Multisensor satellite remote sensing data for heat waves assessment in metropolitan region

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Heat waves are expected to become more frequent and severe as climate changes, with unknown consequences for human health and urban ecosystems. 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 a metropolitan region. The aim of this study is to examine the changes in land use/cover pattern in a rapidly changing city of Bucharest in relation to urbanization since the 1990 till 2010 and then to investigate the impact of such changes on the intensity and spatial pattern of the Urban Heat Island (UHI) effect in the region. Investigation of land cover changes in relation with land surface temperature/emissivity is based on satellite data provided by various sensors Landsat TM, ETM+, IKONOS and MODIS Terra/Aqua. This paper demonstrates the potential of moderate-and high resolution, multispectral and multitemporal imagery to map and monitor the evolution of the physical urban environment in relation with micro and macroclimate conditions very important for summer periods conditions and large European scale heat waves like have been recorded in 2007 year.

1. Introduction

During last period global warming was intensified because the global mean surface temperature has increased since the late 19th century. Extreme climate events including heat waves are a key manifestation of complex systems, in both the natural and human world, being of the great environmental concerns in the twenty first century. The impact of extreme climate phenomena (heat waves and cold spells) is more serious when the extreme weather conditions prevail over extended periods. Surface temperature is expected to continue to increase globally and major changes are likely to occur in the next years. It was estimated that during last years regional surface warming caused the frequency, intensity and duration of heat waves to increase over Europe. Heat waves (HWs) are periods of unusually hot weather that affect human health through heat stress and exacerbate health's problems and people mortality.

In city areas, as urbanization has become an important contributor for global warming, Urban Heat Island (UHI) effect during summer time and heat waves periods will be sure to influence the regional climate, environment, and socio-economic development. Much more, extreme climatic events as heat waves will amplify the UHI effect with severe urban ecosystem health consequences. Remote sensing is a key to mesoscale modeling through specification of land cover distributions and creating spatial products of moisture, reflectance, and surface temperatures. The knowledge of urban surface energy budgets and urban heat island effects is significant to assess urban climatology as well as global environmental change, and human–environment interactions.

Urban systems play a vital role in social and economic development in all countries. Urban environmental changes must be investigated on different spatial and temporal scales in direct relationship with urban climate warming. 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 the 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.

Urban development can profoundly alter the urban landscape structures, ecosystem processes, and local climates. Timely and accurate information on the status and trends of urban ecosystems is critical to develop strategies for sustainable development and to improve urban residential environment and living quality. Urbanization changes land use, often in negative ways, and increases environmental degradation by diminishing biodiversity, lowering ecosystem productivity, deteriorating watershed discharge characteristics, and interrupting biogeochemical cycles [2]. The rates of urbanization are characterized by creating a typology of urbanization trends based on quantities that are indicative to the potential environmental 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 adequate strategies for societal vulnerability reducing [3].

2.Urban Heat Island Effect (UHI)

The term 'urban heat island' was introduced by Manley (1958) [4] and has been extensively used in urban climate research. The urban heat island (UHI) effect describes the influence of urban surfaces on temperature patterns in urban areas as opposed to surrounding areas, being 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 [5]. 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 urban heat island phenomenon can be classified into two types, the canopy urban heat island effect and the land surface urban heat island effect. These definitions are based on the scale and height of their appearance. The canopy urban heat island is affected by local building geometry and materials [6].

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 [7].

3. Land Surface Temperature derived from MODIS satellite data

Geospatial Earth Observation data provided by multispectral, multispatial, multitemporal satellite sensors are useful tools for urban surface analysis of thermal patterns and their relation to urban land cover and biogeophysical characteristics and investigation of the relation between the atmospheric heat island, which consists mainly of the canopy urban heat island, and the surface heat island.

Satellite remote sensing derived land surface temperature parameters of Earth's cover provide great potential for improving the understanding of the urban surface energy budgets, and observing the urban heat island (UHI) effect as well as heat waves monitoring. 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 peri-urban areas. Accurate and up-to-date information on land surfaces and the state of the environment are critical components of urban environmental planning and management.

