JP1.10 APPLICATION OF SATELLITE INFORMATION TO URBAN CLIMATOLOGY

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1. INTRODUCTION

Both the spatial extension of urban areas and the number of inhabitants in cities tend to increase world-wide; nowadays somewhat more than half of the world total population live in urban settlements. The highest continental population density occurs in Europe where about 500 million people (out of 750 million) live in cities (Fenger et al., 1998). The large number of city-dwellers and the socio-economic conditions produce high industrial activity and significantly modify urban air quality. In order to find potential mitigation strategies that facilitate the urban population to adapt to new environmental conditions climatological impacts of urbanization including the urban heat island (UHI) effect must be investigated. In this study the UHI for the Budapest agglomeration area (capital of Hungary, located in Central Europe) and the nine largest cities of the country are evaluated and compared. The applied methodology presented in this paper is mainly based on the analysis of satellite information.

Hungary can be characterized by a special structure of population density, since around one-fifth of the entire country live in the capital, Budapest (1.9 millions out of the total 10.2 million Hungarian citizens). This centralized structure explains and emphasizes the importance of monitoring and evaluating the UHI and other urban climatological modifications due to the large agglomeration around Budapest.

The spatial structure of major streets, buildings and city parks in Budapest is mainly permanent for 100 years; it was developed by the Hungarian Millenium (1896). The unchanged net of radial avenues and concentric boulevards determines and limits the traffic that leads to increasing air pollution. New residential block houses of 15-20 m (4 story buildings) and 30-35 m high (10 story buildings) were built in the 1960s-1970s at the external districts of the city. The downtown area is characterized by 25-30 m high buildings from the late 19th century.

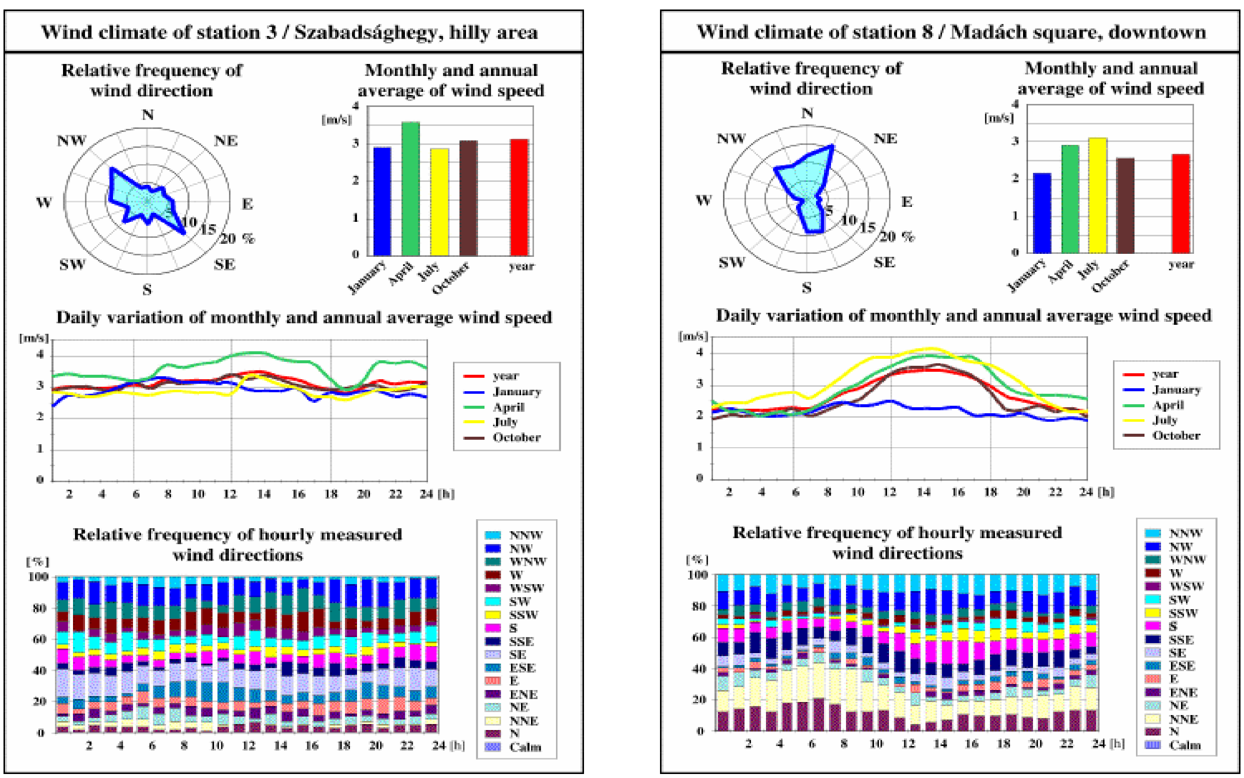

Fig. 1. Wind climatology of stations 3 and 8, representing
the western hilly area and the eastern flat downtown, respectively

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2. WIND CLIMATOLOGY OF THE BUDAPEST AGGLOMERATION AREA

Hourly wind measurements have been observed and recorded for more than seven years in a network that consists of 23 stations representing the capital and its agglomeration (Dezsõ, 2000). These observing stations can be classified according to their locations: they are located in the downtown (4 stations), in the residential (6 stations) and the industrial (6 stations) districts, or in suburb villages (7 stations).

