

The summer surface urban heat island of Bucharest (Romania) retrieved from MODIS images

Sorin Cheval · Alexandru Dumitrescu

Received: 13 November 2013 / Accepted: 4 August 2014 / Published online: 30 August 2014
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Abstract The summer surface urban heat island (SUHI) of the city of Bucharest (Romania) is investigated in terms of its shape, intensity, extension and links to land cover. The study employs land surface temperature (LST) data retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra (EOS AM-1) and Aqua (EOS PM-1) NASA satellites, between 2000 and 2012. Based on the Rodionov regime shift index, the significant changing points in the land surface temperature values along transverse profiles crossing the city's centre were considered as SUHI's limits. The thermal difference between the SUHI and several surrounding buffers defines the SUHI's intensity. The nighttime SUHI's geometry is more regular, and its intensity is slightly lower than during the day, while the land cover exerts a strong influence on Bucharest's LST. In summary, the study proposes a methodology to delimit and quantify the average SUHI based on the statistical significance of the shift between the urban area and its surroundings, and the limitations of the method are mentioned.

1 Introduction

Urban areas generate major disturbances in the natural background climate, altering the values of many meteorological variables, such as temperature, humidity and wind. The modified partitioning of the urban energy balance (Christen and Vogt 2004), the heat input from urban fabric surfaces and the

anthropogenic heat lead to major changes in temperature inside cities. Urban heat island (UHI) is the term associated with the thermal difference between a city and the rural neighbourhood, and it can be defined in various ways, recently reviewed by Schwarz et al. (2011). Usually, the UHI triggers consequences like environmental stress, discomfort for human beings and additional energy costs for cooling the buildings. Urban temperatures may be higher than those in the rural areas in any season, but the most striking impact occurs in the summer, when the UHI amplifies the natural heating of the atmosphere and may lead to dramatic consequences for the life of the urban population (Basara et al. 2010; Tan et al. 2010; Gabriel and Endlicher 2011). During calm and clear-sky nights, the instant temperature in densely urbanized areas can be 5–10 K higher than that in nearby rural areas. It is very likely that the added warmth of the UHI was a contributor to the heat burden on urban residents of the European heat wave of August 2003 that caused an estimated 35,000–50,000 casualty (UNHSP 2007).

Scientists have dedicated constant efforts to explore and understand the UHI's characteristics and functionality, in order to predict its behaviour and eventually alleviate its adverse effects. Arnfield (2003), Rizwan et al. (2008) and Stewart (2011) provided recent overviews, tackling UHI development, features, concepts and recent advancements. This study investigates the summer surface urban heat island (SUHI) of the city of Bucharest (Romania), based on satellite remote sensing data retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra (EOS AM-1) and Aqua (EOS PM-1) NASA satellites. In the past couple of decades, remote sensing has become a valuable source of information, especially in regions with sparse meteorological stations and complex geography, such as the urban areas (Voogt and Oke 2003; Weng 2009). Acknowledging the important role of the urban structure, industry and traffic, or meteorological conditions, in generating and controlling the SUHI, we hereby approach only the link between land cover

Electronic supplementary material The online version of this article (doi:10.1007/s00704-014-1250-8) contains supplementary material, which is available to authorized users.

S. Cheval (✉) · A. Dumitrescu
National Meteorological Administration, 97 Sos. Bucuresti-Ploiesti,
Sect. 1, Bucharest 013686, Romania
e-mail: sorincheval@yahoo.com

and urban surface temperature. Land cover is one of the major factors influencing the urban climate (Vargo et al. 2013), and its relationship with the UHI has been documented for numerous cities, i.e. Athens (Stathopoulou et al. 2007), Leipzig (Schwarz et al. 2012) and Paris (Wouters et al. 2013).

The city of Bucharest is located in the southern part of Romania, with a population of 1.92 million permanent residents (INS 2012), and it covers about 240 km² (44° 30' N and 26° 00' E, 80–120 m a.s.l.). Several studies documented the Bucharest Heat Island (BHI) based on ground or remote sensing data. Using ground-level air temperature measurement in a few representative points, Tumanov et al. (1999) pointed out that the maximum intensity of the BHI during the period May–December 2004 was about 4 °C. Cheval and Dumitrescu (2009) analyzed the geometry, intensity and extension of the surface BHI in July, and Cheval et al. (2009) investigated its behaviour during the heat wave events of July 2007. Zoran et al. (2012) explored satellite imagery from various sources and found a 1–6 °C difference in the monthly land surface temperature (LST) means between the urban perimeter and the rural areas around Bucharest.

The main objectives of this study are to document (1) the characteristics (limits, geometry and intensity) of the surface BHI during the summer months and (2) their relationship with the land cover, based on MODIS images over 2000–2012 and the Corine dataset (Büttner et al. 2012). Furthermore, we aim to complete and validate the results obtained by Cheval and Dumitrescu (2009) with the same methodology, but for a smaller dataset (2000–2006), and time interval (July). Strong correlations were found between the nocturnal LST and air temperature measured at the Bucharest meteorological stations at the same time as the MODIS data, so that one can assume that similar patterns can be claimed for surface and canopy BHI. The lower daytime correlation (Table 1) suggests weaker relations between the Bucharest SUHI and UHI.

