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THERMAL DIFFERENCES WITHIN BUCHAREST TOWN AREA CASE STUDY: 01.07.2006-31.03.2007

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Key words : thermal differences, Bucharest town-area, heat surplus.

Abstract. The thermal differences within the Bucharest town-area, as presented in a case study based on hourly measurements in seven fixed-site monitoring stations, made from 01.07.2006 to 31.03.2007, have clearly revealed the town's thermal superiority over the open spaces around it, even if they are lying at similar or at lower altitudes. The town's heat surplus, which is mainly due to the various building materials, the density and height of buildings, the orientation of main traffic avenues, the distribution of parks and lakes etc., gets more evident during the warm season. Besides, the thermometrical determinations that have been simultaneously performed at two different height levels (2 and 10 m-high above ground surface) of the seven fixed-site monitoring stations show clear differences of air heating processes, mostly due to the different interaction patterns between solar radiation and the underlying active layer.

Introduction

Like many other towns of importance as regards their spatial extent and density of buildings, Bucharest town, ranking as Romania's biggest city, with close buildings and compact street-pavements, exerts deeply modifying influences on air-temperatures, that turn its relatively homogenous territory into a particular space with specific thermal value and time variations. The differences are, obviously, not very large if comparing the monthly air-temperature means, but the ranges of the daily means and the hourly values are often considerable. Among the numerous causes of the thermal differences creating specific urban topoclimatic conditions, the town's active layer surface that has been deeply modified by man's intervention, is one of the most important ones. This surface has physical characteristics that are substantially different from those of the adjoining field areas, also implying different matter and energetic exchange fluxes. The impermeability of the urban active layer surface prevents rainfall water from infiltrating into the ground, thus largely

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reducing the 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 and definitely thermally different even from one place to another, inside the urban area (Ciulache and Ionac, 2008). In the recent years, the urban climate has become a climatological theme of preference worldwide, although its theoretical fundamentals date back to the mid 1960's (Kratzer, 1966) and subsequently developed into an important topic of academic interest, which laid the basis of urban climatology in most respected universities worldwide, Romania included (Ciulache, 1980; Fărcaş, 1999). However, the early studies focused more on the differences between the highest urban temperatures and the background rural areas (Oke, 1973; Spronken-Smith and Oke, 1998; Unger et al., 2001), until more refined calculus techniques were introduced, such as the height of a Gaussian surface (Hung et al., 2006). Later on, the Urban Heat Island (UHI) has been approached from various perspectives, which have been thoroughly revised by Arnfield in 2003. But as technological improvements opened new perspectives, the scientific topic of urban climate has later developed into some remarkable applied overviews (Landsberg, 1981; Oke, 1984), including GIS or remote sensing investigations of the urban heat island (Streutker, 2002; Jin and Shepherd, 2005; Pongracz et al., 2005). Furthermore, Voogt and Oke (2003) reviewed the relevant terminology associated to studies focusing on urban climates based on remote sensing techniques and, since NASA has started collecting data from its seven *Moderate Resolution Imaging Spectroradiometer* (MODIS) sensors aboard the Terra (EOS AM) and Aqua (EOS PM) satellites, they have been intensively exploited for various climate applications (Liu and Key, 2003; Jin et al. 2005), especially to detect both land and air conditions that are largely modified by urban environments (Jin and Shepherd, 2005; Hung et al. 2006). In this respect, Dash et al. (2002), Jin et al. (2007) and Mendelsohn et al. (2007) even argue that the satellite temperature measurements provide better results than the ones obtained by interpolating ground-station temperatures, although other researchers proved that the temporal variations of the UHI could be more efficiently monitored on data provided by ground weather stations recording adequate long-term series. In Romania, the climatic influence of the urban settlements had formerly been documented for Bucharest (Neacşa and Popovici, 1969, 1974; Dumitrescu Elena, 1971) and Iassy towns (Erhan Elena, 1971, 1979) and more detailed instrumental measurements have later contributed to the investigation of the specific characteristics of urban climates in both above-mentioned cities:

Bucharest (Tumanov et al., 1999) and Iassy (Apostol, Sfâcă, Alexe, 2012). Moreover, the spatial extention, geometry and magnitude of Bucharest's urban heat island have more recently been explored and assessed on the remote sensing images provided by the moderate resolution imaging spectroradiometer (MODIS) sensors, both for all the months of July in the 2000–2006 time interval (Cheval and Dumitrescu, 2008) and for the July 2007 heat wave that affected most of Europe (Cheval, Dumitrescu and Bell, 2009).

