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Use of satellite data for land surface radiative parameters retrieval of Bucharest metropolitan zone

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This paper aims to investigate the influences of urban growth and green land cover decrease on land surface radiative properties and metropolitan climate of Bucharest in Romania. Landsat TM/ETM+/8 OLI and time series MODIS Terra/Aqua and NOAA AVHRR satellite data have been used to assess urban land cover– thermal environment over 2000-2018 years. As the city climate system is very sensitive to air and land surface temperature, land surface albedo, NDVI/EVI vegetation index, latent heat flux, these variables could have a significantly feedback to the projected climate change. The results show that the satellite-inferred radiative parameters agree well with the field-observations.

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1. Introduction

Due to rapid urbanization as an important contributor for global warming, European cities face a diverse range of challenges over the coming decades that will influence the climate system at both local and regional scales, environment, and socio-economic development. Climate change and the increase of extreme climate events intensity (like heat waves, flooding, storming, freezing etc.) is of great environmental concern facing mankind in this century.

The Intergovernmental Panel on Climate Change has projected that the global mean surface air temperature will increase by 0.3°C to 4.8 °C by the year 2100, depending on the specific emissions scenario and climate model [1].

Urban heat island (UHI) is one of the important outcomes of land cover surface radiative properties changes induced by urban growth, which represents the difference in albedo, roughness, and heat flux exchange of land surface. The impact of extreme climate phenomena (heat waves and cold spells) is more serious when the extreme weather conditions prevail over extended periods. Is expected as heat waves to amplify the UHI effect with severe urban thermal environment and health consequences. Urban zones are the most affected by the rising temperatures which can be influenced by two factors: the background change in climate and the specific local conditions of the city [2].

In order to develop proper urban planning and decision makers policies it is an acute need to identify the spatio-temporal factors that contribute to (or mitigate) the UHI effect. Vegetation (farmland, forests, grassland) and water bodies and wetlands have cooling effects on urban thermal environment being considered the most common methods to alleviate the negative impacts of the UHI in metropolitan areas [3]. On the contrary, urban artificial landscape composition, such as building and open soil, tends to amplify the UHI effects [4]. In frame of global warming, urban climate is considered to be one of the most important factors for urban ecological environment assessment. Urban landscape contains a variety of land surfaces with different physical composition and contrasting radiative, thermal, aerodynamic and moisture properties. Due to these different surfaces with diverse thermal differences, the surface energy budgets are altered, and directly urban climate is affected. Extensive urbanized land surfaces modify the energy and water balance processes and influence the dynamics of air movement.

Climate change and extreme climate events which occurred in South Eastern Europe as well as in Romania are the great environmental concerns facing scientists in the twenty first century. Air and surface temperatures are expected to continue to increase globally and major changes are likely to occur in the global hydrological and energy cycles. Extreme climate events like heat waves periods are key manifestations of complex systems, in both the natural and human world. It was estimated that during last years the regional surface warming caused the increase of frequency, intensity and duration of heat waves over Europe.

Adverse thermal environment and air pollution at local and regional levels are major environmental issues. Climate and anthropogenic impacts are of increasing concern to societies, particularly in urban regions with high climatic variability and extreme climate events in context of local, regional and global climatic changes.

Satellite remote sensing is a key optospectral tool for monitoring and mesoscale modeling by specification of urban 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. This paper is focused on the influences of urbanization and climate change impacts on urban thermal environment as well as on the relationships of thermal characteristics to other biophysical variables in Bucharest metropolitan area of Romania based on time series Landsat TM (Thematic Mapper)/ETM (Enhanced Thematic Mapper) +/8 OLI (8 Operational Landsat Imager), MODIS Terra/Aqua and NOAA AVHRR data acquired during 2000-2018 period.

2. Urban thermal environment

It was estimated that by 2100 year several regional changes in climate will occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions, increases in frequency, intensity, and/or amount of heavy precipitation in several regions, and an increase in intensity or frequency of droughts in some regions. The on land temperature extremes are projected to increase, extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C [5].

In frame of predicted increase of urbanization and urban population increase, is very important to have realistic representations of urban thermal environment in order to improve the prediction of urban weather and climate. Urban zones are the most affected by the rising temperatures which can be influenced by two factors: the background change in climate and the specific local conditions of the city.

Urban land surface types, including metropolitan regions, play an important role in the energy and water partitioning at the lower boundary of climate models. Unlike rural surfaces, urban land environmental features have reduced vegetation and permeability which highly limit evapotranspiration and infiltration. Specific urban surfaces consist of asphalt road, concrete pavements and buildings that have lower albedo values and higher absorptivity than rural areas. These urban surface properties modify the urban surface energy and water balance in a different way from the natural surfaces. Also, urban geometry patterns could also affect some climate variables like as air temperature and wind speed and direction creating urban canyons where air is confined in small compartments surrounded by building walls. Between buildings air mixing is reduced creating thus favorable condition for concentration of atmospheric pollutants in small areas, with negative impact on health and city infrastructure. The confined air would also reduce ventilation at street level creating warmer spots within the urban canyon and urban thermal discomfort. Besides the built surfaces, also heat-generating fuel combustion traffic cars, heating, ventilation and air conditioning systems, as well as industrial sources can affect at micro and macro scales climate processes.

As an important component of urban ecosystems, urban green spaces play central roles in increasing the economic efficiency, improving air and natural ecological quality and residential living standards [6]. Due to local differences in aerodynamic and thermodynamic properties, such as moisture, albedo, roughness, and thermal storage between the city and its surrounding rural environment urban surface effects are very complex and include: (a) Urban heat island (UHI) effect characterized by higher temperature over urban regions compared to the neighboring rural regions, (b) summer season thunderstorms together with flash flooding (c) enhancement of precipitation in the downwind part of the urban areas and (4) increase in the length of growing seasons [7]

Urban 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 differently regarding urban microclimate [8].

Based on the scale and height of their appearance and altitude measurements, available studies classified UHI effect in three groups: *boundary* UHI (measured from the altitude of rooftop to the atmosphere) - used for mesoscale analysis, *canopy* UHI (measured at the altitude that ranges from the ground surface to the rooftop) - which is most suitable for a microscale studies and is generally derived based on weather station data, and *surface (skin)* - SUHI (measured at the earth surface level).

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. Another important radiative variable 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, several studies forecast increases in the severity, frequency and duration of extreme heat events [9].

Knowledge of urban thermal environment through spatio-temporal monitoring of land surface radiative parameters by remotely sensed imagery is of prime importance for urban climate and human–environment interactions. Remote sensing sensors use measurements of the electromagnetic radiation, usually sunlight reflected in various spectral bands, to characterize the landscape and infer surface properties.

