ISSN 1028-334X, Doklady Earth Sciences, 2016, Vol. 466, Part 1, pp. 70–74. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © M.A. Lokoshchenko, I.A. Korneva, A.V. Kochin, A.Z. Dubovetsky, M.A. Novitsky, P.Ye. Razin, 2016, published in Doklady Akademii Nauk, 2016, Vol. 466, No. 2, pp. 213–217.

GEOPHYSICS

Vertical Extension of the Urban *Heat Island* above Moscow

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Presented by Academician G.S. Golitsyn May 19, 2015

Received May 22, 2015

Abstract—The vertical extension of the urban "heat island" (UHI) has been studied on the basis of long-term data of contact air temperature measurements at three places for the example of Moscow. The existence of steady thermal anomaly related to the city in the form of a UHI in the surface layer at any time of the day and also the existence of a cold layer over it at heights higher than 100 m at night were confirmed. The mean daily altitudinal extension of this anomaly is approximately 300 m.

DOI: 10.1134/S1028334X16010128

The *heat island* (UHI) phenomenon in cities has been known from the first half of the 19th century (it was described for the first time by L. Howard for the example of London); now it is discussed in many aspects everywhere (see [5, 15] and others). The investigation of the Moscow UHI is especially interesting because of the local conditions: flat plain terrain, simple form of the main part of the city since 1960, which is close to a geometrically correct ellipse, approximately symmetrical urban saturation the density of which decreases from the city center to its periphery, and the absence of a coastline and large water reservoirs near the city. Hence, the spatial structure of the UHI in Moscow is comparatively simple and its regularities should be clearly manifested. It is clear that the UHI phenomenon is a three-dimensional one although the spatial differences in the air temperature T field are usually studied only at the standard 2-meter level of measurements at the stations over the surface (see [15] and others for the details applied to Moscow). According to the data of underground water temperature measurements by V.I. Prosenkov, the thermal anomaly in the Moscow area manifests itself even at a depth of 30 m. Systematic measurements at greater depths are lacking; hence, the estimate of the extension of the Moscow UHI into the deep layers of the soil and ground remains unknown.

There are very few estimates of the vertical extension of the UHI in the literature owing to the great cost of high altitude constructions equipped with meteorological sensors. Synchronous launches of tethered balloons showed the cross-over effect temperature profiles at night in the conditions of surface inversion in the city center and beyond its limits for the example of two American cities [13]. Vertical turbulent exchange in the city is stronger, and surface inversions are less intense, on average. Hence, beginning from a specific height (approximately 100 m based on [13]), the temperature here (T) is lower than in rural regions [5, 12]. In other words, at night the UHI in the surface layer above a city regularly changes by a cool layer (CL) in the overlying Ekman layer; both appear owing to the influence of the city. If applied to Moscow, the existence of a night CL above the city at higher altitudes was demonstrated by the measurements using MTP-5 microwave radiometers at three locations [3, 4]. On the contrary, in the daytime, the temperature difference at the city center and beyond its limits is usually positive at all altitudes where the influence of the city exists. It is clear that at some altitude which is the UHI vertical extension above a city the spatial differences in the temperature field should diminish. The altitudinal extension of the UHI depends significantly on the time of the year and the time of the day; based on the data in [5], it ranges from 100 to 300 m, on average. Based on the data from helicopters in New York, it is equal to 300 m, on average [12]. The estimates of intensity of the UHI in Moscow are given in [4] for different altitudes based on the results of long-term measurements using the MTP-5 instruments. However, indirect radiometric data require verification by contact measurements. In addition, the altitudinal range considered in [4] is limited to 300 m. The objective of this work is to get the mean estimate of the upper limit of the UHI extension in Moscow based on

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long-term data and application of all available results of direct (contact) measurements.