The urban surface temperature is of prime importance to the study of urban climatology. Surface and atmospheric modifications due to urbanization and extreme events like heat waves generally lead to a modified thermal climate that is warmer than the surrounding non-urbanized areas, particularly at night. The phenomenon of urban heat island (UHI) is increasing during periods of heat waves.

In urban thermal 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], while for MODIS satellite data is used split-window technique.

MODIS is an EOS instrument that will serve as the keystone for global studies of atmosphere, land and ocean processes. It scans $\pm 55^o$ from nadir in 36 bands, with bands 1-19 and band 26 in the visible and near infrared range, and the remaining bands in the thermal infrared from 3-15 μm. The 36-band MODIS satellite scanner has 1 km^2 pixels at nadir for the thermal infrared bands that will be used for LST. For a given MODIS pixel, the split-window LST algorithm requires emissivities in bands 31 and 32. With 15 emissive bands, the Moderate Resolution Imaging Spectroradiometer (MODIS) on-board the EOS-TERRA platform offers new perspective in earth observation in the infrared spectrum (3-15 $m\mu$). Because chemical components of the atmosphere have various absorption bans, only seven MODIS emissive bands are useful for land surface remote sensing. MODIS has four bands (20, 21, 22, 23) in the 3-5 $m\mu$ atmospheric window. Surface properties in the infrared are specified either in terms of emissivity or reflectance, the emissivity being related to the directional hemispheric reflectance by Kirchhoff's law.

The emissivity estimation is accomplished by the use of linear bidirectional reflectance distribution function (BRDF) models, which have spectral coefficients derived from laboratory measurements of material samples and have structural parameters derived from approximate descriptions of the cover type. The emissivity of a surface is a function of many factors, including water content, chemical composition, structure and roughness. The identification of surface moisture for improved emissivity estimates is under investigation. We will need to apply more information in the classification look-up scheme to refine the estimates.

4. Methods

The surface urban heat island effect and urban heat waves are quantified from remote sensing satellite data for thermal emissivity of land surfaces and the derived land surface temperatures (LSTs) from MODIS Terra/Aqua sensor which are particularly suitable for the land surface temperature due to its global coverage, radiometric resolution and dynamic ranges for a variety of land cover types and high calibration accuracy in multiple thermal bands. The underlying algorithms use other MODIS data as input, including geolocation, radiance fields, cloud masking, atmospheric temperature, water vapor, snow, and land cover. Temperatures are extracted in Kelvin; accuracy of 1 K is yielded for materials with known emissivities [10] Remotely sensed data and above ground air temperatures are not identical, but related [8].

LSTs have the advantage of spatially explicit datasets, compared to single measurement points. The UHI of the canopy layer is determined by measuring air temperatures (usually 2 m above ground) by comparing temperatures from point measurements between the city centre versus surrounding rural areas followed by a classical approach to analyze the difference of urban and rural temperatures. A variety of remote sensing products are also available in time series. Thus, remote sensing satellite data are frequently used for assessing surface UHIs [10] with a variety of indicators.

This work analyses time-series Land Surface Temperature (LST) generated by Moderate Resolution Imaging Spectroradiometer (MODIS) data on-board NASA Terra and Aqua satellites, namely Terra MOD11A2 and Aqua MYD11A2 with a resolution of approximately 1km and aggregated for eight consecutive days. Was computed the monthly mean LST per pixel and time of day by aggregating the available 8-days-mean. Was reported an accuracy of the MODIS products better than 1 ^{o}K for most cases of validation, whereas other studies found larger biases for vegetation at some sites [11]. Based on comparison of different satellites with respect to in-situ measurements of LST in urban areas was found less than 5% differences for MODIS LSTs [12].

5. Study test area and data used

Urban metropolitan region Bucharest described by a star-shaped pattern (Figure 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. 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.

Bucharest is the tenth largest city in Europe and the largest in the South-Eastern part of the continent, having a surface of about 240 km^2 and almost 2 millions of residents.