Measurements of the reflected solar radiation (visible and short waves infrared sensors) provide information on land-cover, extent of urban surface imperviousness and albedo. Thermal radiation (thermal-infrared sensors) gives estimates of surface temperature and surface energy fluxes. Land cover is the actual distribution of physical and biological features of land surface.

Geospatial data of various spectral, angular, and temporal resolutions have been widely used to study the urban land cover changes associated with urban growth, and to retrieve air and land surface biophysical parameters, such as vegetation fraction cover, built-up indices, air and land surface temperatures, land surface radiative fluxes, vegetation indexes, albedo, etc., which are good indicators of urban thermal environment [10].

3. Satellite derived biophysical parameters for urban thermal environment analysis

Satellite remote sensing is the only available way to dynamically monitor the urban environment at regional and global scales. During recent years, several methods were developed to retrieve various biophysical and radiative parameters from different optical sensor observations and provide corresponding parameter products. Geospatial Earth Observation data provided by multispectral, multispatial, multitemporal satellite sensors are very useful for urban thermal environment analysis through: 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 UHI, and the surface heat island; investigation of urban heat balances [11].

With the availability of thermal sensing data such as Landsat TM/ETM/ 8 OLI, thermal infrared (TIR) bands, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) thermal infrared (TIR) images, and the Advanced Very High-Resolution Radiometer (AVHRR-NOAA) thermal channels, study of land surface temperature from thermal images has been a topic of great interest in the remote sensing literature for the last three decades. Thermal data, covering NIR-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) as well as from Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the National Aeronautics and Space Administration’s Terra and Aqua satellite platforms, which pass over the same location on Earth once or twice per day.

Remote sensing can be used to derive spatiotemporally continuous radiative and biophysical variables of urban environment. Empirical algorithms can be used to quickly retrieve surface radiative data sets, but their accuracy cannot be always guaranteed in regions without local calibration. Physical algorithms generally incorporate all relevant physical processes and can be used globally, but their computational efficiency is often low. Use of efficient algorithms developed to calculate urban land surface biophysical parameters by combining a clear-sky model and the parameterizations for cloud transmittances are necessary. In these algorithms, the transmittances for water vapor, ozone, Rayleigh, aerosol, and cloud are each handled across the whole VIS, NIR and IR bands. In addition, the contribution of the multiple reflections between surface ground and the atmosphere are also expressly considered. Based on the new developed algorithms applied to estimate instantaneous radiative parameters with inputs from Moderate Resolution Imaging Spectroradiometer (MODIS) products on board both Terra and Aqua platforms, time series satellite data can be used to efficiently analyze climate and urban land cover impacts on thermal environment. The daily values of parameters are estimated from the two instantaneous values by an upscaling method. The instantaneous and daily estimates are validated with *in situ* data collected by NASA (National Aeronautics and Space Administration). The results indicate that the new applied algorithms on MODIS data products, can effectively retrieve radiative variables with very good accuracy [12], [13].

Multi-scale assessment of urban thermal environment and its dynamics is considered to be an essential step for mitigation and regulation of UHI effects especially in crowded metropolitan areas. The most useful parameter products are retrieved operationally from Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua (Terra-Aqua) satellites, including land surface albedo, spectral vegetation index (NDVI/EVI), leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), aerosol optical depth (AOD), and others.

The main goal of this paper was to develop an integrative approach of satellite data provided from NASA and ESA (European Space Agency) to monitor the key radiative and biophysical parameters that govern the urban thermal environment. Currently, no single sensor can provide data at the desired temporal and spatial scales. Furthermore, the parameters can be mapped at a temporal scale relevant to their dynamics and at a spatial scale that will allow practical assessment and management of their impacts on ecosystem function.

3.1. Land surface albedo

The albedo of a surface is the extent to which it reflects light from the sun. So, land surface albedo is defined as the ratio of reflected to incident radiative flux density, being governed by the radiative interactions between atmospheric multiple scattering and absorption and surface reflection and absorption under specific atmospheric conditions (including clouds), being also dependent of solar zenith angle, dew, frost, and wind which can cause significant diurnal variations in surface albedo. Urban land surface albedo is an essential climate variable required to accurately model the regional and global surface energy budget [14]. It is highly variable in time because of the rapid variation of atmospheric conditions and the slower variations of surface conditions [15], [16].During last decades, the availability of several satellite remote sensing data sets allowed direct estimates of surface radiative fluxes that resolve regional and weather-scale variability over the whole globe with reasonable accuracy (10–15 W/m^2). To estimate albedo from remotely sensed observations, the intrinsic variability in the reflective character of the surface, was described by the Bidirectional Reflectance Distribution Function (BRDF). As an important indicator of surface energy exchange for climate change, satellite-based albedo can provide detailed spatial-temporal information which can help improve land surface process parameterization. Depending on its color and brightness, a change in urban land surface can have a positive (cooling) or negative (warming) effect on climate change. Land surface albedo is dependent by urban ecosystem structure and the optical characteristics of its components, its spatio-temporal dynamics being closely related to ecosystem dynamics. Therefore, impacts of climate change and variations on ecosystem processes could possibly affect surface albedo characteristics. Since the physical climate system is very sensitive to surface albedo, the ecosystems could significantly feedback to the projected climate scenarios through albedo changes.

3.2. Surface latent heat flux

Energy Balance Equation (EBE) is mathematically expressed through:

$$R_n + A = LH + H + G \tag{1}$$

where R_n is the net all-wave radiation (the net incoming and outgoing radiative fluxes), A is the anthropogenic heat flux (the energy released by human activities), LH is the surface latent heat flux (the energy taken up/released with the phase change of water), H is the turbulent sensible heat flux (the energy that heats the air) and G is the net storage heat flux (which includes soil heat flux and also heating and cooling of the complete urban structure). For natural land surface anthropogenic heat flux is attributed to combustion of fuels and industrial sources can be neglected, while for urban areas due to anthropogenic heat discharge A adds to the het flux components. The incoming components are positive and outgoing is counted as negative. The net radiation R_n is the sum of the incoming and outgoing short and long wave components [17].

Net radiation R_n is the dominant term in the Energy Balance Equation (EBE), since it represents the source of energy that must be balanced by the thermodynamic equilibrium of the other terms. The incoming short waves radiation is the portion of the visible energy from the Sun and it can be evaluated from remote sensors. All these parameters are dependent of meteorological data which include wind speed, relative humidity, air temperature and pressure, precipitation, incoming solar radiation and proximity from the water surface.

The surface latent heat flux LH is used to describe the flux of heat discharge from the Earth's surface to the atmosphere being associated with the evaporation and/or transpiration of water at the surface and the subsequent condensation of water vapor in the troposphere. The variations in land surface heat fluxes affect the ecological environment, hydrological processes and the stability of infrastructures. Land surface albedo decrease due to the underlying surface change makes sensible heat flux H gradually dominate in surface energy budget, that impacts negatively urban thermal environment and UHI development [18]. The urban heat-island effect occurs as a result of increased sensible heat flux H from the land surface to the atmosphere near cities. Sensible heat flux H consists of two components, heat radiation due to solar input and heat due to anthropogenic discharge.