Fig. 1 compares wind climate characteristics of two stations representing the hilly Buda part and the flat Pest part of the city, west and east from the river Danube, respectively.

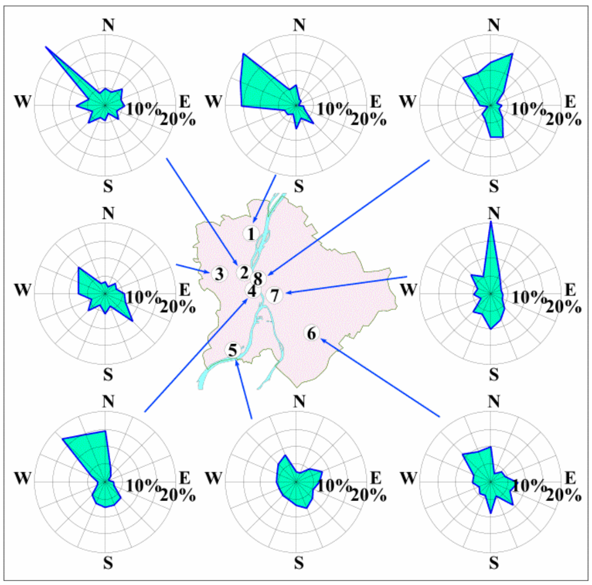

Fig. 2. Modification of characteristical wind direction by orography and built-up areas on urban climate scale in Budapest

Table 1. Description of the wind measuring stations in Budapest

Number/Name	Orographical status	Built-up category
1. Obuda	foothills, valley	family houses
2. Hungarian Meteorol. Service	foothills, valley	residential area, multi-story houses
3. Astronomical Obs., Szabadsaghegy	top of hill	forest
4. Gellerthegy – Citadella	top of hill, near the river	park with trees
5. Budateteny	flat	family houses with gardens, agricultural area, forest
6. Research Institute of Atmospheric Physics	flat	family houses with gardens, industrial area
7. Nagyvarad Square	flat	multi-story houses, main roads crossing, large traffic
8. Madach Square	flat	multi-story houses, business district, large traffic

Eight representative stations have been selected for presenting dominant modifications of the airflow patterns by orographical and built-up areas in Budapest (Fig. 2). Table 1 gives additional information about the eight stations, namely, their names, orographical status, and built-up category. The valley effect can be recognized in case of station 2 since the dominant NW wind is determined by the direction of the valley. In dense built-up areas the geographical position of avenues, broad streets and boulevards explains the dominant N and NNE wind at station 7 and 8, respectively.

3. URBAN CLIMATE STATION

Surface temperature has increased by almost 0.1°C per decade on the average in Budapest this century. Several network systems were established in the last 40 years to observe and record these changes (Mika, 1999). Private companies, health control authorities and the Hungarian Meteorological Service (HMS) started and stopped to maintain various stations by governmental orders. Therefore, lengths of the time series and data quality are not always the best. During the last few years the measuring system was reorganized into a new network and according to the present socio-economical needs some new stations were added to the existing ones. One of them was installed at the Eötvös University in October 1999 (Bartholy and Pongrácz, 2000). The new urban climate station is located at the western riverside of the Danube, north to the Csepel Island.

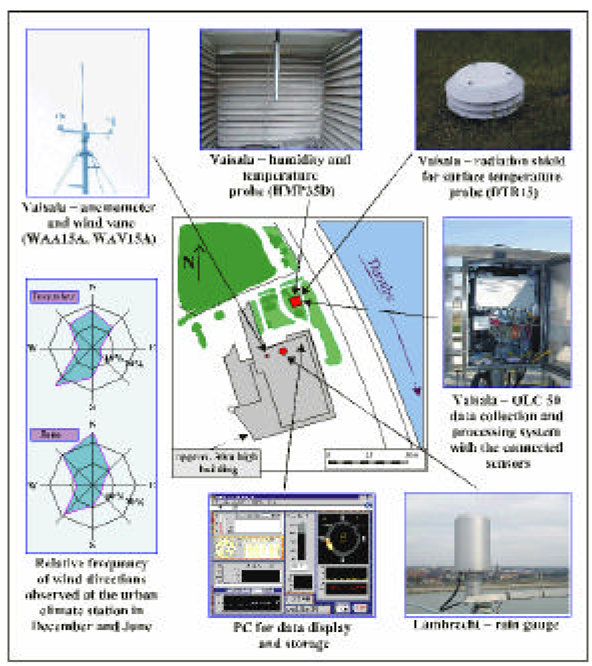

Fig. 3. Urban climate station installed and maintained at the Eötvös University (Budapest, Hungary) with the co-operation of the HMS.