Three sources of regular temperature data at high altitudes exist in the Moscow region, including the Kaluga region: the TV tower in the Ostankino disrtict at the northern part of the city on 7 km from the Moscow Kremlin, the Central Aerological Observatory (CAO) in Dolgoprudnyi (in the vicinity of Moscow located 2 km north of the city boundary and 13 km north of the TV tower), and a high meteorological mast of the "Typhoon" Scientific Production Association (Institute of Experimental Meteorology) in Obninsk (96 km southwest of the Moscow Kremlin center and 102 km from the TV tower). Temperature sensors (platinum resistance thermometers) were installed on the 540-m TV tower at heights of 85, 128, 201, 253, 305, 385, and 503 m and also at a level of 2 m above the land site near the tower. The radiosondes in the CAO are launched twice a day: at 02:30 and 14:30 (Moscow time). Their data in the programming software EOL of the AVK and MARL radars are available within the lower 1 km interval at all heights divisible by 100 m. Finally, regular temperature measurements at the 310-m tower in Obninsk starting from 1958 have been carried out at three levels: 2, 121, and 301 m (and episodic measurements at three additional levels).

The authors developed a joint electronic database of all simultaneous temperature measurements T at the given heights at these three locations for eight years from 2006 to 2013. Gaps in the measurements in separate months occurred at a level of 301 m on the Obninsk mast (in August 2008 and from December 2009 to February 2010). No daytime radio soundings were performed in Dolgoprudnyi in February, July, September, and October 2013; in December 2006, there were no daytime and night-time launches. The greatest possible temperature values in these months at separate heights in Obninsk were obtained using long-term average estimates of vertical temperature gradient in the atmospheric layers in these months in the interval between the levels of 121 and 301 m, while in Dolgoprudnyi we used the monthly mean data of temperature measured at a level of 2 m at Moscow State University (25 km from Dolgoprudnyi). Complete time series of data were restored in both locations using this interpolation; no gaps at measurements on the TV tower occurred. The comparatively small area and population of Obninsk (43 km^2 and 110 000 people) and also the location of the mast in a park in the northern part of the town allows us to consider the results of the measurements here close to the background values characterizing rural regions. The location of the TV tower near the center of the capital reflects the conditions of the UHI. Data of radio soundings in Dolgoprudnyi are intermediate in these time series characterizing the conditions of the outskirts of a big city.

Figure 1 shows temperature profiles for the middle time of the day and night based on the data of all three

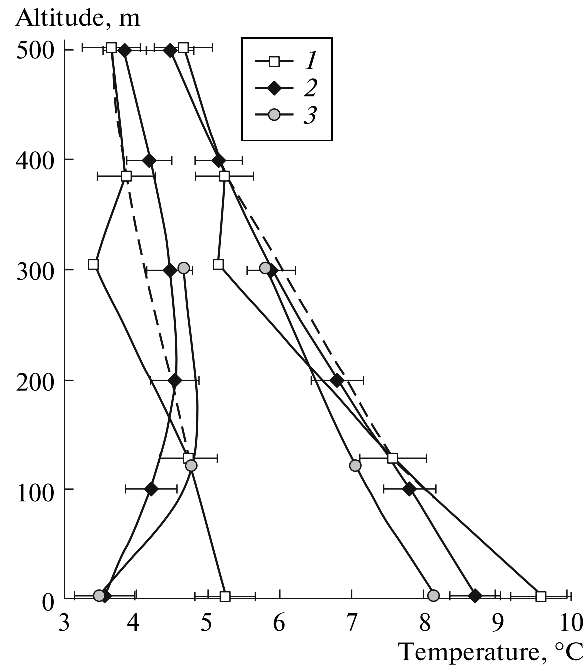

Fig. 1. Air temperature profiles averaged over night time (02:30–03:00) and daytime (14:30–15:00) based on the data of the Ostankino TV tower in Moscow, radio sounding in Dolgoprudny, and a high mast in Obninsk over the period 2006–2013; (*1*) the Ostankino TV tower data at 02:30 and 14:30; (*2*) radio sounding data in Dolgopridny at 02:30 and 14:30; and (*3*) the data of the high mast in Obninsk at 03:00 and 15:00. The confidence intervals for the TV tower and radio sounding data were plotted with a confidence probability of 0.95.

