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Urban Heat Island in Moscow Derived from Satellite Data

M. A. Lokoshchenko[a, b, c*] **and E. A. Enukova**[b]

[a]Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991 Russia
[b]Dubna State University, ul. Universitetskaya 19, Dubna, Moscow oblast, 141982 Russia
[c]Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia
**e-mail: loko@geogr.msu.su*

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Abstract—The results of surface temperature measurements in the Moscow region by Aqua and Terra satellites are presented for the period of 2008–2015. High correlations between radiometer data and station data on air temperature and surface temperature from the Meteorological Observatory of Moscow State University are revealed. However, station data on surface temperature in summer are overestimated by 15 C as compared with satellite data due to the strong heating of the naked site with ground thermometers. The mean intensity of surface urban heat island in Moscow T is 2.6 C; it poorly depends on the selection of boundaries of comparison of the outer area with the city (at distances >60 km differences do not exceed 0.1 C). Numerical experiments demonstrate that if the cloud cover is not higher than 20% of the city area and 50% of the region area, a displacement in the estimates of T is small (0.2 of the value). According to station data at the time of satellite flights, the urban heat island intensity in the air temperature field over Moscow is lower than the corresponding intensity in the surface temperature field obtained from satellite data due to the sparse ground meteorological network and incomplete representativeness of station data (four of five city stations are located in green park zones). According to the ground network data, the intensity of the surface heat island in the daytime hours of satellite flight is by about three times smaller than the mean daily value. On the other hand, T derived from satellite data is overestimated by ~40% due to the impact of anticyclones which enhance the heat island and allow the analysis of images. In the annual course, the surface heat island intensity is maximum in June and July (~4.0 C) and minimum in November (0.7 C). The surface temperature field in the Moscow region is also characterized by the geographic zonality: a total increase in the values toward southeast.

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1. INTRODUCTION

The phenomenon of urban heat island (UHI) was discovered by L. Howard in London in the early 19th century [19]. It is typical of the overwhelming majority of cities and even small settlements [2, 5, 8, 10, 14] in all climatic zones, except for the oasis cities in the dry tropics (they, on the contrary, can be cool islands in the surrounding desert [23]). As known, the air temperature rise in the cities is caused by the higher heat capacity of artificial covers (asphalt, concrete, etc.), by the lower heat loss for evaporation of precipitation (due to its artificial runoff) and for transpiration by plants, by the radiation balance features (an urban industrial haze impeding the nighttime cooling), as well as by direct heat emissions related to the anthropogenic activity. As for Moscow, the near-surface UHI patterns were studied, for example, in [6, 9, 15, 17, 22–24]. Obviously, this phenomenon is three-dimensional; the UHI-related upper-air temperature anomaly over Moscow was described in [11], a phenomenon of the underground heat island in the soil temperature field at different depths under Moscow was investigated in [25].

Usually, UHI in the field of air temperature T_a is studied using data of the meteorological network at the standard height of thermometer installation (2 m). As a rule, network data are reliable and routine but the surface network density is comparatively low. More detailed information about the spatial field of temperature can be obtained using either special route surveys on mobile measuring platforms (motor vehicles or bicycles) equipped with sensors (however, the route surveys are expensive and rare) or infrared satellite imagery (these measurements are constant and regular).

The investigation of UHI in the field of surface temperature T_{sat} based on separate satellite images started in the 1970s for Washington and Baltimore (USA) [10]. The use of radiometer data allowed studying the heat anomalies with high spatial resolution: ~1 km, and, for some space systems (for example, Landsat satellites), even to tens of meters. Currently, the analysis of long-term satellite radiometer data was carried out for Rome (Italy) [18], Bangkok (Thailand) [21], Budapest (Hungary) [29], Erbil (Iraq) [30], Athens (Greece) [31], 28 cities in the north of Western Siberia [27], and many other locations. In some cases, only the examples of individual images are studied: for example, for the conditions of Skopje (Macedonia) [20] and Calcutta (India) [28]. Usually, the images from either Landsat [4, 20, 21, 28, 31] or Terra and Aqua satellites [29, 31] and sometimes from other satellites (for example, ENVISAT [18]) are used for the UHI analysis. An advantage of Landsat satellite radiometer data is their high resolution and that of Terra and Aqua satellites is the large sample of images, because each of them provides the sensing of the Moscow region twice a day. As for Moscow, only the separate examples of satellite images have been presented in the literature till now [4]. The objective of the authors was to study the surface UHI in the Moscow region with high spatial resolution using long-term data of two satellites for the period of 2008–2015. The preliminary results of the analysis for the period of 2009–2013 were published in [16, 26].