2 Datasets and methodology

This work is based on remote sensing LST data retrieved through the summer months (June, July, August—JJA) between 2000 and 2012, over an area of approximately

1,000 km² around the city of Bucharest. Air temperature data from the weather stations operated by the Romanian National Meteorological Administration are used for comparing the values in the corresponding pixels (Fig. 1).

MOD11A1 and MYD11A1 are MODIS/Terra and Aqua land surface temperature and emissivity (LST/E) products respectively, providing per-pixel temperature and emissivity values in a sequence of swath-based to grid-based global products. MOD11A1 and MYD11A1 each supply two night-time and two daytime instantaneous LST images at 1-km resolution (LP DAAC 2013). First, the images from the summer months between 2000 and 2012 were selected, which contain at least one valid LST value within the administrative perimeter of Bucharest. After that, two quality control filters were applied in order to secure the accuracy of the datasets: (1) Only images with at least 10 % valid pixels were used; (2) for each pixel, only data within the interval (average±3 standard deviations) were considered. The selected dataset contains 1,746 daytime images, covering the interval 1000–1400 h UTC, and 1,516 night-time images retrieved between 2100 and 0300 h UTC.

The SUHI's limits, geometry and spatial extension were delimited based on the significant changes identified over 36 transects that cross Bucharest through its conventional centre (University Square), at a 5° step angle (Fig. 1). The shifting points over the cross profiles were determined by the Rodionov test ($p < 0.1$, cut-off=10), and they represent the SUHI limits as demonstrated in a previous report (Cheval and Dumitrescu 2009). The Rodionov test assumes that each data point is independent of the other measurements, so that there is no serial correlation. At the same time, the method is based on the sequential application of the Student's t test in order to detect significant regime shifts in the mean within a dataset (Rodionov 2004; Rodionov and Overland 2005; Marty 2008). In an analysis focused on temperature and precipitation variability, Temnerud and Weyhenmeyer (2008) found that the Rodionov and the Pettitt tests (Pettitt 1979) return similar results. Our examination showed that Pettitt often failed to identify two significant changing points per profile as expected. Therefore, the Rodionov test has been considered more suitable for our datasets and purpose. It has to be pointed out that the method is suitable mainly for

Table 1 Pearson correlation coefficients (r) between the air temperature measured at the Bucharest meteorological stations and LST of the corresponding pixel

	June			July			August		
	Filaret	Baneasa	Afumati	Filaret	Baneasa	Afumati	Filaret	Baneasa	Afumati
Night-time	0.92	0.84	0.87	0.93	0.84	0.90	0.93	0.84	0.90
Daytime	0.74	0.79	0.78	0.76	0.81	0.81	0.80	0.84	0.80

analyzing complete datasets, so that particular situations should be treated cautiously.

SUHI's intensity was computed using the thermal differences from surrounding buffers drawn around the SUHI borders delimited by the changing points of each profile. This approach provides a more relevant perspective on the differences between the SUHI and the neighbouring areas than by the simple comparison of two points (meteorological stations). For any specific application, the SUHI's intensity may be calculated using the corresponding profile.

The land cover information was retrieved from the Corine Land Cover (CLC) version 16 (04/2012) dataset, at 100-m spatial resolution (EEA 2013). The land cover category corresponding to the centre of the MODIS LST pixel was used for correlation.

Several limitations of this approach must be admitted: (1) satellite limitations, (2) accuracy and validation, (3) temporal constraints, (4) spatial resolution, (5) cloudiness and meteorological bias, and (6) drawing the cross profiles. A primary source of inaccuracy is the fact that time series data over a long time span has spatial shifts due to the navigation of the satellite, which triggers differences in the geographical position of the same pixel between the overpasses. With regard to the accuracy and validation, Wan et al. (2004) documented that in ideal conditions, the MODIS LST accuracy is higher than 1 °C in the -10 to 50 °C range, which was confirmed by the product status

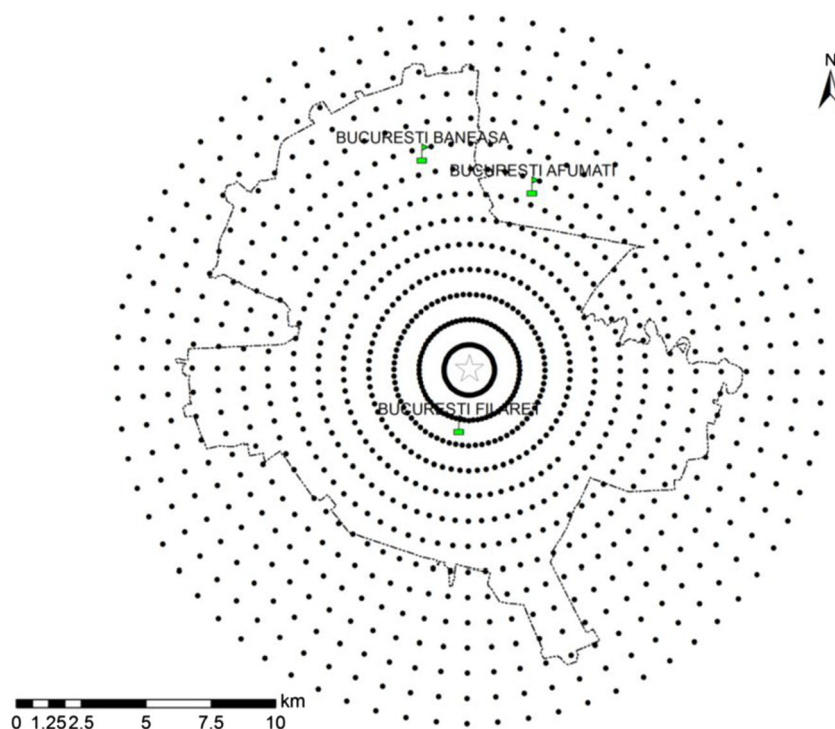
update issued by the MODIS land team validation in 2011 (MODIS land team 2011).

