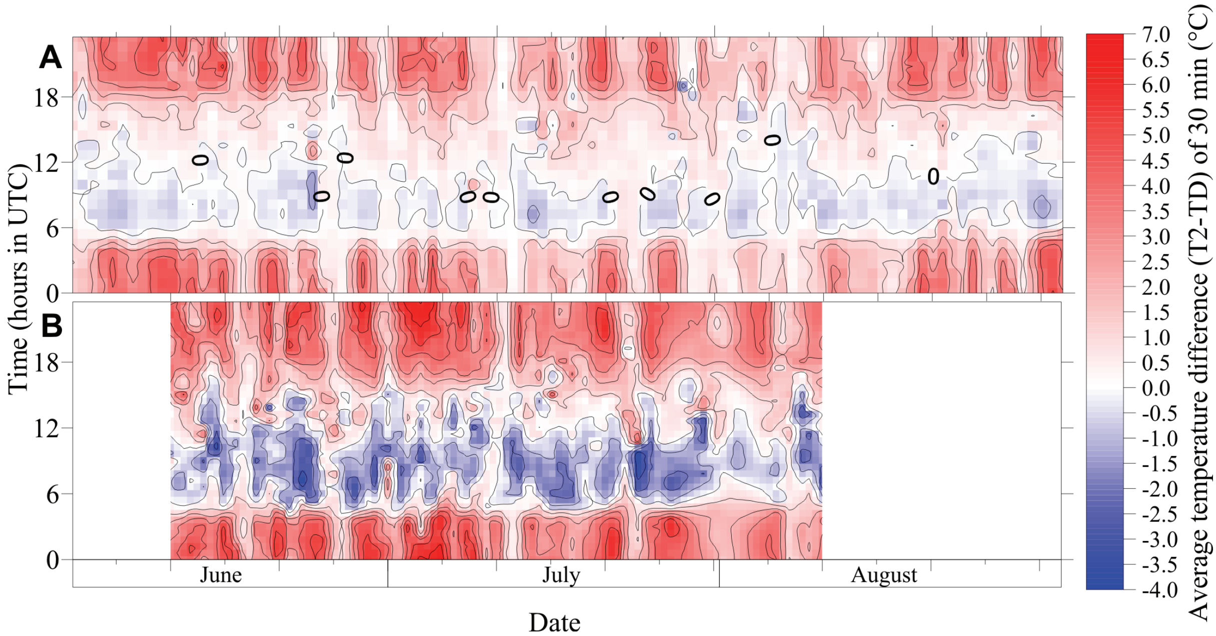

Fig. 8. Average temperature differences [°C] between LCZ 2 and LCZ D (a) in Szeged and (b) Novi Sad (thin isotherms – integer °C, thick isotherms – 0 and 5°C).

5. *Conclusions*

Monitoring urban temperature patterns is an important task that can assist in formulating adaptation and mitigation strategies to meet the challenges of climate change. The use of automatic weather stations is the most suited method for understanding the spatial and temporal characteristics of the urban climate. Although the global network of AWSs is well developed, their presence in cities is still rather rare. The developed urban climate monitoring systems in Szeged, Hungary and Novi Sad, Serbia visualize the observed temperature and relative humidity data along with calculated human comfort index. The results are freely available online. The selection of measurement sites utilized LCZ maps to ensure a representative number and placement of stations within different LCZs.

This study introduces these monitoring networks through a number of analyses using data from the summer of 2014. The temperature and relative humidity sensors at site D/1 in Szeged were validated against the sensors of the Hungarian Meteorological Service's SYNOP station 12982. In the case of temperature, the sensor performance was found satisfactory with slight underestimation. The relative humidity sensor underperformed, but it was deemed acceptable for the purpose of the project.

The evaluation of the daily temperature indices (summer days and tropical nights) revealed that the highest frequencies of tropical nights occur in the most densely built LCZ classes (2, 3, and 5). Based on these results, the control of building densities or the spatial confinement of dense LCZs could be viable adaptation strategies.

Further, in order to assess the thermal behavior of different LCZs under 'ideal' conditions, two periods with anticyclonic conditions were selected. In the case of Szeged, the distinction between the daily temperature cycles of different LCZ classes was quite pronounced. In contrast, while the nighttime temperature surpluses and the daytime temperature deficits were greater in Novi Sad, the thermal cycle of different LCZs was less distinct. The average daily cycle of each LCZ highlights the differences between day- and nighttime processes.

During summer, the diurnal variation of conventional heat island intensity confirms the general knowledge, that is, it remains positive with highest values at night, while negative values occur predominantly during the day.

Overall, it can be stated that the monitoring networks installed in Szeged and Novi Sad serve their intended purposes – as informing the citizens about the most recent temperature, humidity, and thermal comfort measurements – well. Based on the site visit data of the public display (www.urban-path.hu) of the monitoring system, the daily visitor number is around 200 and the two-thirds of it are new visitors from these two cities. Hopefully, this publicity helps the local authorities to decrease the disadvantageous effects of urban climate. They provide beneficial information about the climate of these cities to the public, moreover, the results (based on a short time period) presented in this paper show that the scientific application of the obtained data is also conductive. The spatial and temporal resolution of the network is adequate, and the accuracy of the sensors is satisfactory. The results indicate that the site selection was appropriate, as the sites belonging to different LCZs exhibit distinct thermal behaviors. The planned operation time of these networks will be over 5 years. Future data series will allow for more detailed and versatile climatological analyses in relation to intra-urban climate variations.

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