RECENT CHANGES OF THE URBAN LOCAL CLIMATE USING SATELLITE DATA AND IN-SITU MEASUREMENTS

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1. INTRODUCTION

The urban heat island (UHI) is one of the main environmental effects of cities. UHI can be characterized by its intensity, which means the difference between urban and rural temperature. To determine the UHI intensity, several variables can be used, e.g., regular meteorological air temperature measurements at 2 m level (e.g., Oke, 1973), ground-based air temperature measurements using a moving vehicle (e.g., Unger et al., 2000), surface temperature data calculated from radiation measurements of satellites (e.g., Price, 1979; Pongrácz et al., 2006), or remotely sensed surface temperature measurements placed on board of an aircraft (e.g., Ben-Dor and Saaroni, 1997). When surface temperature is used to describe the urban climate conditions, surface UHI (SUHI) effect can be evaluated. Within the framework of the urban climate research at the Department of Meteorology, Eötvös Loránd University, Budapest (Dezső et al., 2005, Pongrácz et al., 2006, 2010), SUHI effects of several Hungarian and Central European cities (Pongrácz et al., 2009) have been analyzed using remotely sensed surface temperature.

In this paper, the urban climate of only one specific Central/Eastern European capital, i.e., Budapest (Hungary) is analyzed using both satellite-based and in-situ measurements. The Hungarian capital, Budapest is divided by the river Danube into the hilly, greener Buda side on the west, and the flat, more densely built-up Pest side on the east. This study aims (i) to analyze the urban climatological effect on both sides, and (ii) to evaluate the recent climate change adaptation-oriented local programs from a climatological point of view. For these purposes two districts (the 12th and the 9th at the Buda and Pest side, respectively) are selected among the total 23 districts of the city (Fig. 1).

At the Buda side (in case of the 12th district, called Hegyvidék), the analysis focuses on the extended urban vegetation since most of the forested green area is located here (BFO, 2011). The effects of the recent changing of these green areas are analyzed using surface temperature data calculated from MODIS satellite measurements in the infrared channels.

At the Pest side, in the 9th district (called Ferencváros), several block rehabilitation programs have been completed in the recent decades, which resulted in functional and structural changes of special subsections of the district. Their consequent local climatic changes are evaluated on the basis of (i) satellite measurements, namely, surface temperature fields derived from radiation data of infrared channels measured by sensors MODIS (onboard satellites Terra and Aqua) and ASTER (onboard satellite Terra), and (ii) in-situ temperature and relative humidity measurements within the rehabilitation sections. Our main goal is to analyze whether the generally positive changes of the built environment can also be recognized in the UHI effect of this area.

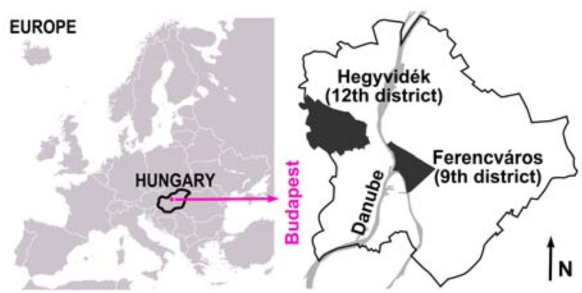

Fig. 1: Geographical location of the target districts within Budapest, Hungary.

2. SATELLITE DATA

Part of the American National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS), satellites Terra and Aqua were launched in December 1999, and May 2002, respectively. They are on 705 km height polar orbits around the Earth with an inclination of 98°. Both satellites are solar-synchronous, Terra crosses the Equator on a descending orbit at 10:30 a.m., and Aqua crosses it on an ascending orbit at 1:30 p.m. Thus, for the Budapest agglomeration area, Terra can provide two images per day (at around 09-10 UTC and 20-21 UTC), as well, as Aqua (at around 02-03 UTC and 12-13 UTC). Five and six instruments are working on satellite Terra, and Aqua, respectively. These instruments measure radiation of various spectral bands and use different spatial resolution (NASA, 1999; 2002). Measurements of sensor MODIS (Moderate Resolution Imaging Spectroradiometer) and sensor ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) are used in this paper.