1. Data and methods

The assessment of the specific air-temperature time and space variations in the Bucharest town-area should include a comparative analysis of longer-time series data (over at least a 30-years period which is necessary to ensure the time representativeness of the data series), obtained both from weather stations located inside the urban area and from weather stations located outside the town-area but in similar physical-geographical conditions, though unaffected by the town's influence. Such ideal conditions are often difficult to be found in case of many Romania's towns, as well as in case of many other towns in the world. This is either because the weather station of the analyzed town is not usually located inside the town-area and consequently, does not provide meteorological information which may be typical of the urban active-layer, or the weather station located in the adjoining rural space, unaffected by the modifying influence of the city, is neither located at the proper distance away from the town, nor is located in different conditions, nor has similar time-series data (Ciulache, 2004). However, the urban thermal characteristics may also be outlined by means of air-temperature data obtained from patented environmental monitoring stations, located in specific observation points, both inside and outside the town of reference, which also make meteorological measurements with standard instruments, on standard conditions. Therefore, in the present study, we have used the air-temperature data provided, from 01.07.2006 to 31.03.2007, by the seven automatic environmental monitoring stations which have been located by the Environmental Protection Agency into some of the most representative points of the larger Bucharest's metropolitan area: Berceni, Cercul Militar, Lacul Morii, Drumul Taberei, Titan, Măgurele, Baloteşti. As the hourly air-temperature measurements (00.00 – 23.00 UTC) were made at both 2 and 10 m-high above ground levels, we could therefore also identify potential vertical air-temperature differences, as useful indicatives of thermal inversions.

2. Results and discussions

Bucharest municipality is lying in the southern part of the country, in the Vlăsia division of the Romanian Plain, at a distance of about 60 km far off the Danube River, 100 km off the Carpathian Mts. and 250 km off the Black Sea shore. The actual territory of the city extends over 53 km from N to S and over 46 km from E to W, on a total area of 1,521 km^2, representing 0,64% of the country's territory. The altitudes of the specific nearly level landforms within the city, range from 54 m (Dâmboviţa river-valley) to 95 m (in the north-lying Străuleşti district); the mean altitudes averaging 80 m-high in most of the town area, which is administratively divided into 6 sectors that radially extend from the centre to the periphery of the town, that is traversed by the canalised Dâmboviţa river (flowing on 266 km right through the historical centre of the town) and the Colentina river (peripherally flowing across the city on a NW-SE direction along 80 km, through 6 regulator lakes which are mainly used for recreational activities) (Ionac, 2005). Despite the fact that Bucharest town area is mainly influenced by the alternate or simultaneous influence of the Western circulation, the East-European Anticyclone, the Mediterranean Cyclones, and the Tropical advections, it is basically lying at the southernmost limit of the specific mid-latitude climate of transition, getting noticeable subtropical (mediterrannean) characteristics (Ciulache, Ionac, 2004), with annual mean temperatures (1961–2006) of 11.3°C, high annual air-temperature range (25-26^{0}C) between the coldest (January: −1.5°C) and the hottest month (July: +22.9°C) and late summer episodic droughts. Its built-in area (totalling 228 km^2 and still vigorously growing) with a permanent population of around 2 million people, has created specific topoclimatic and bioclimatic conditions which could roughly be characterised as highly artificial, since almost all meteorological elements, especially air-temperatures, show visible differences among its various district areas.