2. SATELLITE DATA AND METHODOLOGICAL FEATURES OF THEIR ANALYSIS

The most reliable long-term source of data on surface temperature in the Moscow region is the images of polar orbital Aqua and Terra NASA EOS (Earth Observing System) satellites, where MODIS spectroradiometers are installed. They provide the survey in 36 channels in the range from 0.45 to 14.36 m. The shooting bandwidth is 2330 km but the quality of data decreases on the edges of this zone. The spatial resolution of surface temperature measurements is 1 km under the radiometric resolution of 12 bits, and their accuracy for the land conditions is 1 C [32]. The standard product Land Surface Temperature (LST) was used to calculate surface temperature from MODIS data. It calculates surface temperature proceeding from the spectral brightness of two channels: 31st and 32nd with the wavelengths of 10.78–11.28 and 11.77–12.27 m, respectively. The calibration of data is carried out depending on latitude, radiometer zenith angle, and air humidity. Besides the presence of clouds and smoke plumes, the accuracy of surface temperature measurements is also affected by inhomogeneous terrain, radiometric noise, etc. ScanEx Image Processor software (developed by ScanEx Engineering and Technology Center) used by the authors provides an automatic control of surface temperature data and deletes all cells with obviously unrealistic low values which mark cloud top temperature. The methodological features of measurements from these satellites should be considered: in most cases, the values of T_{sat} characterize temperature of the open surface; however, when sensing the forests with dense canopy or densely built areas, temperature of the surface of canopy or the roofs of individual buildings is measured.

The following daytime images are used for the analysis: the Terra images for 11/12 a.m. Moscow time and the Aqua images for 1/2 p.m. (night sensing data are not reliable as Moscow is situated on the edge of the swath or out of it). A thorough critical control and visual selection of images were required during the work, because in the presence of clouds, the radiometer measures rather their top temperature than surface temperature. The cases when Moscow was located on the swath edge (this leads to significant distortions and radiometric noise) were also excluded.

When working with satellite data, some methodological issues should be solved:

—to compare them with meteorological network data;

—to evaluate an effect of the data averaging domain size on the surface UHI intensity;

—to reveal the maximum coverage of the image with clouds for which the UHI analysis is still possible;

—to estimate a displacement in the estimates of average daily intensity of the surface UHI due to the use of daytime satellite data;

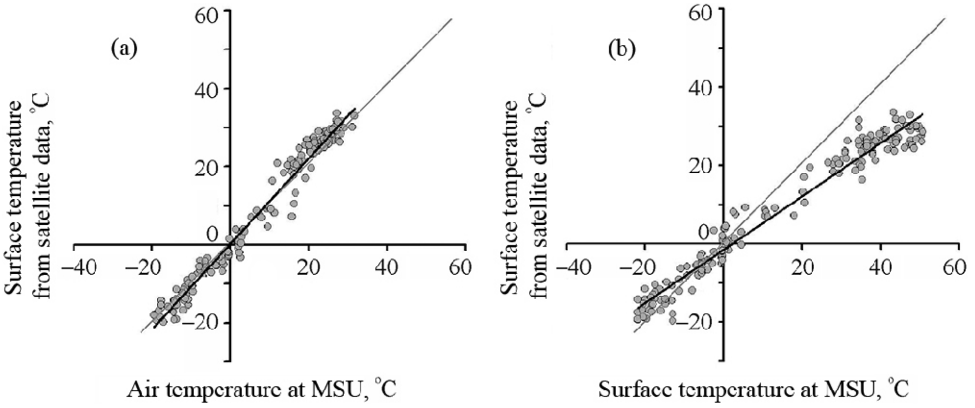

Fig. 1. The comparison of satellite data on surface temperature with station data on (a) air temperature and (b) surface temperature from MSU MO. The thick lines are linear trends; the thin lines are “one-to-one” agreement; the linear regression equations and the values of the standard parameter R^2 of the trend reliability: (a) $y = 1.09x + 0.16$, $R^2 = 0.98$; (b) $y = 0.68x - 1.45$, $R^2 = 0.96$.

