ANALYSIS OF URBAN HEAT ISLAD EFFECT IN HUNGARIAN AND CENTRAL EUROPEAN CITIES USING HIGH-RESOLUTION SATELLITE IMAGERY

Thesis of the PhD dissertation

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STATEMENT OF THE PROBLEM, AIMS

One of the most important issues in climate research is the effect of human activity on environment, which may be analyzed on different temporal and spatial scales, from microclimate studies to global climate modeling. Among the different scales, cities have a special role, because artificial covers (i.e., concrete, asphalt) considerably modify the energy budget of urban regions, and thus, local climatic conditions.

According to the World Bank report, 3 billion people from the total 6.6 billion inhabitants of the World are living in urban regions. The number of cities with more than 100,000 inhabitants is near 3,500. United Nations' studies project that 20% of the world's population will live in cities with more than 1 million inhabitants in 2015. In Europe, 75% of the population live in towns and cities. In Hungary, 68% of the total population live in about 300 cities. Not only the number of inhabitants, but the spatial extension of built-up area is also continuously increasing, therefore the ratio of artificial covers is increasing. These facts highlight the importance of urban climate analysis, and also, the necessity of urban planning, the regulation for maintaining an appropriate green area ratio, the industrial developments considering local climatic conditions, the strengthening of public health regulations, etc.

It is well-known for about 200 years now that there is a temperature difference between urban and rural areas. This phenomenon is defined as the urban heat island (UHI) effect. 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, ground-based air temperature measurements using a moving vehicle, surface temperature data calculated from radiation measurements of satellites, or remotely sensed surface temperature measurements placed on board of an aircraft.

The use of satellite data in urban climatology is possible since satellite sensors are improved, and high resolution thermal information became available. In the last few decades many cities of the world have been analyzed using satellite imagery, but large cities in Central Europe, and especially in Hungary have not been studied with this method. Thus, in the frame of the urban climate research at the Department of Meteorology, Eötvös Loránd University, Budapest, the main aim of this dissertation is to use remotely sensed surface temperature to analyze and compare the UHI effects of the ten largest Hungarian cities (Budapest, Debrecen, Miskolc, Szeged, Pécs, Győr, Nyíregyháza, Kecskemét, Székesfehérvár, and Szombathely), and nine Central European cities with more than 1 million inhabitants (Bucharest, Warsaw, Vienna, Milan, Munich, Prague, Sofia, Belgrade, Zagreb).

METHODOLOGY

Part of the NASA's Earth Observing System (EOS), satellites Terra and Aqua were launched in December 1999, and May 2002, respectively. Main goal of the remote measurements of these missions is to improve our understanding of global dynamics and processes occurring on the land, in the oceans, the cryosphere, and in the lower atmosphere. These measurements and their use play an important role in the development of validated, global, interactive earth system models being able to predict global climate and environmental change accurately enough to assist policy makers worldwide in making decisions concerning the protection and management of our environment and natural resources. The planned lifetime of satellites Terra and Aqua is about 15 years. Data sets measured by these two satellites are effective tools for detailed analysis of UHI effect, for detection of its seasonal and intra-annual changes, and for evaluation of possible reasons of the UHI effect.

Terra and Aqua are on 705 km height polar orbits around the Earth with an inclination of 98°. Both satellites are solar-synchronous, Terra crosses Equator on descending orbit at 10.30 a.m., and Aqua crosses it on ascending orbit at 1.30 p.m. Five instruments are included in satellite Terra, and six in satellite Aqua. These instruments measure radiation with different spectral bands and spatial resolution. Measurements of two sensors are used in our research. The Moderate Resolution Imaging Spectroradiometer (MODIS) is a cross-track scanning multi-spectral radiometer with 36 electromagnetic spectral bands from visible to thermal infrared, horizontal resolution of the visible and infrared measurements is 250 m and 1 km, respectively. Sensor MODIS is carried on-board satellites Terra and Aqua. Another sensor with very fine spatial resolution (15 m per pixel in the 4 visible channels, 30 m per pixel in the 6 near-infrared channels, and 90 m per pixel in the 5 thermal-infrared channels) is installed only on satellite Terra: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). In the frame of EOS program numerous climatic and environmental parameters are determined. These parameters are archived in universal format, using 1200×1200 pixel tiles, they are available as validated, geographically fitted, high-level datasets. In our research, we used MODIS Land Surface Temperature Products, MODIS Land Cover Products, MODIS Normalized Difference Vegetation Index (NDVI) Products and ASTER Surface Kinetic Temperature Products. For covering the whole Central European region data from four different tiles are needed. These products are accessible at the Land Processes Distributed Active Archive Center (LPDAAC) at U.S. Geological Survey.