Because heat fluxes and urban thermal state are very complex at the land-atmosphere interface over cities underlying surface, the research on quantifying the relationship between land use change and urban thermal environment is very important. Several studies have shown that remote sensing provides a unique tool for assessment of urban expansion and land cover changes but also for spatial and temporal distribution of energy and heat fluxes [19].

Remote sensing is of great significance for the study of large-scale and long-term urban thermal environment. Remote sensing technology can simultaneously measure land surface situation in the form of visible bands and land surface thermal condition in the form of thermal infrared bands. The information obtained has good consistency and comparability, and gradually become the main source to estimate urban heat fluxes.

3.3. Land surface temperature (LST)

Land surface temperature (LST) is the radiative skin temperature of the land surface that is measured in the direction of the satellite sensor, representing the average surface temperature in a given unit area at a certain time of day. It is determined by the effective radiating temperature of ground, which controls surface heat and water exchange with the atmosphere [20]. It is an essential parameter of physics of land surface processes on local, regional and global scales for the complex surface-atmosphere interactions and energy fluxes (both sensible and latent) between atmosphere and ground, important for biological processes and climate analysis. The surface temperature depends on the albedo, the vegetation cover, surface roughness, soil thermal inertia and the soil moisture.

LST is a significant indicator of surface energy and moisture conditions. LST retrieved from multisensor satellite data provide a means to understand land surface processes efficiently via consistent periodicity, high-spatial resolution, and global coverage. Satellite-retrieved LST has been widely applied for urban environment to investigate soil moisture, surface energy fluxes, surface hydrology, vegetation dynamics, and environmental and ecological changes. In urban climate studies, the satellite-based LST has the ability to comprehensively describe the complex spatio-temporally temperature distribution in highly heterogeneous urban environments. In urban thermal studies, LST 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. The UHI effect can be measured for the individual thermal images and then compared between different time periods. Urban thermal environment is usually delineated by LST. Most urban surfaces consist of different manmade materials with distinct reflectance and thermal emission.

Land surface temperature extracted from MODIS terra/Aqua satellite data are very useful for urban thermal environmental research. 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 range 3-15 μm [21]. 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, MODIS on-board the EOS-TERRA platform offers new perspective in Earth observation in the infrared spectrum (3-15 μm). 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, and 23) in the 3-5 μm 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 [22]. 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.

3.4. Air Surface Temperature (AT)

Urban air temperature (AT) is considered a significant parameter for a variety of urban issues, and analyzing the spatial patterns of air temperature is important for urban planning and management. Air temperature is generally measured at weather stations at 2 m height with high temporal resolution and accuracy. In a city, natural and artificial materials are mixed at various spatial scales and respond differently to incoming solar radiation, which in turn affects air temperature. Meteorological in field observations together time series NOAA data can provide useful information on city air temperature.

3.5. Vegetation indices

Normalized Difference Vegetation Index (NDVI, Eq. (1)) is a widely used indicator for mapping and monitoring urban vegetated areas using multispectral remotely sensed data. Urban vegetation land cover dynamics is studied by means of vegetation indices (VIs) developed based on combinations of two or more spectral bands, using radiance, surface reflectance (ρ), or apparent reflectance (measured at the top of the atmosphere) values in the red (R), and the near infrared (NIR) spectral bands [23], [24]. This study used Normalized Difference Vegetation Index NDVI expressed as:

$$NDVI = (\rho_{NIR} - \rho_R)/(\rho_{NIR} + \rho_R) \tag{2}$$

As NDVI is known to saturate at intermediate values of Leaf Area Index (LAI), the use of the Enhanced Vegetation Index (EVI) is a better choice. EVI was introduced in order to improve the predictability of LAI in densely forest vegetated areas by considering the uncertainty of atmospheric and background sources [25]. EVI is given by the following relationship:

$$EVI = 2.5\frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + 6\rho_R - 7.5\rho_{BLUE} + 1} \tag{3}$$

while spectral vegetation indices may be transferable between different satellite sensors, there are significant challenges and potential discrepancies associated with the intercomparison of the biophysical products. Different spectral and spatial resolutions and sensor sensitivities, as well as variable ground data can be used for several algorithm trainings.

4. Study test area and data used

Urban metropolitan region Bucharest placed in the South – Eastern part of Romania, being at latitudes 44.33 °N and 44.66 °N , centred at 44.42 °N and longitudes 25.90 °E and 26.20 °E, centred at 26.09°E, is described by a star-shaped pattern (Figure 1),. The city is crossed by the Dâmbovita and Colentina rivers and is surrounded by forests, which makes urban and periurban Bucharest a city with parks, forests and lakes, 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 625 km^2 and almost 2 millions of residents.

Bucharest is among the very large cities highly vulnerable to natural hazards, like earthquakes, and extreme climate events (heavy rains, extreme temperatures). With an increased number of vehicles of between 1990 and 2018 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 thermal environment of Bucharest metropolitan area, was based on time-series MODIS and NOAA satellite data and multispectral and multitemporal cloud free satellite data: Landsat TM 21/08/1990; Landsat ETM 20/08/2007, Landsat ETM 16/08/2012, Landsat 8 OLI 12/08/2018 and radiometric and geometrically corrected.

Fig. 1.Test site of Bucharest metropolitan zone on Landsat 8 OLI 12/08/2018 image

Time series MODIS Terra/Aqua satellite data used for period 2000/2002 - 2018 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 several heat waves periods have been registered, of which summer 2007 and 2012 were the highest. Some *in situ*-monitoring meteorological data as well as ENVI 5.0, IDL 6.3 and ILWIS 3.1 software have been also used.

5. Results

Bucharest metropolitan area has a complex environment that includes buildings, roads, green and blue structures. Urban land cover features have reduced vegetation and permeability that limit evapotranspiration and infiltration. Especially higher air and land surface temperature during summer periods are attributed to increase impervious surfaces which consist of asphalt road, concrete pavements and buildings which have lower albedo and higher absorptivity than in rural regions. These urban surface properties modify the urban surface energy and water balance in a different way from the natural surfaces. Also city morphology and geometry of Bucharest can affect wind speed and direction creating urban canyons where air is confined in small compartments surrounded by building walls. This restricted air in between buildings reduces mixing of air creating favorable condition for accumulation of high pollutant concentrations due intense traffic or industry in small areas, with a negative impact on health and infrastructure. The confined air would also reduce ventilation creating warmer spots within the urban canyon, which results in urban thermal discomfort. Not only the built surfaces, but also heat-generating fuel combustion machines (e.g., cars), heating, ventilation and air conditioning systems, and other anthropogenic processes affect local and large scale weather and micro climate processes.