—to estimate a displacement in the estimates of monthly and annual mean UHI intensity due to the impact of the sample for anticyclonic conditions alone, when clouds are rare and surface temperature data are available.

It is also important to consider a fundamental difference between the pointed station estimates of surface temperature T_s and satellite radiometer measurements T_{sat} averaged over a large area. It provokes an inevitable scatter in the comparison of satellite and station data.

Such comparison was performed using the sample of 163 images of Moscow from both satellites under clear sky in 2011–2013. Radiometer data on T_{sat} in the 1-km^2 unit cell which was the closest to the station location were compared to the results of MSU Meteorological Observatory (MO) measurements of surface temperature T_s and 2-m air temperature T_a. Air temperature was determined from the station thermograph in the closest hour to the satellite flight time (the flight over the Moscow region lasts for ~5 minutes). Surface temperature is measured at the stations once in 3 hours, the nearest time moment was also used for comparison with satellite data. If a satellite flight fell exactly on the middle of the interval between the measurements, the mean value between the neighboring hourly values of T_a or neighboring three-hour values of T_s was calculated for comparison with its data. The results are presented in Fig. 1. Below the mean values and standard deviations are given for the differences between satellite-derived surface temperature T_{sat} as well as between air temperature T_a and surface temperature T_s according to MSU MO station data for 2011–2013:

Period	Winter		Spring		Summer		Autumn		Year	
$T_{sat} - T_a$	–0.8	2.1	0.8	3.5	2.8	2.1	–0.3	2.2	0.9	3.0
$T_{sat} - T_s$	2.1	3.4	–6.2	7.6	–15.0	5.4	–3.4	3.8	–6.5	8.6

It is clear that the statistical relation is close to linear in both cases and is quite high: the correlation coefficient R was equal to 0.98 when comparing T_s and T_{sat} and even 0.99 for T_a and T_{sat}. However, the value of the linear regression coefficient k in the equations is different: for comparison between T_a and T_{sat} it is close to 1 (1.09), whereas the displacement is great for T_s and T_{sat} ($k = 0.68$).

An obvious reason for that is the increased station values of soil surface temperature in the warm season due to the strong heating in the midday hours of the 4 6-m bare excavated area, where ground thermometers are installed [13]. The greatest heating is observed in summer: in this season the site is on average 15 C warmer than the surrounding natural surface (grass and tree crowns). The impact of other possible reasons for the differences in the estimates of T_{sat} and T_s is small.

Only in winter, when TM-3 thermometers are installed on the snow surface, their readings are representative for the surrounding area, and the differences between T_{sat} and T_s are minimal. The MSU area includes many green park zones (the Botanic Garden, etc.). Urban buildings are rarefied here in the radius of 1 km, and there is almost no bare soil in the vicinity of MSU MO. As a result, despite possible expectations, station data on air temperature are in better agreement with satellite-derived surface temperature than station

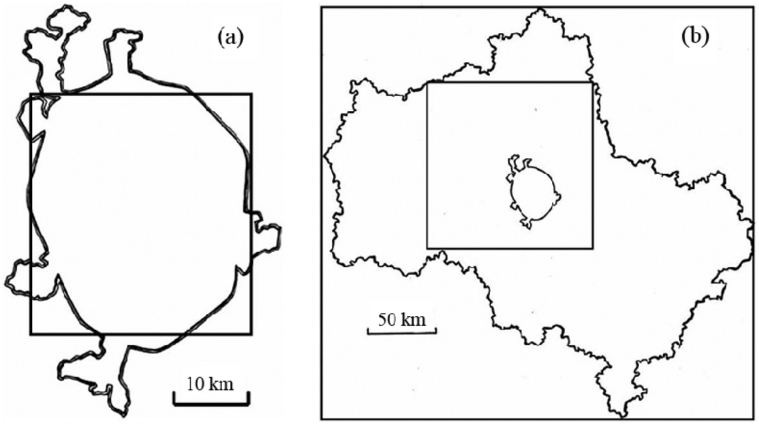

Fig. 2. The boundaries of calculation domains for (a) Moscow and (b) the Moscow region.

data on surface temperature: the sample mean difference between T_{sat} and T_{a} is less than 1 C, whereas the average annual value of T_{s} is on average 6.5 C higher than T_{sat}. The result confirms that surface temperature of excavated sites does not indicate background conditions in the area surrounding the station, especially in the warm season. It should be noted that the comparison between T_{sat} and T_{a} in Budapest revealed their difference from 1.1 to 6.6 C in the daytime and from –1.1 to –1.8 C at night depending on the season [29].

