Urban Heat Island in Moscow at different heights, depths and on the surface

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Abstract. The urban heat island (UHI) in Moscow was for the first time studied not only at the ground air level, but also at different heights, depths and on the surface using stationary, radiosonde and satellite data. Long-term dynamics of the UHI intensity in the ground air layer has been estimated since the end of the 19\textsuperscript{th} century both as traditional ‘maximal intensity’ (the difference between the city centre and rural zone), and as ‘average intensity’ (the difference between all urban and all rural stations). In recent years they have been 2.0 and 1.0 °C, respectively. The quasi-stabilization of both parameters in the second half of the 20\textsuperscript{th} century was probably the result of extensive city growth at that time; the new increase in the UHI intensity seems to be connected with the densification of urban development and heat sources in the last 20 years. The mean daily vertical extension of the UHI in the atmosphere is approximately 300 m. In the upper soil layer (up to 160 cm deep) the maximal UHI intensity was about 1.6-1.7 °C half a century ago. The average UHI intensity at the field of the surface temperature in recent years is 2.7 °C.

1. Introduction
The Urban heat island (UHI) is a well-known geographical phenomenon first discovered in London [1]. Since then, this phenomenon has been found almost everywhere in the world except for oasis cities in dry deserts. Moscow is an excellent object for studying this phenomenon due to its simple ellipsoid shape, flat relief, absence of sea coasts at a distance of at least 600 km from the city, and a symmetrical decrease of the urban built-up density from the city centre to its peripheries. Heat islands are usually studied in the ground air layer using thermometers installed at a height of 1.5-2.0 m above the ground. However, the density of the ground-based meteorological network is usually low. The more detailed structure of UHI can be studied with special measurement campaigns, including the use of either temporary stations or travelling tools equipped with thermal sensors. However, these campaigns are sporadic and short in duration. Satellite radiometric measurements of the surface temperature have high spatial resolution (1 km or less), but they are only available in clear sky conditions, so it is a problem for cloudy climates. Classic reviews about UHI studies are presented in [2-6], etc.

2. Urban heat island in the ground layer in Moscow
The study of the UHI in Moscow using stationary data (measurements by thermometers installed at weather stations at a height of 2.0 m above the ground) has been available since 1879, when two stations in Moscow region, Landmark Institute and Petrovsko-Razumovskoe (now the Mikhelson Observatory), began to operate simultaneously for the first time.
Two versions of the UHI intensity can be used. Traditional, i.e. the maximal intensity $I_{\text{MAX}}$ is the difference between the air temperature $T$ in the city centre $T_C$ and at one or several rural stations $T_R$ outside the city:

$$I_{\text{MAX}} = T_C - \frac{\sum_{j=1}^{m} T_{R_j}}{m}$$

(1)

where $j$ is any of rural stations and $m$ is their number around a city.

Another possible parameter suggested in [7] is the averaged UHI intensity $I_A$. It can be used if there are several other urban stations in the city in the urban periphery around the centre. They usually represent intermediate values of $T_U$ between the conditions of the warmest city centre and the relatively cool rural zone. So, the averaged UHI intensity is:

$$I_A = \frac{T_C + \sum_{i=1}^{n} T_{U_i}}{n + 1} - \frac{\sum_{j=1}^{m} T_{R_j}}{m}$$

(2)

where $i$ is any of the stations in the urban periphery and $n$ is their number.

The long-term dynamics of both parameters in Moscow was discussed in detail [8] for five separate periods (see Fig.1) based on (1) and (2).

![Graph showing long-term changes of the urban heat island intensity in Moscow](image)

**Figure 1.** Long-term changes of the urban heat island intensity in Moscow [8].

The traditional maximal intensity was close to 1.0 °C at the end of the 19th century (1887-1889); 1.2 °C during World War I (1915-1916); 1.5-1.6 °C both in the middle and at the end of the 20th century (1954-1955 and 1991-1997, respectively) and again increased to 2.0 °C in 2010-2014 (Fig. 2). Thus, this parameter in Moscow became twice as high as in the 1880s. It should be noted that there were two different stations in the centre of Moscow: the Landmark Institute until its closure in 1932 and the Balchug station since its foundation in 1946. However, both of them were located close to the Moscow
Kremlin (city centre), and therefore the difference between their thermal conditions seems to be negligible.

**Figure 2.** Air temperature spatial field in Moscow region on average for 2010–2014 [8]. Double lines indicate the contours of Moscow from 1992 to 2012; asterisks are weather stations; bold lines are mean annual isotherms. Arrows indicate the location of some stations outside the figure field.