A series of Landsat TM/ETM/OLI satellite images were used to derive LST of selected urban/periurban areas and their surroundings in the Bucharest metropolitan region in Romania. For understanding the impact of land surface temperature on urban environment in Bucharest, thermal data were selected due to their free availability from MODIS, Landsat and NOAA. Furthermore, land surface temperature is an important climate related measurement. MODIS land surface products available online generated with a lower spatial resolution than Landsat were also used. For increased quality on the results and taking into consideration the size of Bucharest metropolitan zone, the thermal bands for Landsat (that have higher resolution) were used to understand the long-term changes in temperature of the selected areas. After downloading of time series of remote sensing data, nevertheless, extra processing was required when using these datasets because the data need first be converted into meaningful land surface temperatures before interpretation. The data were used to calculate temperature differences between the urban area and the surroundings for quantifying the UHI effect as well as to assess land use/cover changes. These temperature differences were related to environmental variables, surface properties and land cover for deriving relations and interactions between temperatures inside and outside the urban area.

The detection of urban areas inside of each satellite scene was supported by supervised maximum likelihood classification. The classifications were only performed for image sections that are urban areas. The supervised classification of the analyzed images produced the information on urban/periurban areas for each of the considered image mosaics. The classification outputs were converted to vector format and corrected manually after majority filtering to generate spatially consistent urban areas. All urban areas were encircled by a 100 m-zone to define their surrounding area. The surrounding area needed to be small to minimize effects from neighboring periurban areas or steep slopes. The outline of the urban area and their surrounding zones were used together with the information on LST and Normalized Difference Vegetation Index (NDVI) to produce for each observation the mean land surface temperature and the mean NDVI for the urban zones (LST urban, NDVI urban) and for the surrounding zones (LST periurban,NDVI periurban). Areas with anomalies like clouds or artefacts that were identified by e.g. negative LST were excluded from the analysis. Our investigation showed that the largest difference in urban/periurban land surface temperature occurred in the summer season and during the daytime, and the difference seems to be primarily controlled by disparate urban/periurban land use and land cover features. However, the urban/periurban contrast in land surface temperature was much less during the winter time, with much weaker coupling between spatial temperature distribution and land use/cover patterns.

Based on *in-situ* monitoring of meteorological variables and climatic mapping, the impacts of urban constituents such as building, pavement, greenery and water area on UHI intensity and microclimate conditions were analyzed. Results show that UHI intensity reaches up to 4.6 ºC during daytime and 5.7 ºC at night in summer, and 2.2 ºC during daytime and 5.4 ºC at night in winter. The cooling effect of trees is evident during both summer daytime and nighttime, but negligible in winter due to the reduction of leaf area and evaporation. The presence of both green land cover and blue water body result in an increase in air relative humidity levels, which during summer heat waves bring an increased health discomfort. Also, urban trees tend to reduce wind speed and improve thermal comfort in winter. Radiant heat dissipated from buildings and roads is the main contributor to nighttime UHI in both summer and winter seasons.

Based on USGS NOAA data, Fig. 2 presents average summer months (June-August) air temperature AT variations during 1950-2018 years from time series NOAA AVHRR historic data for Bucharest metropolitan region. It is a clear evidence of global warming impacts on air temperature at city level after 1990 year, mostly during heat wave events recorded in 2003, 2007 and 2012 years with an increasing trend till 2018. This confirms the increase of air temperature *in t*he South Eastern part of Romania, result that is in a good accordance with climate models forecasting for South Eastern Europe during next years.

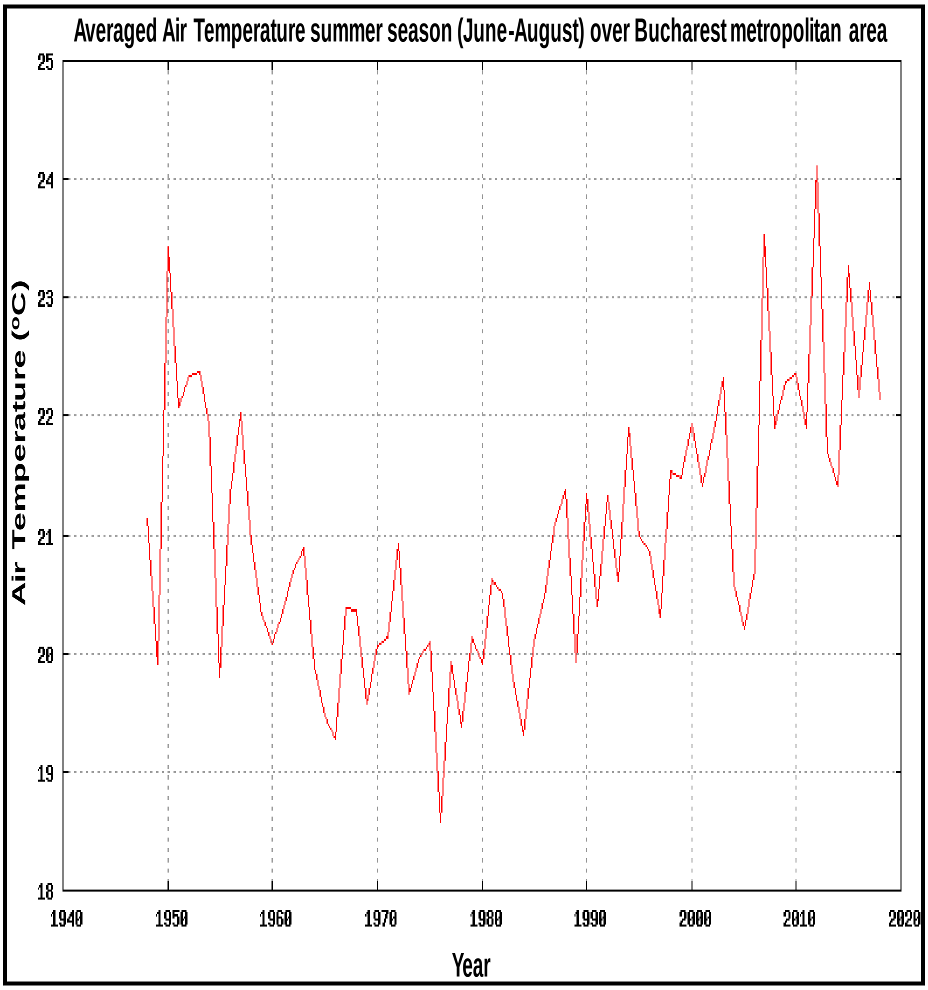

Fig. 2. Average air temperature TA for summer season (June-August) during 1950-2018 in Bucharest metropolitan zone

Continuous changes in the Bucharest urban and peri-urban land cover and land surface properties, in the atmospheric abundance of greenhouse gases and aerosols, as well as in solar radiation alter the energy balance of the microclimate 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 specific properties like 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.