Since the datasets cover daily time intervals, the quantitative analysis addresses mainly the average SUHI. The range of available MODIS images (from the year 2000) might be considered too small from the climatic perspective which traditionally requires at least 30 years of data, but the results are consistent with other studies and even shorter time periods. The assimilation of new data into the proposed methodology will probably not change the patterns identified for the surface BHI's characteristics. Four images per day and 1-km spatial resolution mean a fair compromise for climate studies, but the peak values and terrain details may be obliterated. For example, the differences between the LST and land cover resolutions should be acknowledged as limitations, and the accuracy of the results may increase by addressing this issue.

Cloudiness strictly limits the availability of satellite images, meaning that the results should be considered relevant for clear-sky conditions only. The influences of other meteorological (e.g. air humidity) or anthropogenic factors (e.g. urban profile) which could lead to biases in the LST values were not within the scope of this study.

The cross profiles are drawn based on the expert's judgment (e.g. crossing the centre of the city), so that previous knowledge about the urban shape and structure and its associated heat island is necessary. The methodology is fully replicable to mono-centric cities, where the urban core may be clearly assumed, but some fine-tuning should be used in more complex situations.

Fig. 1 Administrative boundaries, meteorological stations and disposal of the cross profiles around downtown Bucharest (Piata Universitatii, marked with a *white star*)



3 Results and discussion

3.1 Limits and geometry of the Bucharest summer SUHI

LST values may realistically highlight the differences between the metropolitan areas and their surroundings, and various algorithms and concepts for measuring the urban effect have been proposed (Schwarz et al. 2011). Usually, they are based either on statistical or ecosystem/land cover deviations, and the administrative boundaries are extensively used. However, the hottest area in a city differs from such limits most of the time. Plotting the average, maximum and minimum temperature and standard deviations for the summer months, one can remark a major thermal distinction between the city of Bucharest and its neighbourhoods. However, the LST patterns depend strongly on the interpolation algorithms, and classification criteria (Fig. 2), making it difficult to indicate the SUHI's limits objectively. The solution may be a statistical tool capable of emphasizing a clear distinction between the thermal properties of the urban environment and its surroundings, especially when the transition is shallow.

The Rodionov test returned statistically significant changing points in the LST values along each transect covering the city and justified the delimitation of surface BHI for the summer month, for daytime and night-time, respectively. The differences in shape and extensions of the surface BHI are rather small from 1 month to the next (e.g. below 8.5 % between the daytime maximum and minimum, and 2.6 % for night-time areas), so that an aggregated summer SUHI was considered feasible both for theoretical analysis and practical purposes. The aggregation is based on the maximum monthly extension, and the results are displayed in Fig. 3.

The night-time SUHI's shape tends to be regular and compact, and average LST within the Bucharest urban area may reach 22–24 °C in July, compared with 16–18 °C in the bordering rural areas throughout all the summer months. On the contrary, the daytime SUHI is much more irregular, as a result of the higher and more complex energy input, with reduced urban evapotranspiration (Christen and Vogt 2004), combined with heterogeneous land cover types at the urban edges, and a more dynamic atmosphere. The highest average LST values in