The intensity of the surface UHI, i.e., of the thermal anomaly in the surface temperature field related to the city impact is the mean difference in the values of T_{sat} over the samples of all urban and rural 1-km^2 elementary cells:

$$T_{\mathrm{sat}} \quad \frac{{}^{\;\;n}_{i\;\;1}\, T_{\mathrm{M},i}}{n} \quad \frac{{}^{\;\;m}_{j\;\;1}\, T_{\mathrm{Mr},j}}{m}$$

where n and m are the number of cells in Moscow and the Moscow region, respectively; T_{M} and T_{Mr} are surface temperatures in each cell in the city and outside it, respectively.

Such approach to the comparison with rural areas not only for the city center but also for the whole city was also used in [22, 23]. Certainly, there are vast forests and parks on the territory of Moscow which induce local cold islands; their separate analysis is presented in [16, 26]. On the other hand, there are many towns and villages in the areas surrounding Moscow whose surface is more or less urbanized. A neglect of both factors affects an estimate of UHI intensity; however, this impact may be considered small.

It is important to understand how spatially stable the surface UHI intensity estimates are. Different variants of the geometric presentation of Moscow and the Moscow region were chosen for the study. Here, Moscow is considered within its traditional borders from 1992 to 2011. It has a turtle shape: the main ellipse (the Moscow Automobile Ring Road (MARR) built in 1961) and six prominences extending beyond it in different directions. The city territory was represented in calculations in two ways: in the form of the area limited by the real city borders (in Fig. 2a with an accuracy to 20 m) or in the form of the square with the same area (~1000 km^2). The outer domain for comparisons with the city was presented in the form of either the exact vector layer of administrative borders of the Moscow region or the rectangle inscribed into them or circumscribed around them.

The parallel computations using a rough (in the form of the square) and exact presentation of Moscow borders as compared to the rectangle circumscribed around the Moscow region based on the same partial sample of 63 images under clear sky in 2010 to 2013 revealed the mean values of UHI intensity equal to 2.7 and 3.1 C, respectively. Thus, for hypothetic squared Moscow, the UHI intensity is on average 0.4 C lower (the difference amounted from 0.4 to –4.2 C according to data of separate images); it is lower in 52 of 63 cases. The weakening of the surface UHI in conditional "squared" Moscow is not surprising taking into account its greater contribution to its total area of comparatively cold parks close to the square corners going beyond MARR: in particular, the suburban part of the Losinyi Ostrov national park is situated in the northeastern corner of the square.

On the contrary, the experiments with three variants of borders for the territory surrounding Moscow did not reveal noticeable displacements in the estimates. The area of the rectangle circumscribed around the

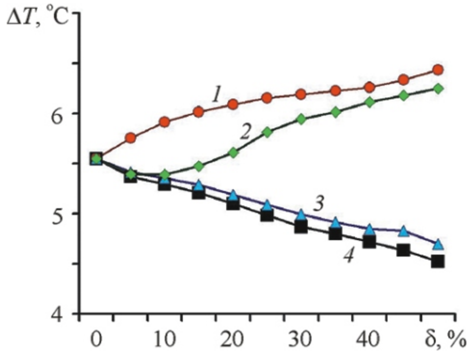

Fig. 3. The results of numerical experiments with the cloud simulation in different parts and different portions of image : (*1*) in the south; (*2*) in the east; (*3*) in the west; (*4*) in the north.