The QLC 50 automated meteorological observer at the climate station at the Eötvös University is maintained by the HMS and data quality is guaranteed by regular calibrations realized by experts of the HMS twice a year. The synoptic automatic measurement device operates without human supervision and it is equipped with several sensors which provide temperature measurements at 2 meter, at the surface, 5, 10, and 20 cm below the surface, relative humidity values, precipitation amounts, global radiance values, wind speed, wind gust, and wind direction measurements at 41 meter above the surface (Fig. 3). Being an automated station, all the measurements are continuous, however, the actual and mean values are recorded at every 10 minutes (Bartholy et al., 2001b).

Special wind climate occurs at the location of the climate station at the Eötvös University since the Buda and the Pilis Hills functions as barriers for the air motions coming generally from north-western direction at this region. The empirical distributions of wind directions measured at the urban climate station show higher dominance of SW and N winds (Fig. 3) both in December and June. The relative frequencies of these wind directions are around 22-28% that is noteworthy considering the average wind direction frequencies.

4. METHODOLOGY OF ANALYZING THE UHI EFFECT OF HUNGARIAN CITIES

As part of the Earth Observing System Program of the American National Aeronautics and Space Administration (NASA) satellite TERRA was launched to a polar orbit at 705 km height in December 1999 with planned lifetime of about 15 years. The first observations started in February 2000 and regular validated measurements are available from July 2000 via Internet (NASA, 1999).

One of the five instruments included in TERRA is the sensor MODIS (Moderate Resolution Imaging Spectroradiometer) providing remote observations. It measures biological and physical processes on the land and the ocean using a cross-track scanning multi-spectral radiometer with 36 electromagnetic spectral bands from visible to thermal infrared (Barnes et al., 1998). MODIS is capable of viewing the entire globe daily at resolutions of 250-1000 m per pixel.

Urban heat islands have been investigated using satellite imagery for 25 years, however, the early studies (e.g., Matson et al., 1978; Price, 1979) evaluated coarse resolution satellite data. The use of surface temperature and vegetation index values in the estimation of UHI intensity has been compared in Gallo and Tarpley (1996).

In this paper, day-time and night-time surface temperature time series measured in the Carpathian Basin are analyzed. Surface temperature is strongly related to surface energy budget, especially to latent and sensible heat flux. Calculation of surface temperature data is based on the thermal infrared measurements of MODIS that are quality controlled and calibrated by surface observations (NASA, 1999). The following seven spectral bands are used to determine the output: 3660-3840 nm, 3929-3989 nm, 4020-4080 nm, 8400-8700 nm, 10780-11280 nm, 11770-12270 nm, and 13185-13485 nm.

Wan and Snyder (1999) developed a model to calculate surface temperature from the spectral observations that can be applied in case of clear weather. This so-called Day/Night MODIS LST (Land Surface Temperature) Method is able to determine surface temperature and emissivity without preliminary known air temperature and water vapor profiles. The problem is underdetermined when we attempt to solve temperature and surface emissivity in N bands simultaneously solely from one-time observation (even if we know the exact atmospheric conditions). We have 2N observations using one during the day and one during the night. The unknown variables are N band emissivities, day-time surface temperature, night-time surface temperature, four atmospheric variables (air temperature and water vapor profiles during day and night), and the anisotropic factor; N+7 altogether. So the radiation transfer equations can be solved if $N \geq 7$.