The comparative analysis of air-temperature values recorded at all the seven urban monitoring stations, over a synchronous time period (01.07.2006 – 31.03.2007), clearly reveals that the town area (especially its central parts) is characterized by higher air-temperatures, even in case of <u>monthly mean values</u> which largely attenuate the individual air-temperature differences recorded on specific synoptic conditions. The previously-mentioned data also indicate an evident value increase, at 2-m high level, from the outskirts to downtown areas and from the outer, more sparsely-distributed house districts to the inner, most densely built-in areas. Consequently, the monthly air-temperature means have constantly kept higher, all through the interval of reference, in the city's heartland area (Cercul Militar) than in the neighbouring rural areas (Baloteşti) (Fig. 1). If analyzing the temperature difference between the highest (July 2006) and the lowest (December 2006) monthly means calculated for each weather ground station all through the period of reference: Berceni – 21.6^{0}C, Cercul Militar – 21.9^{0}C, Drumul Taberei - 23.4^{0}C, Lacul Morii – 18.6^{0}C, Magurele – 21.7^{0}C, Titan – 20.9^{0}C, Balotesti – 20.2^{0}C, it becomes obvious that: lower air-temperature differences are characteristic either of the park areas along Colentina's river regulator lakes in the NW areas or of the peripheral wooded areas in the northern parts of Bucharest city, on one hand, while the higher 2-m level air-temperature differences are specific of the more densely-built and industrialised areas in the SW peripheries, on the other hand, specifically pointing to the artificially climatic role of the ground surface. The topoclimatic role of town's landforms and active layers gets also evident in case of air-temperature variations at 10 m-high above ground surface, which show, for instance, that the corresponding air-temperature values at the Berceni monitoring station are obviously higher than at the lower 2-m high level, over the entire period of analysis. This means that the low-lying, depressionary area on the southern peripheries of Bucharest-city favors, especially in winter, the accumulation and stagnation of subsiding cold air, producing air-temperature inversions, which account for lower air-temperature values to the ground and for the warmer air aloft (Fig. 2). Thermal inversions are also evident for the Balotesti station, all through the period of analyis, probably due to the more intense radiative cooling processes over the open agricultural field areas in the northern peripheries. Moreover, the monthly mean air-temperature space variation at 2-m high above ground surface, reveals higher values on the south-western, well-shaded areas as compared to the open-space north-eastern areas.

The thermal difference often exceeds 2^{0}C in July and previous studies have already pointed out that, during the interval May–December 2004, the maximum intensity of the Bucharest heat island was about 4°C (Tumanov et al., 1999) or that, in case of extreme summer-time weather conditions (heat wave of July 2007), this value reached 3.8°C (Cheval, Dumitrescu, Bell, 2009). However, the monthly means of 2-m high level air-temperature data provided by the seven urban monitoring stations in July 2006 show that the thermal differences between the downtown and the peripheral areas can be as high as 3.5°C (if referring to actual temperature ranges from 24.7°C at Cercul Militar to 21.2°C at Balotesti) (Fig. 3a). These thermal differences may get even higher in December, since air-temperature values in the north-eastern, eastern and south-eastern urban areas are greatly decreasing due to either their lower altitudes, favoring cold air to sink down, or to their exposure to the more frequent northern and north-eastern cold winds, frequently blowing especially in winter (Fig. 3b).

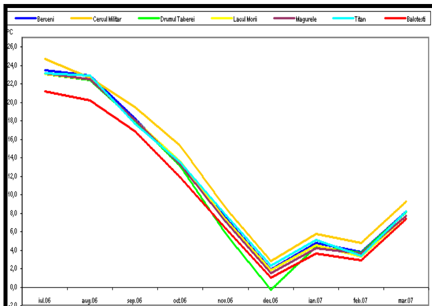


Fig.1 Monthly mean air-temperature variation at 2-m high above ground level, from 01.07.2006 to 31.03.2007

