ANALYSIS OF THE URBAN HEAT ISLAND EFFECT
COMPARISON OF GROUND-BASED AND REMOTELY SENSED TEMPERATURE OBSERVATIONS

Rita Pongrácz*, Judit Bartholy, Enikő Lelovics, Zsuzsanna Dezső
Eötvös Loránd University, Budapest, Hungary

1. INTRODUCTION

One of the most often studied characteristics of urban environment is the so-called urban heat island (UHI) effect (Landsberg, 1985). UHI is the positive temperature anomaly occurring between built-in areas and their surroundings (Oke, 1982). There are several possible methods to determine UHI intensity and to measure temperature from which UHI intensity can be calculated. The often applied method is to observe air temperature by using fixed weather stations (Oke, 1973) or sensors mounted on a moving vehicle (Unger et al., 2001; Bartholy et al., 2009). Another possibility is to use remotely sensed technique (Pongrácz et al., 2006, 2009, 2010), e.g., a multispectral radiation sensor called MODIS (Moderate Resolution Imaging Spectroradiometer). Seven infrared channels of MODIS (Barnes et al., 1998) can be applied to calculate surface temperature (Wan and Snyder, 1999).

The purpose of our research is to compare temperature values observed by ground-based and satellite-based instruments. In the current analysis we used temperature datasets measured between 2001 and 2008 using (i) ground-based air temperature sensors from six weather stations operated by the Hungarian Meteorological Service (HMS) in Budapest (Fig. 1.) and its vicinity; and (ii) satellite-based MODIS surface temperature sensors (NASA, 1999).

Fig. 1: Geographical location of Budapest, the capital of Hungary with 1.7 million inhabitants.

2. DATABASE

In the frame of the climatological study presented here six weather stations (Table I) were selected from the station network of the HMS. Stations 2 and 3 are located in the downtown of Budapest, stations 1 and 4 can be found in the suburbs, and stations 5 and 6 are in the rural region, to the northeast and to the southeast from the city, respectively (Fig. 2). The air temperature observations are available from all these stations from 2001. The weather stations operate real-time automated sensors, which record the meteorological parameters at every hour. However, the relatively small number of working weather stations in and around Budapest is not suitable for detailed analysis of UHI spatial analysis, and the future installation of further weather stations in the region is not realistic due to the high costs.

Table I: Geographical coordinates and elevation above the sea level for the selected weather stations used in this paper.

No./ Name	Latitude	Longitude	Altitude
1./ Újpest	47.57° N	19.07° E	100 m
2./ Kitaibel Pál st.	47.51° N	19.03° E	120 m
3./ Lágymányos	47.48° N	19.06° E	105 m
4./ Pestszentlőrinc	47.43° N	19.18° E	130 m
5./ Penc	47.79° N	19.28° E	240 m
6./ Kakucs	47.25° N	19.36° E	120 m

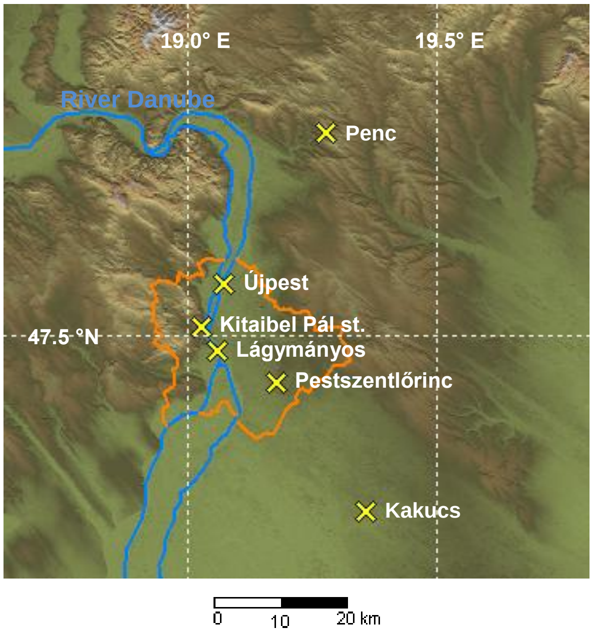

Fig. 2: Geographical location of the weather stations in Budapest and in the rural surroundings. The city limit of Budapest is indicated by an orange line.