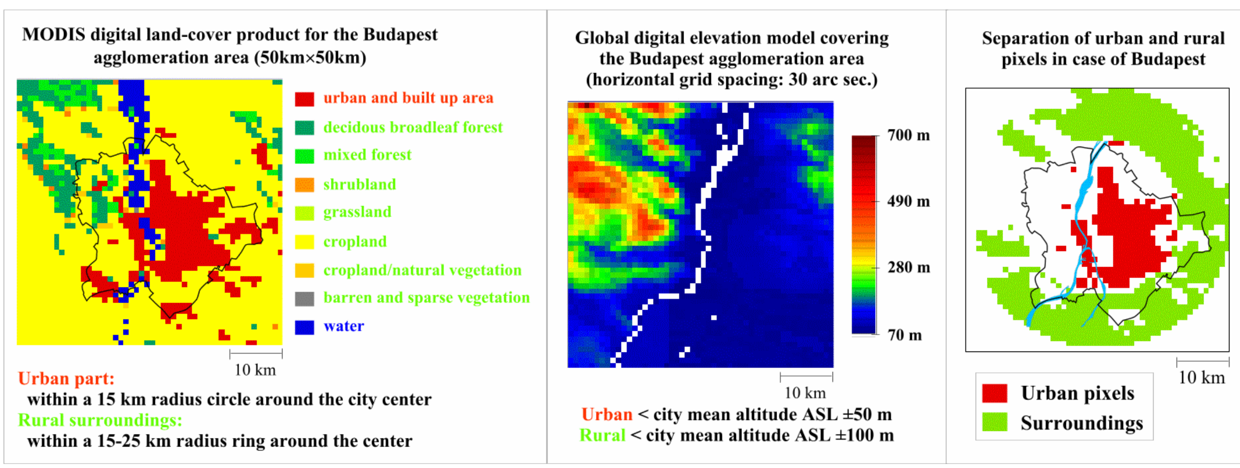

Fig. 4. Structure of the defining scheme for the UHI intensity in case of Budapest.

A linear approximation of the radiation transfer equation in the proximities of reference values of surface temperature and band emissivities results in a simplified form. Combining 14 equations together (2 x 7 bands), the solution for surface temperature and band emissivities should be a linear combination of the band brightness temperatures, each of which corresponds to one of the 14 observations. The applied mathematical form can be written as

$$x_i = \sum_{j=1}^{14} w_{i,j} \cdot y_j + w_{i,0}$$

where x is a vector of the 14 variables including surface temperatures and band emissivities, y_j is the band brightness temperature for observation j, $w_{i,j}$ (i=1,...14 and j=1,...14) and $w_{i,0}$ are the regression coefficients.

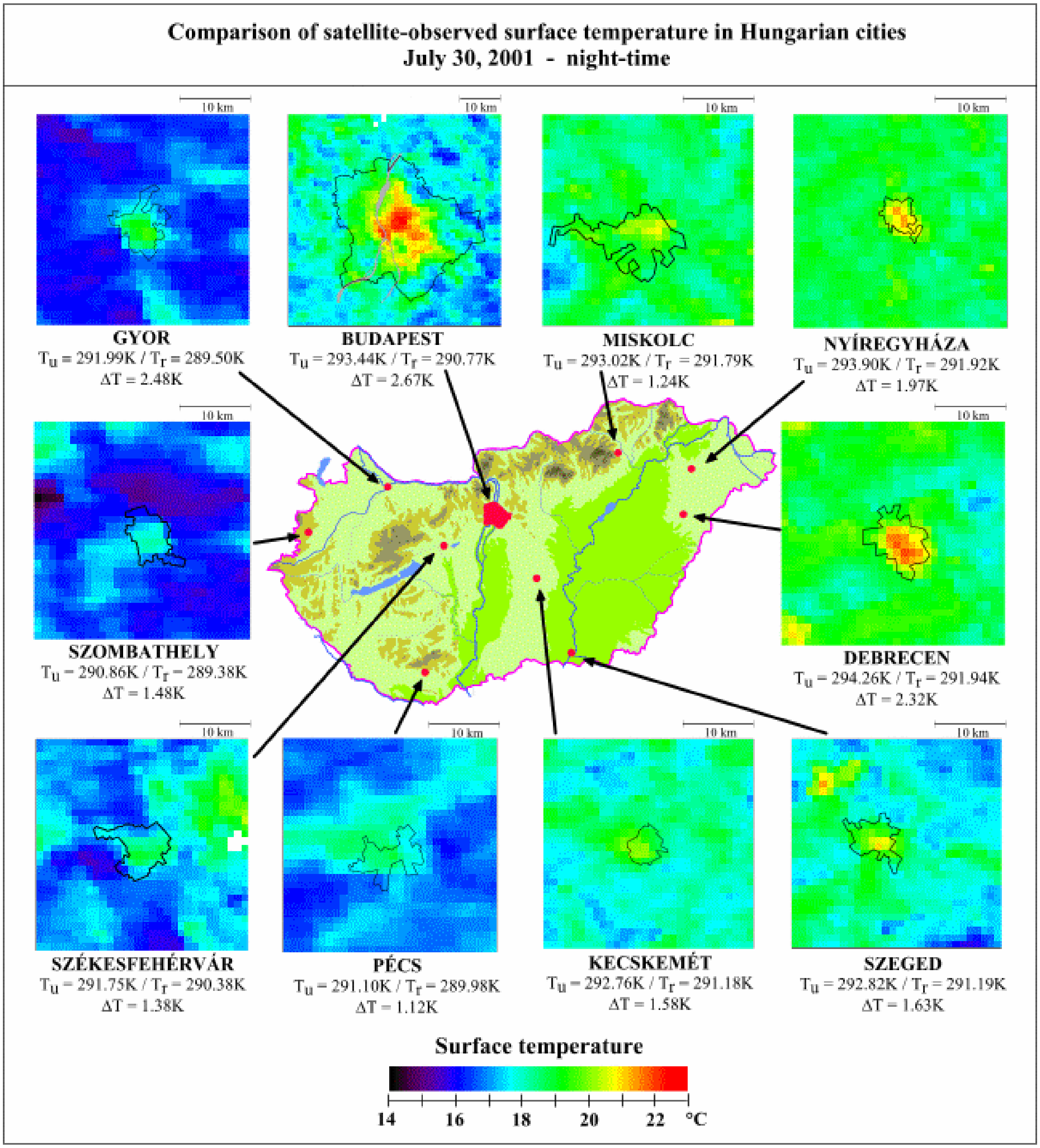

Fig. 5. Comparison of the UHI effect in the ten most populated cities of Hungary on July 30, 2001.