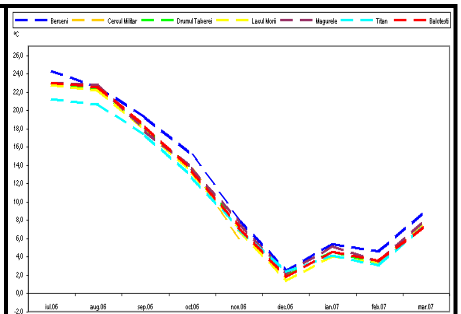
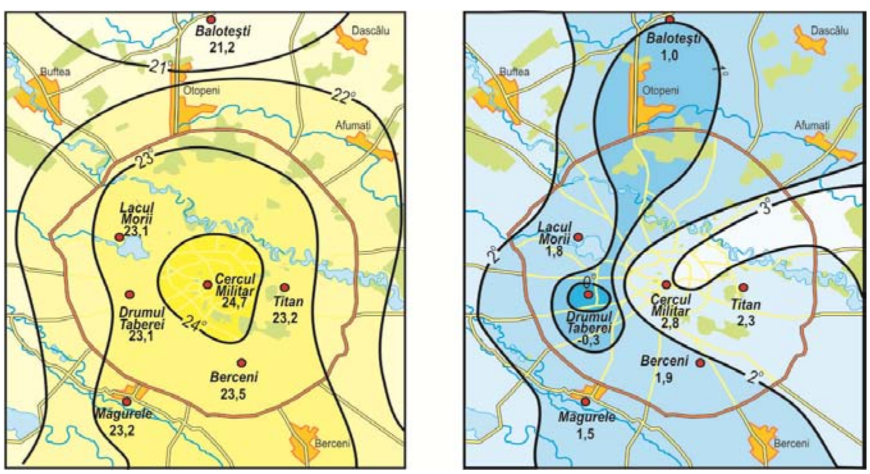


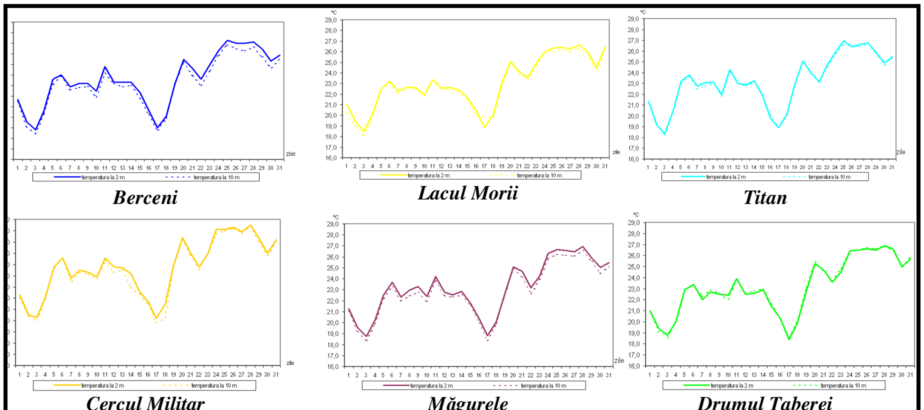
Fig.2 Monthly mean air-temperature variation at 10-m high above ground level from 01.07.2006 to 31.03.2007



a. July 2006 b. December 2006

Fig. 3. Monthly mean air-temperature space variation in Bucharest town-area

If analyzing the daily mean air-temperature values over the entire period of reference (1.07.2006 – 31.03.2007), lower thermal differences between in-town and out-town areas of Bucharest city were recorded in July 2006 and higher in December 2006. However, both values of daily mean air-temperature differences in July 2006 (Fig. 4) and December 2006 (Fig. 5) are strongly influenced by weather processes, which greatly change cloud cover and wind direction and speed, irrespective of the location of the monitoring station, so that their time-evolution looks much the same. Nevertheless, in July 2006, the strong influence of overheated asphalt cover and densely-built space in central downtown areas



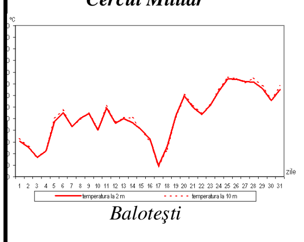
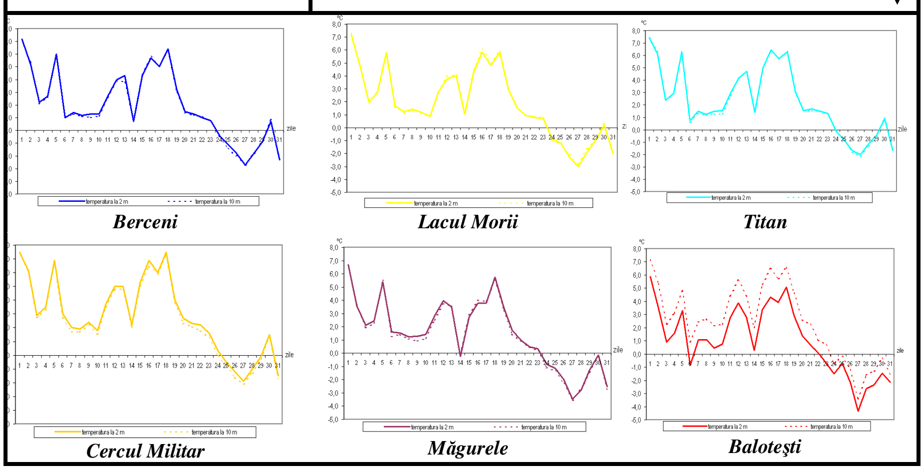


