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Satellite observation of Urban Heat Island effect

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Abstract — Remote sensing is a key application in global-change science and urban climatology. Urbanization, the conversion of other types of land to uses associated with growth of populations and economy has a great impact on both micro-climate as well as macro-climate. By integrating high-resolution and medium-resolution satellite imagery with other geospatial information, have been investigated several land surface parameters including impervious surfaces and land surface temperatures for Bucharest metropolitan area in Romania. The aim of this study is to examine the changes in land use/cover pattern in a rapidly changing area of Bucharest metropolitan area in relation to urbanization since the 1989s till 2010 and then to investigate the impact of such changes on the intensity and spatial pattern of the UHI effect in the region. Investigation of radiative properties, energy balance and heat fluxes is based on satellite data provided by various sensors Landsat TM, ETM+, MODIS and IKONOS. This paper demonstrates the potential of moderate-and high resolution, multispectral imagery to map and monitor the evolution of the physical urban environment in relation with micro and macroclimate conditions. So called effect of "urban heat island" must be considered mostly for summer periods conditions and large European scale heat waves.

Keywords — Urban Heat Island, urbanization, satellite data, Bucharest, Romania.

1 INTRODUCTION

The recent global warming is strongly affecting terrestrial urban systems through serious disturbances due to the increase of greenhouse gases and aerosols, which affect the absorption, scattering and emission of radiation within the atmosphere and alter the energy balance. One expression of this warming is the observed increase in the occurrence of summer heat waves. Conceptually this increase is understood as a shift of the statistical distribution towards warmer temperatures, while changes in the width of the distribution are often considered small. The impact of urban growth on local and regional climate is emphasized by a significant increase in urban temperature and urban heat island developing.

Urban sprawl often appears as an expansion of densely populated areas in the urban fringes due to economic growth and population concentration [1]. Due to the non-vegetated impervious surfaces of extensive constructions, huge quantities of solar radiation are stored and re-radiated in urban areas. These tend to be accelerated by anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources. On the other hand, in developed countries, in response to expanding networks of roads to rural areas and an increasing reliance on the automobile, populations began scattering from cities to suburbs. As a consequence, at the fringe of cities, the rate of land conversion from vegetated to non-vegetated area exceeds the comparative rate of population growth and these low populated urbanized areas often expand disorderly on a metropolitan scale.

Urbanization, the conversion of other types of land to uses associated with growth of populations and economy has a great impact on both micro-climate as well as macro-climate. Urban land covers as the biophysical state of the earth's surface and immediate subsurface, are sources and sinks for most of the material and energy movements and interactions between the geosphere and biosphere. Changes in land cover include changes in biotic diversity, actual and potential primary productivity, soil quality, runoff, and sedimentation rates, and cannot be well understood without the knowledge of land use change that drives them. Therefore, land use and land cover changes have environmental implications at local and regional levels, and perhaps are linked to the global environmental process. Because of the interrelated nature of the elements of the natural environment, the direct effects on one element may cause indirect effects on others. While urbanization is an important driver to environmental change, it is not the only urban–related influence. The conversion of land to urban uses, the extraction and depletion of natural resources, and the disposal of urban heat wastes as well as urbanization in general represent global impacts.

As future climate trends have been predicted to increase the magnitude and negative impacts of urban heat waves in metropolitan areas, there is an urgent need to be developed

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adequate strategies for societal vulnerability reducing [3].

2 URBAN HEAT ISLAND EFFECT (UHI)

The term 'urban heat island' was introduced by Manley (1958) [2] and has been extensively used in urban climate research.

