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URBAN HEAT ISLAND EFFECT OF LARGE CENTRAL EUROPEAN CITIES USING SATELLITE MEASUREMENTS OF SURFACE TEMPERATURE

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1. INTRODUCTION

Urban areas have several significant impacts on the environment. For instance, the atmosphere is heavily polluted due to the industrial and road traffic emissions, therefore, severe smog events often occur over large agglomerations (Sokhi, 1998), especially, during long-lasting anticyclonic conditions. Furthermore, artificial covers (i.e., concrete, asphalt) considerably modifies the energy budget of urban regions, and thus, local climatic conditions. One of the most often analyzed phenomena related to cities is the urban heat island (UHI) effect (e.g., Sundborg, 1950; Oke, 1982). Besides several detailed studies of UHI using ground based measurements (Unger et al., 2001), a more effective tool became available with the use of satellite imagery detected by different sensors on board. The early studies evaluated coarse resolution (7-8 km per pixel) satellite data (Rao, 1972), and the applied methods to calculate surface temperature from spectral observations were very simple (Carlson et al., 1977; Price 1979). These investigations in the 1970s and 1980s concluded that satellite measurements can be applied to detect the UHI effect in case of clear conditions. Traditionally, UHI analysis (Howard, 1833; Oke, 1973) uses air temperature data observed at standard height (1.5-2 m above the ground), while satellite images provide thermal information at ground-level. On the base of observed air temperature data, the maximum UHI intensity occurs a few hours after sunset, while the most intense UHI can be detected during day-time when remotely sensed data are used (Roth et al., 1989; Dezső et al., 2005). In this paper, UHI effects of large cities located in Central Europe (i.e., Bucharest, Romania; Budapest, Hungary; Warsaw, Poland; Vienna, Austria; Milan, Italy; Munich, Germany; Sofia, Bulgaria; Belgrade, Serbia; and Zagreb, Croatia) are analyzed and compared based on remotely sensed thermal information using 1-km spatial resolution.

2. DATA AND METHODOLOGY

In the frame of the urban climate research at the Department of Meteorology, Eötvös Loránd University, Budapest, remotely sensed thermal information is used. The surface temperature is determined (Wan and Snyder, 1999) from the day-time and night-time measurements of seven spectral bands of sensor MODIS (Moderate Resolution Imaging Spectroradiometer): 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). MODIS is a cross-track scanning multi-spectral radiometer with 36 electromagnetic spectral bands from visible to thermal infrared (Barnes et al., 1998), horizontal resolution of the infrared measurements is 1 km. Sensor MODIS is carried on-board satellites Terra and Aqua, which were launched on 705 km height polar orbits in December 1999 and May 2002, respectively. Both satellites are part of the Earth Observing System Program of the American National Aeronautics and Space Administration (NASA).

Table 1. The geographical characteristics of the nine Central European cities used in this analysis. Latitude (φ) and longitude (λ), height above sea level (h), number of inhabitants (P), and spatial extension (A) are indicated.

Name	φ (°N)	λ (°E)	h (m)	P (persons)	A (km^2)
Bucharest	44.12°	26.57°	85	1 921 751	228
Budapest	47.5°	19.05°	105	1 719 342	525
Warsaw	52.17°	16.07°	100	1 692 854	525
Vienna	48.12°	16.57°	183	1 598 626	415
Milan	45.43°	9.28°	120	1 271 898	182
Munich	48.15°	11.3°	310	1 247 873	519
Sofia	42.5°	23.2°	564	1 138 950	215
Belgrade	44.82°	20.28°	117	1 120 092	198
Zagreb	45.73°	16.07°	120	691 721	123

50×50 pixel representations of selected Central European urban agglomerations (Table 1) including their rural environment are determined from a satellite image tile containing 1200×1200 pixels using sinusoid

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projection. The representative areas are divided into urban and rural pixels in case of each city with more than 1 million inhabitants (Brinkhoff, 2004). In order to separate urban and rural pixels, the 1-km gridded MODIS Land Cover Product (LCP) is used. This LCP recognizes 17 categories of land cover following the International Geosphere-Biosphere Program scheme (Belward et al., 1999). Land cover classes are produced by processing the 32-day database using decision tree and artificial neural network classification algorithms to assign land cover classes based on training data (Strahler et al., 1999). Urban built-up part of the selected representative area is defined within the 15-km radius circle around the city center, while rural surrounding pixels may be found within a 15-25-km radius ring around the city center.

Since the topography significantly affects the urban heat island (UHI), hilly regions have to be eliminated. To this process, the GTOPO30 global digital elevation model (DEM) is used. This global data set was developed by the U.S. Geological Survey's (USGS) Earth Resources Observation System Data Center (USGS, 1996). The horizontal grid spacing of this database is 30-arc seconds (approximately 1 km). In our studies urban and rural pixels are within the ±50 m and ±100 m range of the city mean elevation value, respectively.