sources averaged over eight years. We see that the data measured in Obninsk and Dolgoprudnyi demonstrate regular prevalence of surface inversions at night and a profile close to adiabatic in the daytime. We should take into account a small possible shift of the mast data in Obninsk to higher values compared with the other sources owing to the influence of the geographical zonality (the general trend of the annual mean temperature T increase to the southwest). Taking into account the distances between the annual mean isotherms in the center of the European part of Russia, this shift is approximately equal to 0.3°C. In addition, a small systematic bias of estimates is possible in the radiosonde data owing to the sensor inertia: overestimation of the temperature by the radiosonde when temperature decreases with height in the daytime in the entire 500-m layer and at night above the top of the surface inversion and also underestimation of the estimates at night in the layer of this inversion. The inertial coefficient (time constant) α of the copper–manganese thermal resistors MMT used in the Russian radiosondes since 1970s is 5–6 s based on the data of N.S. Kokovin or 7 s based on the data in [14]. An approximate estimate of temperature overestimation by radiosondes in the daytime $\Delta T = \alpha V \frac{\partial T}{\partial z}$ with account for the mean velocity of the sonde ascent V (approximately 5 m/s) and closeness of the temperature gradient to the adiabatic line is consequently in the range from 0.2 to 0.4°C.

Systematic comparisons of the radiosonde data with the measurements on high mast are rarely performed. However, in the international comparison of radiosondes of different models with different values α of the temperature sensors, the data of less inertial sensors among the others can be considered close to the data of temperature measurements at the stationary levels of the mast. For example, the comparison performed in Dzhambul in 1989 showed that, at a level of 850 hPa (approximately 1.5 km), the measurements of the MMT sensor on the Soviet radiosonde (despite its significant inertia) appeared smaller by 0.2–0.4°C compared with the capacity sensor of the Finnish radiosonde RS80-15N and the resistance thermometer of the US radiosonde VIZ-1392, the time constant of which is only 2.5–3.0 s [14]. Thus, cooling of the sensor's surface due to its heat radiation in the infrared range appeared stronger than the expected overestimation of the value caused by inertia. In addition, in the night-time, the inertial error in the layer above the top of the surface inversion is obviously close to zero due to the nonmonotonic temperature profile.

The TV tower data recalculated for five levels require specific explanations. In general, the analysis of meteorological measurements on any tower is more complicated compared to the special masts because the classical requirement of five-fold excess of the outrigger length P relative to the diameter D (in a milder requirement, relative to the radius [8]) is not always satisfied due to the architectural peculiarities of one tower or another. For example, on the Ostankino TV tower, the ratio P/D is close to 1.0–1.5 at all levels except the highest one (503 m), where it is equal to 6.9 and, taking into account the width of the deck, it is even equal to 9.0 (for the example of the Obninsk mast, the ratio P/D is equal to 3.1 at all levels taking into account the width of the working platform). In this relation, a sharp break of the temperature profile in the layer from 305 to 385, which is an imaginary elevated inversion pronounced at any averaging over time that seemingly exists constantly at these heights, raises reasonable doubts.

A qualitatively similar profile was revealed from the TV tower data in the beginning of the 1990s [7]. In various years, attempts were made to find the relation of this peculiarity of the Ostankino data, which demonstrates an almost continually elevated inversion, to different causes: layers of smoke from the forest fires in 1972 [9], heating of the air in this layer by adiabatic compression that appears as a result of seemingly constant downward flows [1], overheated plumes from high chimney-stalks of the plants over the city, manifestation of the real elevated inversion (remains of the night surface inversion) in the morning hours [10], thermal influence of the layer of the urban aerosol haze over the city [11], and so on. A detailed review of the suggested hypotheses is given in [7]. However, it is likely that none of them explains the existence of the broken curve of the temperature profiles at the same heights in different years at any time of the day and under any conditions. The nature of this curve break on the Ostankino temperature profiles still remains unclear. It is possible that the dynamic and thermal influence of the TV tower construction cannot be removed completely at the given ratio P/D at the level of 305 m. Therefore, we shall consider a conventional profile of the TV tower data excluding this level (dashed lines in Fig. 1).