The average UHI $I_A$ intensity can be analyzed over a shorter period since the 1940s, when many weather stations appeared in the city. It was 0.7-0.8 °C in both the middle and late 20th century and rose to 1.0 °C in the 2010s. Probably, the quasi-stabilization of both parameters in the second half of the 20th century was associated with the extensive growth of the city at that time. As shown in [8], the population density in the city centre has dropped significantly since the early 1960s due to the mass resettlement of inhabitants from the overpopulated city centre to its new periphery. It is likely that the new rise in UHI in Moscow over the two past decades is due to the increase of urban density, especially in the city centre, and, in addition, the rapid growth in power consumption since the late 1990s.

3. **Urban heat island in the lower troposphere of Moscow**

Evidently, the UHI is a three-dimensional phenomenon. Its vertical extension was studied using long-term data of stationary measurements at different levels of the TV Tower (located in Ostankino urban district of Moscow, 7 km from the city centre), a high meteorological mast in Obninsk town, Kaluga region (96 km south-west of Moscow centre in almost rural conditions) and according to the data of radiosondes in Dolgoprudny (a suburban town 2 km north of the borders of Moscow). The Ostankino TV Tower is 540 m high and is equipped with meteorological sensors at levels of 2, 85, 128, 201, 253, 305, 385 and 503 m. On the high (310 m) mast in Obninsk there are sensors at three levels: 2, 121 and 301 m. The aerological station in Dolgoprudny has long used Soviet and Russian MRZ radiosondes; their data on T have a spatial resolution of 100 m in the layer up to 1 km. The thermal sensor of these radiosondes was a MMT semi-conductor thermistor with a time constant of 5-7 sec.
To compare the data from all three sources, it should be taken into account that, firstly, the climatic displacement of Obninsk according to the map of mean annual air temperature [9] is +0.3 °C. In other words, Obninsk, due to its southern location, on average, is 0.3 °C warmer than Moscow. In addition, according to international comparisons of radiosondes in Dzhambul in 1989, the T values based on the data of MRZ radiosondes can be somewhat underestimated due to radiation cooling of the sensor surface during its ascent [10].

Table 1. Mean daily air temperature in the layer from 2 to 500-503 m above the ground according to the data of the Ostankino TV Tower, radio sounding in Dolgoprudny and the high mast in Obninsk on average for the period 2006-2013 [11].

| Level of measurements, m | City centre (Ostankino) | Close suburbs (Dolgoprudny) | Far rural zone (Obninsk) |
|-------------------------|------------------------|-----------------------------|-------------------------|
| 2                       | 7.3                    | 5.9                         | 5.9                     |
| 100-128                 | 6.0                    | 5.8                         | 6.0                     |
| 300-305                 | 4.9*                   | 4.9                         | 5.2                     |
| 385-400                 | 4.4                    | 4.4                         |                         |
| 500-503                 | 4.0                    | 3.9                         |                         |

*This value was interpolated between the values at neighboring levels of 128 and 385 m.*

The profiles of T in all three locations were calculated and compared for an average of eight years (2006 to 2013) for both 02:30 a.m. and 02:30 p.m. during radiosonde ascents, which are carried out twice a day. As a result, UHI was observed in the ground air layer at any time, but at night there was an elevated ‘cool layer’ above it [11]. This effect (the opposite difference between the city and the suburbs at night, the so-called crossover effect, when the air above 100 m in the city is cooler due to stronger surface inversions outside the city), apparently, was first discovered by [12]. As can be seen from Table 1, the vertical extension of the UHI on average per day is ~300 m, where all three values are the same, taking into account the Obninsk climatic displacement. A slightly lower (by 0.1°C) value at 500 m in Dolgoprudny may be result of sensor cooling. The same estimation of the UHI vertical extension was obtained for New York using helicopter sounding [13].

4. Underground urban heat island in Moscow

Besides the atmosphere, the urban heat island also exists in the upper soil layer beneath large cities. This phenomenon, the so-called ‘underground urban heat island’ (UUHI), is caused by various factors such as the total heat flux from warmer urban atmosphere into the soil; local downward heat flux from individual buildings; the influence of underground heat sources (heating pipes, subway tunnels, etc.); specific albedo of the surface in the city, less heat loss for evaporation in drier urban soil due to artificial rainfall runoff; warm industrial wastewater drain, etc.

