SPATIAL CHARACTERISTICS OF THE LAND SURFACE TEMPERATURE IN BUCHAREST METROPOLITAN AREA

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Key-words: Land Surface Temperature (LST), Bucharest Metropolitan Area, Landsat-8.

Abstract. Land surface temperature (LST) is the key driving force in the exchange of radiation at the land surface/atmosphere interface and one of the foremost parameters in the physical processes of surface energy exchange locally and globally. Bucharest Metropolitan Area is a dynamic territory, subject to rapid urban growth, the continuous expansion of the city over wider territories beyond its outskirts, thus transposing the thermal characteristics of the new surfaces. For the current study, in order to obtain the LST, a series of Landsat-8 scenes were analyzed. In the case of Bucharest Metropolitan Area, the spatial distribution of LST shows a high concentration of areas more radiant in the urban areas with dense built-up surfaces. Industrial sites and compact residential neighborhoods are characterized by high temperatures contrasting with the green spaces and water surfaces that are "coolness islands". The city's heat island is obvious, but the small difference compared to the surrounding areas is explained by the expansion of the urban metropolitan area with various functions (e.g. services and commercial) in the neighboring urban-rural space. The analysis showed that for the urban space, the largest thermal input is associated with the strong anthropogenic surfaces such as industrial plants, transport infrastructure and facilities (e.g. depots, annexes), airports, followed by the residential areas. The lowest average temperatures belong to green and water covered areas.

1. INTRODUCTION

Over the past century, both rapid population growth and continuous exploitation of natural resources have been the main causes of land-use/cover change worldwide (Zhou and Wang, 2011). In turn, greenhouse gases emissions and land use/cover changes (mainly related to urbanization and agriculture) are the most important anthropogenic factors influencing the regional and global climate (Kalnay and Cai, 2003) by combining both biochemical and biophysical processes (Liu *et al.*, 2016) at the land surface-atmosphere exchange level. Recently, cities have evolved beyond their administrative boundaries, in the form of a spatial and functional pattern known as urban sprawl. The extended urban expansion brings in surface modifications which include the replacement of soil and vegetation with impervious surfaces (e.g. concrete and asphalt), with specific urban structures such as buildings of various heights and densities (Zhou *et al.*, 2011). The rapid changes of land use/cover in urban areas have become a major environmental concern due to environmental impacts, such as the reduction of green spaces and development of urban heat islands (UHI) (Amiri *et al.*, 2009; Sun *et al.*, 2012). UHI is a phenomenon wherein cities have higher temperatures than the surrounding countryside as a consequence of: loss of vegetation and associated evapotranspiration, extended dark surfaces with low albedo (which absorb radiation and release heat), different thermal capacity and heat conductivity of the buildings etc. (Oke, 1982; Voogt and Oke, 2003). Moreover, the expansion of artificial surfaces resulting from urban expansion can be considered as a determinant in increasing transport emissions. A series of studies have shown that the relationship between artificial surface growth and increased CO_2 emissions in transport is very strong, much stronger than those induced by other factors such as population increase or GDP growth (EEA, 2006; Stone, 2008; Bart, 2010). The relationship between

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the components of the built environment and climate change was also stressed in the IPCC Reports (e.g. 2007, 2014), which highlighted that global GHG emissions increased to a large extent due to the following sectors: energy supply, transport, industry, land use and forestry, agriculture and buildings. Thus, strategies to reduce atmospheric CO_2 emissions should include reduced vehicle use, increased energy efficiency of buildings and reduction of deforestation (Metz *et al.*, 2007; Revi *et al.*, 2014).

In urban areas, low-density land use patterns have been also associated with high surface temperatures (Stone and Norman, 2006; Stone *et al*., 2010). Urban expansion severely transforms the soil's properties, reducing its ability to fulfill its essential functions. These effects are obvious in terms of the extent of soil compaction that affects soil functions (Frumkin, 2002; EEA, 2006) and consequently, land use/cover remittance. Land surface temperature (LST) observations based on remote sensing techniques have been widely used to assess the UHI, to develop land surface – atmosphere exchange models and to analyze the relationship between temperature and land use/cover in urban areas (Voogt and Oke, 2003; Amiri *et al.*, 2009). Thus, as a driving force in the exchange of radiation at the interface land surface/atmosphere, LST is a key parameter for assessing the physical processes of surface energy exchange locally and globally (e.g. Zhou *et al.*, 2011; Jiménez-Muñoz and Sobrino, 2003; Jiménez-Muñoz *et al.*, 2014).

Bucharest Metropolitan Area is witnessing a rapid urban growth under the form of urban sprawl, which leads to a continuous expansion of the city over wider territories beyond its outskirts (Kucsicsa and Grigorescu, 2018). As a consequence, the current study is seeking to assess the territorial distribution of LST in relation to the main land use/cover characteristics and to identify the spatial differentiation between the high concentrations of radiant dense built-up surfaces and the green spaces and blue surfaces (recognized as "coolness islands"). The spatial differences will reveal the way environmental changes, mainly in the form of land use/cover changes, urbanization, and agricultural activities, influence local and regional climates.

2. STUDY AREA

Bucharest Metropolitan Area is located in the south-eastern part of Romania, overlapping the central south-eastern part of the Romanian Plain (Fig. 1), also known as the Lower Danube Plain (Bălteanu, 2016). BMA is an urban-rural structure made up of one core city (Bucharest) and about 100 local administrative units (LAU 2 level), grouping over 2,500,000 inhabitants on a surface of nearly 531,292 hectares (Grigorescu *et al.*, 2015; Kucsicsa and Grigorescu, 2017). Over 70% of its territory is agricultural. Over the last two decades, the area was under continuous socio-economic transformations, which largely involved intensive land use/cover changes, making the agricultural land become a great land resource for the spatial expansion of the city over the surrounding rural area. Moreover, the incessant population dynamics have put great pressure on land, leading to extensive sub-urbanisation processes (Grigorescu and Kucsicsa, 2018), conversion of agricultural land into urban sprawl-related categories (e.g. residential, commercial, warehouses), uncontrolled exploitation of the natural resources, environmental pollution etc.

From a climatic point of view, Bucharest Metropolitan Area falls into the temperate continental climate, with a continentalisation trend from west towards east, as a consequence of the main climatic influences observed across the underlying plain region: transitional in the west and excessive-continental in the east (Bogdan *et al.*, 2016). The diversity of local climatic factors, the mosaic of the built-up area with multiple functions, agricultural and natural surfaces has a major influence on the specific climatic characteristics of the metropolitan area. All these factors with quasi-permanent influence change the regime of the different climate components which are transposed to the metropolitan area along with the spatial expansion of the urban sprawl phenomenon.