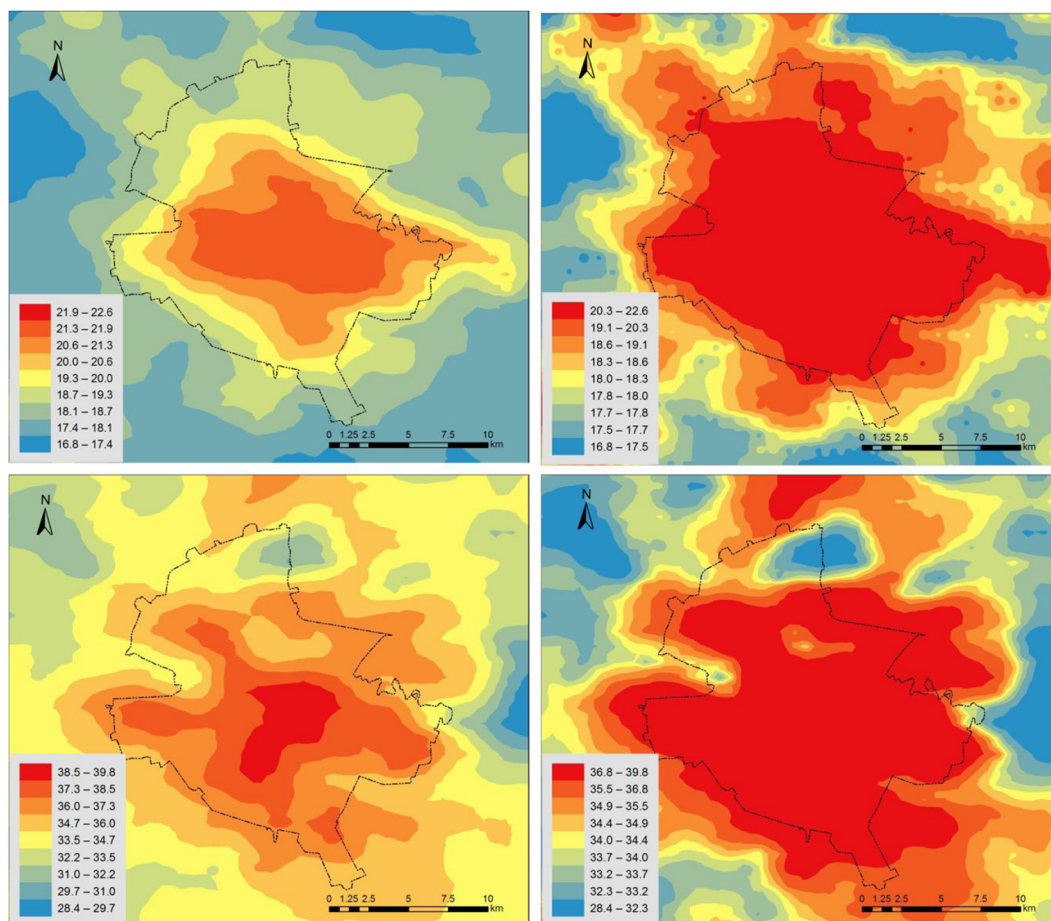
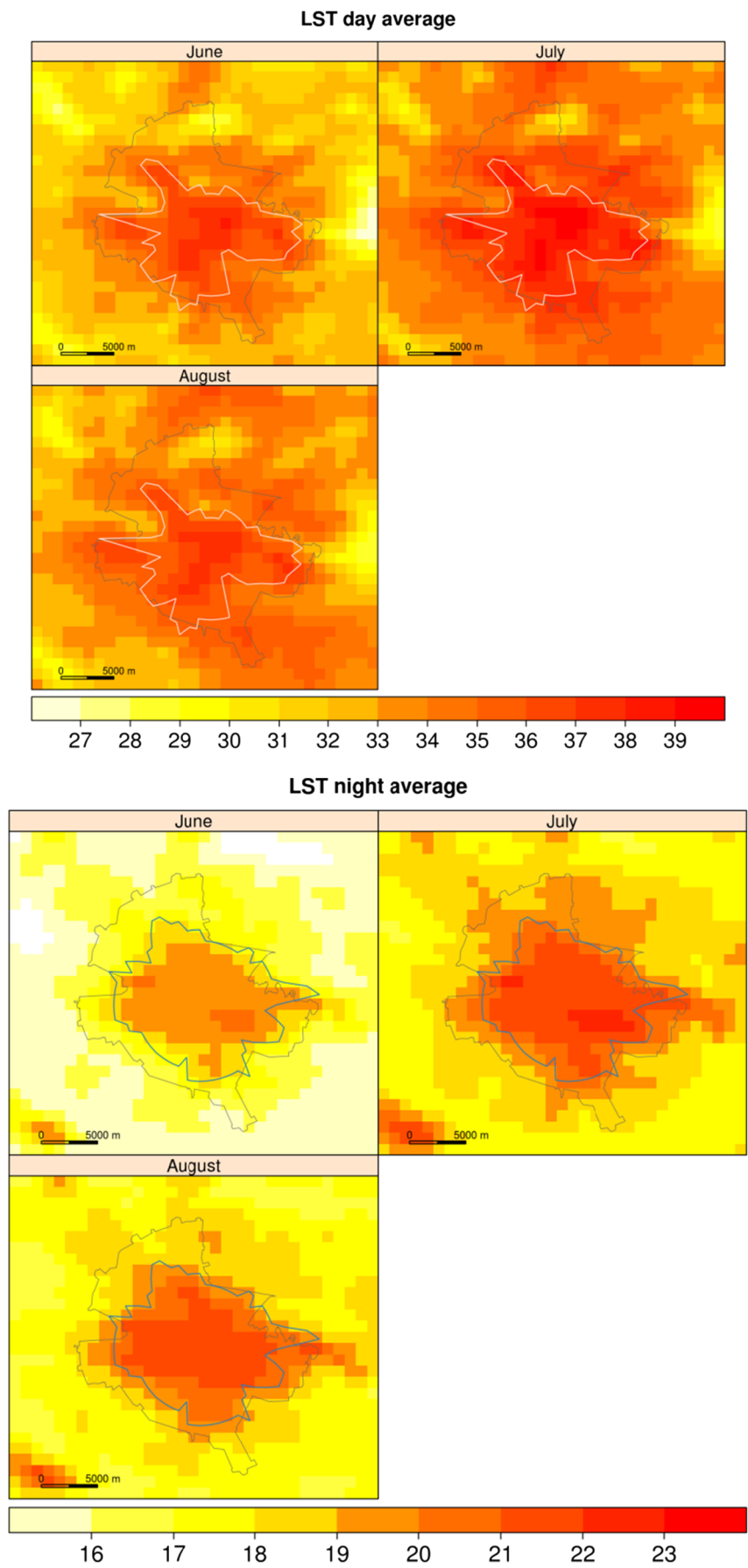


Fig. 2 Average LST values (°C) in July derived from MODIS images, interpolated with inverse distance weighting method and classified according to equal interval (*left*) and quantile criteria (*right*), for night-time (*up*) and daytime (*down*). The LST values correspond to clear-sky conditions

Fig. 3 Average LST values and Bucharest's UHI (*blue* for night-time and *white* for daytime), as retrieved from MODIS images (2000–2012)



the urban perimeters occur in July (39–40 °C), when the fields around the city register 28–29 °C.