Bucharest metropolitan region is under continuous influence of characteristic meteorological-climatic fluctuations of continental climate, and urban thermal environment is highly affected periodically during summer, when are registered severe heat waves periods of time longer than five consecutive days with serious impact on UHI and inhabitants‘ health.

Based on data provided by the MODIS terra/Aqua LST Day/Night data, MODIS MOD11A1/A2 (Terra) and MYD11A1/A2 (Aqua) products (provided by Oak Ridge National Laboratory Distributed Active Archive Center ORNL DAAC,MODIS subsetted land products [26], [http://daac.ornl.gov/MODIS/modis.html] was assessed the LST evolution in the greater area of Bucharest for period 2000-2018.

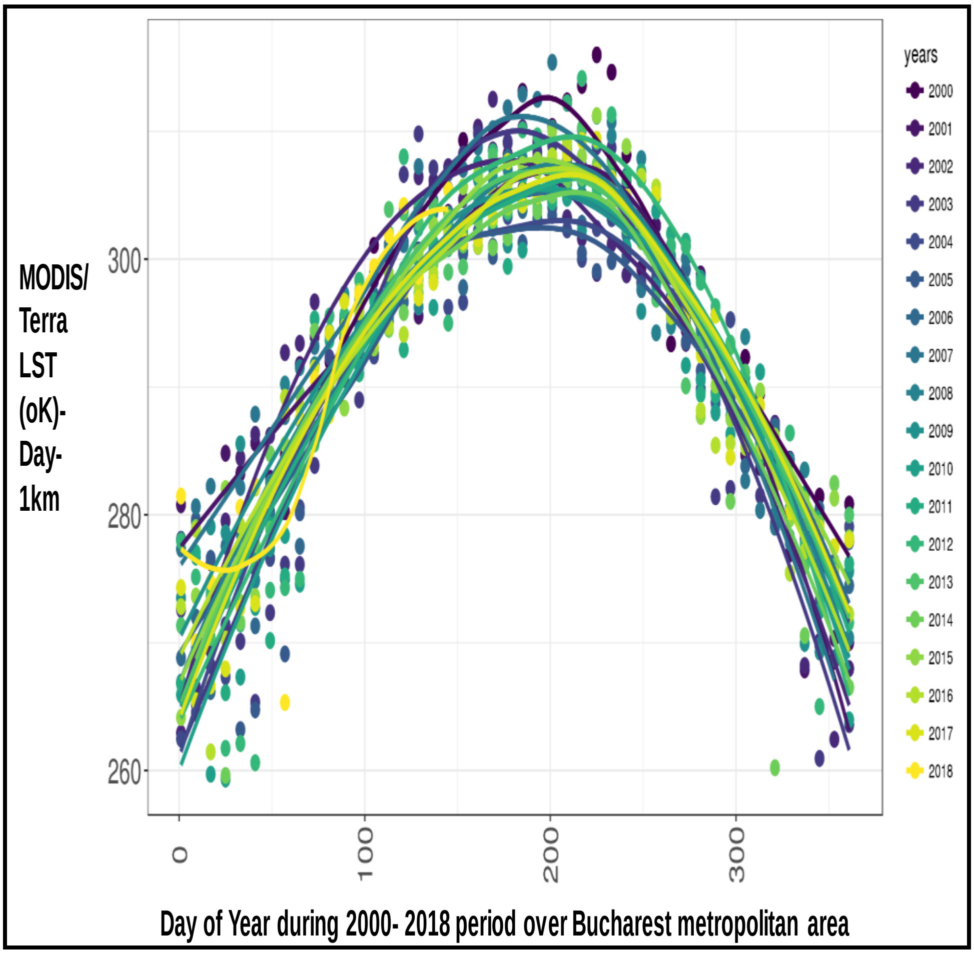

Fig. 3. Land surface temperature LST variation from MODIS/Terra satellite data during 2000-2018 over Bucharest metropolitan zone

Fig. 3 illustrates temporal variation of Land Surface Temperature MOD11A2/LST_Day_1km, Scale Factor = 0.02, Units= Kelvin, pixels having the same land cover as the center pixel represent 40.89% for the same class as the center pixel class- Urban and Built-Up for Bucharest metropolitan area centered Latitude: 44.42 and Longitude: 26.09 for an areal extent of approximately 31 km Wide x 31 km High. This graph also presents the high recorded values for LST during summer periods and heat waves events.

Urban land surface temperature is a major diagnostic parameter to describe the urban thermal environment in cross-scale urban climatic studies. Satellite monitoring and modeling of urban surface temperature at microscale is fundamental to advances in understanding the nature of urban microclimate, and it is essential for diverse studies related to urban pollution dispersion, pedestrian thermal comfort and building energy consumption.

Fig. 4 shows urban land surface temperature anomalies recorded by time series MOD14A2 (MODIS/Terra Thermal Anomalies/Fire mask) product satellite data during 2000-2018 over Bucharest metropolitan zone [27].

Based on recorded air temperature at Bucharest meteorological stations and MODIS Terra derived land surface temperature LST, during summer time period (June-August) a strong correlation between average air surface temperature AT and average land surface temperature LST was observed, Pearson coefficient being R^2= 0.852, with an average LST/AT ratio equal to 1.451.