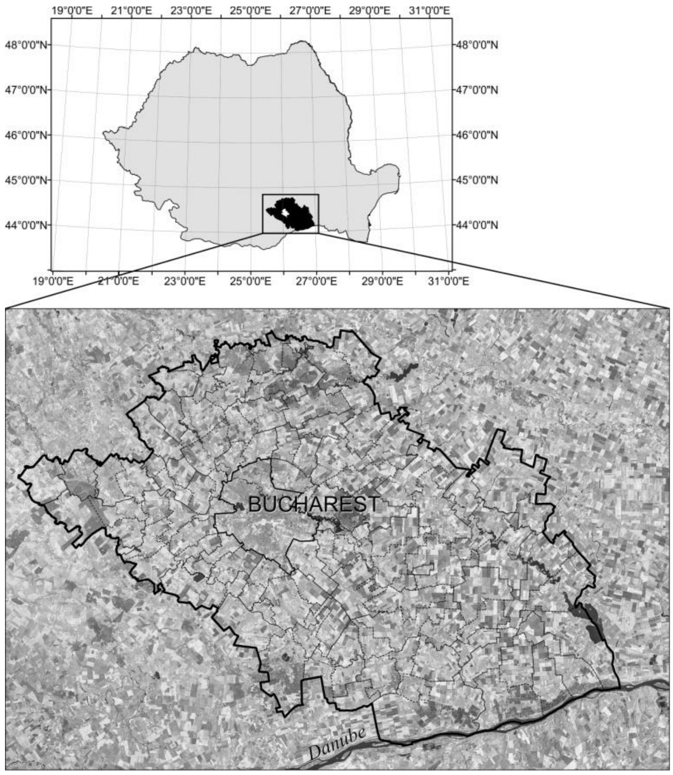


Fig. 1 – Study area location.

The influence of the city can be also noticed in the variability of all climate elements (e.g. temperature, rainfall, humidity) through the “urban heat island” effect, which is highlighted against the surrounding rural space. This effect is generated by the overheating of the built-up space, the nature of the construction materials, land use/cover types, the roads seal coating, the various angle of the solar radiation, population growth, quantity and nature of burned fuels, etc.

Over the past twenty years, Bucharest Metropolitan Area has witnessed an enhancement in climate change signals, in terms of a significant temperature rise, annual precipitation decrease and increase of extreme weather events (e.g. heat waves and drought, heavy rainfall, hail storms, acid deposits) whose occurrence, frequency and duration are closely connected to their main environmental triggers: land use/land cover changes and urban sprawl.

3. METHODOLOGY

As one of the most important parameters in assessing the physical processes of surface energy exchange, LST provides information about temporal and spatial variations in temperature and is of fundamental importance in many urban climatology applications. Due to the high heterogeneity of the land surface characteristics such as vegetation, topography, and soil, LST changes are fast in space and in time. Adequate characterization of the LST distribution and its temporal development, thus require measurements with high spatial and temporal accuracy. Given the complexity of land surface temperature, *in situ* land measurements cannot provide values over wide areas. With the development of space remote sensing, satellite data provides good opportunities for measuring LST around the globe at high temporal and spatial resolution. There are notable differences in the data processing for different sensors due to differences in data acquisition range and the type of calibration used. In the present study, LST has been estimated from Landsat-8 imagery (May 25, 2013). The Landsat-8 sensor has the advantage of 2 bands in the thermal infrared range, which increases accuracy in processing and obtaining LTS.

Due to the importance and wide use of the LST in a great variety of environmental studies (Jiménez-Muñoz and Sobrino, 2003; Jiménez-Muñoz *et al.*, 2014), an extensive range of methodologies have been developed to retrieve it from the satellite data. These methodologies are dependent on the type of the sensor used (the wavelength range of the satellite bands) and the corrections applied. The most frequently used methods for correcting surface radiance for atmospheric effects fall into two categories (Norman *et al.*, 1995): *direct methods*, which are using atmospheric temperature and humidity surveys, collected with probes mounted on balloons and *indirect methods*, which are applying atmospheric corrections directly on satellite data. Direct methods combine *in-situ* measurements of atmospheric temperature and moisture with atmospheric models of radiative transfer, as LOWTRAN and MODTRAN, calculating atmospheric transmittance and radiant path as a function of wavelength (Schott and Volchok, 1985; Goetz *et al.*, 1995). Indirect methods derive atmospheric vertical surveys from satellite data and atmospheric models for radiative transfer. In addition, split-window algorithms using channels 4 and 5 of the Advanced Very High Resolution Radiometer (AVHRR) (Becker and Li, 1990) channels 31 and 32 Earth Observing System NASA's Moderate Resolution Imaging Spectrometer (EOS/MODIS) (Vidal, 1991) or TIR (Thermal Infrared) bands (10 and 11) from Landsat-8 sensor (Jiménez-Muñoz *et al.*, 2014) were widely applied in atmospheric correction of the LST and emissivity for different purposes. After appropriate corrections, LST could be calculated from radiance theoretically corrected by reverse analyse of Planck's equation. However, in real-world applications, these models are usually difficult to apply, due to the low resolution and the requirements for different variables.

In Romania, MOD11_L2 and MYD11_L2 were the most frequently used satellite-derived products in studies regarding the Urban Heat Island (UHI) (e.g. Cheval and Dumitrescu, 2009; Cheval *et al.*, 2009; Cheval and Dumitrescu, 2015) having a high temporal resolution, but a coarse spatial resolution (1km). However, these products are not accurate enough to allow a detailed monitoring of urban spatial variations. Nevertheless, thermal data obtained from Landsat Thematic Mapper (TM), Landsat7 (ETM +), Landsat-8 and other medium resolution satellite sensors (e.g. Aster) are more attractive to undertake local and regional studies in the thermal infrared range, because of their superior spatial resolution (120 m for TM sensor, 60 m for ETM+ sensor and 100 m for Landsat-8). Preferably is to use those two types of data to improve both the spatial resolution and the temporal coverage. In time, several such techniques were created (Gao *et al.*, 2006; Hilker *et al.*, 2009; Zhu *et al.*, 2011; Weng *et al.*, 2014).

In the current paper, the authors have used the Landsat-8 thermal data which has the advantage of being equipped with two Thermal Infrared Bands (TIR) in the atmospheric window 10–12μm. The processing workflow to derive LST values are presented in Figure 2.

The first step is the pre-processing satellite data that aims to remove the noise and distortions from the measured signal coming from the land surface in order to calculate the reflectance parameter (ρBOA (Ωs, Ωv)) characterizing the surface.

In the second step, the digital number (DN) is transformed into radiance values $\mathbf{L_{TOA,\lambda}(\Omega)}$ for thermal bands B10 and B11. This radiance is a complex sum of many influences (Gastellu-Etchegorry, 2015):

$$L_{TOA,\lambda}(\mathbf{\Omega}) = L_{Earth,TOA,\lambda}(\mathbf{\Omega}) + L_{atm,TOA,\lambda}(\mathbf{\Omega}) + L_{mult,TOA,\lambda}(\mathbf{\Omega})$$

where:

$L_{Earth,TOA,\lambda}(\mathbf{\Omega})$ = Solar radiance due to solar flow dispersed by Earth's surface
$L_{atm,TOA,\lambda}(\mathbf{\Omega})$ = Solar radiance due to solar flow dispersed by Atmosphere
$L_{mult,TOA,\lambda}(\mathbf{\Omega})$ = Solar radiance due to solar flow dispersed by Terra –Atmosphere tandem