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Sensor MODIS can be found on both satellites Terra and Aqua. It is a cross-track scanning multi-spectral radiometer with 36 electromagnetic spectral bands from visible to thermal infrared. Horizontal resolution of the infrared measurements is 1 km. In the framework of EOS program numerous climatic and environmental parameters are determined using the raw radiation data. All the parameters are archived in universal format using 1200×1200 pixel tiles, they are available as validated, quality-controlled, geo-referenced, high-level datasets. In our research, we used the following MODIS products: Land Surface Temperature (LST), and Land Cover (Strahler et al., 1999). LST is determined by using the following channels: 3660-3840 nm (channel 20), 3929-3989 nm (channel 22), 4020-4080 nm (channel 23), 8400-8700 nm (channel 29), 10780-11280 nm (channel 31), 11770-12270 nm (channel 32), and 13185-13485 nm (channel 33) as described by Wan and Snyder (1999). On the basis of error- and cloud-free parts of available LST fields, SUHI (surface urban heat island) intensity values are calculated for 2001-2014 for each pixel within the 65×65 pixel representation of the Budapest agglomeration using the rural mean LST value (Bartholy et al., 2012).

Sensor ASTER measures radiation in 14 different electromagnetic spectral bands, out of which 5 infrared channels (i.e., 8125-8475 nm, 8475-8825 nm, 8925-9275 nm, 10250-10950 nm, and 10950-11650 nm) are used to calculate surface temperature (NASA, 2001). ASTER can be found only onboard satellite Terra, and unlike sensor MODIS it is not turned on throughout the entire orbiting time, only for 8 minutes during each individual orbit. Thus, the number of available information for a specific region is extremely limited. Nevertheless, the horizontal resolution of the measurements in thermal infrared channels is 90 m, which is far more suitable for detailed spatial analysis than MODIS data.

3. ANALYSIS OF THE “GREEN” DISTRICT AT THE HILLY WESTERN SIDE

After calculating the SUHI intensity values for each pixel within the 65×65 pixel representation of the Budapest agglomeration using the rural mean LST value for all available images, the pixel representation of the most vegetated-covered district of Budapest is selected (Fig. 2). Monthly, seasonal, and annual averages of SUHI intensity are compared for the built-up and the vegetated pixels within the selected district.

First, seasonal mean structure of the SUHI intensity is shown in Fig. 3. Since the selected subregion of the city is located at the western border, the SUHI intensity is the largest in the eastern part of the district, closer to the downtown area. The positive effect of the vegetation, i.e., less intense SUHI, is clearly visible in all the four seasons in case of all the four periods of the day. The inter-seasonal variance is larger in day-time (morning and afternoon) then night-time (evening and dawn) due to the definite annual cycle of the incoming solar radiation. The overall SUHI intensity difference within the district is the largest (8 °C) in summer during day-time (afternoon).

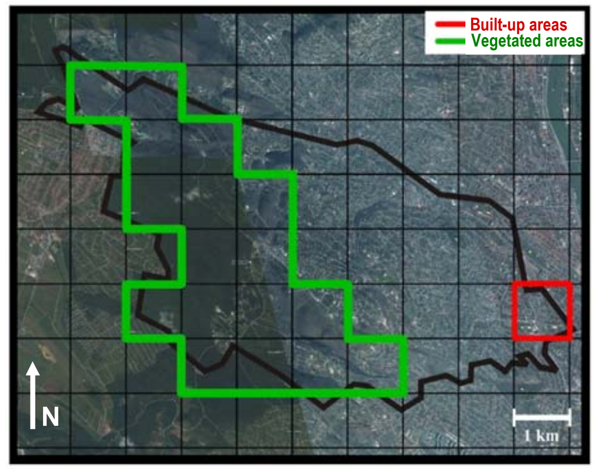

Fig. 2: Built-up and vegetated area of the 12th district of Budapest shown on the MODIS grid over the Google Earth satellite image. Black contour indicates the district area.

