Urban 'heat island' in Moscow by satellite data

Lokoshchenko M.A.[1] and Sorokina E.A. [2]

[1]*Lomonosov Moscow State University, Russia, 119991, Moscow, Lengory, e-mail: loko@geogr.msu.su*
[2] *'Dubna' International University of Nature, Society and Man. Russia, 141982, Moscow region, Dubna, Universitetskaya str., 19.*

Abstract

For the first time the urban 'heat island' (UHI) in Moscow has been studied by long-term data of 'Aqua' and 'Terra' satellites which are equipped by MODIS radiometers. The surface temperature spatial field has been investigated over Moscow region with a 1 km resolution. Totally 108 satellite images for the period from 2009 to 2013 which were received in cloudless conditions on late morning have been analyzed. The surface temperature average value inside real city margins has been compared with the one outside the city (at rural zone in Moscow region) for each separate image during this period. As a result, the urban 'heat island' average intensity by radiometer data has been received as +2.8 ˚C. It varied from –0.1 to +7.7 ˚C so that sometimes on late morning this parameter may be a bit negative. The annual course of the 'heat island' intensity in Moscow has a maximum in spring and in summer and a minimum in autumn. On late morning the air temperature on the 2 m level is in average a bit warmer than the surface one by satellite data, a mean difference between them is about 1 ˚C.

Besides, the intensity of 'cool islands' in urban forests and parks has been separately estimated in the comparison with the non-green urban areas. It has been received that 'cool islands' mean-annual intensity is equal to –1.3 ˚C. The annual course of this intensity is characterized by maximum, i.e. the largest differences, during the vegetation period from April to September (in average –2.2 ˚C) and minimum from October to March (in average –0.4 ˚C).

1. Introduction

Usually urban 'heat islands' are studied on a base of the ground meteorological network data (Böer, 1964; Landsberg, 1981; etc.). However a density of this network is often insufficient and, besides, some stations sometimes do not represent their vicinity so that average estimations of the air temperature may be biased. Unlike them satellite radiometric data represent real estimations of the surface temperature but only in time of satellite flights above an area and only in case of cloudless sky. Thus a sampling number of satellite data about the urban 'heat island' intensity is limited, especially in mid-latitudes. Nevertheless satellite estimations of this parameter have a great importance. Since the 1970s separate examples of satellite data about urban 'heat islands' were started to be used – e.g., for Washington and Baltimore by (Landsberg, 1981). Now giant amount of satellite data is accumulated already, including remotely sensed measurements of the surface temperature. Among others, satellite data were used for studying of the 'heat island' intensity in Budapest, Hungary (Pongracz et al., 2012); of the 'cool islands' intensity in Tokyo, Japan (Honjo and Sawada, 2003); etc. However a use of satellite data for the urban climatology remains insufficient yet. The purpose of this work was to receive a preliminary estimation of the 'heat island' intensity in Moscow city on a base of long-term satellite data.

2. Total urban 'heat island' intensity

First of all let us discuss a total estimation of the urban 'heat island' (UHI) intensity by long-term satellite data for Moscow. As one knows both 'Aqua' and 'Terra' geo-orbital satellites are equipped by MODIS (MODerate resolution Imaging Spectroradiometer) radiometers. The 'Terra' satellite operates since 1999 whereas the 'Aqua' one operates since 2002 continuously. The data of radiometer infrared channels from all images of both satellites since 2009 till 2013 have been used for our analysis. Accordingly to these data the surface temperature is available with a 1 km^2 spatial resolution. Both satellites fly over the central part of European Russia including Moscow region one after another on late morning every day: 'Terra' – from 08:00 to 09:00 and 'Aqua' – from 09:00 to 10:00 UTC/GMT. Each image including MODIS radiometric measurements is carried out during about five minutes. An accuracy of the surface temperature T_s remotely sensed data is about ±0.1 ˚C. Thus there were 3652 images of both satellites during five years. However a cloud cover which exists very often at mid-latitudes doesn't allow a using of the satellite data. Besides, Moscow region sometimes may be located on the edge of image so that in these cases an accuracy of radiometer data is poor. Thus the first step of our analysis was to test every image visually and to choose only cases with cloudless sky and, simultaneously, when Moscow region was located at the central part of an image. As a result only 108 satellite images during five years have been chosen for further analysis.

