Vertical range of urban 'heat island' in Moscow

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Abstract

For the first time the vertical range of the urban 'heat island' over Moscow has been investigated by long-term (during eight years) data of the air temperature *in situ* measurements in the air layer up to 500 m height. The results of measurements at a TV tower of 540 m height in Moscow, by radiosondes at closed rural area (on 2 km to the North from the city margin) and at a high meteorological mast of 310 m height at rural zone (about 100 km to the South-West from the city centre) were analyzed. As it has been received the urban thermal anomaly exists as the urban 'heat island' in the ground air layer all over the day and, besides, as the urban 'cool island' above it at night. As it has been shown in the layer up to 500 m air temperature profiles inside and outside the city asymptotically approach to each other. An intensity of both diurnal 'heat island' and nocturnal 'cool island' gradually decreases with a height so that at 400-500 m level differences become statistically insignificant. In average of a day the air temperature is nearly the same at all locations since the 300 m level already because 'heat island' and 'cool island' effects mutually compensate each other everywhere above. Examples of simultaneous temperature profiling in conditions of extremely cold and hot weather have been discussed as well.

1. Introduction.

There are a lot of studies of the urban 'heat islands' which were analyzed for different cities all over the world. However usually they are investigated only by the data of routine meteorological measurements – as a rule, on the standard 2 m height level above the ground. Evidently the 'urban heat island' is three-dimensional phenomenon and is characterized by extent to both directions – downward and upward. Unfortunately only a few studies about the vertical extent of the urban 'heat islands' are known in the literature. Usually they are based on some results of special scientific experiments during comparatively short time: several separate days or, at least, several weeks – e.g., in (Bornstein, 1968). For example, Duckworth and Sandberg (1954) received simultaneous temperature profiles above three US cities and their suburbs in the evening and nocturnal time using ascents of tethered balloons. They described – probably for the first time – the 'cross-over' effect that means an intersection of temperature profiles above a city and rural zone at night. The reason of it is a more intensive vertical turbulent exchange above a city in the comparison with its suburbs. As a result, surface nocturnal inversion at rural zone is more intensive than in a city – thus, since some level, the air temperature above a city is lower than outside it (Landsberg, 1981).

Regarding Moscow city the 'heat island' and its dynamics in time on the ground level has been analyzed, e.g., by Lokoshchenko, 2014. The 'underground heat island' below Moscow was analyzed in details by Lokoshchenko and Korneva, 2012, 2015. Besides, the 'heat island' effect for Moscow was investigated by the data of microwave radiometer MTP-5 by Kadygrov et al., 2002. However results of indirect passive remote sensing should be tested and confirmed by the data of *in situ* measurements. Thus a purpose of our work was to estimate a top of the urban 'heat island' vertical range in Moscow on a base of long-term direct measurements.

2. Locations and methodology of measurements.

There are three sources of long-term data about the air temperature T profiles in Moscow region (Figure 1): TV tower in Ostankino urban district close to the city centre (on 7 km to the North from Moscow Kremlin); radiosonde station in Dolgoprudny at closed rural area (on 2 km to the North from city margin) and a high meteorological mast in Obninsk (small town) at far rural area on 96 km to the South-West from Moscow Kremlin. The distance from TV tower is 102 km from the high mast and 13 km from the site of radiosonde launching. The TV tower height is 540 m (it was the tallest tower in the world before 1975); it is equipped by thermal sensors (platinum resistance thermometers) on 2, 85, 128, 201, 253, 305, 385 and 503 m. Radiosondes in Dolgoprudny contain a white painted rod semi-conducted thermistor of nearly 2 mm diameter and 10 mm length which has a time constant α = 5-6 sec. (Kokovin, 1966) or 7 sec. (Ivanov et al., 1991). They are launched twice a day, at 3:30 a.m. and 3:30 p.m., and results of T measurements are available with a 100 m spatial resolution. Besides, a high meteorological mast in Obninsk has 310 m height and regular measurements of T are carried out there since