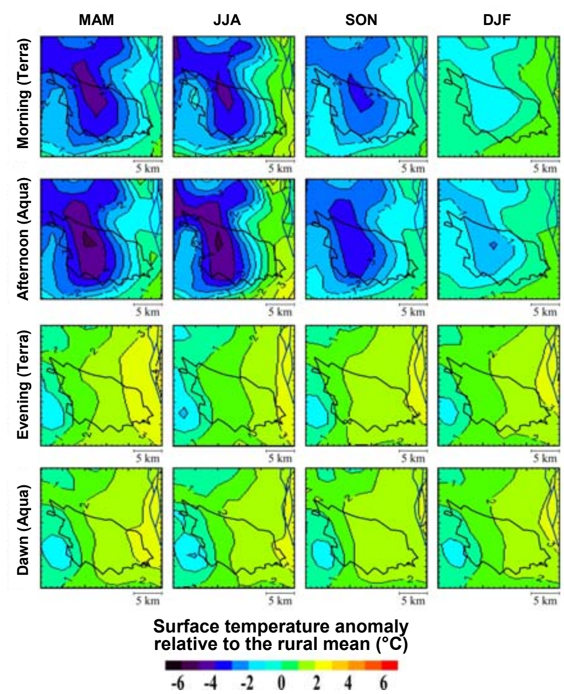

Fig. 3: Seasonal mean structure of the urban SUHI in the 12th district of Budapest, 2001-2014.

Fig. 4 compares the average annual cycle of the monthly mean SUHI intensity in the vegetated and the built-up areas during the four different periods of the day. The inter-monthly variation of SUHI intensity is clearly smaller during night-time than day-time, which is due to the fact the LST, and hence, SUHI intensity is mainly determined by the incoming solar radiation. Furthermore, in case of day-time the larger SUHI intensity in summer and winter, and smaller SUHI intensity in spring and fall can also be identified in the built-up part of the district, whereas the largest cooling effect of the vegetation appears in the spring and summer months.

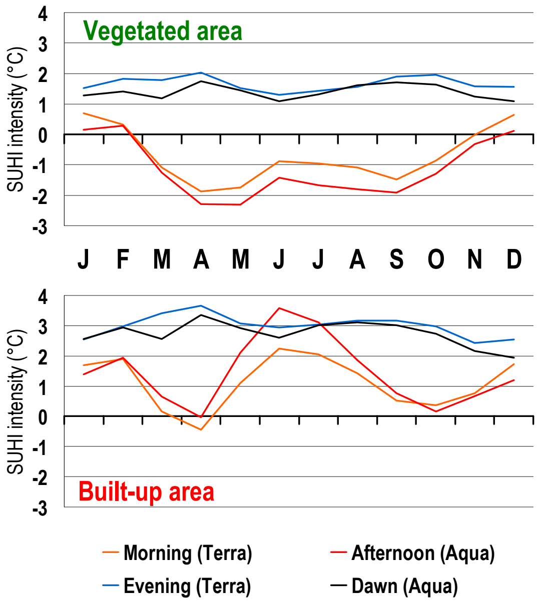

Fig. 4: Annual distribution of monthly mean SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, 2001-2014.

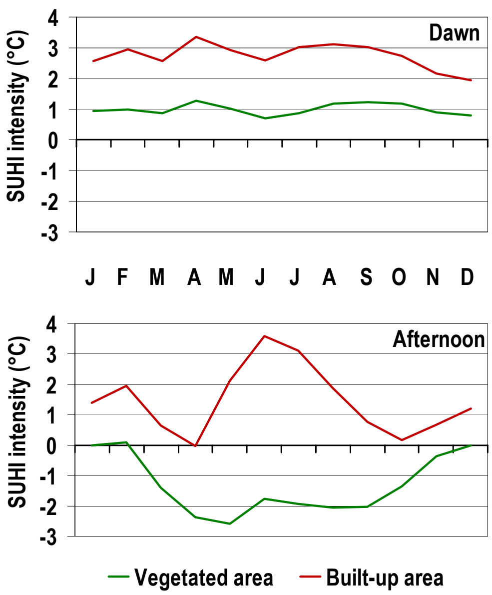

Fig. 5: Annual distribution of monthly mean SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, 2003-2014.

Fig. 5 focuses on day-time (afternoon) and night-time (dawn) period of the day, and compares the SUHI intensity in the vegetated and built-up areas. The difference between the monthly mean SUHI intensity around dawn is about 1-2 °C throughout the whole year, whereas it is more variable at the afternoon: the difference is only around 1 °C from the late fall to the early spring (when the green vegetation, i.e., the forest, loses most of the greenness due to the annual cycle of the continental plants), and increases to about 4 °C by June.