In the Russian Empire, the USSR and the Russian Federation soil temperature has been regularly measured with mercury thermometers in the upper soil layer since the late 19th century. The results of these measurements at five urban and eight rural weather stations in Moscow region, on average for one year (1960), demonstrate a clear positive thermal anomaly in the soil at all different depths up to 320 cm [14,15]; two examples are presented in Fig.3. Unfortunately, later the number of stations in Moscow region decreased, and therefore a detailed UUHI analysis is possible only for only until 1960.
Both UUHI intensity parameters ($I_{\text{MAX}}$ and $I_A$) were calculated according to (1) and (2). Unfortunately, at the central Balchug station, the thermometer at 320 cm was absent, so the $I_{\text{MAX}}$ values are limited only to the 160 cm range. It was found that in 1960 $I_{\text{MAX}}$ was 0.7 °C at 40 cm, 1.0 °C at 60 cm, 1.2 °C at 80 cm, 1.6 °C at 120 cm and 1.7 °C at 160 cm. The $I_A$ values, including the data of Balchug station, range from 0.6 to 0.8 °C in the depth range from 20 to 160 cm. A separate calculation of $I_A$ without Balchug data demonstrates values from 0.4 to 0.6 °C in deeper limits from 20 to 320 cm. However, they are evidently underestimated, because we are comparing only the urban periphery (without the city centre) with the rural zone. The downward extension of the ‘underground urban heat island’ under Moscow cannot be determined from these stationary data, because it evidently extends below a depth of 320 cm.

It should be noted that the spatial field of deep soil temperature (more precisely, groundwater temperature) according to measurements in 35 deep wells [16] demonstrates a positive thermal anomaly in ‘the neutral layer’ at a depth of about 30 m under the city. This anomaly evidently means the same UUHI phenomenon. Its intensity was discovered by V.I. Prosenkov, on average, about 5 °C, although at some local points it was higher (up to 14 °C). However, the specifics of groundwater temperature should be taken into account.

The annual dynamics of the difference between soil temperature in urban and rural areas according to the data of meteorological network reaches a maximum in winter (from $+0.9$ to $+1.2$ °C depending on the depth, see Fig. 4) due to strong urban heating and drops to its minimum in summer (from $-0.5$ to $+0.4$ °C at different depths). The inverse (positive) sign of the UUHI intensity at the depth closest to the surface (20 cm) in July seems to be an unexpected surprise. Probably, this can be the result of some local factors (different degrees of solar illuminance of local areas of the surface, etc.).

The UUHI phenomenon has also been studied in German cities [17]; in Winnipeg, Canada [18]; in Ankara, Turkey [19], and in some other cities.

5. Surface urban heat island in Moscow

In addition to heights and depths, the UHI phenomenon can be also studied using the surface temperature $T_S$. The “surface urban heat island” (SUHI) in Moscow was investigated as a thermal anomaly of the $T_S$ based on long-term data from Aqua and Terra satellites for the period from 2008.
Figure 4. Annual course of the “underground urban heat island” intensity at different depths under Moscow in 1960 [14].

to 2018. Both tools are supplied with MODIS radiometers; the spatial resolution and accuracy of the \( T_S \) radiometric measurements of the land surface are 1 km and \( \pm 1 \) °C, respectively. The results of these measurements in 36 spectral bands from 0.6 to 14.4 μm are automatically converted to the brightness temperature \( T_B \) using the Planck function and, then \( T_B \) is converted to \( T_S \) using the surface emissivity data.

The SUHI intensity is taken as the difference between average \( T_S \) values within the city and in the rural zone around it. Evidently it is similar to \( I_A \) (2). However, there are some methodical problems, and one of them is the cloudy climate of the central part of European Russia: the average cloudiness in Moscow is 7.7 according to long-term observations at the Meteorological Observatory of Moscow University since 1954 [20]. Thus, ideal clear sky conditions are extremely rare events in Moscow: only \( \sim 3\% \) from the total sample of images. However, as shown in [21] satellite images may be used to analyze the SUHI even in the presence of clouds. Numerical experiments to simulate clouds were carried out when some of the cells were cut out from an ideal image of a clear sky, and the SUHI intensity was recalculated only for the remaining cells.

As a result, it was found that if the total amount of clouds (i.e. a part of excluded cells) is less than 20% of the area of Moscow and less than 50% of the area of Moscow region, then the possible systematic error of the SUHI intensity is still relatively small (no more than \( \pm 0.2 \) of the intensity value). According to these conditions the total sample of used images of both satellites was 747 for 489 separate days over 11 years.