The absence of the surface inversion, at least a weak one in the middle of the night based on the data of the TV tower, seems doubtful as well. It is shown in [2] on the basis of synchronous acoustic sounding using three sodars during one month in summer that surface inversions appear more rarely in the Ostankino district in the center of the city (30% of the total time) than in the rural regions near Moscow (42%). For comparison, in the region of Moscow State University, their recurrence based on the same sodar data averaged over 15 years was 37% [6]. However, surface inversions in the middle of night even in the Ostankino region based on the sodar data exist over 80–90% of the entire time, at least, in summer [7]. Therefore, it is possible that a temperature decrease with height in the layer between 2 and 128 m averaged over eight years reflects either microclimatic peculiarities of the thermal conditions in a local vicinity of the land site near the TV tower or can be caused by different locations of the measurement places at 2 and 128 m (the land site is located at a distance of 100 m from the TV tower). Summarizing the previously stated information, we emphasize the exceptional importance and uniqueness of the Ostankino TV tower data at the upper 503 m, which are known to be reliable taking into account the P/D ratio not affected by the influence of the tower (its thin steeple).

We see that a UHI exists during the day and night time in the lower 100-m layer over Moscow; the temperature in Ostankino is higher than in the other two places. The data from the region close to Moscow (Dolgoprudnyi) occupy an intermediate position between the city center and the region far from Moscow (Obninsk). We note that the altitude of intersection between the night temperature profiles in Obninsk and Dolgoprudnyi is obviously underestimated due to the geographical zonality (the data of the high mast are shifted to higher values). At night a high altitude CL exists above the UHI: the mean temperature at 300 m is 4.2°C in Ostankino (the data were interpolated from the data of two neighboring levels), 4.5°C in Dolgoprudnyi, and 4.7°C in Obninsk. In the upper layers, the differences between Ostankino and Dolgoprudnyi naturally decrease so that at a height of 500–503 m both the daytime and night-time values in Moscow and the vicinity coincide to an accuracy of ±0.1°C (correspondingly 3.7 and 3.8°C at night and 4.6 and 4.5°C in the daytime). Strictly speaking, it is not possible to detect the upper boundary of the thermal anomaly related to the influence of the city in the daytime and night-time: the temperature profiles in Ostankino and Dolgoprudnyi approach each other only asymptotically. However, the differences between the samplings of mathematical expectations at these two locations are not statistically significant even with a probability of 0.95 according to the classical Student criterion (all the distributions are close to the normal law according to Pearson's criterion): in both the daytime and night-time, in winter and in summer at the levels of 400–385 m and 500–503 m. Figure 2 shows an example of the statistical distributions of all simultaneous temperature values measured at 02:30 at the heights of 385–400 m in Ostankino and Dolgoprudnyi over eight years in the winter months (a total of 644 readings). We see that the recurrences are very close in all gradations. Their closeness is confirmed also by the confidence intervals in Fig. 1 plotted from the samplings of the annual mean data over eight years, which reflect the interannual variability of the temperature conditions.

Thus, both the daytime UHI and night-time elevated CL gradually diminish with height and a height of 400 m can conventionally be considered the upper boundary of the layer in which the thermal anomaly related to the city is statistically significant.