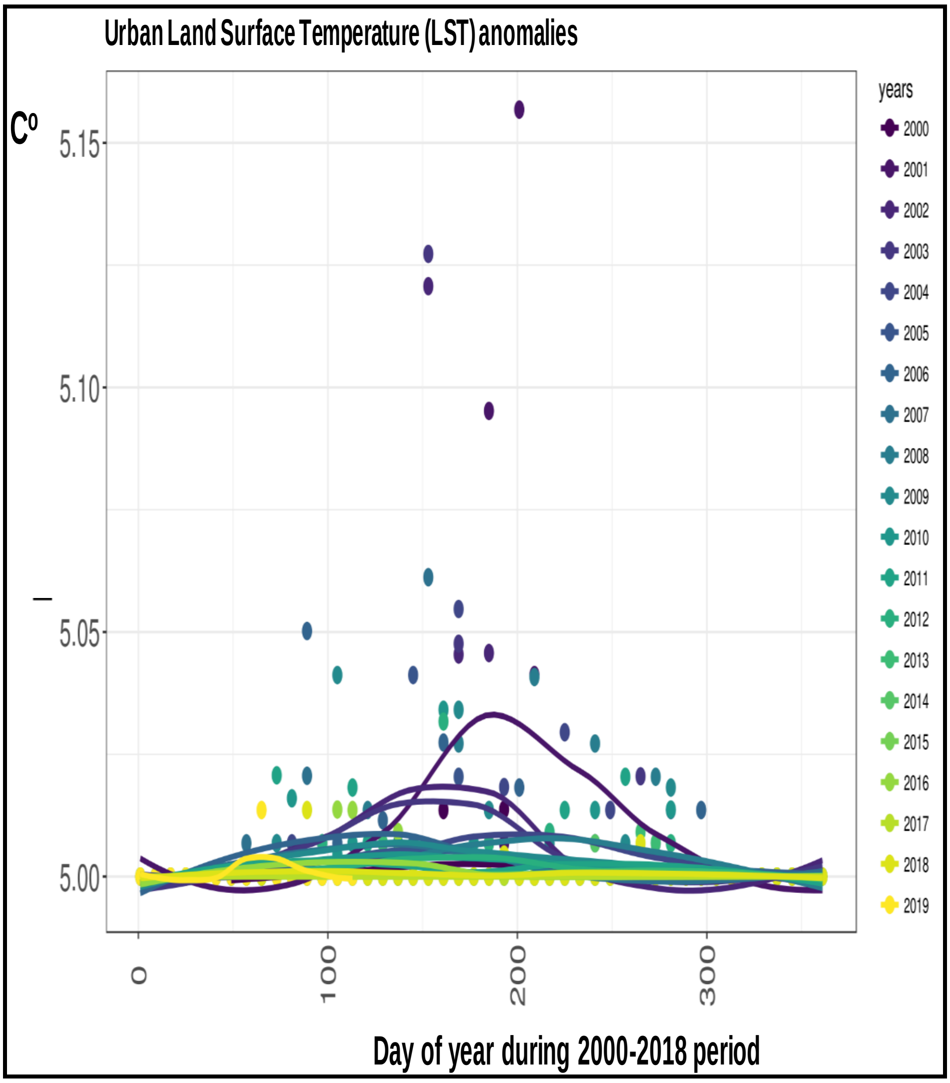

Fig. 4. Land surface temperature anomalies from MODIS/Terra satellite data during 2000-2018 over Bucharest metropolitan zone

Based on averaged Surface Latent Heat Flux data provided by NCEP Reanalysis of NOAA data (www.esrl.noaa.gov) for summer periods 1 June- 31 August of each year from 2000 to 2018 period, for Bucharest area metropolitan zone was represented in Fig. 5. It is clear evidenced the increased values of mean Surface Latent Heat Flux for heat waves summers recorded in Romania (2003, 2007 and 2012 years).

As an important indicator of surface energy exchange for climate change, satellite-based albedo can provide detailed spatial-temporal information which can help improve land surface process parameterization.

The MCD43A3 Albedo Product (MODIS/Terra Albedo Daily L3 Global 500m SIN Grid) [28] provides both the white-sky albedos and the black-sky albedos (at local solar noon) for MODIS bands 1-7 as well as for three broad bands (0.3-0.7µm, 0.7-5.0µm, and 0.3-5.0µm). While the total energy reflected by the Earth's surface in the shortwave domain is characterized by the shortwave (0.3-5.0µm) broadband albedo, the visible (0.3-0.7µm) and near-infrared (0.7-5.0µm) broadband albedos are often also of interest due to the marked difference of the reflectance of vegetation in these two spectral regions.

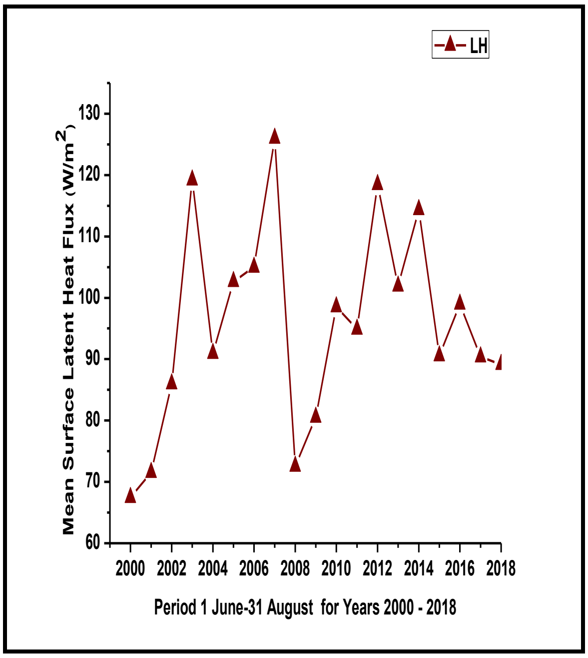

Fig. 5. Average summer period (June-August) Latent Heat Flux LH variation from NOAA satellite data during 2000-2018 over Bucharest metropolitan zone

Table 1 presents monthly mean of the observed meteorological parameters (maximum and minimum air temperature AT, precipitation R, surface solar irradiance) and derived MODIS Terra broad band albedo in visible VIS and near-infrared NIR regions and vegetation index NDVI for 2000-2018 period over Bucharest metropolitan area.

There is a positive correlation between recorded in-situ mean maximum and minimum temperatures and NDVI vegetation indices derived from MODIS Terra MOD13Q1/250m_16_days_NDVI, for 2000-2018 period over Bucharest presented in Table 1, as Pearson correlations coefficients detect almost the same value (R^2=0.87). Also between surface mean solar irradiance and MODIS Terra satellite derived values of NDVI there is a positive Pearson correlation (R^2=0.82). Solar radiations have always positive effects on LST, but with no clear seasonal pattern. There are negative correlations between MODIS broadband albedos the visible (0.3-0.7μm) and respectively near-infrared (0.7-5.0μm) products (MCD43) and NDVI (R^2=-0.61 and respectively R^2=-0.47).

Table 1. Monthly mean observed meteorological parameters and derived MODIS albedo and NDVI for 2000-2018 period over Bucharest metropolitan area.