Moscow region at its extreme points is 94851 km^2; it also includes the parts of the neighboring regions. Together with Moscow, the Moscow region occupies an area of 46570 km^2 and the area of the rectangle inscribed into it is 15955 km^2. It covers only the nearest areas of the region to the city, and Moscow is shifted to its southeast (Fig. 2b). The parallel computations for all three variants of the borders of the outer area for comparison with the city were carried out for the sample of 99 images over the period of 2009–2013; in all three variants, Moscow was presented in its real borders. It was found that the mean intensity of the surface UHI almost did not change: it was equal to 2.8 C for the rectangle circumscribed around the region, 2.7 C for the real borders of the region, and 2.8 C for the rectangle inscribed into it. Thus, the value of UHI intensity is spatially stable and, when moving away from the city for 60 km and more, less significantly depends on the boundaries of the comparison territory. On the contrary, near the borders of Moscow the thermal inhomogeneity is more strongly pronounced.

As noted above, the serious problem of satellite data analysis is frequent dense cloudiness that is impermeable for radiometer measurements. For example, the average cloud cover in Moscow according to the hourly observations at MSU MO from 1954 to 2007 is 7.7 (77%) [1]. It is practically manifested in the fact that clouds usually occupy the whole satellite image of the Moscow region or its significant part. Earlier [16, 26] only cloudless conditions for the entire Moscow region were considered, when total coverage with clouds, haze, or plumes from forest and peat fires (in the summer of 2010) did not exceed 5% of the whole area of the region in the image, and Moscow was located in the swath center. However, the sample of such ideal images is very small: it included only 108 of 3652 images for 2009–2013, i.e., only 3% of their total number. It is difficult to get reliable estimates of annual variations in the surface UHI intensity based on it: for example, it is obvious that the cloudless sky over Moscow is rare in November. Therefore, it was necessary to determine at which cloud coverage of the image its analysis is still possible, i.e., the displacement of surface UHI estimates is relatively small.

For this purpose, the cases of clear-sky anticyclonic conditions were selected for different seasons when reliable radiometer data on surface temperature were available almost for all elementary cells in the image. A number of numerical experiments with the cloud simulation were performed, during which the cells from four directions (west, north, south, and east) with the number multiple of 5% of their total number were alternately removed from the set of values within the vector layer of the Moscow region borders (45955 1-km^2 cells not considering Moscow). The excluded cells represented imagery clouds, which could have existed over the region at that time. At each step after the next “cutting” of the Moscow region map (with removal of 5, 10, 15% of cells, etc.), the surface UHI intensity T was calculated separately. It was required to find out to what extent the partial cloud coverage of the image leads to the displacement in the estimates of UHI intensity.

The results for one of the experiments are presented in Fig. 3. Clouds were completely absent over Moscow under synoptic conditions observed on June 6, 2011. The UHI intensity in the field of T_{sat} was equal to 5.6 C. As the coverage of the Moscow region with conditional clouds increases, the displacement in the UHI intensity estimates occurs quite expectedly with account of geographic zonality. For example, the greater the Moscow region area decreases in the north, the lower the UHI intensity is, because average T_{sat} within the city correlates with the warmer south of the region. On the contrary, if the southern areas of the Moscow region are excluded, UHI strengthens because the remaining northern cells are generally colder. It is noteworthy that the western cells have an effect qualitatively similar to the northern ones, and the impact of the eastern cells is similar to that of the southern cells. As known, the geographic zonality in the Moscow region both in summer [12] and for the year on average [7] is manifested in the total rise in T_a from northwest to southeast. Even if a half of the whole Moscow region in Fig. 3 is excluded from any direction, a change in the UHI intensity does not exceed 1 C, i.e., 0.2 of the intensity value. Similar results were obtained for another experiment performed for a cloudless winter day.

The similar experiments with the removal of a part of cells within traditional Moscow borders revealed the same displacement of intensity estimates (~0.2 of its value) if 20% of Moscow is covered with clouds. Evidently, the thermal inhomogeneity in the city is pronounced more strongly, and, hence, the UHI intensity is more sensitive to the exclusion of a part of the urban surface from calculations. Based on the results of the experiments, it was decided to consider as suitable for analysis all satellite images with no clear radiometric noise, with Moscow located in the center of the swath, and with clouds covering not more than 20% of Moscow area and not more than 50% of the Moscow region. The total number of such images per 8 years (2008 to 2015) was 561 of 5844. Not taking into account repeated images for the same day, the sample included 362 days, for each of which the values were taken either from data of one image (if the second one did not meet the accepted criteria) or in the form of the mean values for two images, if both were of good quality.