The urban heat island (UHI) effect is the temperature increase in the urban areas compared to that in surrounding rural areas and is caused by the increased use of impervious land surfaces covered by anthropogenic material, the complexity of the three dimensional structures of the surface, and the coincident decrease of vegetation coverage, as well as anthropogenic heat discharge due to human activities. Rapid urbanization transforms the natural landscape to anthropogenic urban land and changes surface physical characteristics. By covering the urban areas with specific infrastructure (buildings, roads, parking lots, and other paved surfaces), urban zones usually experience higher solar radiation absorption and a greater thermal conductivity and capacity for releasing heat stored during the day at night. As urban landscape contains a variety of surfaces with contrasting radiative, thermal, aerodynamic and moisture properties, the different surfaces which possess diverse thermal differences alter surface energy budgets, and directly affect urban climate.The conversion of the land use and land cover from rural to urban can impact the trends in temperature similar to that expected under an enhanced greenhouse warming scenario. Also, the presence of buildings alters surface roughness around urban with influences associated with changes in surface properties like urban air quality, surface-forced mesoscale circulation associated with variations in spatial patterns of the surface sensible and latent heat flux, and precipitation over urban areas.

Heat islands can be defined for different layers of the urban atmosphere, and for various surfaces and even the subsurface It is very important to distinguish between these different heat islands as their underlying mechanisms are acting different regarding urban microclimate [4]. Anyway, an urban heat island refers to the excess warmth of the urban atmosphere compared to the non-urbanized surroundings. Atmospheric heat islands are best expressed under calm and clear conditions at night when radiative cooling differences are maximized between urban and surrounding rural locations. The atmospheric heat island phenomenon can be classified into two types, the canopy urban heat island effect and the boundary-layer urban heat island effect. These definitions are based on the scale and height of their appearance. The former occurs on the microscale, and the latter occurs on the local or mesoscale. The canopy urban heat island is affected by local building geometry and materials. On the other hand, the boundary-layer urban heat island is governed by heated air from upwind urban areas and the underlying canopy layer in which the canopy urban heat island occurs [5].

Another important parameter is the heat island intensity, which is defined as the temperature difference between urban and rural zones and is used to delineate heat island areas. As global warming patterns continue, researchers anticipate increases in the severity, frequency and duration of extreme heat events [6].

3 GEOSPATIAL DATA

Geospatial Earth Observation data provided by multispectral, multispatial, multitemporal satellite sensors are significant for the following aspects of urban heat island effects: examination of the spatial structure of urban thermal patterns and their relation to urban surface characteristics; investigation of the relation between the atmospheric heat island, which consists mainly of the canopy urban heat island, and the surface heat island; investigation of urban heat balances.

With the availability of thermal sensing data such as Landsat Thematic Mapper and Enhanced Thematic Mapper, thermal infrared band 6, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) thermal infrared (TIR) images, and the Advanced Very High-Resolution Radiometer (AVHRR) thermal channels, study of land surface temperature from thermal images has been a topic of great interest in the remote sensing literature for the past three decades [7]. Thermal data, covering TIR range 8–12μm, can be acquired in single broadband (e.g., Thermal Airborne Broadband Imager, TABI) or multi-band images (e.g., five ASTER TIR channel images). Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the National Aeronautics and Space Administration's Terra and Aqua satellite platforms

4 BIOGEOPHYSICAL PARAMETERS

Satellite remote sensing derived biophysical parameters of Earth's cover provide great potential for urban land cover construction materials and the composition and structure of urban canopies, for improving the understanding of the urban surface energy budgets, and observing the urban heat island (UHI) effect. Especially high-resolution Thermal Infrared (TIR) imagery has the advantage of providing a time-synchronized dense grid of temperature data over a whole city and distinctive temperatures for individual buildings. Knowledge of urban surface energy budgets and urban heat islands effects is very important for research themes like as urban climatology, global environmental change, and human–environment interactions as well as for planning and best urban management practices.