Month	Mean max. AT (C°)	Mean Min. AT (C°)	Mean R (mm)	Surface Mean solar irradiance (W/m²)	Mean VIS BB Albedo MODIS Terra	Mean NIR BB Albedo MODIS Terra	Mean NDVI MODIS Terra
January	2.0	-6.1	40	211	0.23	0.26	0.09
February	4.8	-3.6	40	346	0.69	0.53	0.22
March	11.9	0.5	40	466	0.51	0.40	0.37
April	18.4	6.8	50	578	0.08	0.24	0.54
May	23.7	11.3	70	727	0.08	0.23	0.62
June	27.9	14.5	80	759	0.08	0.24	0.58
July	29.7	16.6	60	827	0.07	0.25	0.56
August	30.0	15.7	60	799	0.10	0.27	0.52
September	25.6	11.9	40	678	0.08	0.23	0.48
October	18.7	6.7	30	440	0.25	0.31	0.46
November	10.8	2.4	50	307	0.12	0.22	0.40
December	4.6	-3.9	40	180	0.12	0.23	0.36

Fig. 6 presents variation of Enhanced Vegetation Index (EVI) from MODIS Terra satellite data MOD13Q1/250m_16_days_NDVI/EVI_product during 2000-2018 over Bucharest metropolitan zone [29]. It is a clear decrease of green vegetation index during summer months with heat waves. During summers of 2003, 2007 and 2012 years, characterized by recorded strong heat waves and land surface temperature anomalies, the vegetation land cover recorded very low level values reaching 0,35. As heat waves are expected to become more frequent and severe in urban regions in the next years due to climate changes, with unknown consequences for urban ecosystems, ecologically-relevant broad-scale indicators of heat waves based on different satellite land surface temperature data must be identified.

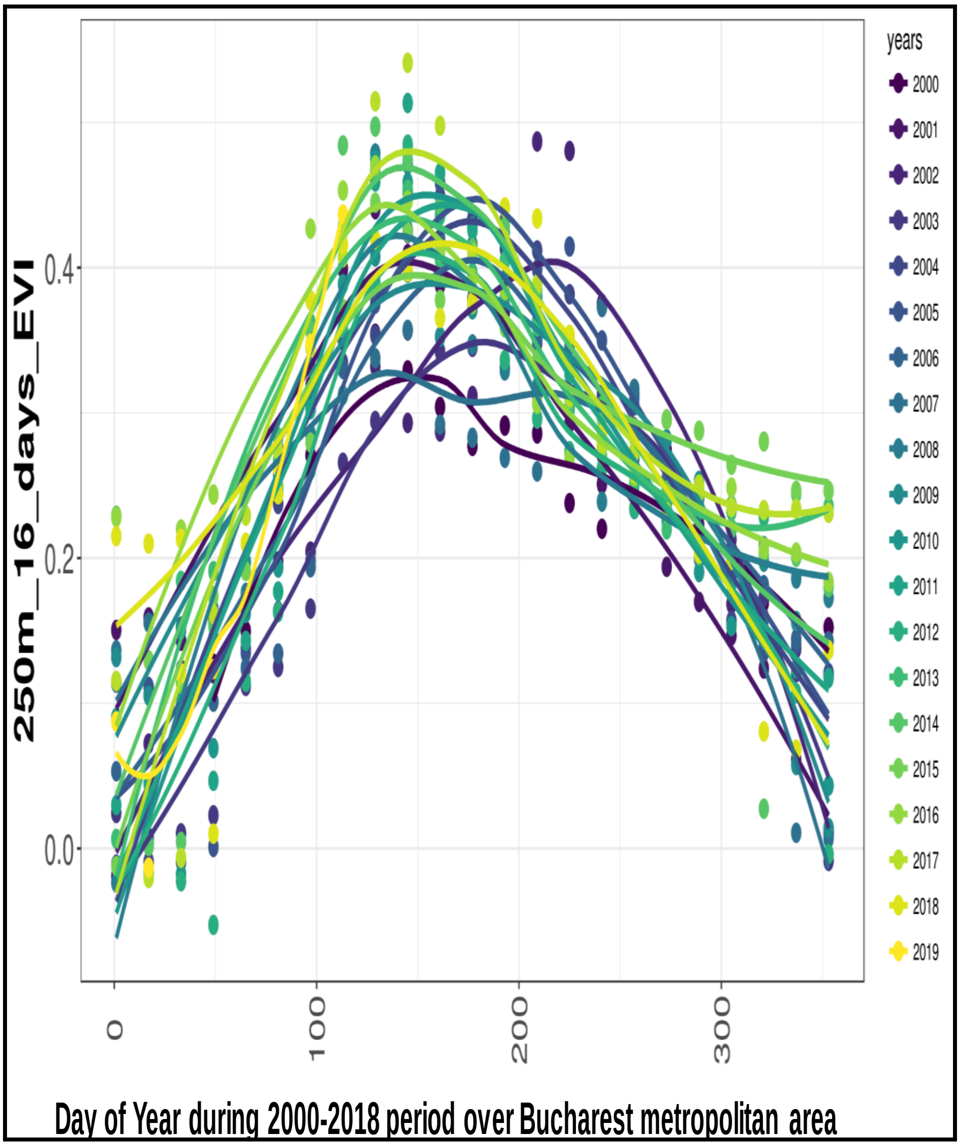

Fig. 6. Enhanced Vegetation Index (EVI) variation from MODIS/Terra satellite data during 2000-2018 over Bucharest metropolitan zone

The general urban surface temperature patterns that are important in determining ecosystem and climatic conditions are therefore directly connected to anthropogenic impacts. It was recorded a clear temporal variation of urban vegetation EVI parameters with a decreasing trend during summer-autumn seasons due to low level of precipitations and increasing levels of land surface temperature. This fact has a negative impact on vegetation land cover in the South-Eastern part of Romania and through this on biomass resources.

Figure 7 shows MODIS Land Cover Classification and legend (Collection 5 IGBP Type_1 2016), selected area 201 km Wide x 201 km High with user selected Area Marked MODIS land cover 60.5 km Wide x 60.5 km High, for investigated metropolitan zone of Bucharest in Romania.

Bucharest expanded in all directions during the investigated period 1990-2018 covered by the available Landsat images satellite images. Change analysis 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.

Vegetation and impervious surfaces are the dominant predictors of urban thermal environment and air temperature AT and land surface temperature within cities [30-33], but there is debate over which is most important, arguing that percentage impervious surface is a better predictor of LST than vegetation [34-36].

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. 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.

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}.

A negative relationship between EVI and LST was obtained for urban vegetation-covered areas and a positive one for water bodies cover, as LST is strongly influenced by land cover and vegetation, low LST values being obtained for dense forested vegetation areas.

At the micro scale, the surface albedo and temperature should have large variations in the all six urban sectors because of the large material and structural versatilities. 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.

Our study based on extraction of urban radiative variables from Landsat TM/ETM/OLI, NOAA Advanced Very High Resolution Radiometer (AVHRR) and the NASA Moderate-resolution Imaging Spectroradiometer (MODIS) satellite data reveals that the low spatial resolution brings uncertainties in mixed pixels, integrating different land cover types signals (like as phenological signals of different vegetation and land cover types, e.g., deciduous forests and nearby grasslands or for different spectral fingerprints of urban surface impervious materials).

