Analysis of the role of urban vegetation in local climate of Budapest using satellite measurements

Rita Pongracz*, Judit Bartholy, Zsuzsanna Dezso, Cathy Fricke
Dept. of Meteorology, Eotvos Lorand University, Pazmany st. 1/a, Budapest, Hungary H-1117

ABSTRACT

Urban areas significantly modify the natural environment due to the concentrated presence of humans and the associated anthropogenic activities. In order to assess this effect, it is essential to evaluate the relationship between urban and vegetated surface covers. In our study we focused on the Hungarian capital, Budapest, in which about 1.7 million inhabitants are living nowadays. The entire city 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. Most of the extended urban vegetation, i.e., forests are located in the western Buda side. The effects of the past changing of these green areas are analyzed using surface temperature data calculated from satellite measurements in the infrared channels, and NDVI (Normalized Difference Vegetation Index) derived from visible and near-infrared satellite measurements. For this purpose, data available from sensor MODIS (Moderate Resolution Imaging Spectroradiometer) of NASA satellites (i.e., Terra and Aqua) are used. First, the climatological effects of forests on the urban heat island intensity are evaluated. Then, we also aim to evaluate the relationship of surface temperature and NDVI in this urban environment with special focus on vegetation-related sections of the city where the vegetation cover either increased or decreased remarkably.

Keywords: urban heat island, surface temperature, Normalized Difference Vegetation Index, sensor MODIS

1. INTRODUCTION

Concentrated human presence of cities significantly modifies the environment, which is mainly due to the artificial cover of roads and buildings. Radiative characteristics of the major building materials (e.g., concrete, asphalt) are quite different from those of soil and vegetation. Specifially, larger portion of incoming shortwave radiation is absorbed by urban artificial cover than the rural mostly vegetated areas due to smaller values of albedo. Moreover, heat capacity of these concrete and asphalt surface covers is greater than that of vegetation. Thus, the absorbed energy is re-emitted for a longer time, and then, extended vertical surfaces absorb and re-emit this longwave radiation several times. Consequently, this modified radiative budget of urban areas results in urban heat island (UHI) effect with higher temperature in the densely built-up areas than in the rural surroundings (Oke, 1982[1]). Inhomogeneity of surface covers within the urban area results in different local climates. For instance, large blocks of building and vegetation covers within the built-up area increase and decrease the urban effect, respectively. The decreasing role of vegetation is analysed in this paper using surface temperature data calculated from measurements remotely sensed by the Moderate Resolution Imaging Spectroradiometer (MODIS) in infrared channels. UHI effect is traditionally analysed on the basis of air temperature, here, surface temperature is used, which provide information on surface UHI (SUHI) effect. SUHI of several Hungarian and Central European cities have been analysed in details (e.g., Dezso et al., 2005[2], Pongracz et al., 2006[3], Pongracz et al., 2010[4]). Here, we aim to evaluate the surface temperature in the urban environment with special focus on vegetated section of the city, the 12th district of Budapest (Figure 1) where most of the urban vegetation can be found in the form of forests (BFO[5], 2011). Budapest, the Hungarian capital is one of the large Central/Eastern European cities, which is divided by the river Danube into a hilly, greener Buda side on the west, and the flat, more densely built-up Pest side on the east.

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[*] prita@nimbus.elte.hu; phone 36 1 372-2945; fax 36 1 372-2904; nimbus.elte.hu

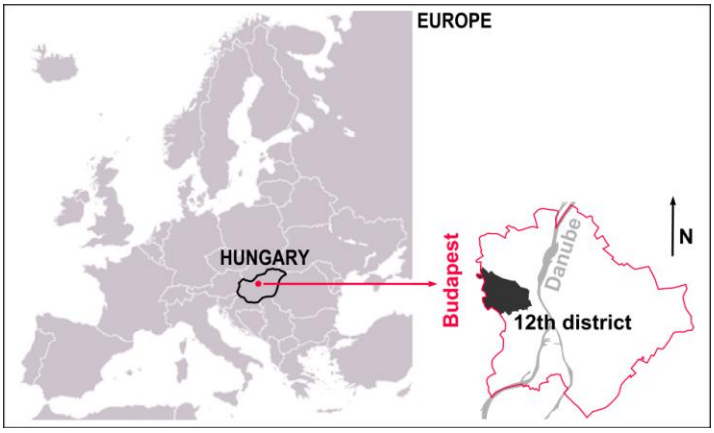

Figure 1. Geographical location of the 12th district within Budapest, Hungary.