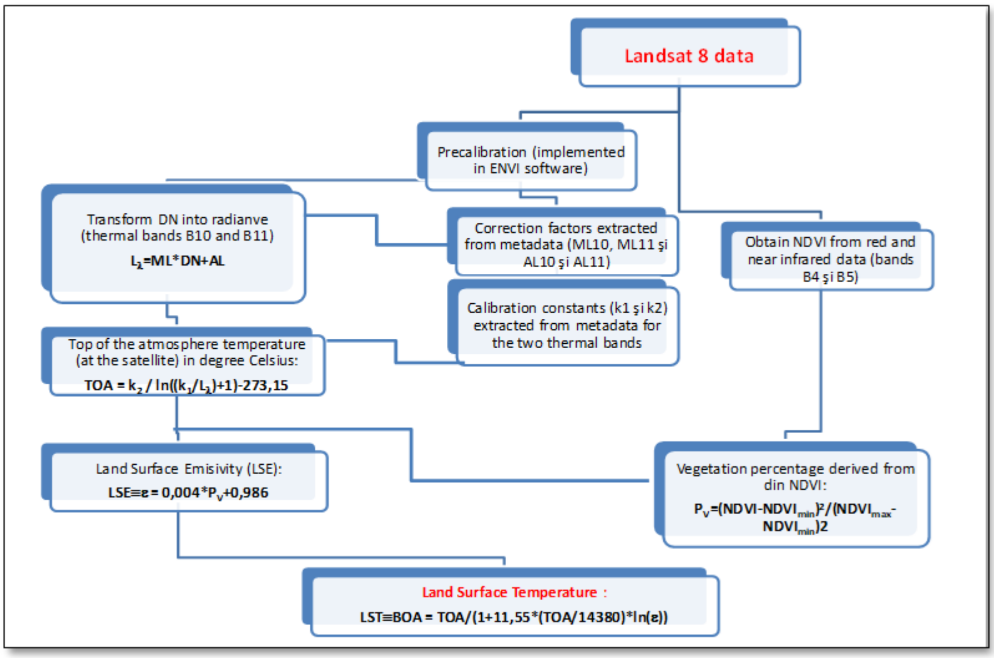


Fig. 2 – The processing workflow for deriving LST from Landsat-8 imagery.

To calculate radiance, correction factors (ML10, ML11, AL10 and AL11) were extracted, and for each of the two thermal bands the following formula was applied:

$$L_{\lambda} = ML*DN + AL$$

Thus, the radiance should be converted into temperature. This is not the actual ground temperature T_{TOA} but the one detected by the satellite and contains a plurality of ground temperature and atmospheric temperature and a complex average atmospheric temperature called brightness temperature. If the target object is considered Lambertian and uniform and surrounded by a surface like him, reflectance can be expressed (Vermote *et al*. 1997) as:

$$\rho = \frac{\pi(L_t - L_p)}{(E_{dir} + E_{dif})\tau + \pi S(L_t - L_p)}$$

where:
ρ is the reflectance; L_t (L_{TOA}) is the radiance at the satellite; S is the atmospheric reflectance; L_p is the radiance passing through the atmosphere; E_{dir} is the direct irradiance on the surface; E_{dif} is the surface level diffused radiance and τ is the total diffuse transmittance from the surface to the atmosphere's upper limit in the direction of satellite.

The relation between LST and radiance for a given wavelength $L_{\lambda(Ts)}$ can be approximated as:

$$\boldsymbol{T_s = \frac{k_2}{\ln(\frac{k_1}{L_{\lambda(T_s)}} + 1)}}$$

where:
T_S is LST in degree Kelvin; k_1 and k_2 are some "calibration" constants of the sensor and $L_{\lambda(Ts)}$ is the value obtained from automatic pre-processing using ENVI software.

For Landsat 8 sensor k_1 = 774,8853 W m^{-2} Sr^{-1} μm^{-1} and k_2= 1321,0789 W m^{-2} Sr^{-1} μm^{-1} (http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html; Schneider and Mauser, 1996).

In order to obtain the T_S values in degree Celsius, we had to subtract 273.15. The obtained LST values are those of a black body, it is, therefore, necessary to correct the spectral emissivity values for the type of material encounter on the terrestrial surface. The emissivity of a surface is influenced by a number of factors such as its chemical composition, structure, water content and roughness. Taking into account that the emissivity for every pixel of a satellite image is a mixture of the emissivity (ε) from the vegetation, soil, and rocks, different models were created to estimate it. One of the most powerful models is the Vegetation Cover Method (VCM) (Valor and Caselles, 1996)

$$\varepsilon = \varepsilon_V * P_V + \varepsilon_G * (1-P_V) * (1-1.74P_V) + 1.7372 * P_V * (1-P_V)$$

where "V" means vegetation and "G" ground and P_V is the vegetation share calculated from satellite images and is a function of Normalized Difference Vegetation Index (NDVI) expressed as follows (Carlson and Ripley, 1997):

$$P_V = \frac{(NDVI - NDVI_{min})^2}{(NDVI_{max} - NDVI_{min})^2}$$

A simplified formula for emissivity is:

$$\varepsilon = 0{,}004 * P_V + 0{,}986$$

Landsat 8 sensor's band B5 (infrared) and band B4 (red) are used to calculate the NDVI. At this moment, the ground temperature values can be corrected and the formula is:

$$LST = T_{SAT}/(1 + 11{,}55*(T_{SAT}/14380)*\ln(\varepsilon))$$

Using spatial analysis functions, distribution maps and statistics (Fig. 6) to extract average temperature for each land cover class (CORINE Land Cover, 2012 and URBAN ATLAS, 2012), the maximum, minimum and mean values were extracted.

4. RESULTS

It is well known that, inside the city of Bucharest temperatures are generally higher than in the surrounding rural areas, both in summer and in winter, due to the overheated artificial land cover and the heat surplus coming from the cooling/heating systems (Vlăducu *et al.*, 2008; Ionac and Grigore, 2013), the busy traffic – due to the almost doubling number of vehicles – and the decrease of green areas, severely affected by the city's expansion (Cheval and Dumitrescu, 2009).

During the day, in May (unlike July or August) the urban heat island emerges from the surrounding space due to farmland's cultivation stage (summer cereal crops are in full vegetation) with some exceptions represented by the abandoned lands or pastures. Throughout the territory of Bucharest, the mean LST value for the date of 25.05.2013 is 25.6°C, with 3.3°C above the average of the metropolitan area (22.3°C) (Fig. 3). The blue and green areas stand out as "islands of coolness", with average surface temperatures of 19.2 – 19.4°C.

In the recent years, the sub-urbanization processes brought in built-up areas expansion (especially residential and commercial) outside the city in the administrative territories of the surrounding localities. These processes are not uniformly distributed across the study area, having been influenced by the existence of major access routes and localities with the potential to develop industrial, commercial and service facilities, as well as second residential houses (e.g. Grigorescu *et al.*, 2015; Ion, 2015; Ion and Pîrvu, 2015; Grigorescu and Kucsicsa, 2017; Kucsicsa and Grigorescu, 2018). This mosaic-like pattern of the built-up areas at the urban-rural interface and even further, within the metropolitan area, resulted in an attenuation of the urban heat island effects in relation to adjacent areas.