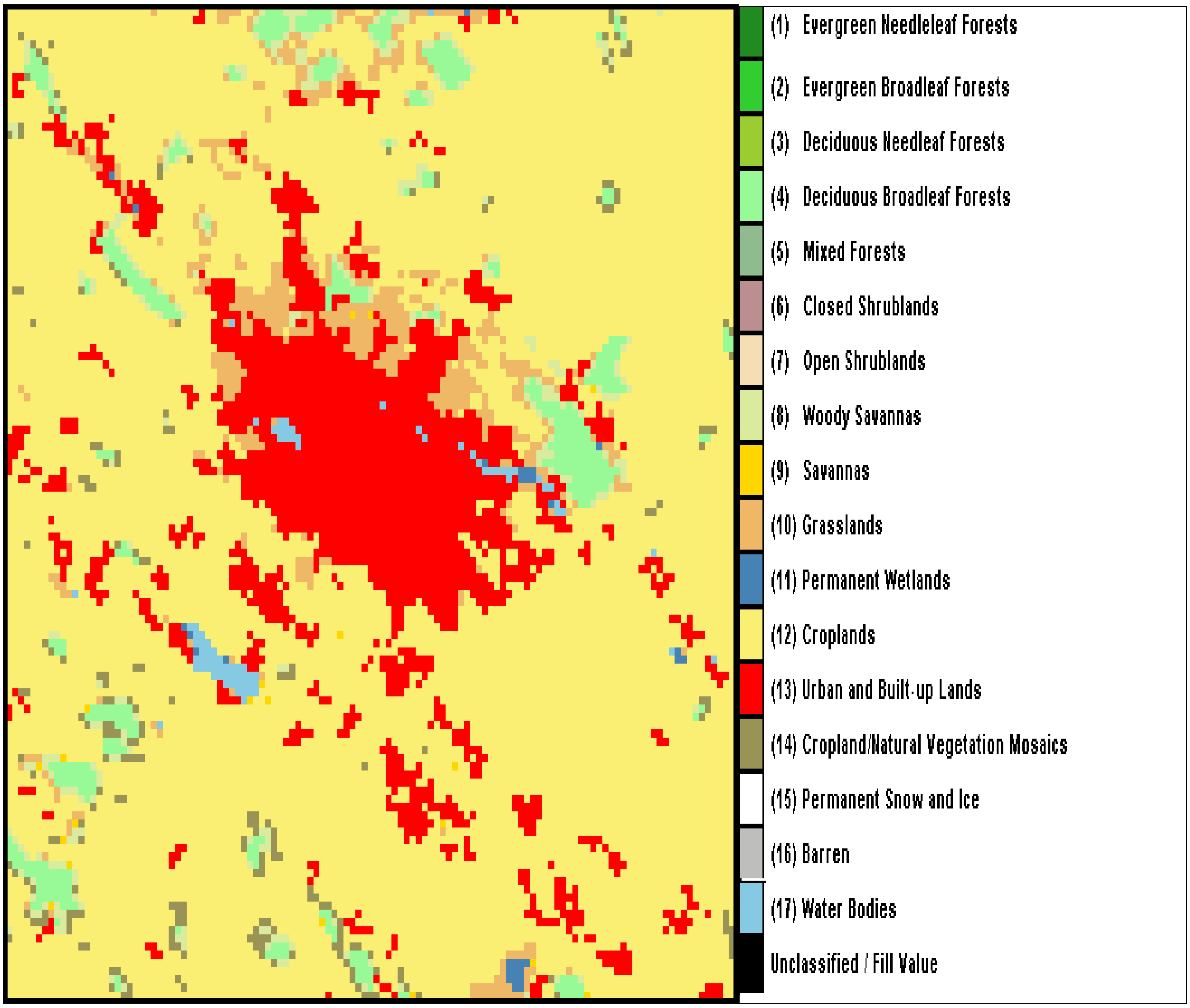

Fig. 7. MODIS Land Cover Classification and legend (Collection 5 IGBP Type_1 2016) 201 km Wide x 201 km High with user selected Area Marked MODIS land cover

Use of new developed algorithms for satellite data analysis and statistical methods will be possible to model the spatial dependences between pixels, their temporal correlation, as well as the (possibly non-linear) relationships between multiple urban radiative and biophysical variables. One important component of these models is the assumption of stationarity, meaning that the statistical model is valid for the entire target domain. This requirement is valid for all types of stochastic models, parametric as well as non-parametric ones. However, the variables that will be modeled are inherently non-stationary, meaning that their properties can strongly vary in both space and time. Spatial non-stationarities occur because a single satellite image can contain several types of landscapes or textural characteristics. Temporal non-stationarities include seasonal variations, for example described as a recurrence of patterns from year to year at a given location. Another important source of temporal non-stationarity is the trends incurred by climate change or low-frequency climatic events.

New satellite generations, such as the Copernicus Sentinel 2/3/4/5, may overcome this issue with higher spatial resolution. Besides noise effects due to atmospheric conditions, snow cover, soil-wetness, viewing geometry and illumination conditions, as well as the distorted signal under overcast conditions, mixed pixels introduce additional effects altering the dominant sensor signal. Noise introduced by these effects can be eliminated by using different methods and algorithms like Maximum Value Composite (MVC) or using dynamic filtering techniques, which can provide reliable satellite derived radiative variables time series. [37].

Geospatial analysis science is evolving at a rate never seen before, driven by novel machine learning algorithms, cheap computational resources and pervasive data availability. In the last decade, artificial intelligence has been widely used for making sense of large volumes of data, for example through the use of classification algorithms. Generation of different radiative satellite derived variables can be provided also from Ground-Based Spectral Measurements, which are used for satellite data validation. Linking small-scale *in-situ* observations with large-scale satellite products is crucial to understand the relationships between optical information and urban ecosystems.

6. Conclusion

The impacts from recent climate-related extremes, such as heat waves and urban heat islands, reveal significant vulnerability and exposure of some urban ecosystems and human society to current climate variability. Knowledge of urban thermal environment through air and land surface temperature spatio-temporal monitoring as well as heat fluxes variation within a city is of prime importance to the study of urban climate and human–environment interactions. Land-cover changes and impact of extreme climate events in metropolitan area of Bucharest are responsible of the increase of the local air and surface temperatures of several degrees compared to those of the periurban rural areas. This effect is quantified by the urban heat island intensity, describing the difference in temperature between the urban locations and the surrounding rural background. Climate change and urban growth result in a greater increase of hot nights for Bucharest city than neighboring periurban areas, increasing the thermal stress and vulnerability to heat waves of urban citizens in a warmer climate compared to their rural zones. Changes in the urban and periurban 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. The continental climate in Bucharest features hot summers, cold winters, and almost four distinct seasons, that must be considered in the future work. 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. Urban climate research is increasingly necessary due to climate change and the ongoing trend of urbanization. While in some urban areas land surface temperature is a good indicator of heat vulnerability, the functional relationship between it, air temperature and thermal comfort still needs further work.

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