4.1. Land Surface Temperature (T_s)

In urban heat island studies, land surface temperature T_s is one of the most important biophysical parameter which modulates the air temperature of the lowest layers of the atmosphere, being of prime importance to the urban environment because of its key role in the energy balance of the surface. Also, LST helps to determine the internal climate among buildings, but also influences energy exchanges that affect the comfort of city dwellers [8]. In order to retrieve T_s from at-sensor satellite and auxiliary data have been developed three methods: single-channel method, split-window technique, and multi-angle method. Because the last two methods require at least two channels, single-channel method is the only method that can be applied to the Landsat TM and ETM platforms, with one thermal channel [9]. In this study, T_s was derived from the corrected Landsat TM and ETM TIR band by using the method described in [10], which does not require atmospheric parameters being widely used. The UHI effect can be measured for the individual thermal images and then compared between different time periods. The retrieval methods of brightness temperature from the TM and ETM+ images are different for Band 6.

1) Brightness temperature from the Landsat TM images

First, the digital numbers DN of thermal band 6 of Landsat TM have been transformed into absolute radiance by formula:

$$L_\lambda = \frac{DN}{255}\left(L_{\max} - L_{\min}\right) + L_{\min} \qquad (1)$$

where L_λ are the spectral radiance, L_{max}, and L_{min}, (mW/ (cm^2.sr)) are spectral radiances for each band having values of L_{max}=1.896 mW/ (cm^2.sr) and L_{min}=0.1534 mW/(cm^2.sr)

Then, spectral radiance is converted to at-satellite brightness temperature in Kelvin, T (K), by the following equation:

$$T_S = \frac{K_1}{\ln\left(\frac{K_2}{\frac{L_\lambda}{b}+1}\right)} \qquad (2)$$

where, K1=1260.56K and K2=60.766 mW/ (cm^2.sr. μm), which are pre-launch calibration constants; b represents effective spectral range, when the sensor's response is much more than 50%, b=1.239(μm) [11].

2) Brightness temperature from the Landsat ETM images

Radiance values from the Landsat ETM+ thermal band have been transformed to radiant surface temperature values using thermal calibration constants supplied by the following relation:

$$T_S = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda}+1\right)} \qquad (3)$$

where T_s is radiant surface temperature (K), K_1 = 666.09 is calibration constant 1, K_2 =1282.71 is calibration constant 2 and L_λ is spectral radiance of thermal band pixels, expressed by the following equation:

$$L_\lambda = gain x DN + offset \qquad (4)$$

where Digital Numbers (DNs) in each band of the Landsat TM and Level 1G ETM+ imagery used were converted to physical measurements of at sensor radiance (LE) using a formula that accounts for the transformation function used to convert the analog signal received at the sensor to DNs stored in the resulting image pixels, gain = slope of the radiance/DN conversion function, DN= digital number of a given pixel, and offset = intercept of the radiance/DN conversion function. Gain and offset values are supplied in metadata accompanying each ETM+ image, and the DN to radiance formula [12].

5 STUDY AREA AND DATA USED

Urban metropolitan area Bucharest described by a star-shaped pattern (Fig.1), placed in the South – Eastern part of Romania, is bounded by latitudes 44.33 °N and 44.66 °N and longitudes 25.90 °E and 26.20 °E. Its central region has the main coordinates: latitude 44°25′N, longitude 26°06′E. The city is crossed by the Dâmbovita and Colentina rivers and is surrounded by forests, which makes Bucharest a city with large green areas, which have come parks and, at the same time, places for rest and entertainment, such as: Baneasa, Herastrau, Floreasca, Tei, Lebada

Fun area. Herastrau Park is the largest in the city, being situated on the Colentina River, including the Herastrau and Floreasca lakes, providing special opportunities of entertainment.