2. 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 solar-synchronous polar orbits around the Earth with an inclination of 98°. Satellite Terra crosses the Equator on a descending orbit at 10.30. Satellite Aqua crosses the Equator on an ascending orbit at 13.30. 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 operating on satellite Terra, and Aqua, respectively. These instruments measure radiation of various spectral bands and use different spatial resolution (NASA, 1999[6]; NASA, 2002[7]). Here, measurements of sensor MODIS are used, which can be found on both satellites. MODIS 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 the 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), Land Cover (Strahler et al., 1999[8]), and Normalized Difference Vegetation Index (NDVI). LST is determined by using the following seven 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[9] (1999). Composite NDVI values (Didan, 2015[10]) valid for 16-day-long period are used in our analysis, which are the MOD13A2 and MYD13A2 products (Didan et al., 2015[11]) using Terra and Aqua measurements, respectively. In this paper, LST time series from 2001 measured in the morning and late evening (in CET) by satellite Terra, and time series from 2003 measured in the afternoon and before dawn (in CET) by satellite Aqua are analyzed. Therefore, two measurements are available daily for the 2001-2002 period, and four measurements are available daily since 2003. In order to cover the agglomeration area of the Hungarian capital within the Central/Eastern European region, the specific products are accessible via the Land Processes Distributed Active Archive Center (LPDAAC) at the U.S. Geological Survey (USGS). After downloading the available satellite images, they are filtered considering the land surface data availability, i.e., erroneous and cloudy images (exceeding 50% of cloud cover) are not used in the current analysis. In winter time less images can be used than in other periods of the year due to more often foggy (or cloudy) weather over the Carpathian basin.

SUHI intensity values are calculated for each pixel within the 65×65 pixel representation of the Budapest agglomeration area using the rural mean LST value for all available images (Bartholy et al., 2012[12]). Then, the pixel representation of the most vegetated-covered district of Budapest is selected (Figure 2). Monthly, seasonal, and annual averages of SUHI intensity are compared for the built-up and the vegetated pixels within this selected district. Moreover, NDVI values averaged for months are analysed for the pixels within the 12th district of Budapest.

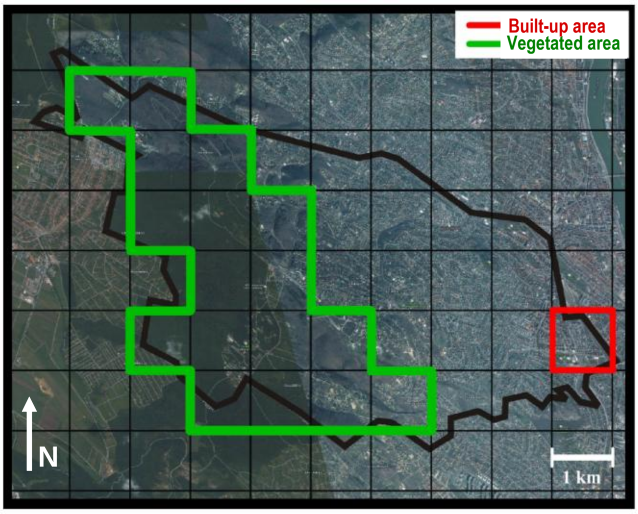

Figure 2. Built-up and vegetated area of the 12th district of Budapest shown on the MODIS grid over the Google Earth satellite image. Black contour indicates the district area.

3. RESULTS AND DISCUSSION

First, seasonal mean structure of the SUHI intensity is shown in Figure 3. Since the selected subregion of the city is located near the western border of Budapest, 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) than 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).

Figure 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 autumn 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.

Figure 5 focuses on one day-time (afternoon) and one 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 intensities 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 late autumn to early spring when green vegetation (i.e., forest) loses most of the greenness due to the annual cycle of continental plants. The difference of monthly mean SUHI intensities increases to about 5 °C by June.