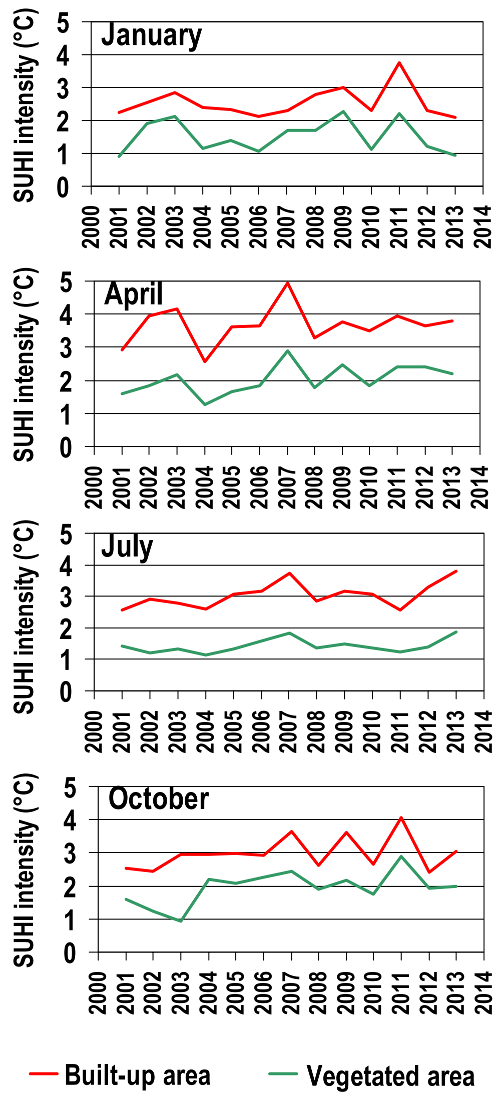

Fig. 6: Trend analysis of the monthly mean SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, based on Terra/MODIS measurements.

Finally, Fig. 6 compares the trend analysis of monthly mean SUHI intensity values in the evening for both the vegetated and built-up areas. Slight increasing trend can be identified in both types of subregions for all the four months. The difference between the monthly SUHI intensity values are 1-2 °C, which can be considered as the overall effect of the vegetation.

4. ANALYSIS OF THE HETEROGENEOUS DISTRICT IN THE OUTER CENTRAL CITY AREA

Ferencváros, the 9th district of Budapest is located near the river Danube in the southern central part of the city, which is very heterogeneous and consisting of 3- and 4-storey old buildings, block houses with either 4 or 8 levels, brown industrial areas, and large areas occupied by the railways system. Partly due to the functional and structural changes of special subsections of the district substantial local climatic changes occurred in the past few decades. From the local government concentrated efforts were made to complete several block rehabilitation programs already starting from 1980s. Since 1993 in the most densely built inner part of the district entire blocks were renovated and modified in order to create more livable environment for the citizens. Within the framework of these programs inner parts of the blocks were demolished, thus, inside the blocks more common green areas could be created. Moreover, several parks have been enlarged, and small green areas have been created along the streets (Local Government of Ferencváros, 2010). The overall increase both in terms of number and spatial extension of green areas is illustrated in Fig. 7.

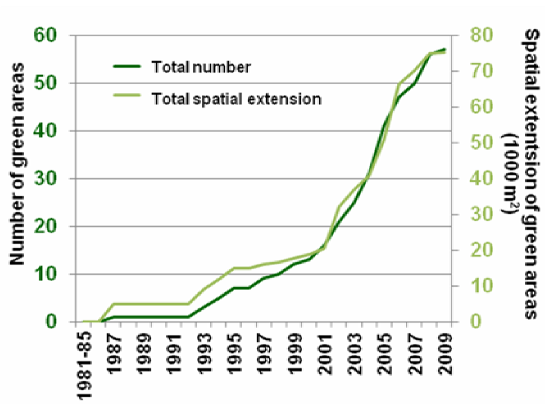

Fig. 7: Increase of the green areas in Ferencváros district of Budapest.

Here, the climatic effects are evaluated on the basis of satellite measurements, namely, surface temperature fields derived from radiation data of sensors MODIS and ASTER. From the surface temperature data rural mean values around Budapest are used to calculate pixelwise SUHI intensity. Due to the data availability the temporal analysis is mainly based on MODIS data, whereas the spatial analysis uses ASTER data.