Bucharest is among the very large cities highly vulnerable to natural hazards, like earthquakes, heavy rains or extreme temperatures. With an increased number of vehicles of about 6 times between 1990 and 2010 and the decreasing surface of urban green due to urbanization, the urban climate has suffered major changes.

Intense traffic and some industries placed in the surroundings of the city whose activities causes high concentration of heavy metals (sometimes above the acceptable limits), makes Bucharest one of the most polluted capitals in the Europe.

Investigation of urban development and heat island and heat wave for Bucharest urban area, Romania was based on time-series MODIS and NOAA satellite data and multispectral and multitemporal cloud free satellite data: Landsat TM 21/08/1990; ETM 20/08/2007, and

radiometric and geometrically corrected, pan-sharpened, multi-spectral IKONOS sub-scene of 1 m pixel resolution acquired 27/07/2005, 10/08/2007. 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.
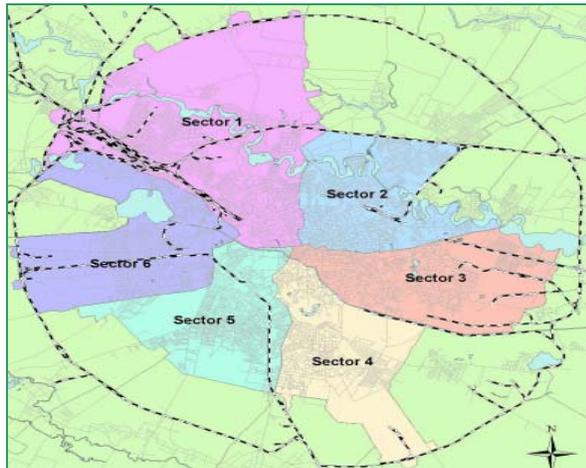

Fig. 1.Test site urban Bucharest zone with 6 sectors

MODIS Terra/Aqua data used were characterized by surface spectral temperature and emissivity. The images have been divided in several sub scenes, chosen as study areas, covering a part of Bucharest town. During analyzed period have been registered several heat waves periods, of which summer 2007 was the highest. Some in situ-monitoring meteorological data as well as ENVI 4.7, IDL 6.3 and ILWIS 3.1 software have been also used.

6. Results

Bucharest metropolitan region is under continuous influence of characteristic meteorological-climatic fluctuations of continental climate, periodically during summer, are registered heat waves for periods of time longer than five consecutive days with serious impact on urban heat island and inhabitants' health. using the land surface thermal Based on data provided by the MODIS terra/Aqua LST Day/Night data, MODIS MOD11A1 (Terra) and MYD11A1 (Aqua) products (provided by Oak Ridge National Laboratory Distributed Active Archive Center ORNL DAAC,MODIS subsetted land products, [http://daac.ornl.gov/MODIS/modis.html] from, we were able to assess the LST evolution in the greater area of Bucharest for summer heat waves periods as well as to evaluate and delineate urban heat island (UHI) pattern, and magnitude. Present research focuses on the periods of months May- August from the 2007–2010 years time interval. As the land cover has a significant influence on the extension and the geometry of the Bucharest UHI, a

strong correlation was performed. The Land Surface Temperature (LST) derived from MODIS data in the Bucharest urban area was compared with the rural surrounding area for night and for daytime.

Changes in the urban and peri-urban land cover and land surface properties as well as in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing, which is used to compare how a range of human and natural factors drive warming or cooling influences on regional and global climate. Given the ability to define land cover characteristics at the site level based on attributes such as physiognomy, horizontal and vertical structure of built environment, vegetation phenology and leaf morphology, direct parameterisation and mapping using remotely sensed data can enhance the ability to characterize and monitor these important biogeophysical parameters.