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

Finally, relationships between NDVI and SUHI intensity values are compared for May, June, July, August, and September in Figure 7 in case of a vegetation-covered pixel and the built-up pixel of the 12th district of Budapest. These two types of surface cover are well separated in all the four periods within day and night. Vegetation cover evidently results in greater NDVI values (exceeding 0.7 in general) than built-up cover (lower than 0.6). Moreover, greater SUHI intensity values occurred over the built-up area (definitely positive SUHI, 2-4 °C in the evenings and dawns; and mostly positive SUHI in the mornings (0-3 °C) and afternoons (0-4 °C)) than in case of vegetation cover (where SUHI values are between -1.5° and +0.5 °C in the evenings and dawns; and SUHI is definitely negative in the mornings (between -3 °C and 0 °C) and afternoons (between -3.5 °C and -1 °C)). Negative SUHI intensity values clearly indicate the modification of the urban effect, which is evidently due to the extended vegetation (i.e., forest) within the urban area.

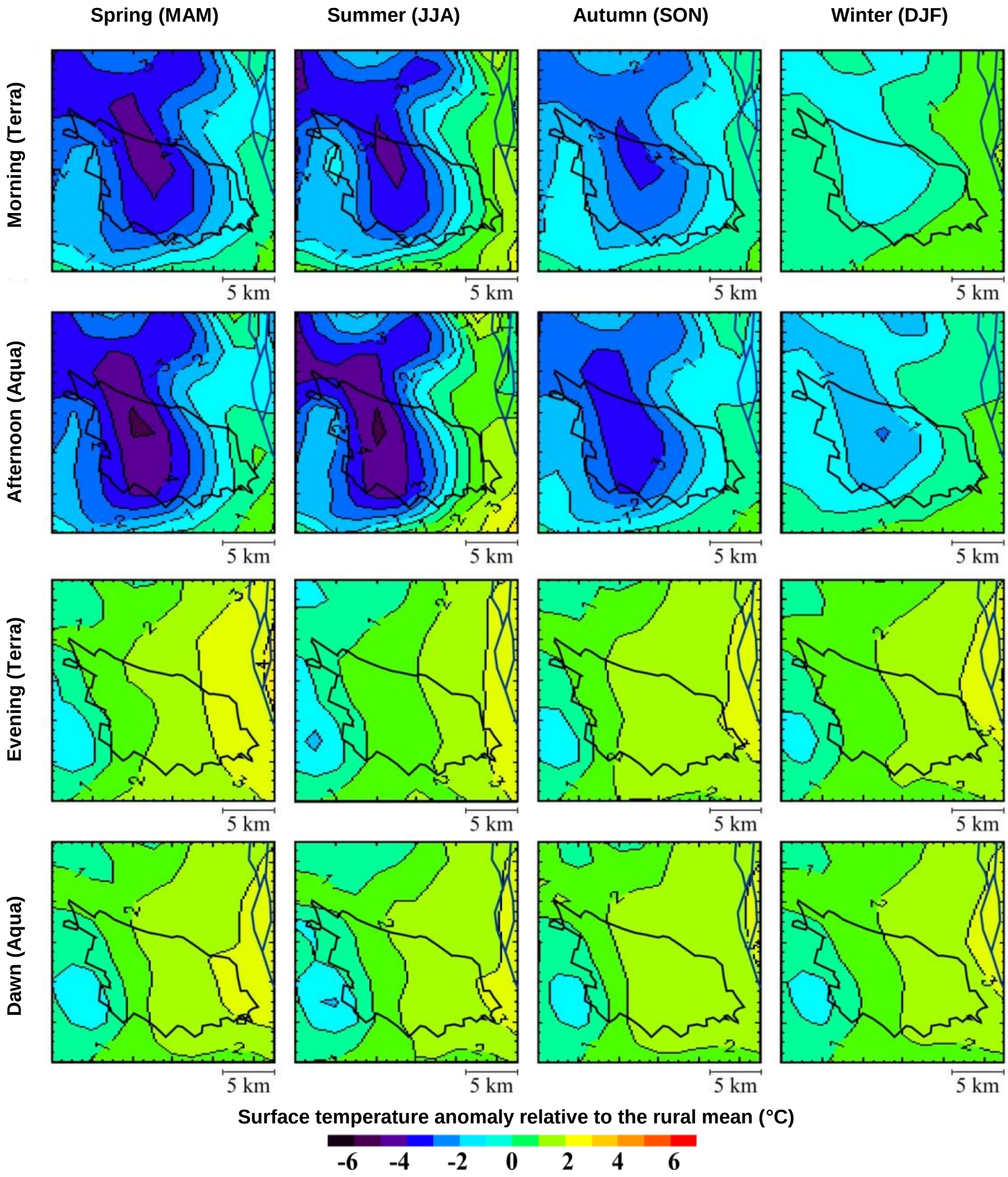

Figure 3. Seasonal mean structure of the urban SUHI in the 12th district of Budapest, 2001-2014. Reference rural mean values are calculated from the LST values of non built-up pixels (according to the MODIS Land Cover product) around the city within ±100 m sea level height difference relative to mean sea level height of the city.

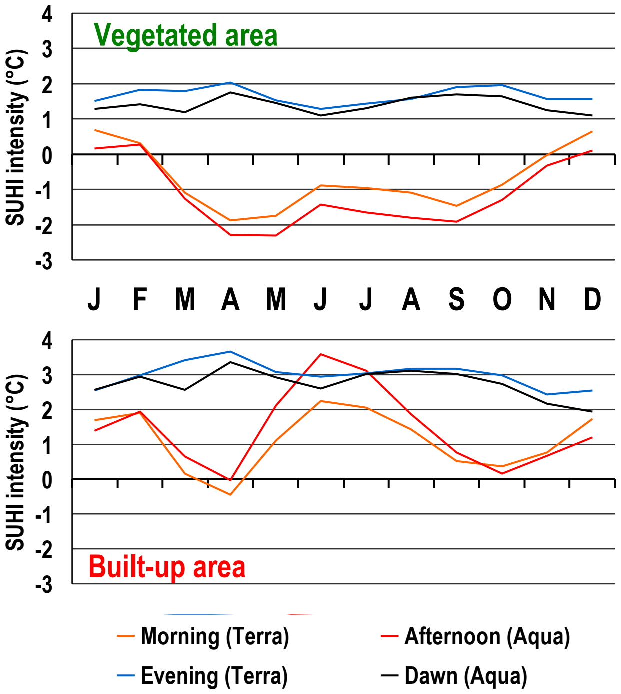

Figure 4. Comparison of the annual distributions of monthly mean SUHI intensity in different parts of the day and night in vegetated (upper panel) and built-up (lower panel) areas of the 12th district of Budapest.

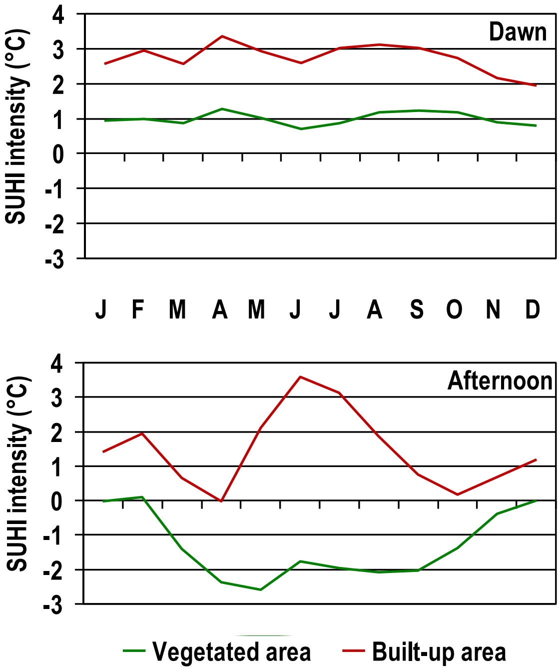

Figure 5. Comparison of the annual distributions of monthly mean SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, based on Aqua/MODIS measurements.