Fig. 4. Daily mean air-temperature variation JULY 2006

Fig. 5. Daily mean air-temperature variation DECEMBER 2006

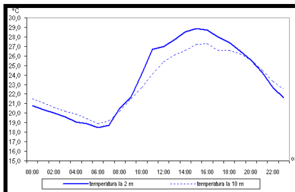


(Cercul Militar station) is self-evident in producing constantly higher air-temperature values as compared to all the other in-town areas, as well as in shaping an urban heat island in the very heartland area of the city. Thermal differences also appear in December 2006, when the thermal peak on the 16th is absent at Măgurele and the winter-time thermal inversion gets stronger at Baloteşti, where the 10-m high air-temperature prophile indicates constantly higher values than at 2-m high level.

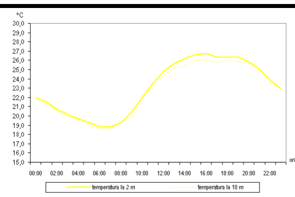
Generally, the objective instrumental air-temperature data recorded at all seven monitoring stations indicate that the town-areas are warmer than the surrounding rural areas and the downtown central areas are also warmer than the outskirts areas. In this case, the artificial heating in winter may play an important role in increasing the thermal differences between the urban and rural areas since they get larger and larger with the onset of artificial heating equipments in late autumn (Ciulache, 2006). Nevertheless, artificial heating is not the only cause of the above-mentioned differences. On the contrary, in winter, the presence of the snow-cover determines a noticeable increase of thermal differences between inside and outside town areas. This is mainly related to the fact that, outside the city, the snow-cover is homogenous and clean (the high albedo and IR emittance coefficient values greatly diminishing its heating) on one hand, while inside the city, the snow-cover is discontinuous and rather dirty (with much lower albedo values), on the other hand.

Air-temperature daily variation shows that both minimum and maximum hourly values are delayed between the inner and outer parts of the city. The highest hourly air-temperature values is usually reached around 14.00 hrs in the downtown areas and 2 hrs later (at 16.00 hrs.) at Măgurele and Baloteşti, in the peripheral rural areas (Fig. 6). Consequently, the lowest hourly air-temperature values usually occur, in December, at 06.00 hrs in the outskirts areas and at 08.00 hrs in the downtown areas (Fig. 7).

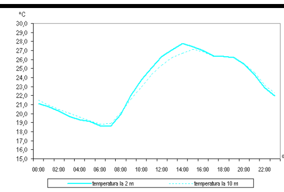
The greatest thermal differences between the outer and the inner parts of Bucharest city are obviously produced in summer, towards evening, when the intense radiation cooling processes over the open-air field areas largely reduce air-temperature values, whereas the crossover radiation of the town's buildings substantially contribute to the additional heating of the town's underlying surface and air, thus maintaining air-temperatures at constantly high values. The slower heating of the underlying town surface and the faster heating of the adjoining open-air field areas largely account for less thermal differences in summer, at noon. On the contrary, in winter, the town areas remain warmer than the rural areas, even at noon hours. But the values of the negative differences are very small.