Figure 4 shows the variation of the mean LST along N-S and W-E transects in July, and the shifting points retrieved by the Rodionov test, assumed as BHI limits. A similar approach is applied for all transects. The nocturnal SUHI is always visibly framed by two distinctive changing points for each of the 36 profiles, whereas the diurnal regime changes are sometimes indicated by one, two or three points, making the net SUHI delimitation more difficult. The decrease in temperature from the city centre to its periphery and rural surroundings is not linear, meaning that the statistical test may return significant thermal differences between adjacent urban surfaces (e.g. constructions sites, ponds, green areas) taking place by day and assign them as changing points. However, LST values may increase again considerably beyond these points, meaning that the SUHI limit could be assigned to a second change point. Overall, the nocturnal change points are well grouped at 7–8 km around Bucharest’s downtown, but during the day, one finds two alignments placed at 3–4 and 7–8 km, respectively (Fig. 5). They are simultaneously active, showing that the LST is decreasing from downtown to the periphery in two major steps. For the clarity of the demonstration and based on

Fig. 4 Night-time (a, b) and daytime (c, d) average LST in July along N-S and E-W cross profiles through Bucharest. The black squares mark the significant regime shift index values ($p < 0.1$), and the dotted lines represent the average between the changing points. Downtown (University Square) is situated at 15 km

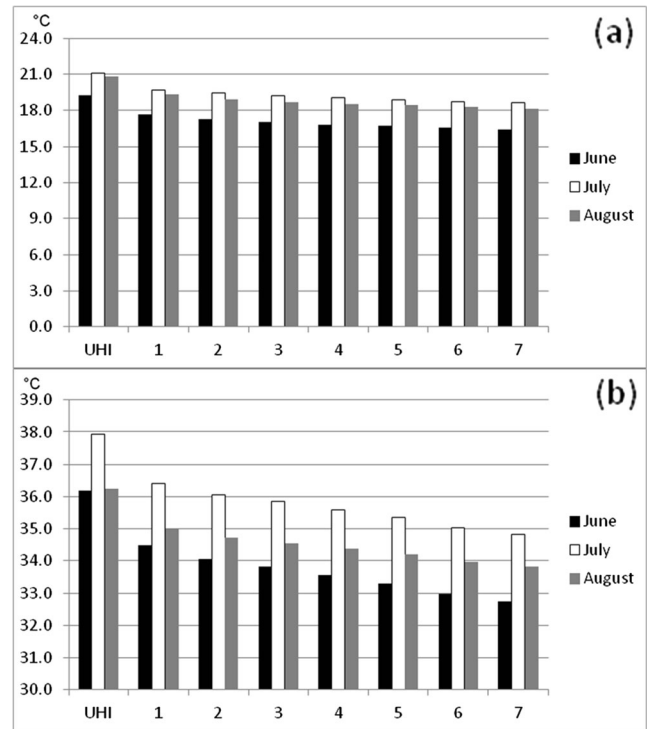
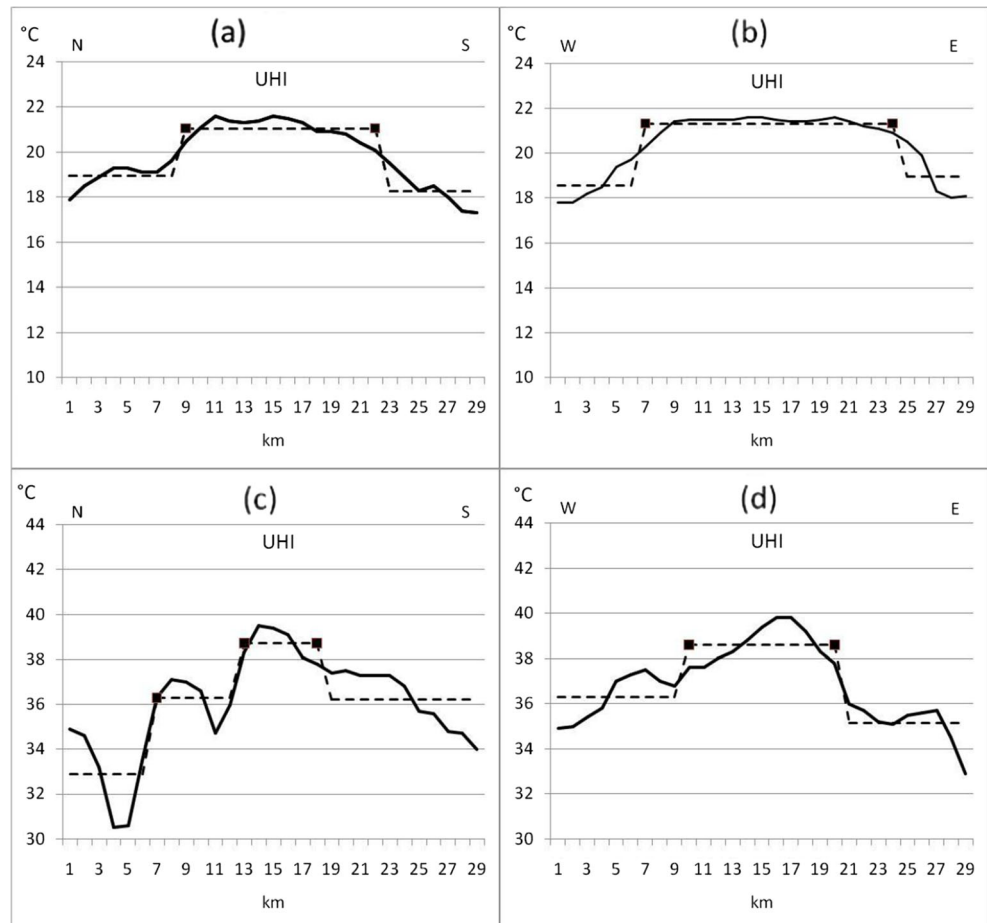