In this study, higher LST values are reported in the Aqua LST data in comparison to the Terra LST data as MODIS Terra overpass time is considered between 08:30 and 10:30 UTC, while Aqua overpass time is considered between 11:30 and 13:30 UTC for metropolitan study area. Thus, Aqua data acquisition is closest to the time that maximum of temperature is recorded. In general the increase of LST ranges from 3 to 12° K, depending mainly on the relative land cover type. The highest LST increase, of the order of $6–14^o$ K, is observed in the built urban and industrial areas at the periphery of the city. Smaller increase is observed in agricultural and forested areas ($5–14^o$ K), and near surface water lake Ciurel and Dambovita river. The different values of LST increase are attributed to the difference in the emitted radiance from each land type and/or the urban heat island effect.

Fig. 2. shows an IKONOS (10/08/2007) image of Bucharest city and peri-urban zone.

Bucharest expanded in all directions during the 21 years period covered by the available satellite images. Change analysis during period of (1990 -2010) from Landsat TM and ETM+ and IKONOS satellite data showed a strong urban growth inside of the town but also

in peri-urban 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). Figure 2 illustrates a classification of urban land cover based on IKONOS 10/08/2007 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 Figure 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 peri-urban 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 [15], 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.
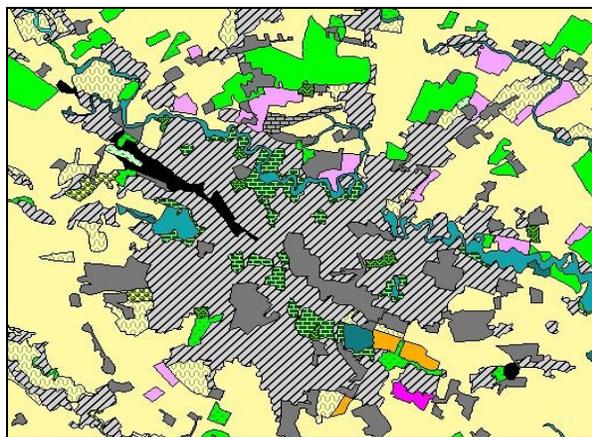

Fig. 3. V-I-S classification of Bucharest, on Landsat ETM 20/08/2007 image.

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 1990s till 2010 and then to investigate the impact of such changes on the intensity and spatial pattern of the UHI effect in the region with heat waves conditions.

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) [16]. Such analysis is very helpful in urban mesoscale models and urban climate studies.

Preliminary results of MODIS terra/Aqua LST Day/Night data analysis provided by NASA from 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 [17].

Vegetation was classified by using the spectral pattern of VNIR band reflectance of Landsat ETM 20/08/2007 with the minimum distance method. Since the boundary zones of urban and peri-urban vegetation coverage were often misclassified, NDVI parameter was used to distinguish vegetation from soil and built 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 peri-urban Bucharest zone was established based on the remote sensing-based elements like: flat pavement, road, industrial area, low-rise dwelling, mid-/high-rise dwelling, commercial/business area and low-rise building, vegetation, forest [18]. In Bucharest urban and peri-urban areas, the range of net radiation extracted from Landsat ETM data during summer was in the order of 690- 810 Wm^{-2}, function of the subregion tested areas as the net radiation is partitioned to sensible heat and storage heat.

This work analyses also the Land Surface Temperature (LST) generated by Moderate Resolution Imaging

Spectroradiometer (MODIS) data onboard TERRA and AQUA satellites for period of 2007-2010 years. The temporal evolution of the heat wave was considered using MODIS LST data, while the surface temperature anomaly was also estimated.

During summer heat events of 2007 year, based on Landsat ETM data 20/08/2007, extracted net radiation was recorded in the range of 800- 950 Wm^{-2}.