In the present analysis the ten largest cities of Hungary with more than 80 thousand inhabitants have been selected according to the population data of the Hungarian Ministry of Interior (2000). The pixel representations of the selected urban settlements (including their rural environment) have been determined from the total 1200x1200 pixels containing the Carpathian Basin at the upper half of the satellite image. Since 20% of the country population live in Budapest (which means ten times more inhabitants in the capital than in any other large city), furthermore, the difference between the spatial extensions of Budapest and other cities are similar, therefore, the agglomeration of the capital is represented by 50x50 pixels from the entire satellite image, while other selected cities are represented by only 30x30 pixels. The representative areas have been divided into urban and rural pixels in case of each city – hilly regions have been eliminated (center panel on Fig. 4) when calculating the UHI intensity since they significantly affect UHI. Also, the MODIS land-cover product is applied to separate urban built-up and rural surrounding areas (left panel on Fig. 4). The finally separated areas are demonstrated on the right panel of Fig. 4 in case of Budapest. Comparing spatial averages of observed values converted to urban and rural surface temperature UHI effects have been analyzed for the selected large cities located in different regions of Hungary.

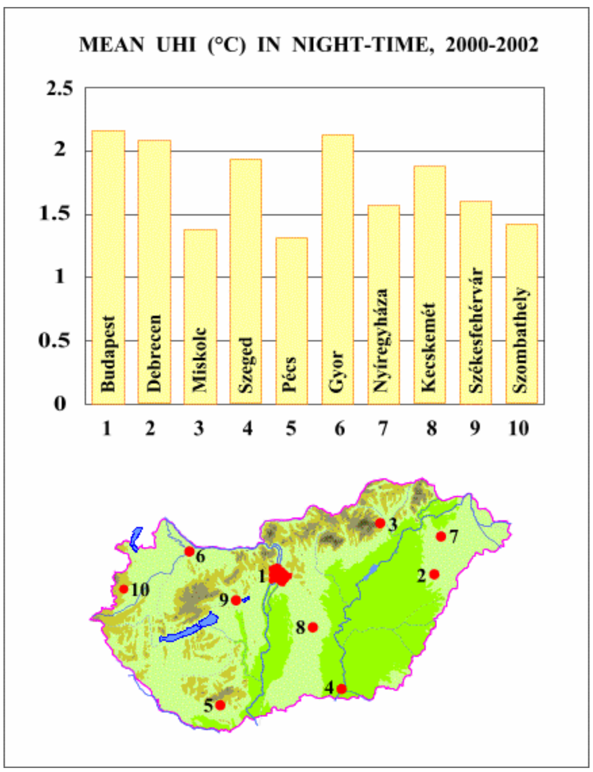

Fig. 6. Mean UHI intensity of the ten most populated cities of Hungary (July 2000 – July 2002).

5. COMPARISON OF UHI IN HUNGARIAN CITIES

In this section spatial structures of the UHI of several large cities of Hungary depending on seasons and different macrocirculation conditions are analyzed and compared.

Fig. 5 provides spatial structures of the surface temperature fields for the ten largest cities of Hungary on a clear night (July 30, 2001) when anticyclonic macrosynoptic situation dominated the weather in the Carpathian Basin. The mean temperature increased from west to east. Geographical locations of the cities are shown on the topographical map of Hungary. The UHIs are significant in case of each city, the difference between the mean temperature of urban and rural parts ranges around 1.1-2.7°C on this summer night. The most intense UHI effect occurred in Budapest. Furthermore, orographical modification of the UHIs can be recognized, especially, in case of Pécs.