For the temporal analysis two pixels are selected from Ferencváros district (Fig. 8). Pixel I is located in the densely built-up region of the area where many block houses participated in the rehabilitation program, whereas pixel II represent a 4-storey buildings' community with large trees and many green areas.

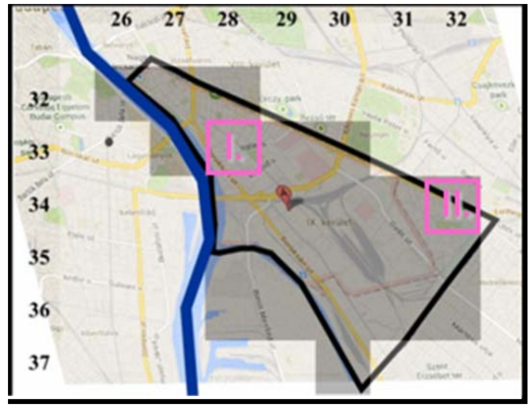

Fig. 8: Pixel representation of Ferencváros on the MODIS grid. Pixels I (28;33) and II (32;34) are used for trend analysis shown in Figs. 9 and 10, respectively.

Monthly mean SUHI intensity values and average surface temperature in June are shown in Figs. 9 and 10 for pixels I and II, respectively.

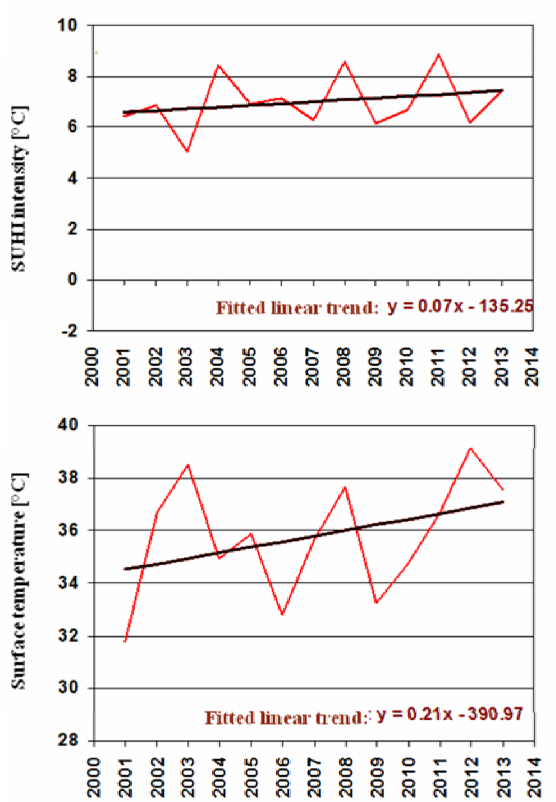

Fig. 9: Trend analysis for pixel I (28;33), MODIS measurements in afternoon, June.

For this analysis, a summer month is selected with the afternoon measurements, when the SUHI intensity of the city is the largest (Bartholy et al., 2012). The fitted linear trends are positive in both pixels considering either SUHI intensity or surface temperature values. However, due to the large variability the trend coefficients are not significant at 0.05 level. The comparison of the two selected pixels suggest that the average surface temperature (and thus the mean intensity as well) is larger overall by about 1-2 °C in pixel II than in pixel I, which highlight the necessity of further increase of the green areas in the more densely built-up sections of the city. Moreover, finer spatial resolution may result in more details about the exact differences within the district.