3. SURFACE URBAN HEAT ISLAND INTENSITY

Let us consider the results of the analysis of Moscow UHI in the field of surface temperature based on Aqua and Terra satellite data for 8 years on average. Let us consider that the intensity of this phenomenon is a difference in the average values of T_{sat} within the traditional borders of Moscow and within the rectangle the Moscow region is inscribed in. As a result of averaging all images accepted for analysis (561), the mean value of surface UHI intensity over Moscow was equal to 2.8 C, and the standard deviation = 1.4 C. On average for the sample of 362 values on individual days with the averaging of values based on data from all paired images for the same day, the intensity did not change: 2.8 C, = 1.3 C. However, a possible displacement in the mean estimate due to different availability of data for separate months (from 11 images in November to 48 images in March and May) should be considered. When normalizing the intensity by the annual course, i.e., when computing it as the average of 12 monthly mean values (with the identical weight for each month in the overall average annual estimate), a more exact value was equal to 2.6 C. It is stable in time: earlier, for the smaller period of 2009–2013 on average and for a smaller sample of images for cloudless days only, the average annual intensity was also 2.8 C as a simple mean for the entire sample [26] and 2.6 C when it was normalized by the annual course [16]. The values of in separate months vary from 0.7 to 1.6 C, no clear seasonal patterns are observed in their variations.

For different days, the UHI intensity varies in a wide range: from –0.2 to 7.7 C; according to the data of individual images (without averaging the repeated ones for the same day), its lowest value reached –0.4 C. Only 8 of 561 images demonstrated a negative value of intensity which was close to 0 C. On average for separate days, the intensity was weakly negative in 3 of 362 cases only. It is noteworthy that the negative or close-to-zero values are almost always observed in autumn, most often in November. For example, all three cases with $T_{\text{sat}} < 0$ C fell on November (November 18, 2013; November 8 and 12, 2008). In general, autumn days made up all the first 16 and 27 of the first 30 lowest values of intensity for the sample of 362 days. On the contrary, the highest values of this parameter were observed in all other seasons: for example, the record high value (7.7 C) was registered on April 16, 2013, the second highest value (6.2 C) was registered on June 12, 2011, and the third one (6.1 C) was recorded on January 19, 2010 and August 8, 2012. All these cases of abnormally intense surface UHI were associated with Moscow located in the anticyclone center or in the low-gradient pressure field with a high pressure background. The lowest intensity of this phenomenon is typical of very windy autumn days, when Moscow is situated in the zones of intensive gradient flows on the periphery of anticyclones or ridges.

The comparison of the surface UHI in the field of surface temperature with the near-surface UHI should be careful and cautious, because these are different physical-geographical phenomena. Nevertheless, it is known that the UHI intensity at the height of 2 m, that is often weakly negative in the morning, is usually close to 0 C in the midday hours as well as based on satellite data (the examples are given, for example, in [5, 10]). The mean UHI intensity in the field of T_a in Moscow in the early 2010s was equal to 1.0 C for the comparison of data of all Moscow and all Moscow region stations and 2.0 C for the comparison of data for the city center only (Balchug station) with data from all Moscow region stations [23]. Thus, the surface UHI is pronounced more strongly than the near-surface UHI.

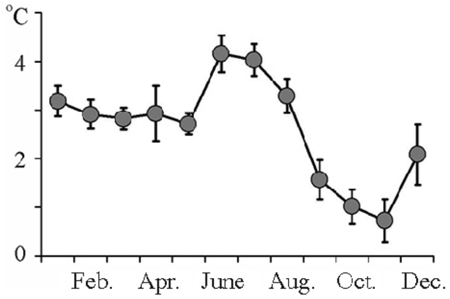

Fig. 4. The annual variations in the intensity of the surface urban heat island in Moscow. The confidence intervals are calculated with the probability of 0.95.

It is possible to determine the intensity of the surface UHI from data of satellites only during their daytime flight. A rough estimate of average daily intensity can be obtained using ground-based network data. For this purpose, the results of hourly measurements of T_a at four Moscow (MSU MO, VDNKh, Balchug, and Tushino) and 13 Moscow region stations for 2014 and 2015 were used. Thus, the intensity of the near-surface UHI in the field of 2-m T_a was calculated for $n = 4$ and $m = 13$ using equation for calculation of T_{sat}. The calculation was provided both for two years (730 days) and for 12:00 for all days.