Fig. 5 Number of significant change points identified along the LST transects crossing the Bucharest downtown (University Square), for night-time (a) and daytime (b)

expert judgement, the SUHI was hereby drawn by the shifting points nearest to the centre.

The high correlation coefficients between the MODIS LST values and the air temperature recorded simultaneously in standard conditions at the Bucharest meteorological stations (Table 1) suggest that canopy UHI and SUHI may have very similar characteristics, especially if one takes into account the inherent differences related to the measurement procedures. The correlation is higher for night-time values illustrating the more stable regime in terms of the radiation budget and atmospheric dynamics. Similar findings were reported for other cities (Benali et al. 2012), illustrating the potential use of MODIS LST for predicting air temperature, but the lower correlations between daytime air temperature and LST should trigger caution in such applications.

3.2 Intensity of the Bucharest summer SUHI

Generally, the intensity of the UHI is the thermal difference between the values measured within the urban perimeter, often at a meteorological station, and the ones retrieved in a rural neighbouring spot (Oke 1973; Unger et al. 2001). The main criticism may refer to the relevance of the two points for representing the local climate, since heterogeneity and land cover/land use dynamics are very active geographic features of large urbanized areas. Besides, it is difficult to compare the intensity values of two different cities, unless measurements are performed in very similar local conditions. This study uses the differences between the LST values within the UHI, and the ones calculated for surrounding buffers with various widths (1 to 7 km), as quantitative indicators for the SUHI intensity.

Figure 6 and Table 2 reveal that, during the summer months, the LST decreases continually with distance from Bucharest’s downtown. The highest difference between the urban perimeter and the rural neighbourhood occurs in July, by daytime, when the SUHI’s average temperature is 37.9 °C, the proximal buffer (0–1 km) has 36.4 °C, and the largest buffer (0–7 km) registers 34.8 °C. The temperature decrease between the UHI and the periphery areas is higher for daytime than for night-time in June and July but lower in August. Similar patterns are observed for maximum and minimum LST values (not shown here).

3.3 Land cover influence on the Bucharest summer SUHI

The CLC dataset 2006 (level 2) illustrates that urban fabric, arable land, permanent crops and forest are the main land cover types in the area of about 1,000 km² (35×35 km) centred on the city of Bucharest, while pastures and water bodies induce even more diversity.

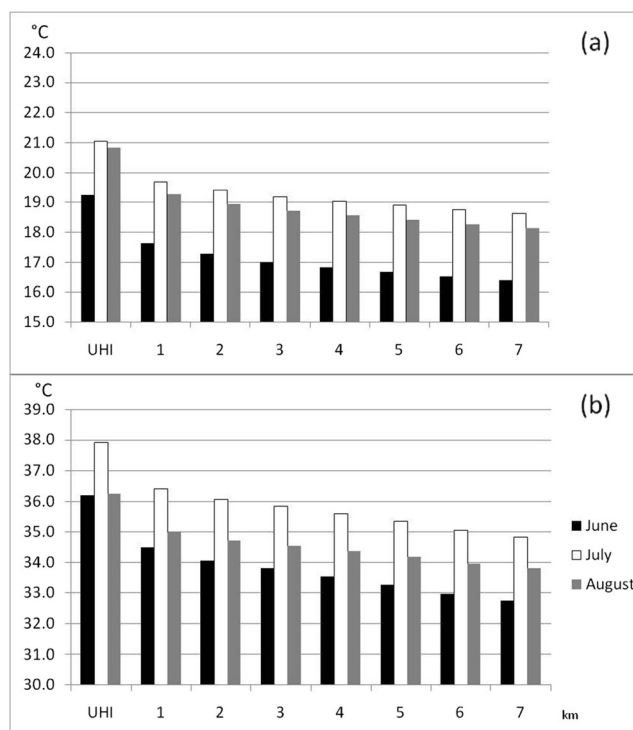


Fig. 6 Mean LST values (°C) for the UHI and the surrounding buffers of 1 to 7 km, for night-time (a) and daytime (b)