3. RESULTS AND DISCUSSION

UHI intensity of the selected large cities is defined as the difference between spatial averages of observed values converted to urban and rural surface temperature. Annual mean night-time UHI intensity is around 2-3 °C (Dezső et al., 2005). Basically, more populated cities exhibit more intense heat island. Orographical modification, distribution of land cover types of rural surroundings (i.e., portions of cropland, grassland, and forest), and urban air quality disturb this relationship. Analyzing the 6-year-long time series of satellite-based observations (between 2001 and 2006), our results suggest that the annual variation of monthly mean UHI intensity is larger in day-time than in night-time (Pongrácz et al., 2006). The most intense UHI effect occurs on summer days when monthly mean UHI intensity is around 4-6 °C. Direct solar radiation and thermal inertia can be considered as possible reasons. UHI intensity is larger in night-time than in day-time in the spring and autumn months, which is in contrast with the summer UHI intensities. This considerable difference can be explained partly by shorter day-time lengths in these equinox seasons than in summer, and partly by the relatively high values of air humidity and often occurring cloudy weather.

Furthermore, spatial structures of the UHI effect between 2001 and 2006 is analyzed and compared depending on seasons (Dezső et al., 2005; Pongrácz et al., 2006). In order to analyze the temporal variation of the UHI structure of the Central European agglomeration areas, time series of the monthly mean differences of surface temperature of each pixel and the rural mean along the major cross-sections (i.e., N-S, W-E, NW-SE, NE-SW) are compared (Pongrácz et al., 2006, 2008). In case of each city, the characteristical cross-section is selected on the basis of the representativeness of geographical and orographical features of the city and its surroundings.

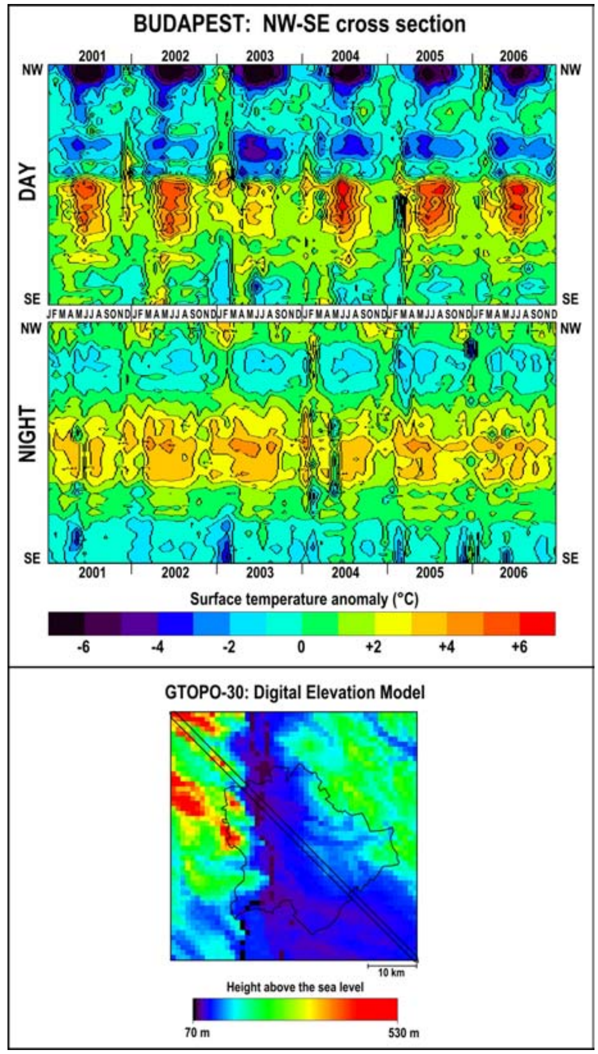

Fig. 1. Annual variation of monthly mean surface temperature in the characteristical NW-SE cross-section of Budapest based on day-time (upper panel) and night-time (lower panel) MODIS remote observations, 2001-2006.

As an example, Fig. 1 illustrates this analysis in case of Budapest (located in Hungary, 47.50°N, 19.08°E, 120 m above sea level) where the NW-SE cross-section was selected (Dezső et al., 2005) as being the most representative of the orographical variability of the city and the surroundings area. According to the results, the downtown regions (administrative and commercial center) can be clearly recognized due to the positive anomaly values larger than +5, +6 °C, and +3,

+4 °C in day-time and night-time, respectively. Annual variation of the monthly mean values is more pronounced in day-time than in night-time. The maximum anomaly occurs in summer months in both cases. The difference between the warmest and the coldest surface temperature exceeds 15 °C in summer. The western part of the city is hilly covered by forests, so its surface is relatively cold. The downtown area (located on the left bank of the river Danube and characterized by 25-30 m high buildings from the late 19th century) can become very hot on summer days.

Similarly to Budapest, the difference between the warmest and the coldest surface temperature exceeds 15°C in summer days where mountains are near the city (e.g., Munich and Sofia). UHI in Sofia is very special, since Mountain Vitosa (2224 m) is located very close to the Bulgarian capital (mean elevation of Sofia is 550 m), that results in large temperature gradient within the selected rural area around the city, especially in summer (Pongrácz et al., 2008). In case of the Central European cities where the surroundings are less elevated and the orographical difference is less than 100 meter (e.g., Bucharest and Warsaw), the maximum difference between the warmest and the coldest surface temperature is about 10°C, and it occurs in summer (Pongrácz et al., 2008).

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