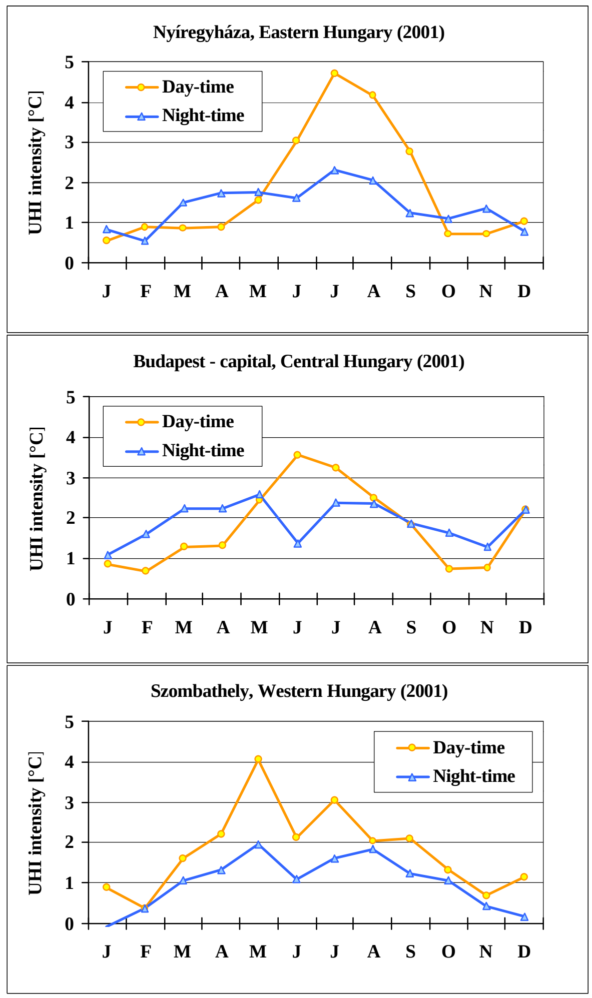

Fig. 7. Annual variation of monthly mean UHI intensity during day-time and night-time in 2001.

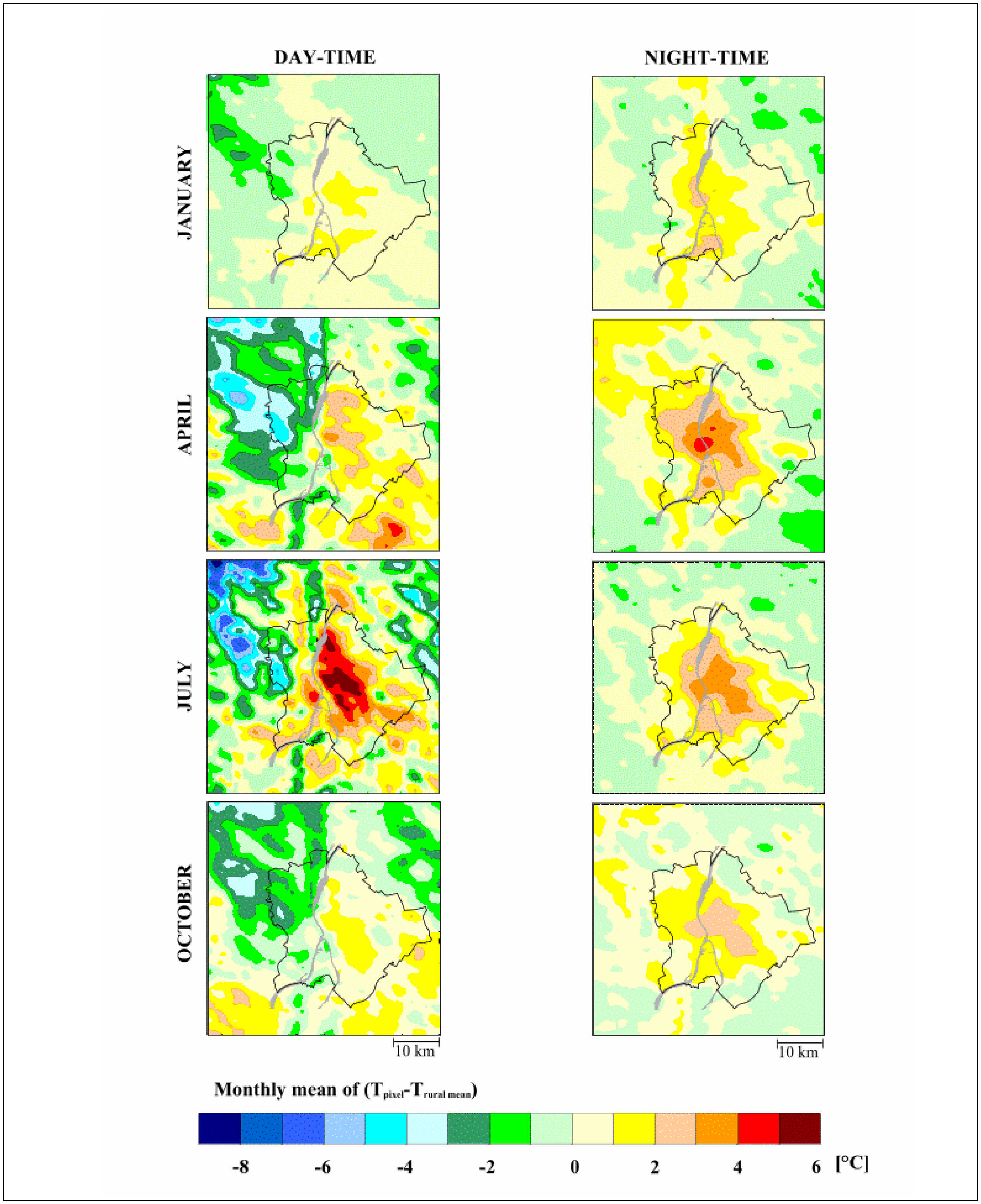

Fig. 8. Annual variation of monthly mean UHI structure in Budapest (50 x 50 km) in 2001.