Another important problem is the correct sizing of the outer rural zone. Three options for this were tested: the real boundaries of Moscow region (47,000 km², see Fig.5); a small inscribed rectangle within these boundaries (16,000 km²) and a large described rectangle around them (95,000 km²). As a result of our calculations, it was found that the SUHI intensity does not significantly depend on the size of the outer rural zone around the city which is compared with the urban area: the difference in intensity depending on this size is only about \( \pm 0.1 \) °C if this size is more than 16,000 km² [21]. So, the described rectangle, which has the largest area, was chosen to calculate the SUHI intensity: it covers the entire territory of Moscow region and nearby areas of neighboring regions.

As one can see from Fig.5 the mean annual \( T_S \) in Moscow region ranges from 4 to 9 °C.
Figure 5. Map of surface temperature over Moscow region on average for the period 2008–2018 by the data of Terra and Aqua satellites. The °C scale is shown on the left. The standard Surfer10.1 program with spatial resolution 15 km was used. Orange and purple circles represent the boundaries of Moscow region and the city of Moscow, respectively.

The overall geographical zonality is expressed in the general increase of values from northwest to southeast. Besides, a clear positive heat anomaly exists in Moscow and in its close eastern suburbs. This is confirmed by two closed isotherms around the city (+7 and +8 °C) and, in addition, by a semi-closed isotherm (+7 °C). Thus, the mean annual SUHI intensity appears to be close to 2.5 °C. Another zone of high \( T_s \) values (+8...+9 °C and even slightly higher) is located in the southeastern part of the Figure. This can be explained mainly by the general climatic zonality and, possibly, by the additional influence of the SUHI of the city of Ryazan.

The annual course of the SUHI intensity is presented in Figure 6. It is noted by a clear maximum in summer (4.3 and 4.0 °C in June and July, respectively) and a minimum in autumn (1.0 and 1.1 °C in October and November, respectively). In winter and spring, the values are intermediate. These seasonal differences are statistically significant even with 0.999 confidence probability. The main probable cause is the vegetation cycle: rich vegetation in summer causes heat loss for the transpiration of trees and grass in the rural zone and, as a result, the greatest difference between \( T_s \) in the city and in the surrounding zone. On the contrary, the decay of vegetation in late autumn leads to minimal differences in \( T_s \) within and outside the city. In winter, the snow cover in the rural zone is usually continuous, whereas in the city, higher air temperatures lead to frequent thawed patches, so the ground is partially bare. But even in the case of continuous snow cover in the city, it is usually dirty and grey, i.e. it has a lower albedo compared to the rural zone. That is why the SUHI intensity in winter and in spring is not as low as in late autumn.
Figure 6. Annual course of the SUHI intensity in Moscow on average for the period 2008–2018 based on the data of Terra and Aqua satellites. Confidence intervals are calculated for the 0.001 significance level.

The mean annual intensity of the SUHI in Moscow over 11 years is 2.7 °C (it varies from −1.3 to +7.7 °C in some images). Extremely high values are connected with strong anticyclone conditions in the centre of anticyclones or on the ridge axes. Extremely low and even negative values are observed, as a rule, in late autumn at the periphery of anticyclones or ridges in the zones of intensive gradient currents, when the wind is very strong.

6. Summary of results

Thus, for the first time, the UHI intensity in a large city was estimated at various heights, depths and at the surface using different methods. All estimations obtained and discussed above are summarized in Fig.7.

This combined result needs some additional comments. First, different time and different length of the averaging periods for separate UHI estimations are a significant problem. As shown in [7,8], the general tendency of the UHI in Moscow is its strengthening in time. Thus, the oldest estimations of the UUHI intensity obtained from measurements of soil temperature in 1960 may not be comparable with other values.

In addition, there is another issue related to the SUHI. As can be seen, satellite data of radiometric measurements demonstrate the highest (2.7 °C) intensity value among other sources. However, it should be noted that this value seems to be biased (overestimated), since satellite data are available only with a clear sky, which is connected with anticyclone conditions (location of a site close to the anticyclone centre, ridge axis, saddle or any weak-gradient baric field). These synoptic situations lead to a larger difference of T between urban and rural areas due to intensive cooling of both the surface and the ground air layer outside the city at night with the cloudless sky and calm weather (or light wind).
Figure 7. Estimations of the urban heat island intensities in Moscow at different heights, depths and on the surface.