At the micro scale, surface albedo and temperature should have large variety in the 6th urban sectors because of the large material and structural versatilities [19]. 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. Figure 4. MODIS Land Cover Classification and legend (Collection 5 IGBP Type_1 2005) 201 km Wide x 201 km High with user selected Area Marked MODIS land cover.
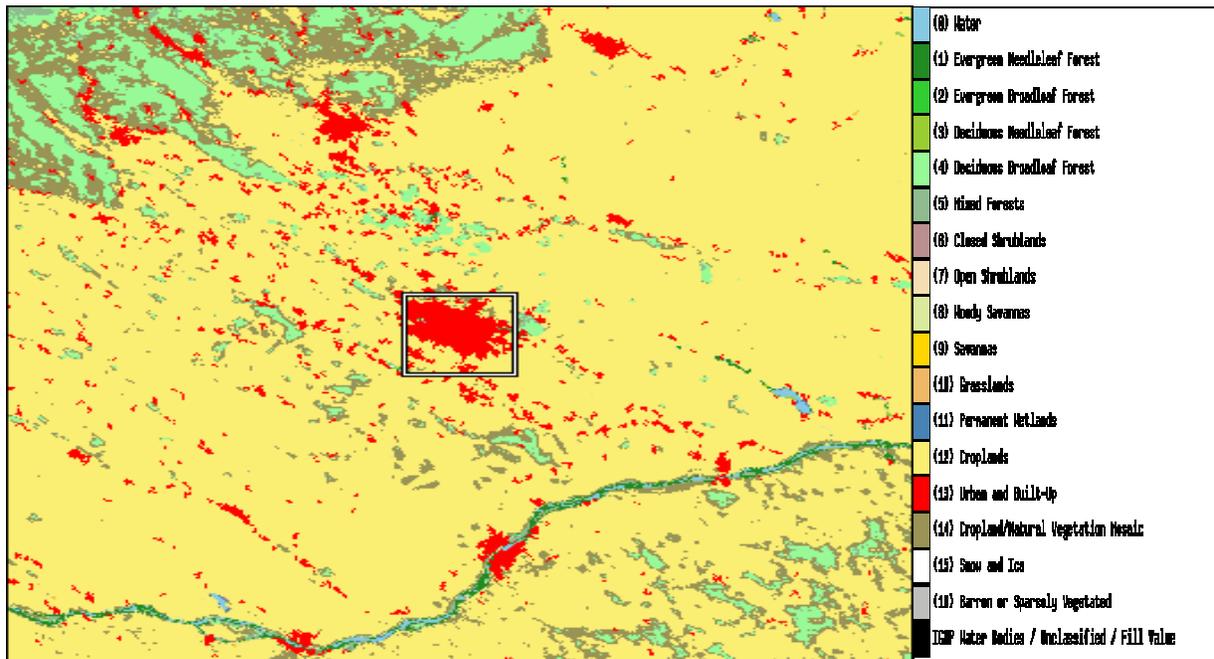

Fig. 4. MODIS Land Cover Classification and legend (Collection 5 IGBP Type_1 2005) 201 km Wide x 201 km High with user selected Area Marked MODIS land cover

Fig. 5 is showing land surface temperatures variability during 2007-2010 based on MODIS LST/Day data for Bucharest metropolitan region. 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.

Regarding the LST recordings from MODIS data for

extremely severe hot July 2007 affecting the area of Bucharest has shown that the nighttime land surface temperature of Bucharest's UHI of July 2007 was intensified and extended in comparison to the multiannual pattern, and the diurnal one was dissipated. It is very likely that the persistence of an extremely hot air mass moderates dramatically the influence of the city on the daytime surface temperatures.