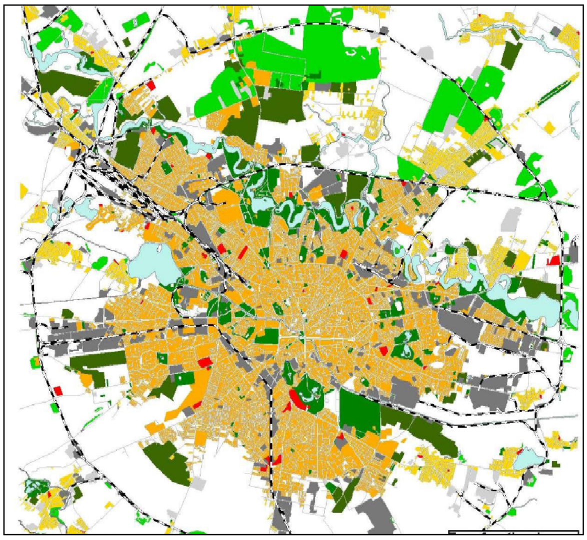

Fig. 1.Test site urban Bucharest area

Bucharest is one of the most crowded capital in Eastern Europe and maybe the most polluted. Economical development results in traffic increase (presently six times increase in comparison to 1990 year) as well as some industries placed in the surroundings of the city whose activities causes high concentration of heavy metals (sometimes above the acceptable limits). Multi-spectral and multi-temporal satellite imagery provide the most reliable technique of monitoring of different urban structures regarding the net radiation and heat fluxes associated with urbanization at the regional scale. Investigation of radiation properties, energy balance and heat fluxes for Bucharest urban area, Romania was based on multispectral and multitemporal cloud free satellite data: Landsat TM 27/08/1989, 21/08/1990; Landsat ETM:23/07/2002, 12/09/2004, 20/08/2007, 16/07/2010, ASTER 16/07/2005, 31/08/2010 and radiometric and geometrically corrected, pan-sharpened, multi-spectral IKONOS sub-scene of 1 m pixel resolution acquired 27/07/2005, 12/09/2007 and 12/07/2009. This imagery is produced by merging 11-bit of 1 m resolution panchromatic 450-900 nm and 4 m resolution multi-spectral - blue 450-530 nm, green 520-60 nm, red 630-720 nm and near infrared 770-880 nm channels via principal component. ASTER data used were characterized by surface kinetic temperature (Level 2B03), surface spectral emissivity (2B04), VNIR surface spectral reflectance (2B05V), SWIR surface spectral reflectance (2B05S), and relative digital elevation model (DEM) (4A01).The images have been divided in several sub scenes, chosen as study areas, covering a part of Bucharest town. In situ-monitoring meteorological as well as ENVI 4.7, IDL 6.3 and ILWIS 3.1 softwares have been also used.

6. RESULTS

Bucharest expanded in all directions during the 21 years period covered by the available satellite images. Change analysis during period of (1989 -2010) from Landsat TM and ETM+ and IKONOS satellite data showed a strong urban growth inside of the town but also in periurban areas as an increase of overcrowded urban area for all 6 sectors belonging to Bucharest metropolitan area.

Urban temperature trend analysis by using the annual mean of daily minimum temperatures reflects the degree and continuity of the minimum temperature trend in a year. To estimate the influence of urbanization on the thermal environment, trends of the temperature differences between the targeted station and a rural station have been commonly used. By subtracting the rural station data, the influence of background climate can be minimized and the influence of the land cover on the temperature can be clearly extracted. Since the long-term temperature change is often non-stationary, we need to investigate the times series data set. In order to investigate the existence of turning points and the trend of time series temperature data, will be applied a statistical approach to detect variation (structural changes). Fig.2 illustrates a classification of urban land cover based on IKONOS 12/07/2009 image.

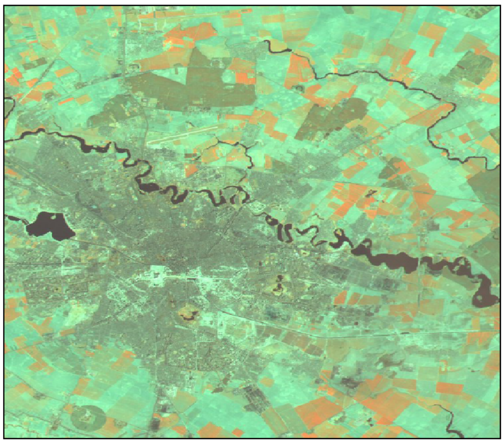

Fig.2 Classification of Bucharest urban land cover, IKONOS 12/07/2009 image.