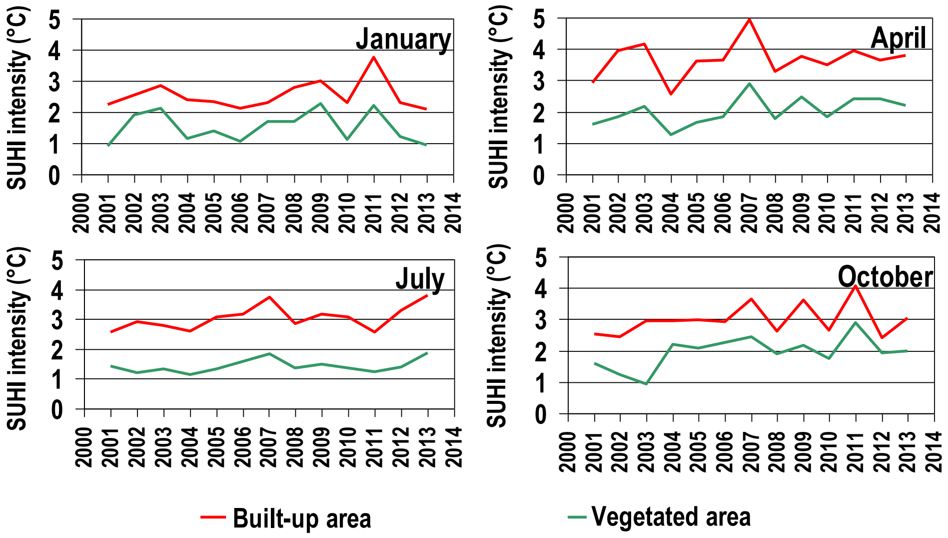

Figure 6. Trend analysis of the monthly mean SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, based on Terra/MODIS measurements in evenings (at around 20-21 UTC).

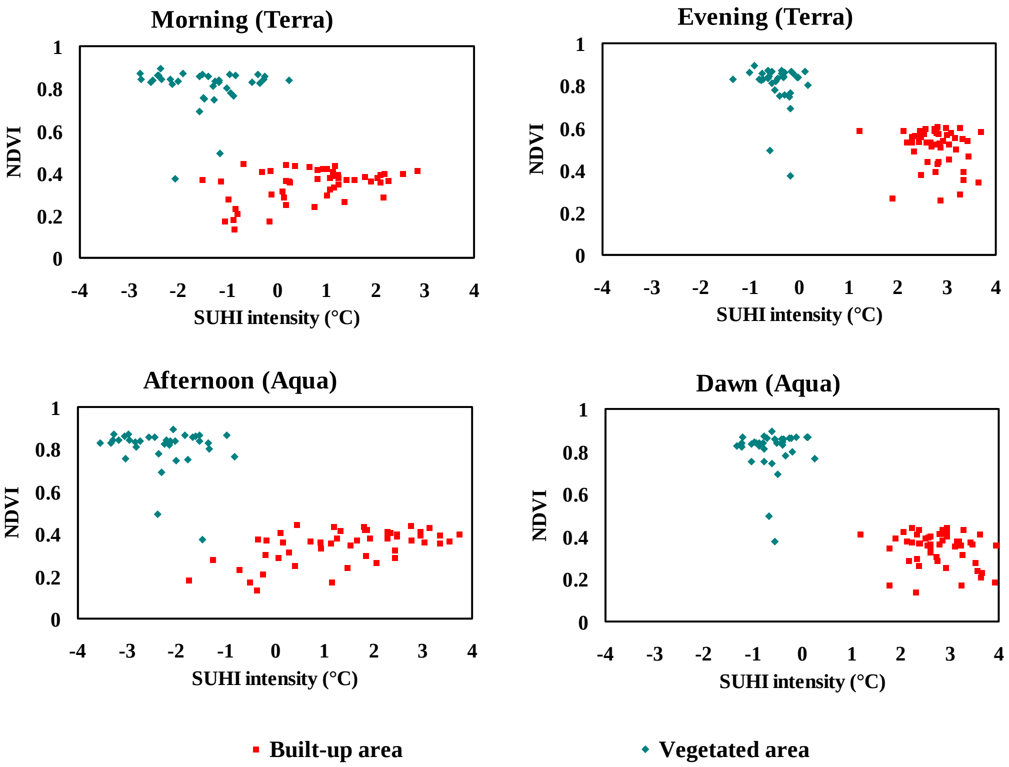

Figure 7. Comparison of the relationship between monthly NDVI and SUHI intensity in vegetated and built-up areas of the 12th district of Budapest, based on MODIS measurements (from May to September).

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