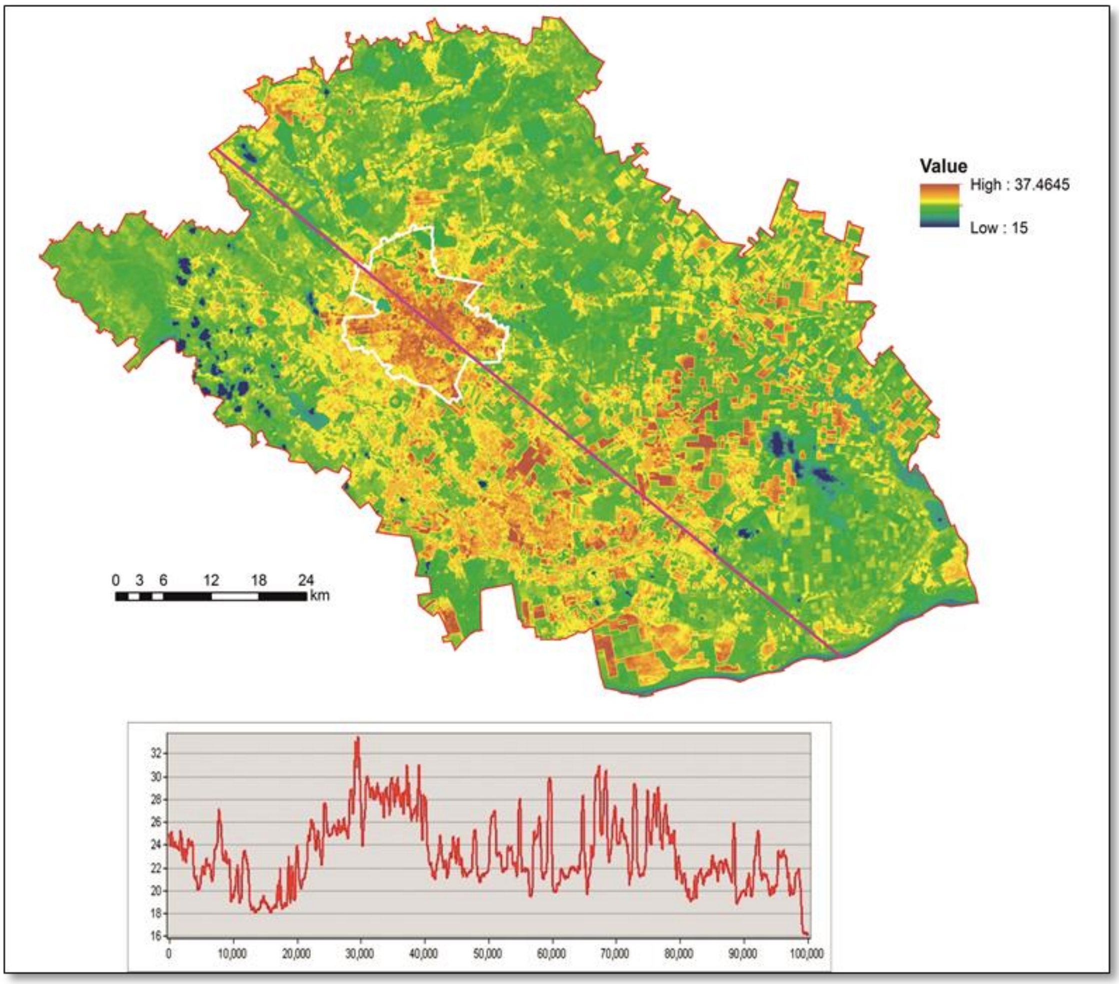


Fig. 3 – The spatial distribution of LST across the Bucharest Metropolitan Area (25.05.2013) (upper graph) and along a NV–SE transect (lower graph).

There are also differences inside the city of Bucharest itself, between the 6 administrative subunits (sectors) and between downtown and peripheral areas (Fig. 4). For example, the coolest areas are located in the northern part of the city (Sector 1), with temperatures ranging between 18.39 and 36.26°C. In these areas LST has the lowest mean value of 24.25°C due to the cooling effect of Băneasa Forest, Herăstrău Park and Colentina River. Inside these areas, LST maintain high within the sealed surfaces belonging to the Băneasa Airport area and to the commercial area of the Băneasa Shopping City. The "hottest" district of the city is Sector 2 with an average LST of 26.35°C. It includes the largest part of the city centre with narrow streets, close-packed buildings, few green spaces, many replaced over the course of time by nonporous surface (asphalt, stone, and concrete) with low reflective capacity, that absorb (>70%) and store solar energy increasing the surface temperature. The significant increase of vehicle number after 1990 (an annual increase of over 13%, Fistung, 2006) also contributed significantly to the heating process, because they released heat into the urban atmosphere. Some previous studies have indicated that this heat contribution together with that coming from the air conditioning could be as much as one-third of that received from solar energy (e.g. Xu and Chen, 2004). This central area has a LST of 29–31°C.

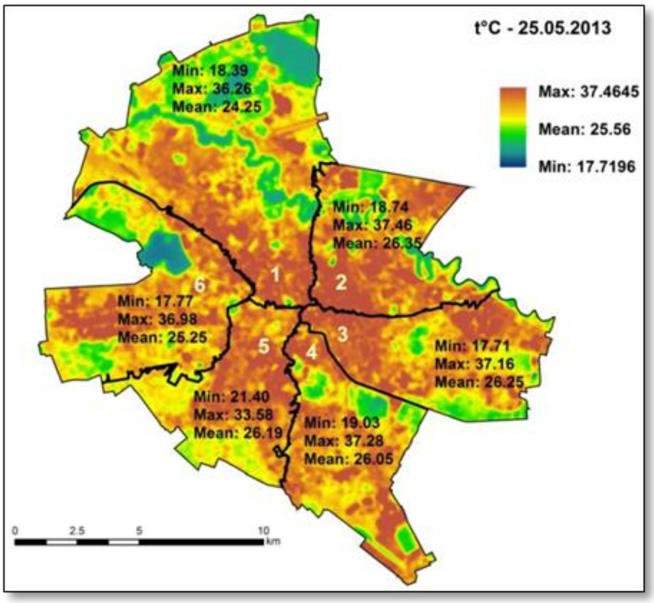


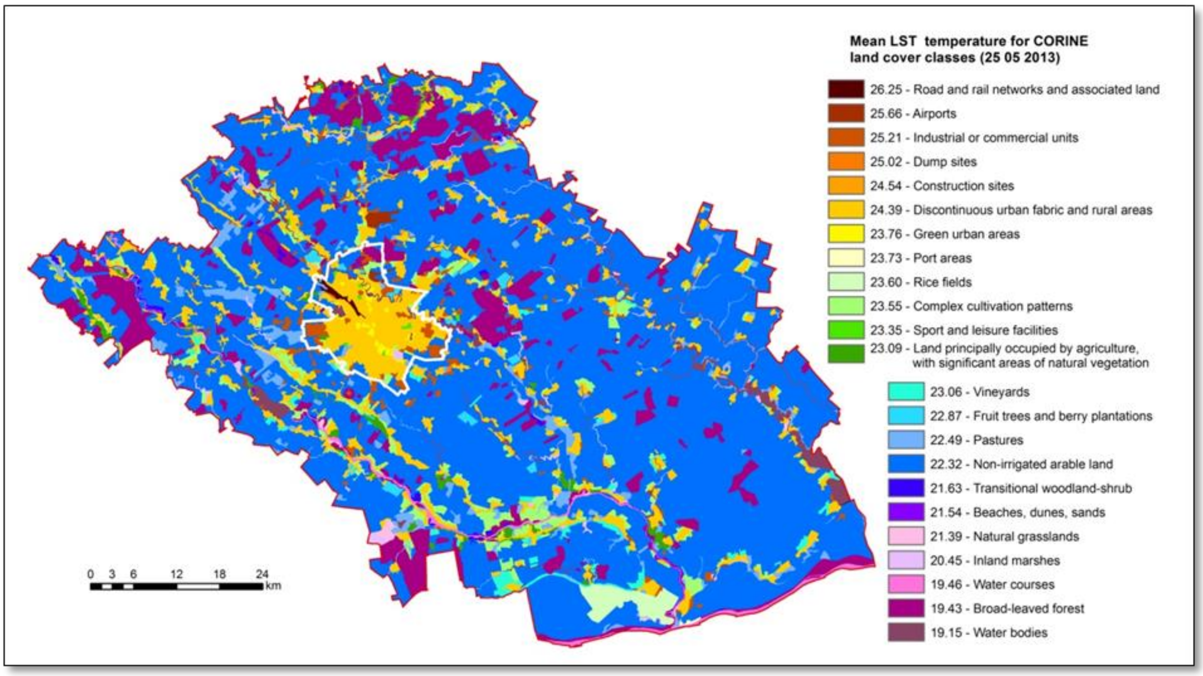
Fig. 4 – Spatial distribution of LST (25.05.2013) in the Bucharest City.