On average for these two years, daily mean air temperature was equal to 7.49 C in Moscow and 6.46 C in the Moscow region; average temperature for the noon only was 9.17 and 8.84 C, respectively. Thus, the average daily intensity of the near-surface UHI based on these data was equal to 1.03 C like on average for the period of 2010–2014 [23] with an accuracy to 0.1 C, and the intensity at 12:00 (the mean time of the satellite flight with an accuracy to an hour) was 0.33 C. It may be supposed that the average daily intensity of the surface UHI, as well as of the near-surface UHI, is three times higher than its midday value and is probably equal to about 7.5–8.0 C.

It is also necessary to take into account an inevitable displacement in the satellite-derived intensity estimates, because cloudless and few-cloud days are associated with anticyclonic weather, when UHI is more strongly pronounced at any altitude. To evaluate this displacement, the near-surface UHI intensity based on station data was calculated separately only for satellite flight hours for cloudless or few-cloud days, when the images (in total, 173 images per two years including the repeated images for the same day) were of good quality and were accepted for analysis. The time difference between the satellite flight over the region and the closest station thermograph reading did not exceed 30 minutes. If the flight time fell exactly on the middle of the hour, the mean value between the neighboring hourly observations of T_a at all stations were used for comparison with satellite data (like for the analysis of MSU MO data).

The mean value of T_a during the satellite flight per two years was 11.45 C for Moscow and 10.98 C for the Moscow region. Thus, the average intensity of the near-surface UHI based on ground-based network data for the time moments of the images accepted for the analysis was equal to 0.47 C, i.e., it was 40% higher than the mean intensity at 12:00 for all days of 2014 and 2015. This result may be considered as an overall estimate of UHI intensification under the influence of anticyclonic conditions. It may be supposed that this estimate is close both for the near-surface and surface UHIs. Probably, the mean intensity of the surface UHI in the midday with account of cloudy days for which no radiometer data are available is also about 1.5 times lower than the above value, i.e., it is slightly below 2 C.

It should also be noted that the near-surface UHI intensity over Moscow in the field of air temperature based on ground network data for the satellite flight hours is much lower than in the field of surface temperature. This is partly an effect of insufficiently high density of the network and incomplete representativeness of station data: four of five Moscow weather stations (MSU MO, VDNKh, Tushino, and Mikhelson Observatory) are situated in green park zones, and only Balchug station indicates the conditions of the densely built urban areas.

The analysis of annual course in the surface UHI intensity in Moscow (Fig. 4) demonstrates that its highest values (~4 C) are observed in the beginning and middle of summer (June and July), and the lowest ones (0.7 C) are registered in late autumn (November); in winter and spring, the values are intermediate. Taking into account confidence intervals, it is obvious that differences with the significance level of 5% are statistically reliable both between the conditions for June and July and winter and spring months and be-

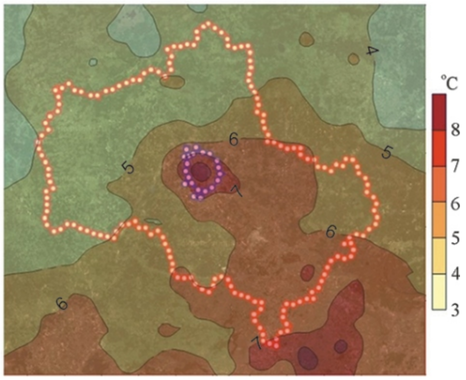

Fig. 5. The map of average surface temperature for the Moscow region based on Aqua and Terra satellite data for 2008–2015. The light-colored dots outline the borders of Moscow and the Moscow region.