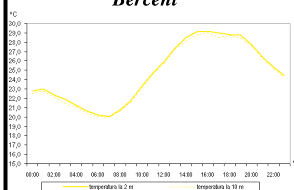
Berceni



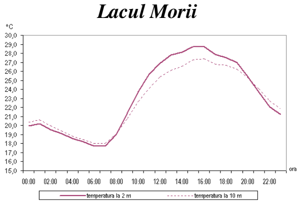
Lacul Morii



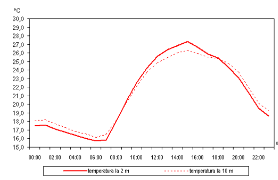
Titan



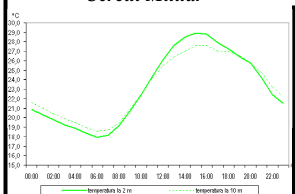
Cercul Militar



Măgurele



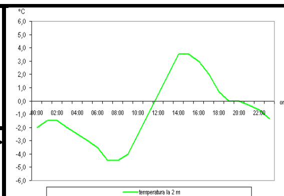
Baloteşti



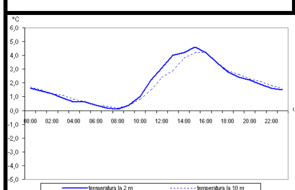
Drumul Taberei

Fig. 6. Hourly air-temperature variation JULY 2006

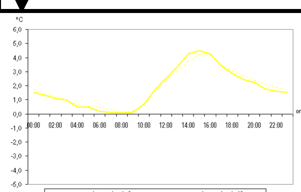
Fig. 7. Hourly air-temperature variation DECEMBER 2006