After 1990, the typical industrial landscape dating back to the socialist period characterized by the block of flats and large industrial surfaces becomes a landscape with unprecedented changes. The relict industrial landscape has been abandoned/demolished or replaced by new industrial and commercial units (Mirea *et al.*, 2012). It this case, the microclimate was found similar to that of the central area with LST exceeding 30°C.

The LST analysis on land cover classes (CORINE Land Cover and URBAN ATLAS) showed that inside the urban space, the largest thermal input is associated with the extended impervious surfaces, such as industrial and commercial units (25.2°C), roads and railroad and associated facilities (depots, annexes) (26.3°C), airports (25.7°C), followed by residential areas (24.4°C) which accounts for 10.97% of the whole surface of the study area. The lowest average LST belong to lakes (19.2°C), rivers (19.5°C) and to the surrounding broadleaf forests (19.4°C), all representing 12.94% of the total surface. Nearly 70% of the Bucharest Metropolitan Area's surface is covered by agricultural terrains, most of them non-irrigated crops, thus reaching a mean surface temperature of 22.3°C (Fig. 5).

For a more detailed analysis of the LST value range within the administrative borders of Bucharest, we used the land cover classes derived from the EU Urban Atlas 2012. In this regard the "coolest" areas (19.64°C) are the forests located in the northern part, and the "hottest" belong to the continuous urban fabric (imperviousness/sealing levels = S.L. > 80%) and the industrial, commercial, public, military and private units classes (Fig. 6).

The former industrial and residential landscape of socialist period, which was subject to structural and functional changes over the last decades, revealed high LST values (over 3°C) on the thermal images. LST shows also a great variation in value range in relation to the so-called "urban relief", expressed as an alternate between the building structures (e.g. block of flats of different levels, the wide range of construction materials in use dominated by metallic roofs and pavements made up of heat-conducting materials) and the "canyon boulevards", which lead to complex air flow patterns and to a general decrease in wind speeds of up to 20–30% in contrast to peripheral areas (Vlăducu *et al.*, 2008). All of these aspects are well differentiated depending on the characteristics of the urban topo- and micro-climates.



Table

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Rowid	LABEL_RO	ZONE-CODE	COUNT	AREA	MIN	MAX	MEAN	STD	SUM
19	Road and rail networks and associated land	19	5460	4914000	20.11721	34.59087	26.24927	2.314505	143321
15	Airports	15	10572	9514800	18.39655	35.24551	25.6601	2.005286	271278.6
13	Industrial or commercial units	13	84959	76463100	9.570423	37.46451	25.21182	2.887845	2141971
21	Dump sites	21	527	474300	23.02957	26.86414	25.01763	0.935038	13184.29
18	Construction sites	18	748	673200	21.28769	27.9543	24.53587	1.812409	18352.83
6	Discontinuous urban fabric and rural areas	6	523240	470916000	14.990767	36.98294	24.38991	2.223975	1276178
16	Green urban areas	16	12078	10870200	19.3549	31.19855	23.76164	1.807908	286993.1
23	Port areas	23	1423	1280700	17.50206	32.51557	23.72847	2.81077	33765.61
22	Rice fields	22	47399	42659100	18.47199	29.21015	23.60432	2.626376	1118821
8	Complex cultivation patterns	8	169477	152529300	16.56392	36.01159	23.54907	2.287267	3991026
12	Sport and leisure facilities	12	6249	5624100	18.37712	29.06577	23.35138	2.115616	145922.8
4	Land principally occupied by agriculture, with significant areas of natural vegetation	4	40264	36237600	14.34434	31.18738	23.08514	2.205406	929499.9
17	Vineyards	17	51733	46559700	8.740409	30.41758	23.0552	1.721871	1192715
7	Fruit trees and berry plantations	7	33470	30123000	17.66722	35.25978	22.87013	2.090524	765463.1
5	Pastures	5	198569	178712100	11.039585	35.48156	22.48689	2.922292	4465200
1	Non-irrigated arable land	1	373234	3359110000	11.261094	36.26681	22.31533	2.514663	8328850
9	Transitional woodland-shrub	9	15696	14126400	16.29872	29.01175	21.62818	2.372139	339475.9
20	Beaches, dunes, sands	20	5826	5243400	9.982221	26.26743	21.53481	1.617516	125461.8
14	Natural grasslands	14	14432	12988800	14.4802	27.85685	21.38662	2.388826	308651.8
11	Inland marshes	11	40250	36225000	16.19478	27.15807	20.45221	2.287094	823201.4
2	Water courses	2	52111	46899900	7.566537	29.32249	19.45686	3.451078	1013916
3	Broad-leaved forest	3	513046	461741400	5.335799	30.78623	19.42526	1.19145	9966054
10	Water bodies	10	131080	117972000	7.154289	29.32721	19.14573	1.747299	2509622

0 (0 out of 23 Selected)

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Fig. 5 – Mean LST value for the CORINE land cover classes found across Îthe Bucharest Metropolitan Area (25.05.2013).

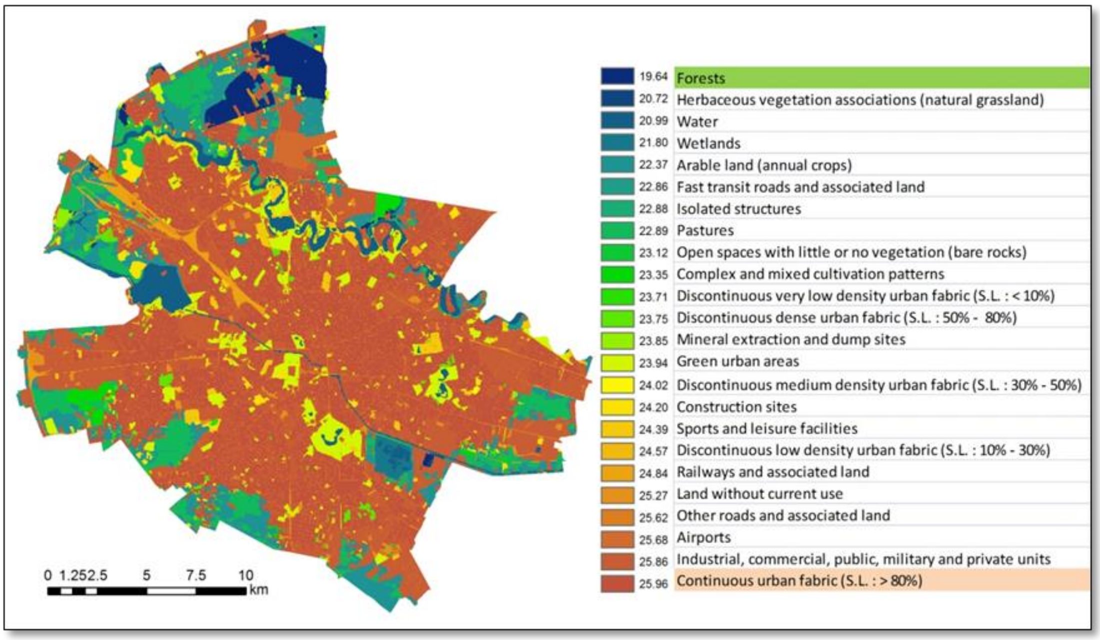

Fig. 6 – Mean LST value attributed to the land use classes of the Urban Atlas 2012 across Bucharest City (25.05.2013).