The remotely sensed MODIS data are available from satellites Terra and Aqua starting in 2001 and 2003, respectively. Both satellites are on 705 km polar orbit as part of the NASA's Earth Observing System. The surface temperature are calculated using seven spectral channel (i.e., 3660-3840 nm (channel 20), 3929-3989 nm (channel 22), 4020-4080 nm (channel

* *Corresponding author address*: Rita Pongrácz, Eötvös Loránd Univ., Dept. of Meteorology, Pf. 32. Budapest, Hungary, H-1518; e-mail: prita@nimbus.elte.hu

23), 8400-8700 nm (channel 29), 10780-11280 nm (channel 31), 11770-12270 nm (channel 32), and 13185-13485 nm (channel 33)) radiation with 1 km^2 spatial resolution covering a relatively large region. Terra provides 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). Obviously, the MODIS observations can be used for urban studies only in case of clear conditions (no clouds). The ground-based observations at the weather stations provide air temperature data representing only the local surrounding of the weather station, while a single grid point value of the satellite-based surface temperature values represents a much larger area. The nearest grid point to each weather station is selected for the presented study.

3. METHODOLOGY

For the satellite-measured data pixels are classified as urban or rural (Fig. 3) using the MODIS Land Cover Product categories, satellite images of the Google Earth, distance from the city centre, and the GTOPO30 global digital elevation model. Urban pixels are defined as the built-in area within the city border, excluding the areas where the elevation according to GTOPO30 is 50 m higher or lower than the mean elevation of Budapest. Rural pixels can be found around the urban pixels, excluding the built-in and water region and the pixels exceeding 100 m difference from the mean elevation of the city (Dezső et al., 2005).

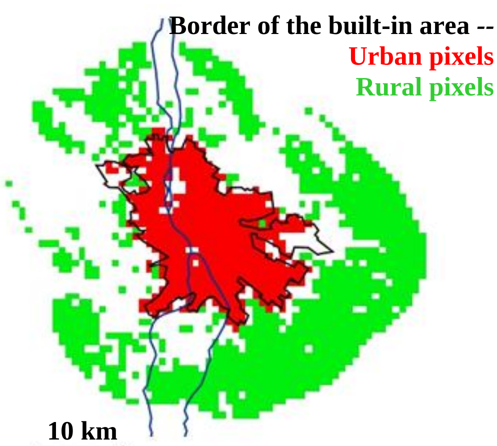

Fig. 3. Definition of urban and rural pixels, and the border of the built-in area around Budapest.

The average of the surface temperature in urban and rural pixels are defined as urban, and rural mean, respectively. Analysis of these average time series can be found in Pongrácz et al. (2009).

4. RESULTS AND DISCUSSION

First, ground-based air temperature and satellite-based surface temperature time series are compared for every station. Fig. 4 illustrates the results of the frequency distribution of temperature differences for station 3 (Lágymányos) for each season. The average night-time difference is the largest in winter (-2.27 °C), and the smallest in summer (-1.57 °C). During day-time the largest average difference occurred in summer (5.57 °C), and the smallest in winter (0.52 °C). The difference between the day-time and night-time temperature differences is the largest in spring and summer.