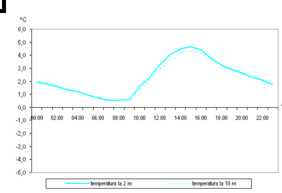
Drumul Taberei



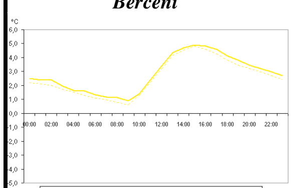
Berceni



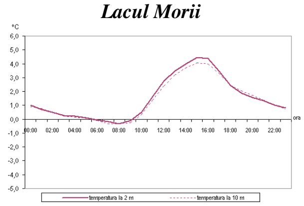
Lacul Morii



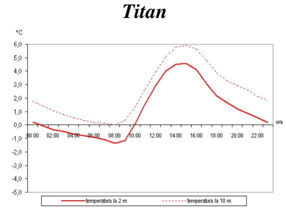
Titan



Cercul Militar

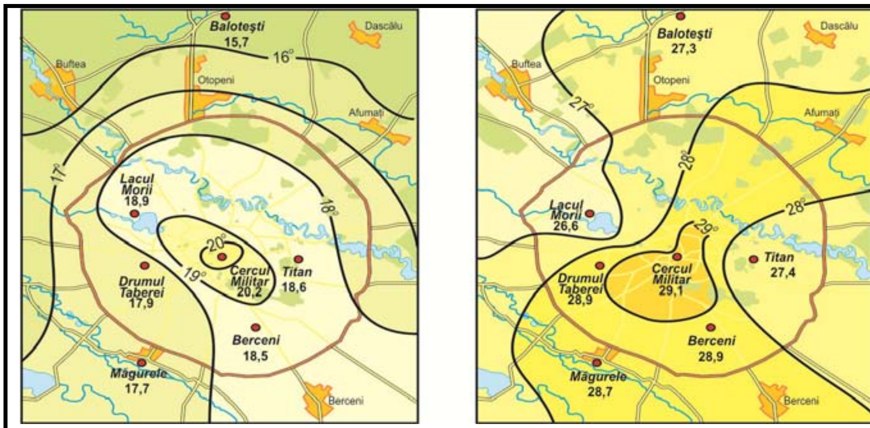


Măgurele



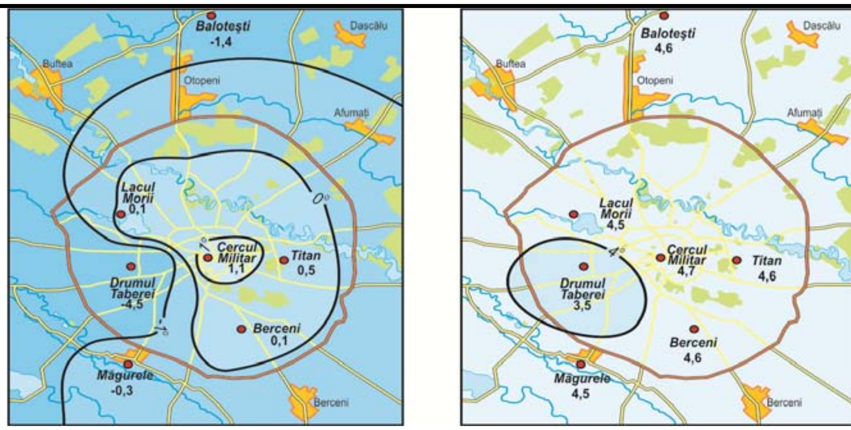
Baloteşti

Likewise, the hourly air-temperature space variation in Bucharest town-area reveals substantial thermal differences between the city's inner and outer parts. For instance, in July, at 06.00 hrs, the warmer area is restricted to the very small heartland of the city and the southern, most densely-built peripheries are definitely warmer than the northern, open-air rural spaces (Fig. 8a), while at 15.00 hrs, the cooler areas extend along the Colentina river-valley and its regulator lakes (Fig. 8b). In December, at 08.00 hrs, the air just above the ground surface keeps warmer only in the same small downtown area as in July, but the thermal differences between the city and the surrounding rural areas are largely attenuated and, therefore, air-temperature values are more evenly distributed around the urban nucleus (Fig. 9a). At 15.00 hrs., there are almost no thermal differences within Bucharest town-area and its surrounding rural peripheries, probably mainly due to the effect of winter artificial heating, except for a little area in the south-western, most densely built-in area of the city (Drumul Taberei) (Fig. 9b).



a. 06.00 hrs. b. 15.00 hrs

Fig. 8. Hourly air-temperature space variation in Bucharest town-area
JULY 2006



a. 08.00 hrs. b. 15.00 hrs.

Fig. 9. Hourly air-temperature space variation in Bucharest town-area DECEMBER 2006

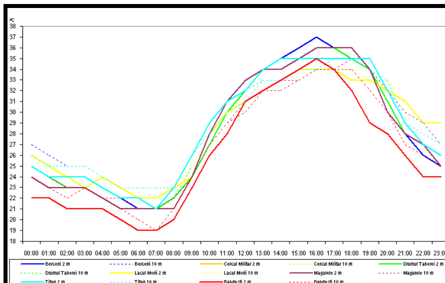


Fig. 10. Hourly air-temperature variation 20 AUGUST 2006

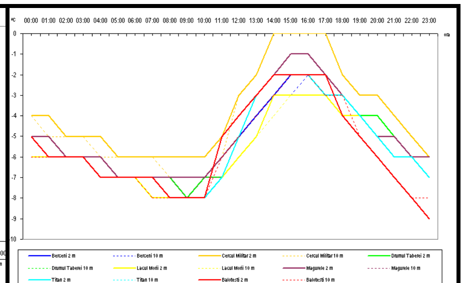
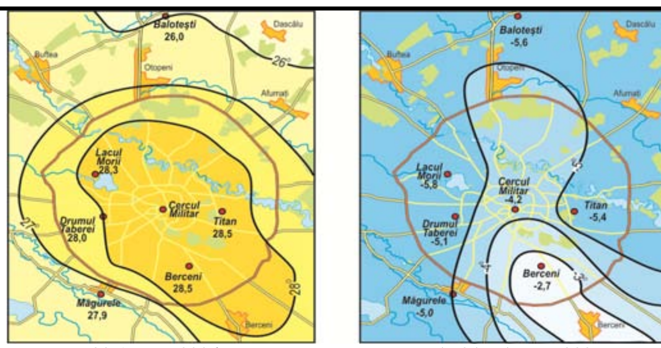


Fig. 11. Hourly air-temperature variation 24 FEBRUARY 2006

The thermal differences between the central and peripheral parts of Bucharest town-area are even more pronounced on days with extreme air-temperatures. In this respect, the 20th August 2006 and the 24th February 2007 were the hottest andrespectively, the coldest days, when all monitoring stations recorded the highest and respectively, the lowest air-temperature values in all the interval of reference. In the former case, one can notice air-temperature differences of at least 3^0C between the most densely built-in areas (Berceni) and the garden and park areas along the Colentina lakes (Lacul Morii). Moreover, the maximum air-temperature values occur at least 1 hour later in open space areas than midtown (Fig. 10). In the latter case, the thermal differences between outside and inside areas of the city are increasing, all in-town monitoring stations recording higher air-temperature values than the out-town ones. Besides, the lowest minimum values occur much earlier in the downtown area (06.00 - 09.00 hrs at Cercul Militar) than in the surrounding rural areas (08.00 – 09.00 hrs at Baloteşti) (Fig. 11).