Let us consider the daily mean values of temperature at each of the levels at three locations, which are summarized in table. For the data of Dolgoprudny we used in the calculation the mean difference between the mean temperatures at two measurement times (02:00 and 14:00) and and the daily mean temperature based on the stationary data of Moscow State University. We see that the UHI is manifested in the surface layer also on the basis of the daily mean data despite the more southern location of Obninsk. Taking into account the probably overestimated data by 0.3°C of the mast compared with Moscow owing to the geographical zonality, the UHI also exists in the layer 100–128 m, while in the layer 300–305 m the daily mean temperature is the same at all three locations. The same values are observed in Ostankino and Dolgoprudnyi also at 385–400 m. At the upper level of comparison 500–503 m the difference between them is equal to +0.1°C and can be explained either by the erroneous instrumental correction to the TV tower sensor's data or radiation cooling of the radiosonde. We note that the mean temperature profiles at this level averaged over each individual year show differences between the estimates in Ostankino and Dolgoprudnyi from –0.3 to +0.3°C, while the standard deviation of the mean difference based on the eight-year sampling is 0.2°C so that the difference and even its sign depend on the selected time period.

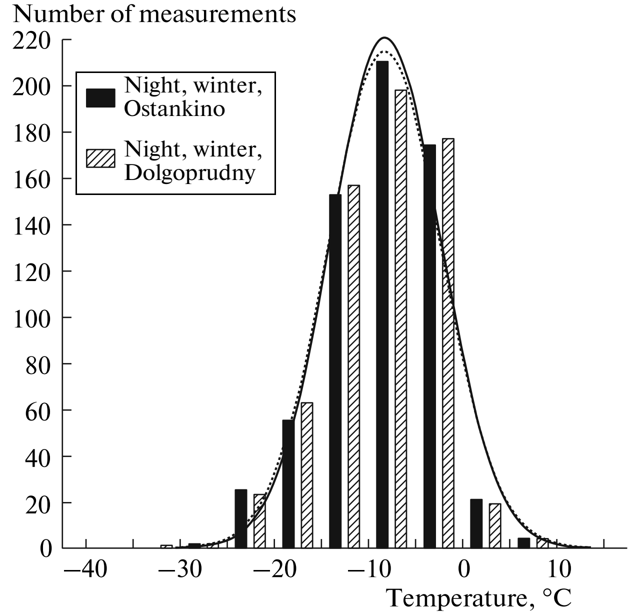

Fig. 2. Statistical distributions of air temperatures based on the data of simultaneous measurements at the Ostankino TV tower (black bars) and radio sounding in Dolgoprudny (bars with hatches) at 02:30 in the winter months from 2006 to 2013. The ordinate axis shows the number of measurements (sampling number). Solid lines show the distributions corresponding to the normal law for both locations.

Thus, beginning from an altitude of 300 m, there are no significant and stable in time spatial differences in the air temperature field above a large city: on average, the daily mean temperature is the same at all three locations because the effects of the daytime UHI and night-time CL mutually compensate each other.

The data presented here allow us to make the following conclusions.

A large city forms a thermal anomaly in the atmospheric boundary layer with different signs. It is mani-

Daily mean air temperature in the layer from 2 to 500–503 m based on the data of the Ostankino TV tower, radio sounding in Dolgoprudny, and the high mast in Obninsk over the period of 2006–2013

Level of measurements, m	City center (Ostankino)	Outskirts of the city (Dolgoprudny)	Background conditions (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	

* The value was interpolated taking into account the values at levels of 128 and 385 m.

fested in the form of a UHI in the daytime at least up to 500 m and in the night-time only in the surface air layer up to the heights of 100 m. In the night time at heights greater than 100 m, the thermal anomaly of the city exists in the form of an elevated CL above the UHI owing to the cross-over effect of the temperature profiles in the city and outside its boundaries (more intense surface inversions outside the city).

The intensity of the daytime UHI and elevated CL in the night time above the city gradually decreases to zero with height. At the heights of 400 and 500 m, the spatial differences in the temperature field are not statistically significant both at night and during the day.

The phenomenon of the UHI, on average, over the day is also clearly seen in the surface air layer and at a level of 100 m. At a height of 300 m above Moscow, the thermal anomaly related to the influence of the city does not exist in the daily average data. Thus, this level characterizes the altitudinal extension of the thermal anomaly related to the city.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research, project no. 14-05-00594.

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Translated by E.G. Morozov