A principal question is a possibility to compare space-averaged satellite data of the surface temperature T_s with a traditional data of the air temperature T by point measurement at meteorological stations on the 2 m level above the ground. For this purpose we used the results of the T morning measurements at Meteorological Observatory of Lomonosov Moscow State University which is situated on the South-Western part of the city. These results have been compared with a value of T_s by satellite data at the closest to the Observatory location 1 km^2 square. A sampling of simultaneous point *in situ* measurements of T (received by thermometer at Stevenson screen on the 2 m level) and space-averaged radiometric measurements of T_s was equal to 43; the average difference between them ($T–T_s$) was received as +0.9 ˚C; standard deviation σ = 3.6 ˚C. Thus, satellite data about T_s are in average comparatively close to the traditional measurements of T – at least, on late morning. It is appropriate mention here that the same difference ($T–T_s$) in conditions of Budapest region is varied from +1.1 to +1.8 ˚C at night and from –1.1 to –6.6 ˚C at midday depending on a season (Pongracz et al., 2012).

One more problem was to determine city margins on images. It should be noted that Moscow city since 1992 has a form like a turtle which is close to ellipsoid. The first our approach was a use of simple rectangle, close to square, which area (1000 km^2, red color at the left part of Figure 1) is almost equal to the real city area (991 km^2). Use of real margins (blue color at the right part of Figure 1) was the second approach and it is evidently more correct. Either one or another figure with fixed co-ordinates was used later for any image. An average T_s value inside Moscow city has been calculated on a base of sampling number of separate 1 km^2 squares (either 1000, or 991). This value was compared with an averaged value of T_s outside the city, i.e. in a rural outer area of Moscow region around the city. Real administrative bounders of Moscow region are too complicated so that the form of its area was conditionally accepted as a big outer circumscribed rectangle which lines are tangent to four extreme points of the real province. The area of this rectangle which has been used for both approaches is equal to 106,590 km^2 (without the city – 105,590 km^2 for the rectangle or 105,599 km^2 for real 'turtle' figure) whereas the real area of Moscow region as an administrative province is 44,379 km^2. Thus Moscow region at our analysis partially involves areas of neighboring provinces at the centre of European Russia.