5. DISCUSSIONS

A large body of scientific literature (e.g. Pătroescu and Bordușanu, 1997; Pătroescu *et al.*, 2004; Iojă and Pătroescu, 2004; Enciu *et al.*, 2008; Ionac and Grigore, 2013; Cârstea *et al.*, 2013; Cheval and Dumitrescu, 2015, 2017; Cheval *et al.*, 2017; Vânău *et al.*, 2015) and research projects (e.g. Urban Heat Island Monitoring under Present and Future Climate – UCLIMESA; Ecogeochemistry of Great Urban Areas and their Periurban surroundings in the Context of Sustainable Development – ECOGEOURB) have been focused on the relationship between land use/cover of Bucharest or its metropolitan area and LST distribution, UHI shape and aspect. All these studies have used a great variety of data sources, methods, areal shapes and scales and emphasized the thermal differences created by specific topoclimatic conditions.

In the present study, in order to better highlight the urban heat island effect and of the thermal differences between the city and its surrounding territory, we compared LST data derived from Landsat-8 satellite imagery with *in-situ* measurements carried out within ECOGEOURB project on two topoclimatological profiles crossing the city of Bucharest from E to W and from NNV to SSE (Enciu *et al.*, 2008; Vlăducu *et al.*, 2008) (Fig. 7). Among the numerous causes of the thermal differences creating specific urban topoclimatic conditions, the town's active layer surface under the significant change by human intervention is one of the most important. This surface has physical characteristics that are substantially different from those of the adjoining areas, implying different matter and energetic exchange fluxes. Moreover, this surface is impervious and decreases the infiltration of rainwater and stormwater into the ground, thus largely contributing to the reduction of heat consumption in the evaporation process. Consequently, the heat resulted from the radiation budget is mainly consumed in the process of heating the underlying surface and from here, in the process of heating the ground surface and the overlying air. This actually makes urban air warmer as compared to the surrounding outskirts areas, which is also thermally different even from one place to another, inside the urban area (Ciulache and Ionac, 2008). As a consequence, the continuous rising temperatures in urban areas creates an uncomfortable bioclimatic environment for residents, which results in an increasing demand for cooling, especially during hot weather episodes (Rinner and Hussain, 2011).

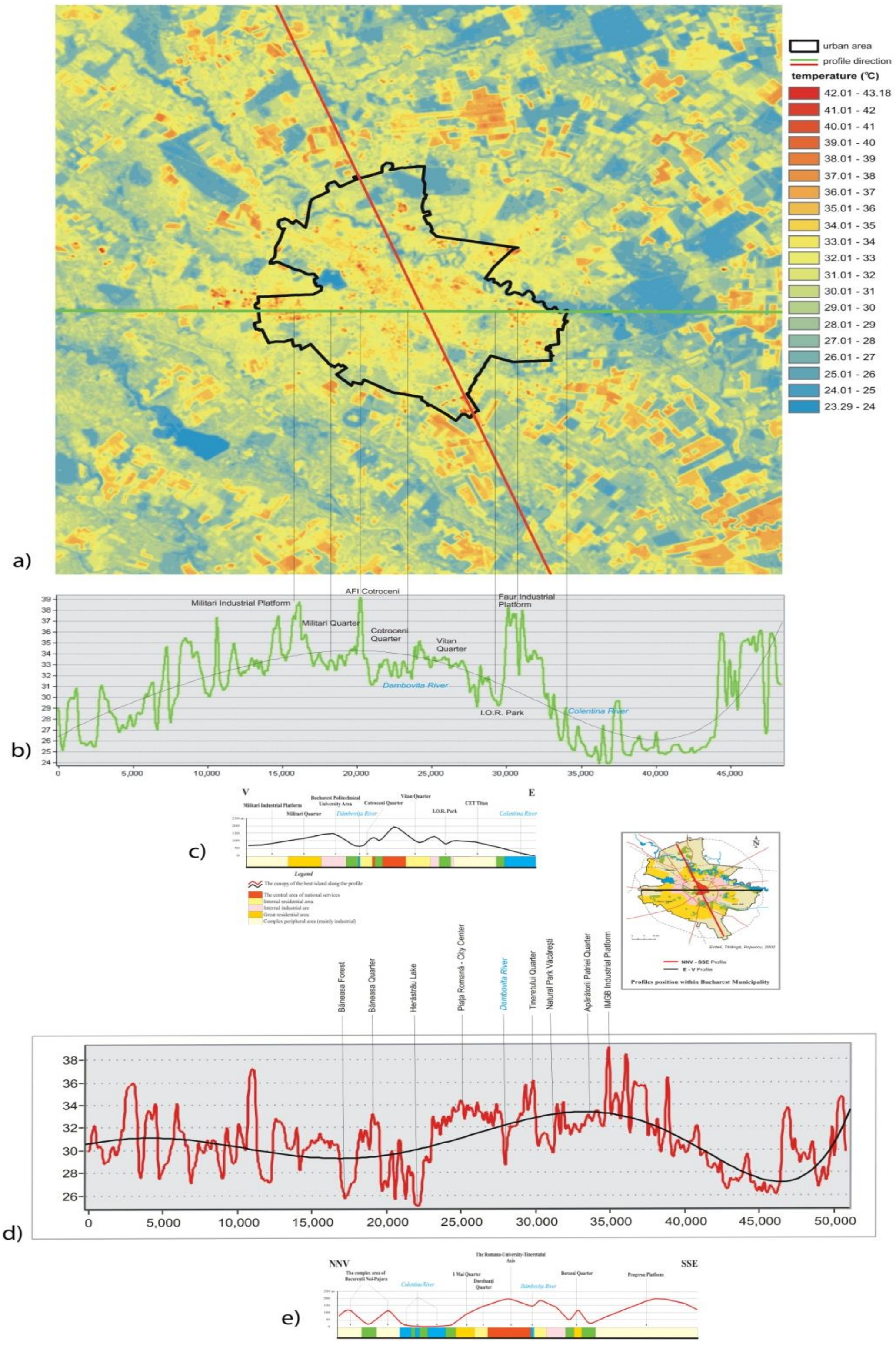

Fig. 7 – Spatial variability of LST in the Bucharest city and its surrounding areas: a) LST distribution patterns; b) E–W LST profile matching the E–W topoclimatological profile (c); d) NNV–SSE LST profile matching the NNW–SSE topoclimatological profile (e).

6. CONCLUSIONS

The analysis of the LST spatial distribution in the Bucharest Metropolitan Area distinguished several aspects:

– Noticeable spatial differences between the urban area and the non-urban territory, as well as great differentiations within the urban area itself; however, in some cases, differences are attenuated by the expansion of the urban metropolitan area with various functions in the neighboring urban-rural space;

– Urban areas have similar characteristics in terms of heat, despite the high diversity and fragmentation;

– Industrial sites and residential neighbourhoods detach themselves as “hot spot” areas, with peak LST values of up to 37.5°C, against the green and blue surfaces acting as “islands of coolness”, in which LST is generally up to 30°C lower;

– In the surrounding rural areas with predominantly agricultural land use, LST values show a greater heterogeneity, with slight differences depending on the land use type and development stage of the crops.