The space distribution of daily mean air-temperature values in the two thermally extreme days best reveal the influence of local relief forms and altitude. On the 20th August 2006 (Fig. 12a) the form of Bucharest's "heat-island" is more regular, extending over a wide area all over the built-in areas, while on the 24th February 2007, it is highly irregular, with warmer southern, low-lying peripheries greatly favoring the stagnation of cold air and the occurrence of thermal inversions (Fig. 12b). The corresponding space distribution of hourly air-temperature values on the two thermally opposite days also shows that, at 06.00 hrs, for example, the southern and south-western peripheries are warmer than the northern ones both on 20th August 2006 (Fig. 13a) and on 24th February 2007 (Fig.14a), while at 15.00 hrs, the former peripheral areas keep warmer only on the hottest day (Fig. 13b); the dominant northern and north-eastern cold-air advections reducing the extent of the "heat-island" to a relatively small area longitudinally centered along the town's main avenues with heavy traffic and dense buildings, which provide shelter against the main air-currents and use great amounts of artificial heating (Fig. 14b).

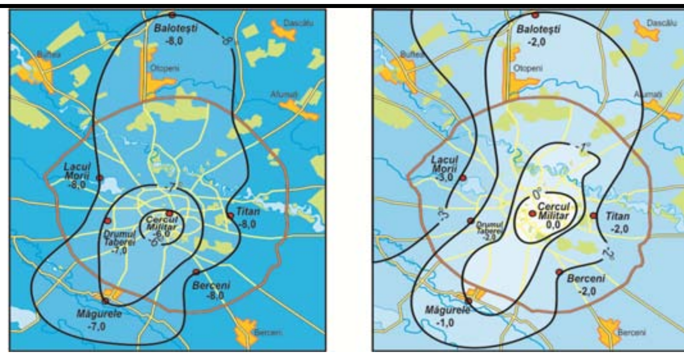


a. 20 August 2006 b. 24 February 2007

Fig. 12. Daily mean air-temperature space variation in Bucharest town-area

a. 06.00 hrs. b. 15.00 hrs.

Fig. 13. Hourly air-temperature space variation in Bucharest town-area
20 AUGUST 2006



a. 08.00 hrs. b. 15.00 hrs.

Fig. 14. Hourly air-temperature space variation in Bucharest town-area
24 FEBRUARY 2006

Conclusions

Generally, air temperatures in Bucharest city are higher than in the surrounding rural fields, both in summer, due to the overheated artificial land cover, and in winter, due to the heat surplus of the heating systems and busy traffic. Therefore, Bucharest city, like many other towns of importance when referring to their surface area and total population, has clearly shaped an urban heat island (UHI) around its heartland areas. By analyzing the air temperature data in the interval 1.07.2006 – 31.03.2007, a maximum monthly air-temperature difference of 3.5°C was calculated between the downtown and the peripheral areas. Lower air-temperature differences between the highest (July 2006) and the lowest (December 2006) monthly means are characteristic either of the park areas along Colentina’s river regulator lakes in the NW areas or of the peripheral wooded areas in the northern parts of Bucharest city, and higher 2-m level air-temperature differences are specific of the more densely-built and industrialized areas in the SW peripheries. However, the low-lying area on the southern peripheries of Bucharest-city favors, especially in winter, the accumulation and stagnation of subsiding cold air, producing air-temperature inversions. The daily mean air-temperature values over the entire period of reference indicate lower thermal differences between in-town and out-town areas of Bucharest city in July 2006 and higher in December 2006. However, both values are strongly influenced by weather processes, which greatly change cloud cover and wind direction and speed, irrespective of the location of the monitoring station. The greatest thermal differences obviously occur in summer, towards evening, when the intense radiation cooling processes over the open-air field areas largely reduce air-temperature values, whereas the crossover radiation of the town's buildings substantially contribute to the additional heating of the town's underlying surface and air, thus maintaining air-temperatures at constantly high values.

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