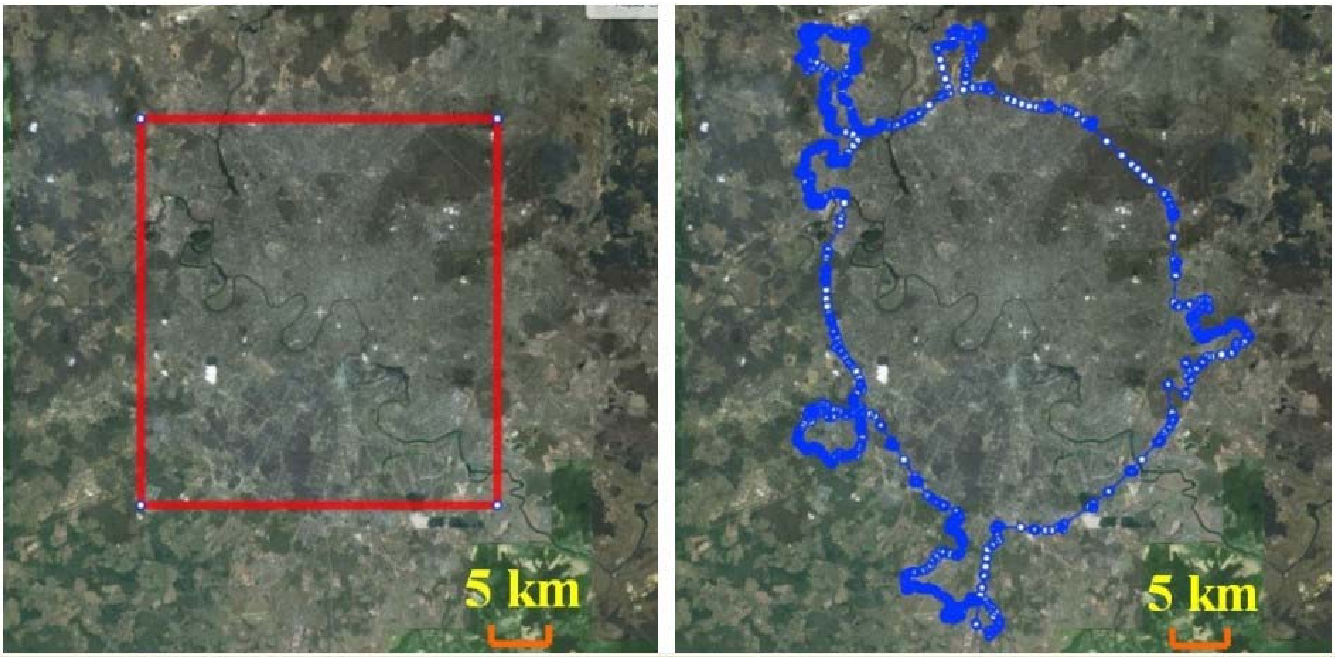

Figure 1. Margins of Moscow city on satellite image: simple square (red color, left) and real (blue color, right). Scale is presented by yellow color.

Firstly a simple rough approach of Moscow city as the rectangle was used for the period from 2010 to 2013. During that time 72 images in cloudless conditions have been chosen and used for analysis. Preliminary estimation of the average urban 'heat island' intensity, accordingly to 'rectangle approach' was equal to 2.6 ˚C. However, later more accurate approach of real city margins has been applied for the same data sampling. As a result more correct intensity has been received for the same data sampling (72 images) as 3.0 ˚C. It is not a surprise that the latter value is a bit higher because the edges of rectangle involve suburban areas where green zones predominate under the urban area.

Later only the second approach has been used and a sampling has been increased up to 108 images including 2009 year. As a result the urban 'heat island' intensity in average of five years is equal to 2.8 ˚C. This parameter varied at some cases from –0.1 to +7.7 ˚C so that sometimes on late morning it may be a bit negative. It is not a surprise because more heat capacity of building walls and asphalt covering in a city leads to longer thermal inertia not only of their cooling in the evening and at night but of their heating on the morning as well. As a result, on the morning the urban surfaces may be a bit cooler than natural ones outside a city. Indeed, this effect was described in classic literature – e.g., for Karlsruhe city according to (Böer, 1964). It should be noted that, accordingly to the traditional T measurements of the network of ground meteorological stations in Moscow and Moscow region, the maximal urban 'heat island' intensity, i.e. a difference between city centre and rural zones, in 1990s was equal to 1.6–1.8 ˚C. The 'arial' UHI intensity, i.e. a difference between whole urban zone (not only its central part) and rural zones, which is better comparable with satellite data, was even less for the same period: only 0.8–0.9 ˚C (Lokoshchenko, 2014). Probably, the reason of differences between results of *in situ* measurements and remote sensed data is a poor density of the ground meteorological network and non-representative location of some stations. Besides an average value of the 'heat island' intensity in Moscow, its annual course has been studied by satellite data too. Accordingly to our data sampling (108 cases), it has a maximum in spring and in summer (about 4 ˚C) and a minimum in autumn (nearly 1 ˚C). However this conclusion is preliminary because a sampling is not enough yet for detailed analysis of the annual course.

3. Local 'cool islands' intensity

One more task of this work, besides general estimation of the UHI intensity, was an estimation of the 'cool islands' intensity in Moscow city. The whole area of the city has been divided into four types of the surface including urban forests and parks, open water (river and lakes), area of dense urban saturation and all the rest (grasslands, separate buildings, etc.). As a result, the average surface temperature may be calculated separately for each of these types and compared both with each other and with conditions of rural zone outside the city.

As it is known green zones inside a city (separate parks or forests) usually represent 'cool islands' inside a total 'heat island' (a city) due to additional heat losses for transpiration and some other factors. E.g., a well-known example of a local 'cool island' is the Imperial palace in Tokyo, Japan with surrounding gardens around it where the air temperature at night is 3-4 ˚C less than in outer part of the city (Narita et al., 2009). Urban parks create 'cool islands' almost everywhere all over the world – e.g., one more example is Beer-Sheva, Israel (Shpirt et al., 2006).