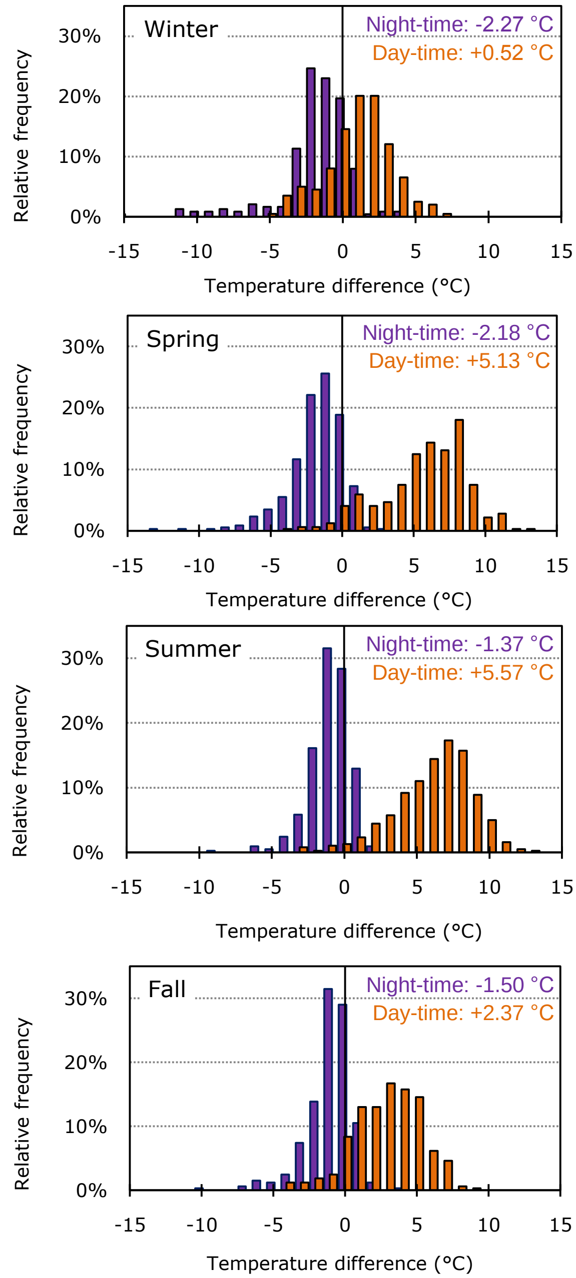

Fig. 4: Relative frequency of the difference between satellite-based and ground-based temperature values at Lágymányos.

The seasonal distributions clearly show that the day-time surface temperature is generally larger than the air temperature (especially in summer and spring), and the night-time surface temperature is smaller than the air temperature. This can be explained by the well-known feature of the radiation transfer: both day-time warming and night-time cooling of the boundary layer of the atmosphere proceeds from the surface. During night-time the surface temperature is less in case of the Aqua measurements than for the Terra observations, especially, in summer.

The average temperature (which is defined as the average of the monthly mean temperatures because remotely-sensed observations are available more often in summer than in winter) is higher for the satellite-based observations than for the ground-based measurements. The difference is about 1 °C. The warmest region is in the downtown (Lágymányos, Kitaibel Pál street), then, in the suburbs (Pestszentlőrinc, Újpest), and the coldest conditions occurred in the rural region (Kakucs, Penc). The average satellite-based temperature of Kakucs and Penc can be considered as a good estimate for the rural mean temperature, the correlation coefficients of the anomalies are 0.995, and the average monthly difference is less than 0.4 °C.

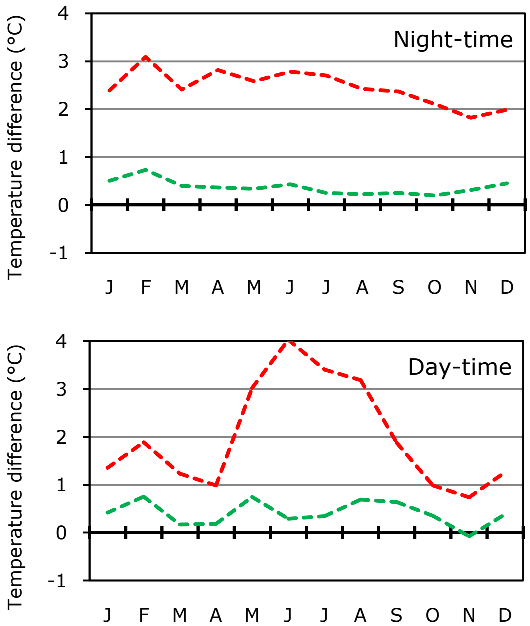

Fig. 5: Temperature difference of **urban mean** and **rural mean** temperature from the average of the two rural stations: Kakucs and Penc.

The annual distributions of the urban and rural mean temperature compared to the average satellite-based temperature of the two rural weather stations Kakucs and Penc (T_{KP}) are shown in Fig. 5 both for night-time and for day-time. The rural means are very close to the monthly mean values of T_{KP} considering either the night-time or the day-time observations. The average differences between the urban monthly mean and T_{KP} are 2.0 °C, and 2.5 °C in day-time and in night-time, respectively. However, the largest monthly difference (4.0 °C) can be identified in day-time during summer since the annual variability is larger in day-time than in night-time.