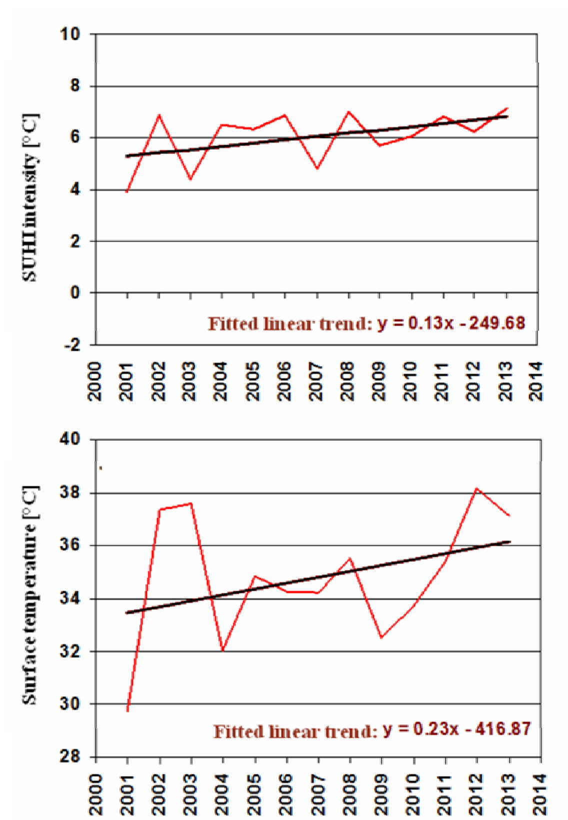

Fig. 10: Trend analysis for pixel II (32;34), MODIS measurements in afternoon, June.

Evidently, 1 km spatial resolution is too coarse for detailed analysis on house block scale. For this purpose, 90 m horizontal resolution ASTER data is more suitable than MODIS data. Available ASTER measurements covering the Budapest agglomeration area, more specifically, the Ferencvaros district form three different images (Fig. 11). Pixelwise SUHI intensity values are compared for a summer, a spring, and a winter day (6 July 2001, 4 May 2002, and 2 February 2003, respectively). The reference rural mean surface temperature value is calculated from the MODIS measurements for the particular days since ASTER images do not include the entire agglomeration area together with rural surroundings, thus, rural mean surface temperature cannot be determined on the basis of ASTER data only. The rural mean surface temperature value is very different in February (below 0 °C) from those in either July or May – when they were above 30 °C. Nevertheless, the calculated anomaly values enable us to identify warm and cold spots of the district.

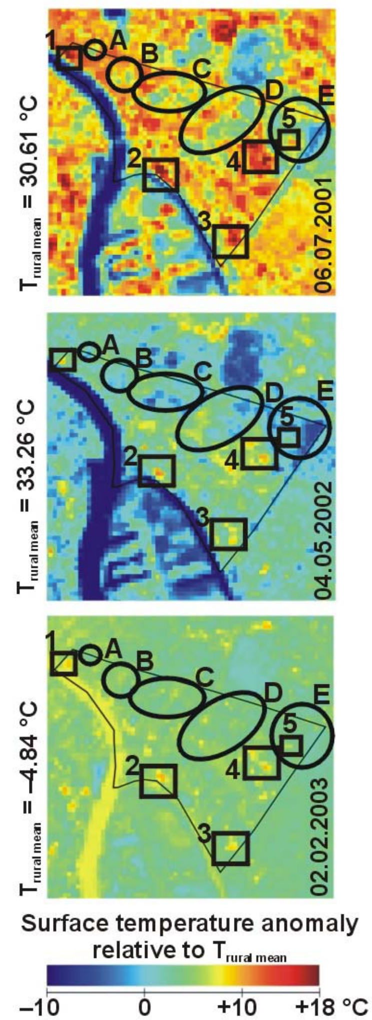

Fig. 11: Case studies for ASTER data. A, B, C, D, and E indicate cold spots, whereas 1, 2, 3, 4, and 5 indicate warm spots, detailed description of them is given in Figs. 5 and 6, respectively.

Detailed descriptions of five major cold spots are shown in Fig. 12. These identified cold spots are basically all green areas with large trees, extended parks. The pixels of the spots are clearly colder than the adjacent pixels around them. However, their surface temperatures are still larger than the rural mean. Due to the large incoming solar radiation, the summer SUHI intensity values are the largest. Moreover, in winter – when the incoming solar radiation is much smaller – the SUHI intensity values themselves, as well, as the spatial variance of the SUHI intensity field are much smaller than in the rest of the year.