In this dissertation, surface temperature time series from 2001 to 2008 measured in the morning and late evening by satellite Terra, and time series from 2003 to 2008 measured in the afternoon and before dawn by satellite Aqua are analyzed. Therefore, two measurements are available daily for the 2001-2002 period, and four measurements for the 2003-2008 period. In case of Terra/MODIS Land Surface Temperature the data set contains ca. 3000 files, and 12 GB information per tile. In our research for the entire Central European region, ca. 22.000 files and 75 GB information are processed. In the eight-year long period, there are only a few days per year with missing data because of the error of the satellite or the sensor.

For the satellite-based surface UHI analysis missing data may occur, because the surface temperature at cloudy weather refers to the cloud-top instead of the land surface. In our work the UHI intensity are determined only for those days, when at least 50% of the total urban pixels were cloud-free in MODIS images. In case of Hungarian and Central European cities, satellite data can be used for UHI effect analysis at 37-47% and 30-47% of all days, respectively. The distribution of appropriate data during the year is not equal, in winter 5-10 days of the months are cloud-free, while in summer 15-25 days.

Comparing this data frequency to other urban climate research techniques, it can be concluded, that this method provide very high spatial and temporal data density. In case of regular 2 m level air temperature measurements, data are available very often, but the number of urban climate stations in a city is limited due to financial reasons. Mobile (car or aircraft) measurements have very good spatial resolution, but these experiments cannot be carried out very often on a long-term basis because of the high costs. Another important fact supports the applicability of the satellite-based UHI analysis, namely, that clear, anticyclonic weather conditions help UHI development, so the strongest UHI phenomena can be examined with this method.

After data collecting and filtering, grid coordinates of the cities are determined in the satellite image tiles containing 1200×1200 pixels. 65×65 pixel and 30×30 pixel representations of Central European and Hungarian urban agglomerations are selected, respectively, including the rural surroundings. The representative areas are divided into urban and rural pixels in case of each city. In order to separate urban and rural pixels, the 1-km gridded MODIS Land Cover Product, the Google Earth high-resolution satellite maps, and the GTOPO30 Digital Elevation Model is used. Google Earth satellite maps are effective tools to separate built-up and natural covered areas. On the base of these maps, the real built-up area inside of the official border is determined for each city. Then, the resulting contour-line is used on the 1 km spatial resolution grid for counting the total number of pixels representing the city. Thus, the “mean radius” of the city can be calculated as follows:

$$r_{urban} = \sqrt{\frac{N_{pixel}}{\pi}}$$

where N_{pixel} is the total number of pixels inside the city contour. Mean radius (r_{urban}) refers the theoretical radius of the city in case of a circle-shape structure.

Since the topography significantly affects the UHI, hilly regions have to be eliminated. To this process, the GTOPO30 global digital elevation model is used. The horizontal grid spacing of this database is 30-arc seconds (approximately 1 km).

Urban part of the total agglomeration area is defined by the following three criteria:

- pixels located within the city contour based on Google Earth maps,
- urban and built-up pixels according to the MODIS Land Cover Product Database,
- pixels within the ±50 m range of the city mean elevation value.

Rural part of the total agglomeration area is defined by the following three criteria:

- pixels located outside the city contour based on Google Earth maps, and the distance from this contour line is less then the mean city radius (r_{urban}),
- not urban and built-up nor water pixels according to the MODIS Land Cover Product Database,
- pixels within the ±100 m range of the city mean elevation value.

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. Using the selected representative area of these Hungarian and Central European cities, the spatial structures and the temporal variation of UHI can be determined for the morning, afternoon, late evening, and before dawn.

RESULTS AND DISCUSSIONS

The most important results of the dissertation are summarized a follows:

(1) The results suggest that the UHI effect can be detected in each selected Hungarian and Central European cities. Annual average values of the temperature differences between urban and rural areas range between 1 °C and 3 °C.