In the remaining part of the analysis the rural mean temperature (T_{rural}) is defined as the average temperature observed at Kakucs and Penc for both satellite-based and ground-based measurements. Fig. 6 shows the monthly mean temperature differences relative to monthly mean values of this T_{rural} for each weather station and the urban mean. The largest variability of the differences can be identified in case of day-time satellite-based surface temperature (upper left graph). The differences are positive throughout the year in Lágymányos and Pestszentlőrinc, and they are similar to the differences between the urban mean temperature and T_{rural}. The smallest differences between the monthly mean temperatures and T_{rural} occurred in case of the day-time ground-based air temperature (lower left graph) where the largest difference values do not exceed 1.5 °C in any weather station. According to the ground-based measurements UHI intensity is 2-3 times stronger during night-time than day-time.

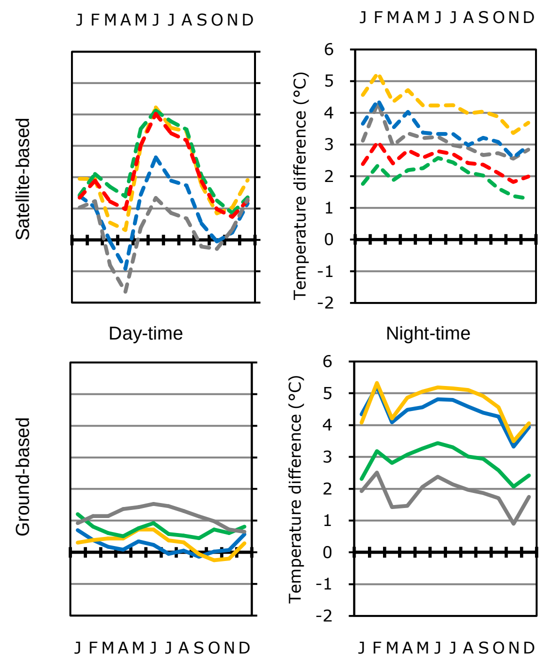

Fig. 6: Monthly mean UHI intensity at the urban weather stations (ground-based) and their 1 km^2 surrounding (satellite-based).
(Applied colours: **Újpest**, **Kitaibel Pál st.**, **Lágymányos**, **Pestszentlőrinc**, **urban mean**)

During night-time the overall difference between the satellite-based and the ground-based analysis (upper and lower right graphs of Fig. 6, respectively) are smaller than during day-time. In Újpest (located in the suburbs) the monthly temperature differences are larger in case of the satellite-based values than in case of the ground-based measurements. In the other three stations they are either similar or slightly smaller.

The time series of UHI intensity defined as the difference between the average temperature of the four weather stations of Budapest and the average temperature of the two rural weather stations (T_{rural}) are shown in Fig. 7. The day-time UHI intensity is between 0 °C and 2 °C when using the ground-based temperature values, the average for 2001-2008 is 0.6 °C. The largest intensities occurred in winter and summer. When using the satellite-based measurements, the variability of the day-time monthly UHI intensity is larger, in summer the UHI intensity exceeded 3-4 °C, whereas the average throughout the whole studied period is 1.5 °C. In some years, the UHI intensity in spring is negative, which implies faster warming of the surface in the rural region than inside the city. During night-time the UHI intensity values determined using the satellite-based or the ground-based temperature observations differ much less than during day-time. The correlation coefficients of the intensity time series are 0.7 and 0.5 for night-time and for day-time, respectively. The average UHI intensities throughout the whole 2001-2008 period are 3.2 °C based on the satellite-based surface temperature, and 3.4 °C, based on the ground-based air temperature. This means that the UHI intensity is slightly weaker when using the satellite-based observations than the ground-based measurements.