Figures 7 and 8 refer to the LST and SUHI in connection with the land cover types extended over at least 10 km² in the area of interest. It appears that the LST is highly dependent on land cover type. Urban fabric and industrial surfaces register the highest values both by day and night, while inland wetlands and waters remain considerably warm by night and join the forest as the coldest surfaces during the day. The study has revealed the very strong influence of the urban water bodies on the LST. For example, one can remark the shift between the daytime and night-time SUHI at the northern edge

Table 2 Differences between the UHI’s average LST (°C) and the surrounding buffers

	Month	Buffers around UHI (km)						
		0–1	0–2	0–3	0–4	0–5	0–6	0–7
Night-time	June	1.6	2.0	2.2	2.4	2.6	2.7	2.9
	July	1.4	1.6	1.9	2.0	2.1	2.3	2.4
	August	1.6	1.9	2.1	2.3	2.4	2.6	2.7
	Summer	1.5	1.8	2.1	2.2	2.4	2.5	2.7
Daytime	June	1.7	2.1	2.4	2.6	2.9	3.2	3.4
	July	1.5	1.9	2.1	2.3	2.6	2.9	3.1
	August	1.2	1.5	1.7	1.9	2.0	2.3	2.4
	Summer	1.5	1.8	2.0	2.3	2.5	2.8	3.0

of Bucharest, which illustrates the influence of the Colentina River and its associated meanders and lakes (Fig. 7). Similarly, at the western periphery, the Ciurel Lake makes the difference between night-time and daytime UHI.

Acknowledging the limitations induced by the different spatial resolutions of land cover and MODIS LST, it is worth discussing the case of the ‘artificial, non-agricultural vegetated areas’, including ‘green urban areas’ and ‘sport and leisure facilities’. They comprise about 16 km² and refer to urban parks, other green perimeters, open sport fields, etc. with surfaces that are often less than 1 km² in area each. The cooling effects of such areas have been well documented (Spronken-Smith and Oke 1998; Ren et al. 2013). Nevertheless, the summer LST over the artificial, non-agricultural vegetated areas is considerably higher than the average of the surfaces with close thermal characteristics like forests and urban ponds and even higher than ‘urban fabric’ which is expected to be the hottest spot in a large city (Table 3).

4 Conclusions

Remote sensing satellite products have a strong potential for use in climate studies, as they may provide a continuous spatial coverage of the Earth. Additionally, the time span of the datasets has increased considerably in the recent years, and the temporal and spatial resolutions are appropriate. For example, the MODIS LST products proved their utility for predicting air temperature in urban areas (Benali et al. 2012) or for spatio-temporal prediction of daily temperatures (Hengli et al. 2012).

This study uses the 2000–2012 LST dataset retrieved by the MODIS sensors placed aboard NASA satellites to examine the Bucharest Surface Heat Island characteristics during the summer months. We propose a methodology for identifying the SUHI’s limits and the derived geometry based on the statistically significant changes along LST cross profiles. The study claims that the intensity calculated as the difference between the LST within the SUHI’s limits and several surrounding buffers is an efficient and flexible tool for describing the average thermal state of the urban–rural transition. The

Fig. 7 Administrative boundaries of Bucharest, land cover types, night-time and daytime UHI (black and, respectively, yellow lines), meteorological stations (flags) and University Square (white star)