Mean night-time UHI intensity is shown on Fig. 6, where the cities are ranked according to the number of their inhabitants starting with the capital. Basically, more populated cities exhibit more intense heat island, and only orographical modification disturbs this relationship by decreasing the UHI intensity. Since Budapest, Miskolc, and Pécs are located in hilly regions, partly or entirely, their mean UHI is less intense than expected. Although the city of Kecskemét is small, its central location on the Great Plains may explain the larger mean difference between the temperature of urban and rural areas. Finally, in case of Gyõr the surroundings contain several cold spots because of the large floodplain of the river Danube that results in more intense UHI than expected.

Analyzing the 2-year-long time series of satellite-based observations the results suggest that the annual variation of monthly mean UHI intensity is larger in day-time than in night-time (Fig. 7). The most intense UHI effect (4-5°C monthly average) occurs during day-time, in the summer season. Direct solar radiation and thermal inertia can be considered as possible reasons.

Furthermore, Fig. 7 demonstrates that the largest monthly mean UHI intensity occurs later for cities located in the eastern part of the country (July), while earlier in western urban areas (May).

Spatial structure of monthly mean UHI intensity of the Budapest agglomeration area has been analyzed in details (Bartholy et al., 2001a). Fig. 8 illustrates the spatial structure of UHI in Budapest in January, April, July, and October both during day-time and night-time. The monthly mean difference between the temperature of each pixel and the rural mean temperature is presented on the maps. The warmest part of the city is the downtown area (administrative and commercial center) on the left bank of the river Danube. The western part of the city is hilly covered by forests, so its surface is relatively cold. The difference between the warmest and the coldest surface temperature exceeds 15°C in summer. The downtown warm spots are 4-6°C and 2-3°C colder on winter days and nights, respectively, than in summer.

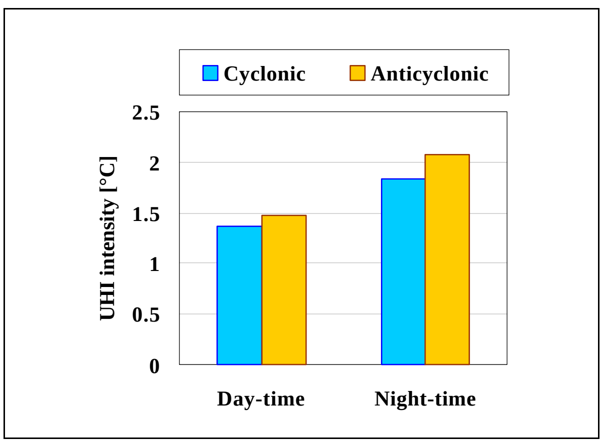

Fig. 9. Annual mean UHI intensity of Budapest depending on the macrocirculation pattern.

More detailed spatial analysis with finer resolution (90 m per pixel) surface temperature data can be performed by using the remote observations of sensor ASTER upon availability of cloud-free satellite images.

Furthermore, UHI intensity has been analyzed under different dominant macrocirculation conditions. Satellite images can be used only in case of clear weather. However, it is possible, that the weather conditions are mostly cloudy in Hungary on a particular day, but when the satellite observes the surface temperature above the Budapest agglomeration area, it happens to be mainly cloud-free, so remote sensing information can be used. The results suggest (Fig. 9) that the UHI is more intense in case of high air pressure system dominancy (anticyclonic conditions) above the Carpathian Basin than in case of cyclonic macrocirculation conditions, especially in night-time when the difference is significant at 0.1 level. Also, night-time UHI intensity is significantly larger (at 0.01 level) then day-time intensity both in cyclonic and anticyclonic weather conditions.

Finally, satellite and ground-based observations have been compared keeping in mind that regularly observed temperature by the meteorological services of the entire world is measured at 1.25-2 meter height in a sheltered white box as the WMO standards require, while satellite data sets are representatives of surface characteristics. According to Roth et al. (1989) mean values of satellite-based surface temperature are higher with larger standard deviation than ground-based temperature observations. Their correlation ranges usually about 0.7-0.8 (Nichol, 1996). Fig. 10 (right panel) presents scatterplot diagram and linear regression analysis of daily minimum temperature based on ground observations in Budapest and surface temperature measured by satellite TERRA. These two variables are very strongly correlated (0.95). Also strong linear correlation (0.93) have been found between daily maximum temperature and satellite-based surface temperature. Their scatterplot diagram and linear regression analysis are shown in the center panel of Fig. 10, while the left panel provides the same for observed air temperature at 12pm (where the correlation coefficient value is 0.93, as well). Note that equation of regression relationship is $y=ax+b$, here a is less than 1, and b is not 0, especially in case of Tmax.