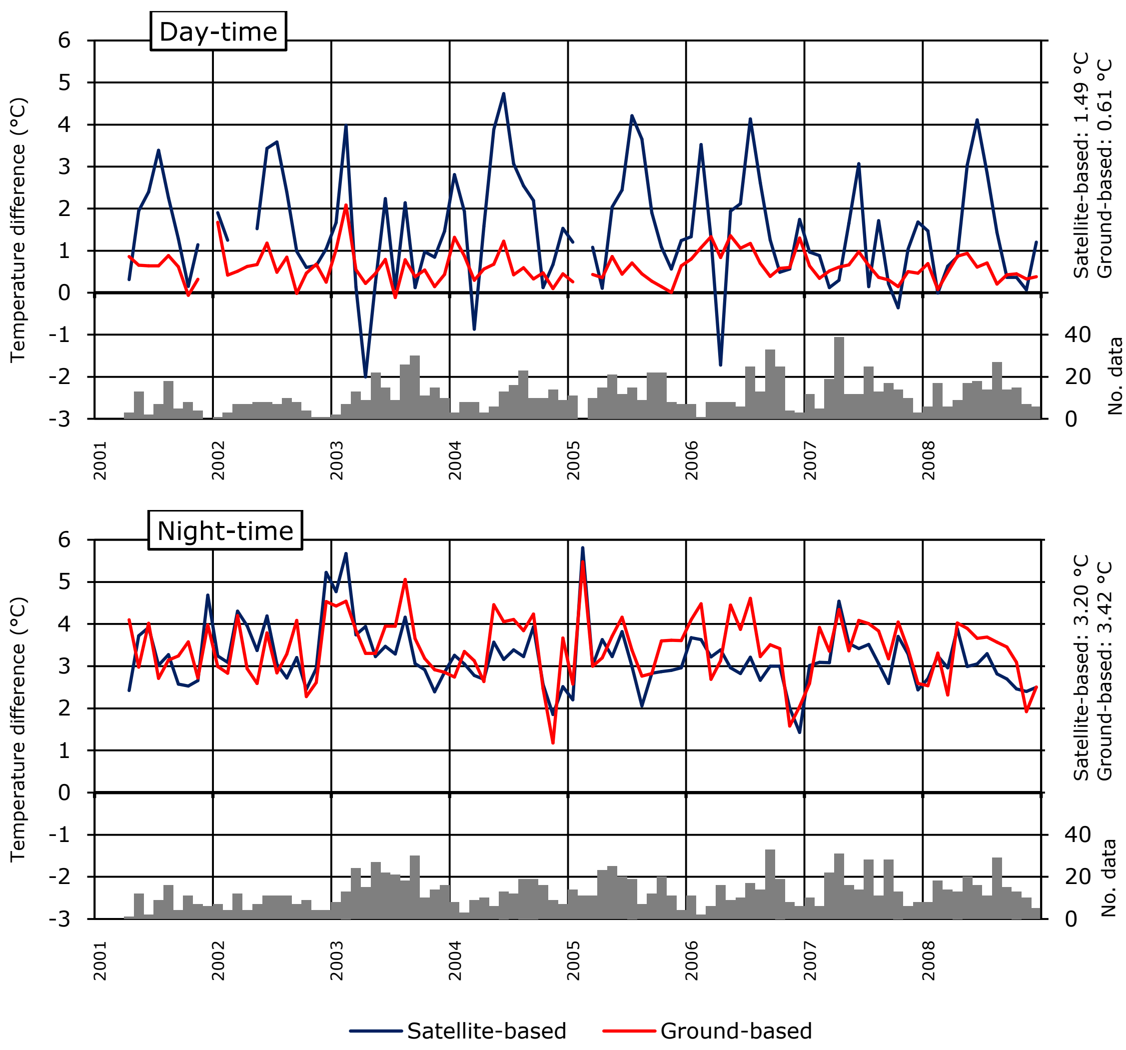

Fig. 7: Monthly mean temperature difference between urban weather stations and rural weather stations, with number of available data between 2001 and 2008

5. CONCLUSIONS

Satellite-based and ground-based temperature observations have been compared in this paper for the Budapest agglomeration area located in Central/Eastern Europe. Based on the results presented here, the following conclusions can be drawn.

- Satellite-based surface temperature is higher (lower) than ground-based air temperature during day-time (night-time). This can be explained by the well-known feature of the radiation transfer: both day-time warming and night-time cooling of the boundary layer of the atmosphere proceeds from the surface.
- The difference between the satellite-based and the ground-based temperature values are the largest in summer and spring.
- The largest variability of the UHI intensity can be identified in case of day-time satellite-based surface temperature.
- According to the ground-based measurements UHI intensity is 2-3 times stronger during night-time than day-time.
- During night-time the UHI intensity values determined using the satellite-based or the ground-based temperature observations differ much less than during day-time.

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