The current study provides insights into the spatial differentiations between different land use/cover categories in terms of surface heating across the metropolitan area of the largest and most dynamic city in Romania, Bucharest. Our results could be useful for the sustainable planning of the urban-rural interface and metropolitan area, through maintaining the proper ratio between built-up areas with different functional uses and the green and blue surfaces. Specific action might include: the development of a green-yellow belt in the proximity of the city; the preservation of the existing natural protected areas (e.g. Comana Natural Park, Snagov Lake and Forest, Ciornuleasa Forest) and recreational forests (Pasărea Forest, Cernica Forest) which are often overexploited by tourists; the maintenance of a better state of quality of the urban rivers and lakes etc. Hence, the outcomes of the current study raise attention on three main issues: (1) land management, especially agricultural land abandonment and inappropriate use under the great pressures of sub-urbanization processes (2) environmental quality – the state of the forest and water-covered areas under the intensive touristic and development stresses and (3) the quality of life in residential areas (e.g. the low share of recreational space, the great density of impervious surfaces).

A perspective work would be to perform a more detailed analysis of LST distribution patterns across the Bucharest Metropolitan Area by using new LST datasets derived from the fusion of the moderate spatial resolution Landsat with the high temporal resolution MODIS data, in order to better highlight the spatial thermal differences and relate them with their underlying factors.

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REFERENCES

Amiri, R., Weng, Q. Alimohammadi, A., Alavipanah S.K. (2009), *The Spatial-Temporal Dynamics of Land Surface Temperatures in Relation to Fractional Vegetation Cover and Land Use/Cover in the Tabriz Urban Area, Iran,* Remote Sensing of Environment, 113, pp. 2606–2617.

Bart, I.L. (2010), *Urban sprawl and climate change: A statistical exploration of cause and effect, with policy options for the EU,* Land use policy, **27**, *2*, pp. 283–292.

Bălteanu, D. (2016), *The Relief Units. The Pericarpahian Regions*, in: Bălteanu D., Dumitraşcu M., Geacu S., Mitrică B., Sima M. (Eds.), Romania: Nature and Society, Publishing House of the Romanian Academy, Bucharest, pp. 82–101.

Becker, F., Li., Z.L. (1990), *Towards a local split window method over land surfaces*, International Journal of Remote Sensing, **11**, pp. 369–393.

Bogdan, Octavia, Dragotă, Carmen, Micu, Dana (2016), *The climatic potential*, in: Bălteanu D., Dumitraşcu M., Geacu S., Mitrică B., Sima M. (Eds.), Romania: Nature and Society, Publishing House of the Romanian Academy, Bucharest, pp. 102–130.

Carlson, Toby N., David A. Ripley (1997), On *the relation between NDVI, fractional vegetation cover, and leaf area index*, Remote sensing of Environment, **62**, *3*, pp. 241–252.

Carstea, E. M., Ioja, C. I., Savastru, R., Gavrilidis, A. (2013), *Spatial characterization of urban lakes*, Romanian Reports in Physics, **65**, *3*, pp. 1092–1104.

Cheval, S., Dumitrescu, A. (2009), *The July urban heat island of Bucharest as derived from MODIS images*, Theoretical and Applied Climatology, **96**, pp. 145–153.

Cheval, S., Dumitrescu, A., Bell, Aurora (2009), *The urban heat island of Bucharest during the extreme high temperature of July 2007*, Theoretical and Applied Climatology, **97**, pp. 391–401.

Cheval, S., Dumitrescu, A. (2015), *The summer surface urban heat island of Bucharest (Romania) retrieved from MODIS images*, Theoretical and Applied Climatology, **121**, *3–4*, pp. 631–640.

Cheval, S., Dumitrescu, A. (2017) *Rapid daily and sub–daily temperature variations in an urban environment*, Climate Research, 73, pp. 233–246. https://doi.org/10.3354/cr01481.

Ciulache S., Ionac N. (2008), *Topoclimatic and Microclimatic Differences in the Piteşti Town-Area*, „Present Environment and Sustainable Environment", **2**, Edit. Universității „Al. I. Cuza" din Iași, pp. 117–124.

EAA Report (2006), *Urban sprawl in Europe: the ignored challenge*, **10**, *2*, 56 p.

Enciu, P., Bălteanu, D., Dragotă, Carmen-Sofia, Grigorescu, Ines, Dumitrică, Cristina, Popescu D.C., (2008), *Cadrul natural al Municipiului Bucureşti şi al zonelor înconjurătoare*, in Geo-Atlasul municipiului București, Edit. Est-Falia, București, pp. 2–50.

Fistung, D. (2006), *Un posibil model de reducere a efectelor negative determinate de traficul rutier din Bucureşti asupra mediului și sănătății populației*, Revista Economică, **1**, pp. 35–65.

Fitzpatrick, P. and Stephens, G. (1995), *Solar Zenith Angle algorithms* (source code available from: http://www.liv.ac.uk/~mark/met.htm).

Frumkin, H. (2002), *Urban sprawl and public health*, Public health reports, vol **17**, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1497432/pdf/12432132.pdf

Gastellu-Etchegorry, J. P. (2015), *Atmospheric corrections. Fundamentals*, 6^{th} ESA Advanced Training Course on Land Remote Sensing, 14–18 September 2015, Bucharest.

Gao, F., Masek, J., Schwaller, M., Hall, F. (2006), *On the blending of the Landsat and MODIS surface reflectance: Predicting daily Landsat surface reflectance*, IEEE Transactions on Geoscience and Remote sensing, **44**, *8*, pp. 2207–2218.

Goetz, S. J., Halthore R. N., Hall, F. G. Markham B. L. (1995), *Surface temperature retrieval in a temperate grassland with multi-resolution sensors*, Journal of Geophysical Research, **100**, D12, pp. 25397–25410.

Grigorescu, Ines, Kucsicsa, Gh. (2017), *Spatial and temporal dynamics of urban sprawl in the Romanian Plain over the last century*, Rev. Roum. Géogr./Rom. Journ., **61**, *2*, pp. 109–123

Grigorescu, Ines, Kucsicsa, Gh., Mitrică, Bianca (2015) *Assessing Spatio-Temporal Dynamics of Urban Sprawl in the Bucharest Metropolitan Area over the last century*, Land use/Cover Changes in Selected Regions in the World, **X**, (Eds. Bicik I., Himiyama Y., Feranec J., Kupkova Lucie), Charles University in Prague, Faculty of Science, pp. 19–27, Prague, the Czech Republic.

Hilker, T., Wulder, M. A., Coops, N. C., Linke, J., McDermid, G., Masek, J. G., White, J. C. (2009), *A new data fusion model for high spatial-and temporal-resolution mapping of forest disturbance based on Landsat and MODIS*, Remote Sensing of Environment, **113**, *8*, pp. 1613–1627.

Ion, Florentina (2015), *Change of land-use patterns in a suburbanized area: The Bucharest municipality as case study*, Forum Geografic, **XIV**(*1*), pp. 64–74. doi:10.5775/fg.2067-4635.2015.174.i.

Ion, Florentina, Pîrvu, D. (2015), *Territorial discrepancies in the rural-urban fringe zone of Bucharest*, Scientific Bulletin – Economic Series, **14**(*1*), pp. 56–63.

Ionac, Nicoleta, Grigore, Elena (2013), *Thermal Differences within Bucharest Town Area. Case Study*: 01.07.2006/ 31.03.,2007, Present Environment and Sustainable Development, **7**, *2*, pp. 21–36.