Supervised classifications of individual land covers have been performed using the reflective bands of the Landsat TM and ETM + as well as IKONOS data. For classification in Fig.3 the overall accuracy was approximately 91%.The classes selected for these supervised land cover classifications are based on the V-I-S model which divides urban and periurban land cover composition into three major categories-vegetation-V, impervious surface-I, and soil-S. These three general categories have highly contrasting responses in terms of energy flux (absorption, retention, emission) and moisture dynamics (uptake, evapotranspiration, runoff), which in turn affect energy flows. The V-I-S model was developed explicitly for ecological purposes, as distinct from the more common urban land use classifications. The thermal response per land cover type is assessed according to the thermal band 6 (TIR) within Landsat TM and ETM+ imagery. UHI intensity is related to patterns of land use/cover changes (LUCC), e.g. the composition of vegetation, water and built-up and their changes.

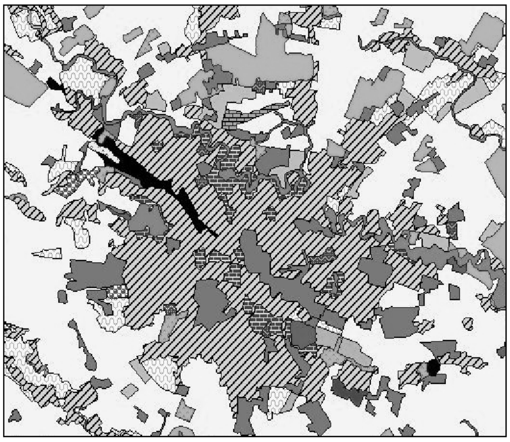

Fig.3. **V**-I-S classification of Bucharest, on IKONOS 12/07/2009 image

The aim of this study is to examine the changes in land use/cover pattern in a rapidly changing area of Bucharest metropolitan area in relation to urbanization since the 1989s till 2009 and then to investigate the impact of such changes on the intensity and spatial pattern of the UHI effect in the region.

Our analysis showed that higher temperature in the UHI was located with a scattered pattern, which was related to certain land-cover types. In order to analyze the relationship between UHI and land-cover changes, this study attempted to employ a quantitative approach in exploring the relationship between temperature and several indices, including the Normalized Difference Vegetation Index (NDVI). Such analysis is very helpful in urban mesoscale models and urban climate studies.

Preliminary results of our TIR bands analysis from Landsat TM and ETM + as well as for TIR ASTER Channels shows maximum and minimum energy readings of individual land covers, according to training sites selected in the supervised classification. Not surprisingly, water shows the lowest maximum energy reading and lowest minimum reading of each of the land cover types. The impervious surfaces such as light and dark impervious and bright roofs show among the highest minimum and also the highest maximum readings. This suggests that impervious surfaces tend to absorb incoming light energy and retain heat energy more readily than do natural surfaces. Bright roofs show the largest within-class variation among training sites. This is undoubtedly due to the difference in pitch and aspect of the roofs within the training site. The anomaly, however, is the dry soil category, with the largest within-class variation by training site. Dry soil also contains both the highest minimum and the highest maximum readings. This is a direct reflection of the hot dry climate in this urban environment during summer periods. These areas are affected by increased air pollution, having a high density population and big automobile traffic that exists in the urban area and especially in the central part of Bucharest town. In order to compare the seasonal and day–night differences of urban surface heat balance, ASTER data of 16/07/2005 were acquired for clear sky condition. Vegetation was classified by using the spectral pattern of VNIR band reflectance with the minimum distance method. Since the boundary zones of urban and periurban vegetation coverage were often misclassified, NDVI parameter was used to distinguish vegetation from soil and builded areas. The thresholds of NDVI for division of vegetation were decided manually for each date. Based on this procedure, rural areas were classified into five land cover types: field, paddy field or orchard, lawn, forest, and bare soil. The land cover map for urban and periurban Bucharest area was established based on the remote sensing-based elements like: flat pavement, road, industrial area, low-rise dwelling, mid-/highrise dwelling, commercial/business area and low-rise building, vegetation, forest. In Bucharest urban and periurban areas, the range of net radiation extracted from ASTER data during summer was in the order of 690- 810 Wm^{-2}, function of the subregion tested area as the net radiation is partitioned to sensible heat and storage heat. At the microscale, surface albedo and temperature should have large variety in urban sectors because of the large material and structural versatilities. However, surface albedo and temperature variations are diminished at 90-m spatial resolution of TIR ASTER channel. The storage heat flux exceeds the sensible heat flux in urban areas, whereas the sensible heat flux is higher than storage heat flux in industrial areas. In particular, negative storage heat flux appears at a number of industrial points. This tendency shows that high surface temperature in the industrial area is induced by mass energy consumption, because most of the anthropogenic heat discharge is transferred to the atmosphere as sensible heat. Fig.4 is showing a land surface temperatures map based on ASTER 16/07/2005 data. The city center, Otopeni and Baneasa airports and major roads with high traffic values were found to have the highest land surface temperature values, while parks with vegetation, neighboring forests, farmlands, and gardens had the lowest land surface temperature values.