tween winter and spring (except December) and autumn months. The differences between the highest summer and the lowest autumn values of UHI intensity remain significant with an arbitrarily high confidence probability (even with 0.9999). The differences in the surface UHI intensity are induced by the contrast between thermal and radiative properties of the surface in the city and out of it. The highest intensity in the middle of summer is probably caused by the most active vegetation phase at that time and, hence, by the greatest heat loss for transpiration by plants in rural areas (there are fewer plants in the city). It is due to the same factors that the highest (in absolute value) intensity of local cool islands in the Moscow forest parks is also registered in summer [16, 26]. The summer maximum of UHI intensity in the annual course according to Terra and Aqua satellite data (also ~3–4 C and more) was also registered in Budapest [29]. On the other hand, differences in the thermal properties of the surface decrease in late autumn as the vegetation cover dies off: the UHI intensity is minimal at this time. In winter and early spring, the conditions are intermediate: the snow cover in rural areas is usually solid and clean, whereas it is locally absent in a significant part of the city (in the city roads are cleared from snow, and thawed patches are formed earlier in spring) and, in addition, is contaminated. The differences in surface albedo, as well as the effect of comparatively warm city roofs and anthropogenic heat sources evidently determine a stronger surface UHI in winter as compared to autumn.

The annual course of the near-surface UHI intensity in Moscow varies with time, because various determining factors act in different directions. For example, the impact of urban heating and related heat emissions can cause an intensification of UHI in winter. On the other hand, clear nights and air stagnation that also lead to the intensification of this phenomenon are more frequent in summer. As a result, different studies make controversial conclusions on the annual variations in the Moscow UHI intensity based on the data analysis for different time periods: the maximum in winter in 1977–1988 [6] and 1991–2002 [24]; the maximum in summer in 1959–1987 [15] and from the late 1990s till now [6, 9]; the equivalence of winter and summer values in some periods [6].

4. SURFACE TEMPERATURE IN THE MOSCOW REGION

Let us consider the general patterns of the surface temperature distribution for the whole Moscow region. Figure 5 presents the map of average values of T_{sat} calculated using the standard interpolation software Surfer10.1 based on the data of the same sample of images for 2008–2015 with the grid spacing of 15 km. It is clear that besides the clearly pronounced heat anomaly over Moscow, there is a noticeable increase in T_{sat} east and southeast of Moscow. The highest average annual surface temperature to 8 C and higher is registered in Moscow and the border areas of the Ryazan region. The lowest values from 3 to 4 C are observed west of the Moscow region, in the eastern areas of the Smolensk and Tver regions.

Such distribution of the surface temperature field is associated with the physical-geographical features of the Moscow region. For example, the contribution of forest lands to the total area of the districts is minimum in the southeast of the Moscow region (on average from 10 to 30%) and even below 10% in the southernmost districts, Zaraiskii and Serebryanoprudskii (the mean area covered by forests in the Moscow region is about 40%). It is obvious that forestless open areas are generally drier and warmer as compared to the canopy surface. In addition, the Meshchera Lowland east of Moscow is characterized by the prevalence of sandy and sandy loam soils [3], which are usually also drier and warmer as compared to loam. The similar distribution with the highest values southeast of Moscow is observed for average air temperature T_a in July, as well as for the sum of $T_a > 10$ C [12]. The authors of that paper explained this by an increasing frequency of the intrusion of warm tropical air masses from Kazakhstan and Central Asia in summer in the direction southeast of Moscow. Thus, the field of average values of T_{sat} in the Moscow region does not come to the geographic zonality alone and indicates the action of different factors.

As for the surface UHI over Moscow, it is manifested in Fig. 5 in the form of two closed and one semicircular isotherms. The average value of T_{sat} for four grid cells with an area of 225 km^2 each covering most of Moscow is 7.3 C. In the other 437 cells around Moscow, where Moscow is not present or occupies less than a half of the area, $T_{sat} = 5.4$ C; only in the near Moscow region in the radius of 30 km from the city borders (on average for 32 cells around the city), $T_{sat} = 5.9$ C. Certainly, the above estimate of the surface UHI intensity (2.6 C) is more precise as it is based on data with the higher resolution, 1 km. It is also obvious that higher average surface temperature in the near Moscow region indicates the influence of the large nearest suburbs, each having its heat island. However, this influence rapidly decreases as the radius of the comparison domain grows: at the distance of 60 km from Moscow, i.e., within the area approximately equal to the inscribed rectangle in Fig. 2b, the mean value of $T_{sat} = 5.4$ C, as well as in the entire region. So, the further extension of the domain for comparison with the city does not lead to the changing values. The issue of the most accurate estimation of UHI intensity depending on the radius of the analyzed suburbs is methodologically difficult: a too large comparison domain complicates the problem as it will require a separate consideration of climate zonality.

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