Ioja, C., Patroescu, M. (2004), *The role of the parks in Bucharest City Urban Ecosystems: Case study Herăstrău Park*, Lucrarile Seminarului geografic Dimitrie Cantemir **25**, pp. 235–242.

Jiménez-Muñoz, J. C., Sobrino, J. A. (2003), *A generalized single-channel method for retrieving land surface temperature from remote sensing data*, Journal of Geophysical Research: Atmospheres, **108**(D22).

Jiménez-Muñoz, J. C., Sobrino, J. A., Skoković, D., Mattar, C., & Cristóbal, J. (2014), *Land surface temperature retrieval methods from Landsat-8 thermal infrared sensor data*, IEEE Geoscience and Remote Sensing Letters, **11**(*10*), pp. 1840–1843.

Kalnay, E., Cai, M. (2003), *Impact of urbanization and land-use change on climate*, Nature,**423**, *6939*, pp. 528–531.

Kucsicsa, Gh., Grigorescu, Ines (2018), *Urban growth related to distance explanatory factors in Bucharest Metropolitan Area. Spatial and temporal assessment using logistic regression*, Journal of Urban Planning and Development, ASCE Library, **144**, *1*, http://ascelibrary.org/doi/10.1061/%28ASCE%29UP.1943-5444.0000415.

Liu, J., Shao, Q., Yan, X., Fan, J., Zhan, J., Deng, X., Huang, L. (2016), *The climatic impacts of land use and land cover change compared among countries*, Journal of Geographical Sciences, **26**, *7*, pp. 889–903.

Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.) (2007), *Intergovernmental Panel on Climate Change* (Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change) Cambridge University Press, Cambridge UK and New York (www.ipcc.ch/ipccreports/ar4-wg3.htm).

Mirea, D., Vânău, G., Niculae, M., Dincă, C. (2012), *Industrial landscape expansion and evolution in Bucharest's District 4*, Forum Geografic, **XI**, *1*, pp. 26–35. doi:10.5775/fg.2067-4635.2012.022.i.

Neacşa, O., Popovici, C. (1969), *Influence of the urban landscape on some parameters of the air temperature in the city of Bucharest*, Institute of Meteorology, Bucharest, pp. 293–304, (in Romanian).

Neacşa. O., Popovici, C., Tuinea, P., Popa, G. (1974), *Contributions to the climatology of Bucharest*, Institute of Meteorology and Hydrology, Bucharest, pp, 5–53 (in Romanian).

Norman, J. M., Divakarla M., Goel N. S. (1995), *Algorithms for extracting information from remote thermal-IR observations of the Earth's surface*, Remote Sensensing of the Environment, **51**, pp. 157–168.

Oke, T. R. (1982), *The energetic basis of the urban heat island*, Quarterly Journal of the Royal Meteorological Society, **108**, *455*, pp. 1–24.

Pătroescu, M., Iojă, C., Necşuliu, R., Brăilescu, C. (2004) *The quality of oxygenating surfaces. The green areas of Bucharest. A case studies*, Revue Roumaine de Geographie, **47–48**, pp. 205–216.

Rinner, C., Hussain, M. (2011), *Toronto's urban heat island—Exploring the relationship between land use and surface temperature*, Remote Sensing, **3**, *6*, pp. 1251–1265.

Revi, A., Satterthwaite, D.E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R.B.R., Pelling, M., Roberts, D.C., Solecki, W. (2014), *Urban areas*, In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535–612.

Schneider, K., Mauser W. (1996), *Processing and accuracy of Landsat Thematic Mapper data for lake surface temperature measurement*, International Journal of Remote Sensing, **17**, pp. 2027–2041.

Schott, J. R. W. J. Volchok. (1985), *Thematic Mapper thermal infrared calibration*, Photogrammetric Engineering and Remote Sensing, **51**, *9*, pp. 1351–1357.

Stone, B. (2008), *Urban sprawl and air quality in large US cities*, Journal of Environmental Management, **86**, *4*, pp. 688–698.

Stone, B., Norman, J. M. (2006), *Land use planning and surface heat island formation: A parcel-based radiation flux approach*, Atmospheric Environment, **40**, *19*, pp. 3561–3573.

Stone, B., Hess, J.J., Frumkin, H. (2010), *Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities?*, Environmental health perspectives, **118**, *10*, pp. 1425–1428.

Sun, Q., Wu, Z., Tan, J. (2012), *The relationship between land surface temperature and land use/land cover in Guangzhou, China*, Environmental Earth Sciences, **65**, *6*, pp. 1687–1694.

Valor, E., El Caselles, V. (1996), *Mapping land surface emissivity from NDVI. Application to European, African and South-American areas*, Remote Sensing of Environment, **57**, pp. 167–184.

Vânău, G., O., Iojă, I., C., Onose Diana Andreea, Şandric, I., Grădinaru Simona, Uţă Mihaela (2015), *Air temperature regula-on by urban trees and green infrastructure Environment at crossroads: smart approaches for a sustainable future*, PROCEEDINGS of the International Conference Environment at a CrossrOads: SMART approaches for a sustainable future, Book of abstracts, Bucharest, 157 p.

Vermote, E. F., El Saleous, N. Z., Justice, C. O., Kaufman, Y. J., Privette, J. L., Remer, L., Roger, J. C., & Tanre, D. (1997), *Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: background, operational algorithm and validation*, Journal of Geophysical Research-Atmosphere, **102**, D14, pp. 17131–17141.

Vidal, A. (1991), *Atmospheric and emissivity correction of land surface temperature measured from satellite using ground measurements or satellite data*, Int. J. Remote Sensing, Vol. **12**, No. *12*, pp. 2449–2460.

Vlăducu, M., Tâştea, D., Dragotă, Carmen-Sofia, Grigorescu, Ines, Kucsicsa, Gh. (2008), *Urban influences on air temperature and relative humidity of moist air distribution in Bucharest Municipality. Heat Island*, Annals of the University of Craiova, nr. **10**, Series: Geography, New Series, pp. 13–20, http://analegeo.ro/wp-content/uploads/2010/07/Articolul-2-Marin-Vladucu.pdf.

Voogt, J. A., Oke, T. R. (2003), *Thermal remote sensing of urban climate*, Remote Sensing of Environment, **86**, pp. 370–384.

Xu, H.Q., Chen, B.Q. (2004), *Remote sensing of the urban heat island and its changes in Xiamen City of SE China*, Journal of Environmental Sciences, **16**, *2*, pp. 276–281.

Zhou, W., Huang, G., Cadenasso, M. L. (2011), *Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes,* Landscape and Urban Planning, **102**, *1*, pp. 54–63.

Zhou, X., Wang, Y. C. (2011), *Dynamics of Land Surface Temperature in Response to Land-Use/Cover Change,* Geographical Research, **49**, *1*, pp. 23–36.

Weng, Q., Fu, P., Gao, F. (2014), *Generating daily land surface temperature at Landsat resolution by fusing Landsat and MODIS data*, Remote Sensing of Environment, **145**, pp. 55–67.

*** NASA Goddard Space Flight Centre (GSFC) (2016), *Landsat 8 (L8) Data Users Handbook. Version 2.0,* March 29, Sioux Falls, South Dakota, USA, 98 p.

*** ECOGEOURB – Ecogeochemistry of Great Urban Areas and their Periurban surroundings in the Context of Sustainable Development https://www.icpa.ro/proiecte/Proiecte%20nationale/ECOGEOURB/index.htm.

***UCLIMESA – *Urban Heat Island Monitoring under Present and Future Climate* http://uclimesa.meteoromania.ro/ro/acasa.

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