Google Earth Image	ASTER: 06.07.2001	ASTER: 04.05.2002	ASTER: 02.02.2003	Desription of the area for the period 2001-2003
A	ΔT: 6 – 7 °C	ΔT: -1 – 0 °C	ΔT: 3 – 4 °C	**Markusovszky square:** park to be developped
B	ΔT: 7 – 8 °C	ΔT: 0 – 1 °C	ΔT: 3 – 6 °C	**Ferenc square** park, with trees and grass area
C	ΔT: 4 – 6 °C	ΔT: -5 – 1 °C	ΔT: 3 – 6 °C	**St. Stephen and St. Laszlo Hospital:** park with trees
D	ΔT: 3 – 5 °C	ΔT: -3 – 2 °C	ΔT: 3 – 6 °C	**Merenyi Hospital, building community:** abandonned, non-properly maintained area
E	ΔT: -3 – 8 °C	ΔT: -7 – 2 °C	ΔT: 1 – 4 °C	Large, developped trees and green area within the **4-storey buildings community**

Fig. 12: Cold spots identified in the case studies of ASTER data.

Google Earth Image	ASTER: 06.07.2001	ASTER: 04.05.2002	ASTER: 02.02.2003	Desription of the area for the period 2001-2003
1	ΔT: 12 – 13 °C	ΔT: 9 – 10 °C	ΔT: 6 – 7 °C	**Covered market place**
2	ΔT: 12 – 13 °C	ΔT: 11 – 12 °C	ΔT: 8 – 9 °C	**Industrial area / factory,** abandoned industry
3	ΔT: 12 – 13 °C	ΔT: 8 – 9 °C	ΔT: 7 – 8 °C	**Gas station** (cross section of Soroksári road and Határ road)
4	ΔT: 12 – 13 °C	ΔT: 9 – 10 °C	ΔT: 7 – 9 °C	**Industrial area / factory**
5	ΔT: 9 – 10 °C	ΔT: 3 – 4 °C	ΔT: 5 – 6 °C	**Shops** at the 4-storey buildings community

Fig. 13: Warm spots identified in the case studies of ASTER data.

A similar list of the main warm spots is collected in Fig. 13. In these pixels, the SUHI intensity values in July are clearly above 10 °C. In early May, SUHI intemsity values of the warm spots are around 10 °C, except the supermarket area within the 4-storey buildings community. This area is especially vegetated with large, mature trees around, that is why the positive vegetation effect is partially eliminating the SUHI effect in spring-time when the shadows of the trees are the most effective. Finally, in winter-time the SUHI intensity values of the warm spots are smaller compared to the other two months, however, the differences of the surface temperature values between the selected warm spots and the rural mean are still around 7 °C, thus, the actual surface temperatures of these hot spots are above 0 °C despite of the freezing rural environment.

In addition to the satellite-based analysis, we have recently started an in-situ urban measuring program in the rehabilitation region of the district. In this urban climate measurement program air temperature and relative humidity are recorded with Voltcraft HT-200 instruments along a pre-defined path consisting of 22 measuring points (Fig. 14), which covers the studied area.

201: Ferenc bld. / Tompa st.	101: Ferenc bld. / Tompa st.
202: Bakáts sq. / Tompa st.	102: Tompa st. / Liliom st.
203: Bakáts sq. / Ráday st.	103: Liliom st. / Tűzoltó st.
204: Ráday st. 42	104: Tűzoltó st. / Bokréta st.
205: Ráday st. / Biblia st.	105: Ferenc sq.
206: Ráday/Erkel st	106: Balázs st. / Thaly st.
207: Kálvin sq.	107: Univ. Building
208: Lónyay st. / Gönczy st.	108: Kerekerdő Park
209: Csarnok sq.	109: Márton st./ Gát st.
210: Building Bálna	110: Mester st. /Viola st.
211: Nehru Park	111: Mester st. / Tinódi st.
212: Boráros sq.	112: Boráros sq.

Fig. 14: Measuring points along the predefined path.

The measuring sites are selected at different representative points of the district, such as green parks, narrow streets, paved squares and roads. The whole measuring path is divided into two parts, where the measurements are recorded simultaneously (from 101 to 112, and 201 to 212 with the identical starting and ending sites, i.e., 101 is identical to 201, and 112 is 212) lasting about 1-1.5 hours. Then, the measurements are recorded along the same two paths but in reverse order (i.e., starting from 112/212, and ending at 101/201). In order to temporally adjust the measurements, two records from the consequent (and reversed) partial paths are averaged over each site resulting in an average value being representative for a virtual time. More precisely, since the moving speeds between sites and the distances between sites are not perfectly identical, this virtual time is given as a 10-20 minute time period. For calculating the urban heat island intensity, temperature measurements are compared to the hourly recorded data of the Budapest synoptic station (ID number: 12843) located in the southeastern suburb district of the city. Similarly, difference between relative humidity measurements are calculated and analyzed.