Instrumental observations and reconstructions through the NCEP/NCAR Reanalysis 40-year Project of global and hemispheric temperature evolution reveal a pronounced warming during the past ~150 years [20]. One expression of this warming is the observed increase in the occurrence of 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. As Figure 6 shows, for investigated test city center area, Bucharest, defined by latitudes(26.08 E to 26.1 E) and longitudes (44.45 N to 44.4 N), from time-series NOAA satellite data (http://www.esrl.noaa.gov) for analyzed period 1950 to 2010, during last twenty years was recorded a pronounced increase of temperature variability, with maximum changes in during summer periods.
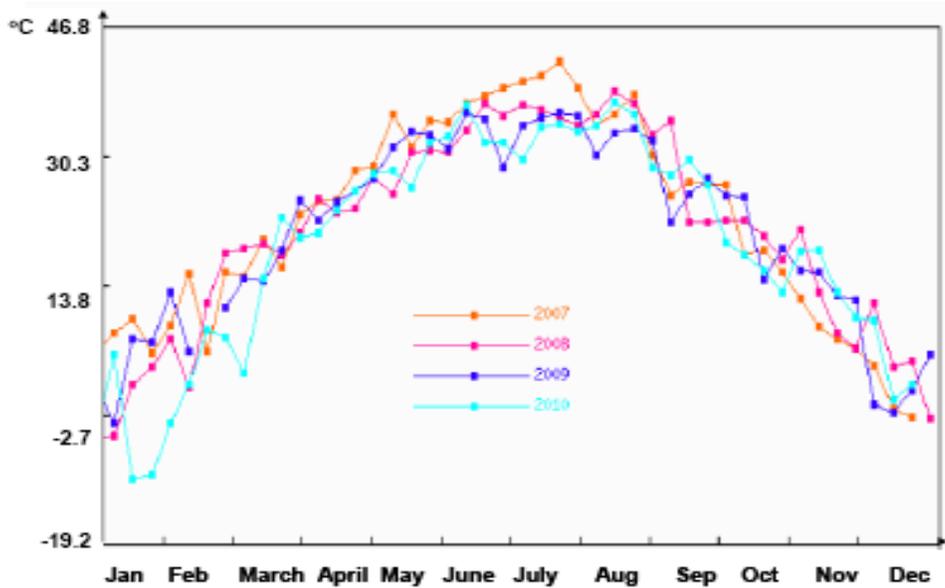
*Fig. 5. LST variability during 2007-2010 period extracted from time-series MODIS TerraDay data for Buchares
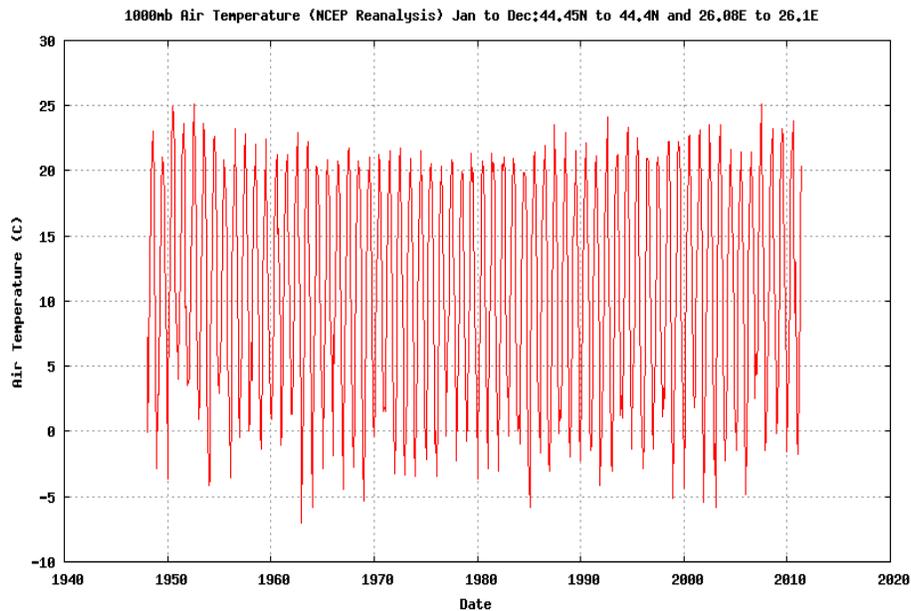t metropolitan region.*

*Fig. 6   . Temperature variability over Bucharest test area during 1950- 2010 period from time-series
NOAA satellite data.*

7. Conclusion

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.

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 1990 to a more contiguous pattern of urban heat islands in 2007, along with the high urbanizing rate during the last years. The urban sub scene 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.

Recent European heat waves have raised interest in the impact of land cover conditions on temperature extremes. At present, it is believed that such extremes are enhanced by stronger surface heating of the atmosphere, when soil moisture content is below average.

Acknowledgements

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