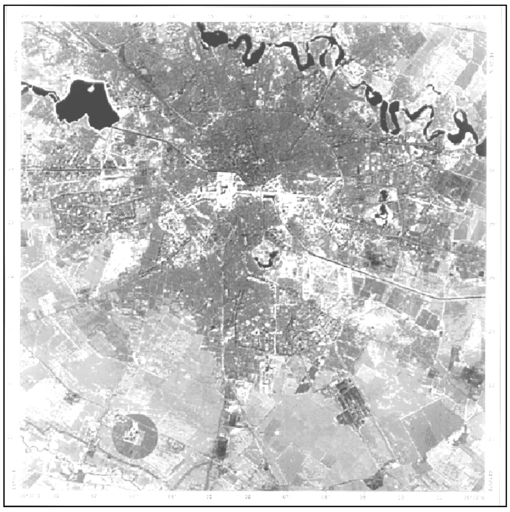

Fig.4. TIR ASTER land surface temperatures map based on ASTER 16/07/2005 data

Satellite data analysis stressed a clear temperature contrast between the central, median and peripheral zones of Bucharest city. Information on the spatial pattern and temporal dynamics of land cover and land use of urban areas is critical to address a wide range of practical problems relating to urban regeneration, urban sustainability and rational planning policy as well as for more sustainable urban transport policies.

7. CONCLUSION

The results suggest that the spatial pattern of the urban heat islands (areas with relatively high temperatures) in Bucharest town has changed from a scattered pattern (bare land, semi-bare land and urban area were warmer than other areas) in 1989 to a more contiguous pattern of urban heat islands in 2004, 2007 and 2009, along with the high urbanizing rate during the last years. The urban subscene areas of high temperature have been consistent with built-up areas, which can be seen by comparing land use/cover with temperature maps. Multi-spectral and multi-temporal satellite imagery provide the most reliable technique of monitoring of different urban structures regarding the net radiation and heat fluxes associated with urbanization at the regional scale. Investigation of radiation properties, energy balance and heat fluxes in Bucharest urban area, Romania is based on satellite data from various sensors (LANDSAT TM, ETM, SPOT and SAR) and in-situ monitoring data, linked to numerical models and quantitative biophysical information extracted from spatially distributed NDVI-data and net radiation. For detailed land use classifications in a digital form is possible to analyze in a statistical way these properties. Owing to surfaces material properties the so called effect of "urban heat island" must be considered mostly for summer periods conditions. Satellite thermal infrared data between 8 - 14 µm are very suited for surface temperatures analysis of urban areas which are several degrees higher than on surrounding rural areas. Results are validated by in-situ monitoring data. Urban local land cover, grass, concrete, soil, water, etc., largely dictates the energy exchanges between the earth and atmosphere. The urban heat island has been described as ''one of the most clearly established examples of inadvertent modification of climate''.

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