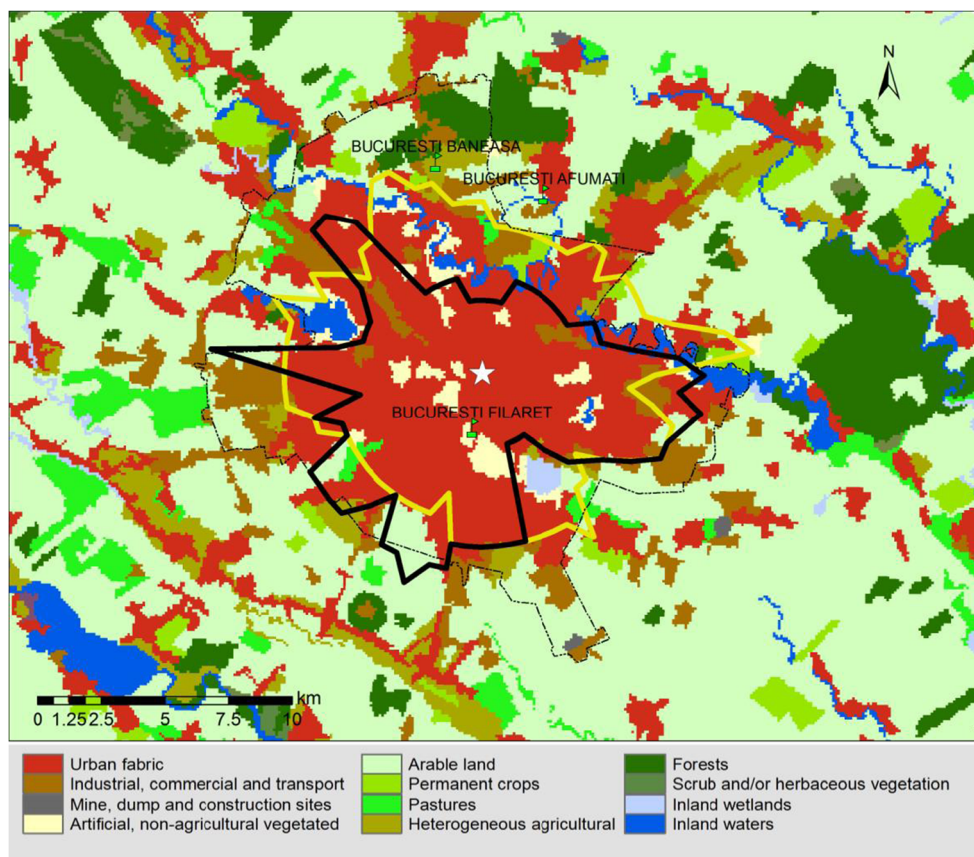
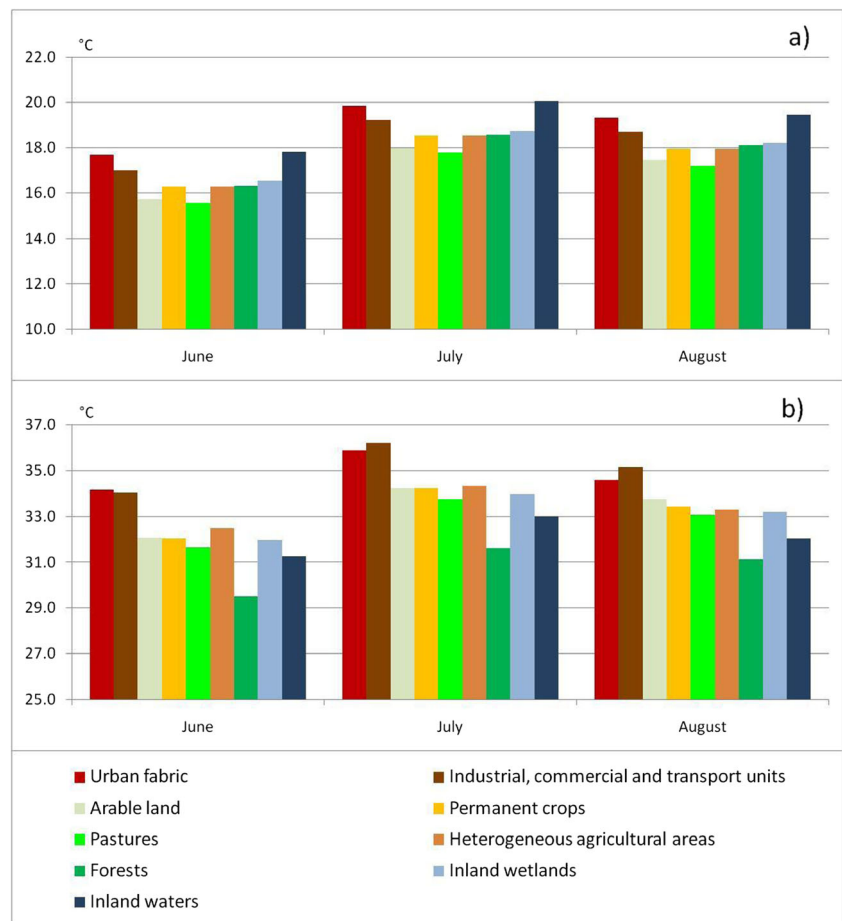


Fig. 8 Summer mean LST values (°C) over land cover types over Bucharest metropolitan area (a night-time and b daytime)



method secures the weight of comparing the SUHI's intensity of different urban areas.

There are little variations between summer months, but the SUHI's shapes and intensities under clear-sky conditions are very specific to night-time (regular and 2–3 °C less in the 7-km width buffer) and daytime (more irregular and steeper temperature decrease). In both cases, strong relationships with the land cover can be assumed, but MODIS LST products

should be used cautiously for quantitative analysis as a consequence of their spatial resolutions.

The results confirm, extend, update and enhance previous studies performed over the same area, with similar techniques (Cheval and Dumitrescu 2009). The substantiation refers to comparable SUHI patterns and similar results, the extension addresses a longer time interval (all summer months instead of July only), the period is updated from 2000–2006 to 2000–2012 and the enhancement means a considerably denser transverse network (from 8 to 36 profiles) and computation of the LST values for different land cover categories.

The limitations of the approach are rather general and applicable to any remote sensing study, and they do not interfere with the quality of the output for this specific study. Refinements and corrections, comparison and combinations with other techniques and more in-depth investigations regarding the land cover influence would probably lead to quantitative adjustments of the SUHI's limits and geometry delimited here.

Table 3 Summer mean LST values (°C) for different land cover categories over Bucharest

	Night-time	Daytime
Urban fabric	19.0	34.9
Artificial, non-agricultural vegetated areas	20.3	35.1
Forests	17.7	30.8
Inland waters	19.1	32.1

Acknowledgments The authors would like to warmly acknowledge Sergiu Ioan (National Meteorological Administration, Bucharest) and Sam Hardy (University of Manchester) for their support in improving the English used in this paper and Prof. Dr. Eng. Dan Constantinescu, for his long-term encouragement and highly competent suggestions regarding urban climate research. We also thank to the two anonymous reviewers for their useful comments and suggestions.

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