A relative intensity of local urban 'cool islands' (UCI) has been calculated in the comparison with surrounding 'heat island' around them. For this purpose a special analysis has been made for urban forests and parks in Moscow by satellite data. Totally 23 separate green parks having an area not less than 0.5 km^2 have been contoured manually and, then, a total vector layer of these green zones has been created. The forest area of the biggest park on the North-East of the city, so-called in Russian 'Losiny Ostrov' (that means 'Elk Island'), is 38.8 km^2 only inside the city (a total forest area of this national park including its outer part outside city margins is about 96 km^2). In fact it is not a simple urban park but, rather, giant primeval forest where elks and other big mammals dwell. From the other hand, an area of the smallest park from our sampling is only 0.51 km^2. As it was mentioned above the 'Terra' and 'Aqua' satellites' remotely sensed data are available with a resolution of 1 km^2. Thus none of separate 1 km^2 squares inside the city, which may be 'green' in average, may be missed by

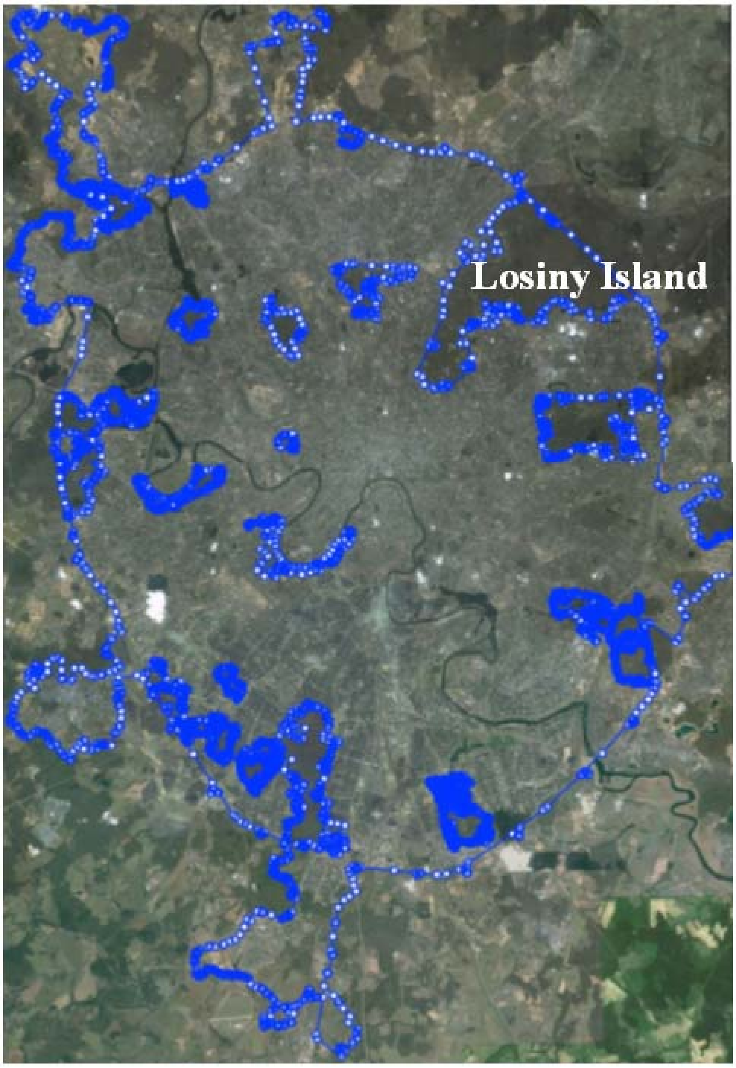

Figure 2. Total vector layer of all parks in Moscow with an area ≥ 0.5 km^2. Margins both of the city and of separate urban parks are shown by blue lines.

created vector layer. It should be noted that a total area of all 23 parks is equal to nearly 126 km^2, i.e., about 13 % from a total urban area of Moscow city (991 km^2). Really this part may be a bit more because a lot of small parks didn't be taken into account.