(2) The most intense UHI occurs in daytime in the summer period (June-July). The maximum value of UHI intensity detected in the selected cities exhibits high variability: it exceeds 6 °C in case of Milan, 4-5 °C in case of Munich, 3-4 °C in case of Warsaw, Budapest, Vienna, Prague, Sofia, Zagreb, Debrecen, Miskolc, Pécs and Szombathely, 2-3 °C in case of Bucharest, Belgrade, Győr, Nyíregyháza and Székesfehérvár, and 1-2 °C in case of Szeged and Kecskemét. The least intense day-time UHI effect occurs in March-April and in October-November, the intensity is smaller then 1 °C, or in some cases it can be even negative. Annual variation of the monthly mean values is more pronounced in day-time than night-time. The most and least intense night-time UHI effect can be detected in summer and winter, respectively, the difference between maximum and minimum values is around 1 °C for most of the cities. The maximum of night-time UHI intensity exceeds 2-3 °C in case of the Central European large cities, and 1-2 °C in case of the Hungarian cities.

(3) Using the representative area of the selected cities, the seasonal mean difference between the temperature of each pixel and the rural mean temperature is determined for the morning, afternoon, late evening, and before dawn. Thus, the seasonal mean spatial UHI structure is determined. The warmest part of each city is the downtown area (administrative and commercial center), but especially in case of the larger cities, more than a single UHI center can be detected.

(4) Using the spatial continuous surface temperature data, the effect of ground-based objects with a characteristic size of 1 km^2 on UHI can be analyzed. Large industrial areas, shopping centers, airports are significantly warmer than their surrounding area, while parks, forests, lakes and rivers significantly decrease the UHI effect.

(5) In order to analyze the temporal variation of the UHI structure, time series of the monthly mean differences of surface temperature of each pixel along the major cross-sections (i.e., N-S, W-E, NW-SE, NE-SW) and the rural mean are compared for the 2001-2008 period. Using these time-series, the temporal variation of the effect of different objects on surface temperature field can be examined.

(6) Both the structural and cross-section analysis show that the difference between the warmest and the coldest surface temperature values exceed 15 °C in summer. This occurs often especially in case of cities located in hilly regions (e.g. Budapest, Sofia, Vienna, Prague, etc.).

(7) Although, annual variations of the monthly mean values of UHI intensity in individual years are similar, but there is some difference among them. The detected differences are

related to the temperature and precipitation conditions of the actual years. For instance, in 2003 and 2007, UHI was less intense in summer in the Hungarian cities (and some of the Central European cities, too) than in the other years. In both years, summers were extremely hot and dry, resulting in a humidity deficit in the rural surroundings as well, as in the urban area. Because of the less intense evapotranspiration, the surface of rural areas became warmer than in other years. Thus, smaller difference could be detected between the urban and rural mean surface temperatures. Analysis of the Normalized Difference Vegetation Index (NDVI) values for urban and rural areas supported this hypothesis.

(8) Daily variation of UHI intensity is compared, using four observations per day (morning, afternoon, late evening, and before dawn). Monthly mean UHI intensity values are similar in the morning and the afternoon, and also in late evening and before dawn. UHI is more intense in the afternoon than in the morning, and less intense before dawn than in the evening.

(9) ASTER Surface Kinetic Temperature fields for the selected cities are available only for a few days. Case studies for a summer and a winter day are accomplished by identifying special pixels in the 11th district of Budapest according to the characteristical surface cover (concrete buildings, parks, residential areas, mountains, etc.) and evaluating the values of high-resolution (90 m per pixel) surface temperature observed by ASTER. The surfaces of large industrial halls, factories, shopping centers, and car parks covered by asphalt have the highest surface temperature values, reaching 45 °C on an ordinary summer-day. Parks, forests, lakes and rivers significantly decrease the UHI effect.

Further plans include continuous extension of the database, and completion of the analysis presented in this dissertation, for the period after 2008. We are planning the acquisition of new ASTER surface temperature data to study the climatic effects of architectural projects (residential complexes, shopping centers, etc.) on surface temperature characteristics of selected districts in the last decade. Thus, the results may serve as a basic guide to take into account the climatic aspects for decision-makers to formulate urban planning regulations, and for local authorities to issue building permits.

As another important outcome of our research, the results may be used in terms of climate change. Climate models predict an increasing frequency and intensity of warm temperature related extreme climatic conditions. However, the spatial resolution of regional climate models is coarser (usually about 50 km) than the characteristic size of the cities, therefore, the urban effect in these models is not included. In urban areas, the temperature values are shifted to the warm extremes both because of the global warming and the UHI effect. Thus, the increasing ratio of built-up areas may strengthen the UHI intensity.

The long-term goal of our research is the application of the results of urban climate analysis in urban planning and architectural regulations, which could help the urban inhabitants to adapt and mitigate to the changing environment.

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