As a result, the UHI in clear anticyclone conditions, as a rule, is stronger than the average for the entire period. The value of this bias was estimated using data from the ground-based meteorological network. The UHI intensity in the ground air layer (at a height of 2 m) as the mean difference between 4 urban stations within the city and 13 rural stations in Moscow region was calculated separately for the entire period of two years (2014 and 2015) and only for the days when satellite data were available (173 images from both Aqua and Terra). As a result, Lokoshchenko and Enukova [21] found that the UHI intensity on cloudless days is 40% higher than the average of the entire period (all 730 days). Thus, using this correction, we can assume that the reliable SUHI intensity is close to 1.9 ºC.

In the ground air layer and in the subsurface soil layer, the UHI intensity is 2.0 ºC or less. At 100 m, the intensity is only 0.3 ºC; at 300 m and higher, UHI goes to nothing.

7. Conclusions

1. The urban heat island is a three-dimensional phenomenon and can be found both in the lower troposphere and in the upper soil layer.
2. Vertical upward extension of the UHI in Moscow on average for a day is reduced to zero from about 300 m; downward extension into the soil is much more than several meters.
3. The specifics of satellite data on the surface temperature $T_s$, available only under clear sky conditions, leads to an overestimation of the SUHI intensity. Nevertheless, this intensity in the field of $T_s$ is close to the data of ground-based meteorological network (2.7 ºC).
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References
[1] Howard L 1818 The Climate of London, deduced from Meteorological Observations, made at different places in the neighbourhood of the metropolis; in two volumes, Vol.1 (London: W. Phillips) p 346
[2] Kratzer P A 1956 The Urban Climate (Das Stadtklkima) (Braunschweig, Germany) p 221
[3] Böer W 1964 Technische Meteorologie (Leipzig: B.G. Teubner Verlagsgesellschaft, GDR), p 232, in German
[4] Landsberg H E 1981 The Urban Climate (New York, USA: Academic Press) p 275
[5] Oke T R 1978 Boundary Layer Climates (London, UK: John Wiley and Sons) p 372
[6] Oke T R, Mills G, Christen A and Voogt J A 2017 Urban Climates (Cambridge, UK: Cambridge University Press) p 525
[7] Lokoshchenko M A 2014 Urban Climate Urban heat island in Moscow 10 3 550-562
[8] Lokoshchenko M A 2017 J. Appl. Meteor. and Climatology Urban heat island and urban dry island in Moscow and their centennial changes 56 10 2729–45
[9] Kobysheva N V et al. 2001 Climate of Russia ed N V Kobysheva (St.Petersburg, Russia: Gidrometeoizdat Publ) p 655, in Russian
[10] Ivanov A, Katz A, Kurnosenko S, Nash N and Zaitseva N 1991 WMO International Radiosonde Comparison, Phase 3, Instruments and Observing Methods Rep. No. 40 WMO/TD_No 451 (Dzambul, 1989) p 172
[11] Lokoshchenko M A, Korneva I A, Kochin A V, Dubovetsky A Z, Novitsky M A and Razin P Ye 2016 Doklady Earth Sciences Vertical Extension of the Urban Heat Island above Moscow 466 1 70–74
[12] Duckworth F S and Sandberg J S 1954 Bulletin of American Meteorological Society The Effect of Cities upon Horizontal and Vertical Temperature Gradients 35 5 198-207
[13] Bornstein R D 1968 J. Appl. Meteorology Observations of the urban heat island effect in New York City 7 575-82
[14] Lokoshchenko M A, Korneva I A 2015 Urban Climate Underground urban heat island below Moscow city 13 1-13
[15] Alekseeva L I et al. 2017 Moscow Climate in Conditions of Global Warming ed A V Kislov (Moscow: Moscow University Press) p 288, in Russian
[16] Prosenkov V I 1974 Prospect and protection of mineral resources Changes in the temperature and salinity of underground waters in Moscow 12 36-41, in Russian
[17] Menberg K, Bayer P, Zosseder K, Rumohr S and Blum P 2013 Science of the Total Environment Subsurface urban heat islands in German cities 442 123–33
[18] Ferguson G and Woodbury A D 2007 Geophys. Res. Lett. Urban heat island in the subsurface 34 L23713
[19] Turkoglu N 2010 Environmental monitoring and assessment Analysis of urban effects on soil temperature in Ankara 169(1–4) 439–50
[20] Abakumova G M, Gorbarenko E V, Nezval E I and Shilovtseva O A 2012 Climatic Resources of Solar Energy in the Moscow Region (Moscow: LIBROKOM) p 310, in Russian
[21] Lokoshchenko M A and Enukova Ye A 2020 Russian Met. Hydrology Urban Heat Island in Moscow Derived from Satellite Data 45(7) 488-97