During the 2-year-long research project further unsolved problems arised that are planned to be included in our future analysis, namely, (1) investigation of the influence of different surfaces and cover materials on urban climate, (2) analysis of the linkage between the satellite sensed surface temperature field and the complete urban surface temperature (including vertical walls, street canyons, green patches, etc.). In order to fulfill these future goals we plan to use very high resolution (90 m) surface temperature data measured by sensor TERRA/ASTER: Finally, based on the results of the project, we started a joint research program with the Budapest Technical University on developing architectural standards of building technologies and materials for the present and the changing climate conditions and increasing energy demands.

6. FURTHER CLIMATOLOGICAL APPLICATION OF SATELLITE INFORMATION

Besides urban climatological application time series of fine resolution satellite images perform important contribution to monitor and analyze recent hydrological events occurred in the Carpathian Basin. Hydrology/climatology related use of satellite based information includes analysis of flood event characteristics, continuous monitoring of the spatial extent of inland water surfaces, estimating the major causes of extremely large run-off, etc. Decadal-scale changes in land-cover /land-use strongly influence the hydrological balance of watersheds. Some theories suggest that floods occurred in the last few years on the upper flow of the river Tisza (the second largest river in Hungary, tributary stream of the river Danube with total length of 962 km) may be a consequence of forest cut over large areas in the Carpathian Mountains. Comparison of satellite images from the last 20 years will be applied to evaluate these theories. The above-mentioned issues are under our research scope ad some of the preliminary results will be presented.

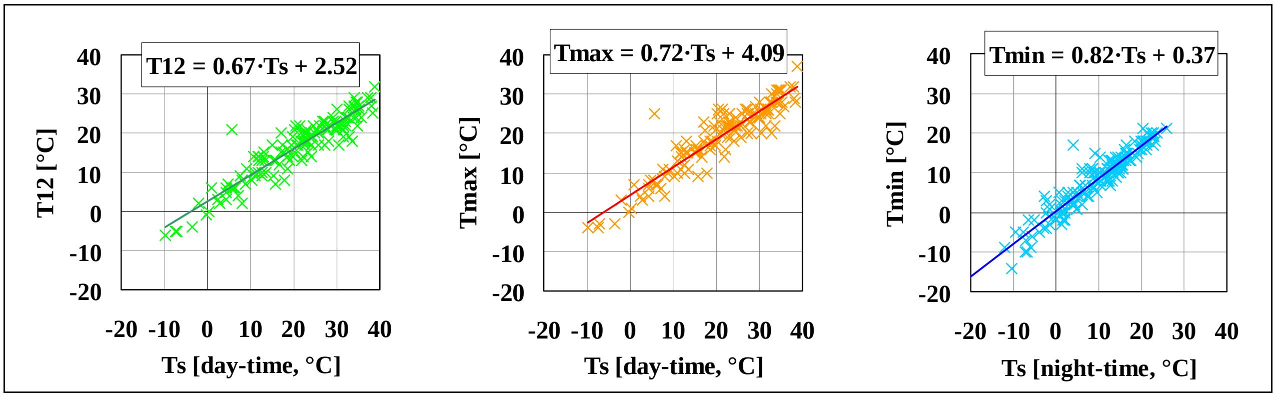

Fig. 10. Linear relationship between the ground-based temperature observations (T12/Tmax/Tmin) and the surface temperature (Ts) measured during day-time/night-time by satellite TERRA.

7. CONCLUSION

First, general climatology of the capital metropolitan area is presented with special emphasis on wind and temperature. In order to make detailed analysis of urban areas data collection from different sources and their quality control was needed.

Then, large cities of the Carpathian Basin have been selected and their urban and rural pixel representations have been determined. Day-time and night-time surface temperature time series measured by the instrument MODIS of satellite TERRA have been analyzed. Urban and rural spatial averages have been calculated and compared for each selected city.

The analysis suggests that UHI intensity detected in the selected Hungarian cities exhibits high variability. Average values of the temperature differences between urban and rural areas range between 1 K and 3 K. Population of the cities is the main factor of determining UHI intensity that is modified by orography.

Monthly mean spatial structures of UHI have been determined, concluding that the most intense UHI occurs in the summer period (MJJA). Further results suggest that the UHI is more intense in case of anticyclonic conditions above the Carpathian Basin, especially in night-time than in case of cyclonic weather situations.

Finally, very strong correlations have been found between ground-based temperature observations (especially in case of daily minimum temperature) and remotely sensed data.

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