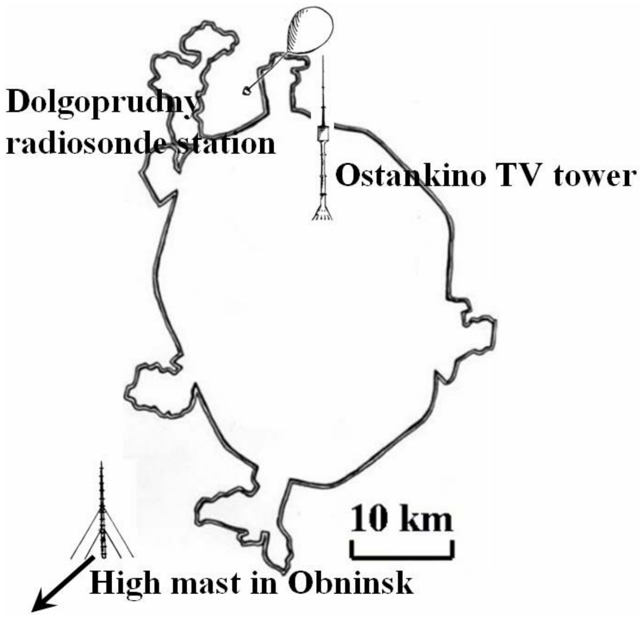

Figure 1. Three sources of the air temperature data in the lower troposphere in Moscow region. Closed line represents margins of the city; scale is shown below. High mast in Obninsk is located on 96 km to the South-West from Moscow centre.

1958 at three levels: on 2, 121 and 301 m. However a great distance between Obninsk and Moscow should be accounted in the comparison with the other used data because of total geographical zoning. Accordingly to climatic handbooks a mean annual air temperature in the central part of European Russia grows from North-East to South-West so that T values in Obninsk are nearly 0.3 ˚C higher than in Moscow with the account of a distance between mean-annual isotherms (e.g., Kobysheva, 2001).

One more principal methodic problem is a comparison of mast/tower data with radiosondes measurements. From one hand, inevitable inertia of thermal sensor leads to an overestimation of T values at any heights during a day and above a surface inversion top at night, and, vice versa, to an underestimation of T values inside the surface inversion layer below its top. Thus, an approximate value of the T systematic overestimation by radiosondes in the afternoon is about: $\Delta T = \alpha \cdot V \cdot \partial T/\partial z = 0.2–0.4$ ˚C, where V is a typical rate of radiosonde's ascent. Unfortunately, only a few comparisons between data of radiosondes and mast sensors are known. However we can use results of international comparisons between different types of radiosondes supposing that the measurements of the most sensitive sensor among others (i.e. with the least time constant α) and of a stationary mast sensor are close to each other. One of such international comparisons of different radiozondes types took place in Dzhambul, USSR in 1989. According to its results the T values by the Soviet thermistors despite of its big time constant were mostly lower than T values by Finnish and USA thermistors with less time constant of 2.5–3.0 sec. (Ivanov et al., 1991). Hence the thermistor cooling due to its thermal infrared radiation seems to be more significant than *a priori* expected overestimation of T values due to inertia.

The measurements of air temperature at TV tower also have some methodic problems. For correct measurements in order to avoid the thermal effect from the tower construction the radial line's length P has to exceed at least five times the tower diameter D, but sometimes this condition is hardly realized. Thus, at Ostankino TV tower P/D ratio is only about 1.0–1.5 at all levels except the highest one (503 m) where it is equal to 6.9 (with the account of balcony width – even 9.0). Hence, an imaginary elevated inversion by TV tower data in the air layer from 305 to 385 m in average of eight years seems to be doubtful. Similar T profiles were registered there also in 1990-s and possible explanations of this effect were discussed in (Lokoshchenko et al., 1993, 2015). The cause of this inversion remains unclear yet. It may be either a result of tower thermal influence on sensors or some local phenomenon in Ostankino district. Thus, let us compare below air temperature profiles with an exception of the 305 m height level from the data of TV tower (dashed lines on Fig. 2). It should be noted that the air temperature data at the highest 503 m level is obviously reliable because of high P/D ratio there.