The measuring program started in early spring of 2015. The measurements are scheduled once a week (on Friday), from about noon until the late evening. The on-going measuring program involves BSc students specialized in Earth sciences and MSc students specialized in meteorology, therefore, 8 dates were completed in the 2015 spring semester (20 and 27 March; 3, 10, 17, and 24 April; 8 and 15 May), and another 8 dates in the 2015 fall semester (18 September; 2 and 9 October; 6, 13, 20, and 27 November; and 4 December). During the summer, three consecutive days were selected for the measuring program in early July (6, 7, and 8 July), and the last Friday of August (28 August). We are planning to extend further the measuring program at the study area and complete several entire years of measurements, so the seasonal cycle of temperature and relative humidity differences will be analyzed as well, as the inter-annual variability and changes.

Among all the measuring dates one is selected here for presenting the preliminary results of our analysis. Since UHI together with a heatwave result in excessive heat stress for humans, and thus, significant health consequences, measurements on one of the heatwave days (7 July) occurred in the summer 2015 are presented. The entire heatwave period in the Carpathian Basin was dominated by a strong anticyclone over Central/Eastern Europe with clear sky conditions. The averaged air temperature values and the differences compared to the Budapest-Pestszentlőrinc synoptic station throughout the day – starting from about 2 p.m. to 9 p.m. – are shown in Fig. 15.

The warmest site was the Boráros square, which is a large paved square near the river Danube with main stations of the public transportation system and partially surrounded by 4-storey buildings. The recorded temperature exceeded 38 °C between 2 p.m. and 4:30 p.m. The coolest sites were the greener spaces (i.e., park along the Danube, 211; park in the rehabilitation area, 105). Towards the evening (starting around 5:30 p.m.) the cooling rate until the end of the measurements (around 9 p.m.) at all the measuring sites was about 1.5-2 °C/h. However, the air temperature stayed still above 30 °C. As far as the UHI intensity, the largest values occurred at the largely paved Boráros square (112=212). The largest temperature difference between our measurements and the Budapest-Pestszentlőrinc synoptic station exceeded 4 °C.

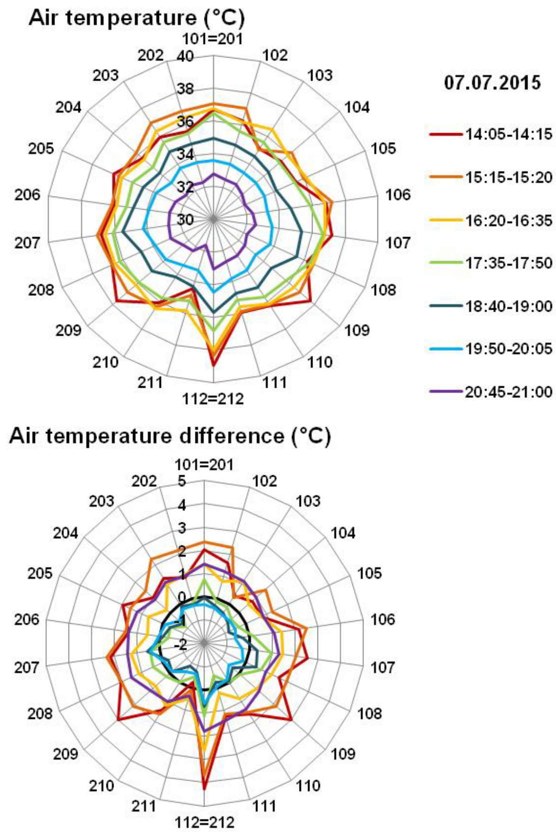

Fig. 15: Averaged temperature (upper panel) and UHI intensity values (lower panel) along the measuring path during the 7 measuring periods, 7 July 2015.

As already mentioned, the measuring program has just started, and we are planning to continue throughout 2016 and beyond in order to build year-round datasets for analysing the seasonal cycle of temperature and relative humidity differences as well, as the diurnal changes and the spatial structure within the study area.

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