Margins of separate green areas inside Moscow city at common vector layer have been determined precisely with an accuracy of their location about ±50 m. An example of such determination is presented on Figure 3. As one can see a margin of the park (blue line) has been created as solid vector layer (having fixed co-ordinates and, hence, constant for any other image) with the account of separate buildings and even small glades and clearings.

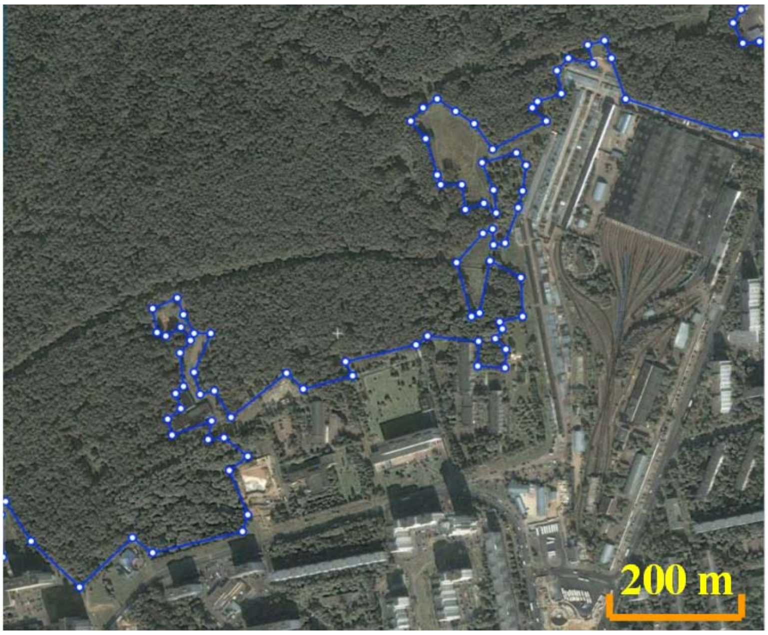

Figure 3. An example of created vector layer of a green zone margin (Alyoshkinsky park, Latsis street) on a base of satellite image of Moscow. Margin is blue color; scale is presented by yellow color.

As a result, the mean intensity of 'cool islands' in Moscow has been calculated on a base of 84 satellite images for the same period 2009-2013 and it has been received as –1.3 ±1.1 ˚C; the latter value is standard deviation σ. Other words, green forests and parks inside Moscow city are in average on 1.3 ˚C cooler than all the rest urban area (865 separate 1 km^2 squares). It should be noted that in conditions of Tokyo, accordingly to satellite data, a difference between green and non-green urban areas was larger: 2.7 ˚C (Honjo and Sawada, 2003).

The annual course of the UCI intensity is presented on Figure 4. As one can see it has a maximum of absolute

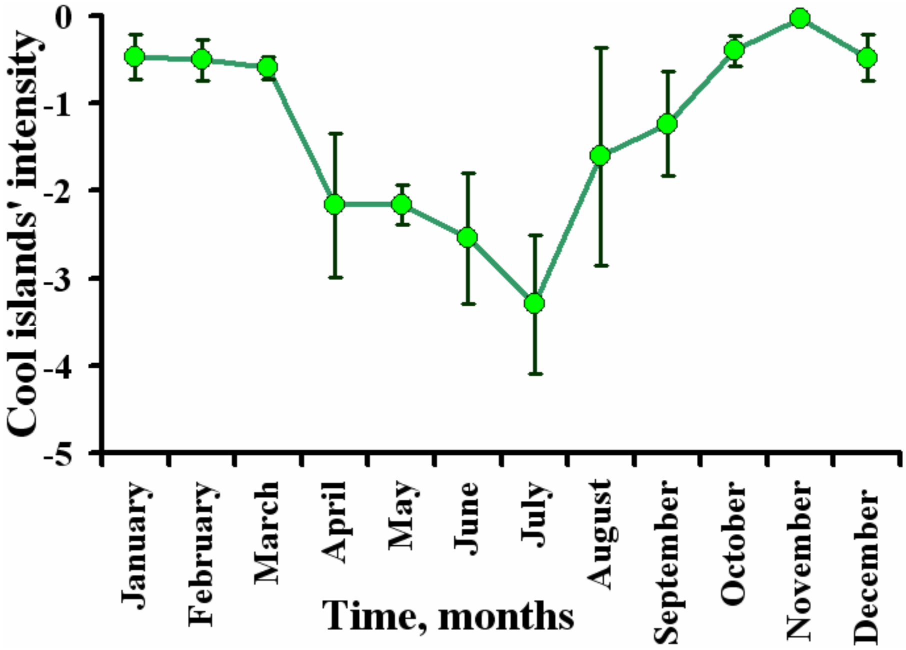

Figure 4. Annual course of the air temperature average difference between forests and non-forest areas ('cool islands' intensity) inside Moscow city for the period 2009-2013. Confidence intervals are calculated with a 0.95 confidence probability.

values (i.e. largest difference of the mean T_s values between green and non-green urban areas) in the warm season from April to September: –2.2 ˚C in average for these months and up to –3.3 ˚C in July.

From another hand, the cold season from October to March is connected with the minimal UCI intensity (i.e. the smallest differences between forests and the rest urban territories): from –0.03 ˚C in November to –0.6 ˚C in March, in average for the whole season –0.4 ˚C. The mean-annual value of the UCI intensity is equal to –1.3 ˚C.

Evidently, maximum of the UCI intensity from April to September is connected with a vegetation period and, hence, with a hidden heat loss to transpiration of trees. A sharp grow of the UCI intensity absolute values from March to April is explained by disappearing of snow cover and starting of vegetation period at that time. It should be noted as well that gradual grow of the UCI intensity absolute values up to July is connected with grow of leaves (the most of trees in central part of European Russia are broad-leaf). In winter in conditions of snow cover differences of the heat balance between forests and non-forested areas are minimal so that the UCI intensity is close to zero.

As one can see differences between seasons are in general statistically significant with the account of confidence intervals for the 0.05 significance level. However it should be noted that this conclusion is preliminary because data sampling of used images during separate months are insufficient yet: it varies in the range from only one case in November to 15 cases in May. More accurate results about the UCI intensity annual course will be received in future.

4. Conclusions

1. Accordingly to remotely sensed satellite data about the surface temperature the urban ‘heat island’ intensity in Moscow city on late morning in average of five years is equal to 2.8 ˚C; it varied from –0.1 to +7.7 ˚C depending on a season and weather events.
2. A mean difference between point *in situ* measurements of the air temperature and space-averaged for 1 km^2 area radiometric indirect measurements of the surface temperature is nearly of 1 ˚C on late morning.
3. Average intensity of the urban ‘cool islands’ (local parks and forests) is –1.3 ˚C in the comparison with the rest non-green urban areas in Moscow. This parameter is maximal on the warm season and minimal on the cold one because of heat loss to transpiration.

Acknowledgment

Authors are much grateful to Dr. Mikhail Zimin and other employees of ScanEx Research and Development Center for their great help. This work was partially supported by the Russian Basic Research Foundation (project no. 14-05-00594).

References

Böer W., 1964. Technische Meteorologie, Leipzig, B.G. Teubner Verlagsgesellschaft, GDR, in German.

Honjo T. and Sawada D., 2003. Analysis of surface temperature in urban green spaces by using LANDSAT TM data. *Proceedings of the ICUC-5*, Lodz, Poland, **Vol.2**, pp.265-268.

Landsberg H.E., 1981: The Urban Climate. *Academic Press, New York.*

Lokoshchenko M.A., 2014: Urban ‘heat island’ in Moscow. *Urban Climate*, **Vol.10**, part 3, pp.550-562.

Narita K., et al., 2009: Cold air seeping from an urban green space, Imperial Palace, in Central Tokyo. *Proceedings of the ICUC-7*, Yokohama, Japan, paper index: B3–1.

Pongracz R., Bartholy J., Lelovics E., Dezso Z, Dobi I., 2012. Satellite- and ground-based urban heat effect of the Budapest agglomeration area. *Proceedings of the ICUC-8, Dublin, Ireland, paper index 486.*

Shpirt S., Potchter O., Bar P. and Yaakov Ya., 2006: Micro-climate behaviour in various urban parks located at a hot, arid climate zone. The case of Beer-Sheva, Israel. *Proceedings of the ICUC-6*, Göteborg, Sweden, pp.250-253.