3. Spatial differences in air temperature profiles in Moscow region.

Let us compare air temperature profiles at three sites over Moscow region averaged for eight years from 2006 to 2013 which are presented on Figure 2. As can be seen the 'heat island' effect exists in the ground air layer up to 100 m – air temperature in the city (TV tower) is higher than at close to the city rural zone (Dolgoprudny) and more higher than at far rural zone (Obninsk). The intersection point of nocturnal T profiles in Obninsk and Dolgoprudny is most likely underestimated because of geographical zoning (air temperature in Obninsk is shifted to higher values). At nocturnal time a 'cool island' exists above 'heat island', so that at the 300 m height average

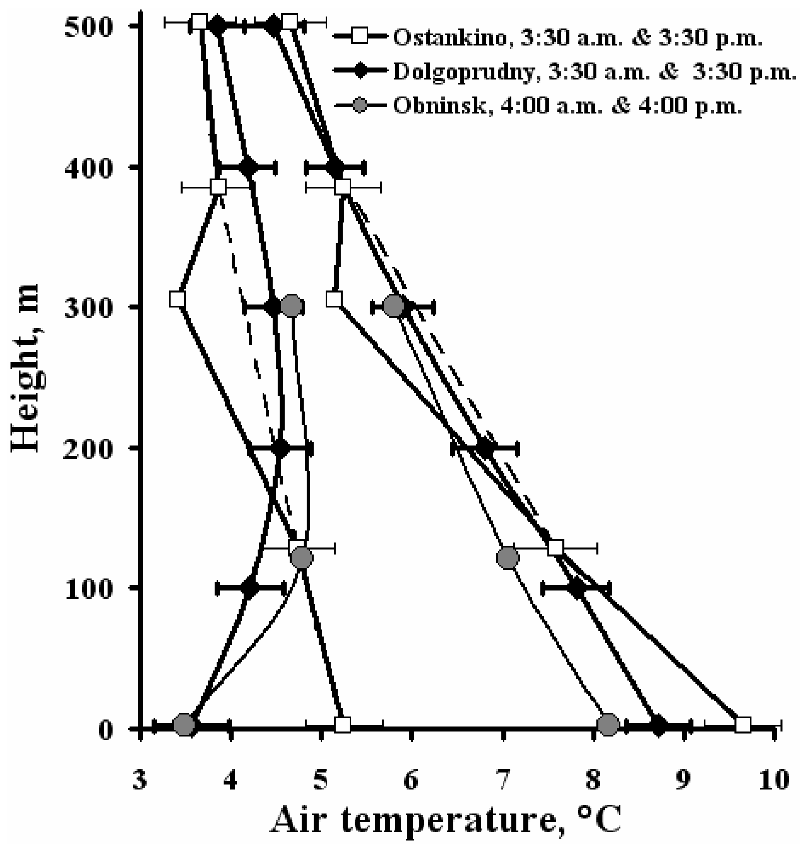

Figure 2. Average nocturnal (3:30 – 4:00 a.m.) and diurnal (3:30 – 4:00 p.m.) air temperature profiles by the data of Ostankino TV tower in Moscow, radiosondes in Dolgoprudny and high mast in Obninsk for the period 2006-2013. The confidence intervals are calculated with a significance level of 5%.

T value is equal to 4.2 °C in Ostankino (an interpolated value between 128 and 385 m), 4.5 °C in Dolgoprudny and 4.7 °C in Obninsk. Above this level thermal differences between Ostankino and Dolgoprudny decrease so that at the level of 500-503 m they are already almost coincide each other with the ±0.1 °C accuracy (at night 3.7 and 3.8 °C, at midday 4.6 and 4.5 °C correspondingly). Unfortunately we couldn't correctly detect the upper limit of thermal anomaly, as T profiles at heights 500-503 only asymptotically approach to each other. However, the statistical differences between mean values of T at both these locations according to Student criteria are statistically insignificant even with the confidence probability of 0.95. This is true both for diurnal and for nocturnal profiles at the levels of 385–400 m and 500–503 m. An example of the nocturnal T values statistical distribution in winter at the heights 500-503 m is presented on Figure 3 (data sampling is 640 separate measurements). As it is seen frequencies of T values are close to each other at all histogram gradations. Besides this conclusion is confirmed as well by confidence intervals on Figure 2, which represent a variety of mean annual T values for eight years. Hence, both diurnal 'heat island' and nocturnal 'cool island' gradually go to nothing with a height so that a level of 400 m may be considered as the top of the layer in which the urban thermal anomaly is certainly detected.

Average daily T values at three locations are shown in Table 1. These values in Dolgoprudny are calculated from the average of nocturnal and diurnal T values with correction to its daily course using hourly data about the ground air temperature at Moscow State University. Despite of the southern location of Obninsk the urban 'heat island' is revealed on the ground also by the average daily T values. With the account of probable overestimation of Obninsk T values by 0.3 °C due to geographical zoning the urban 'heat island' is detected at the level of 100–128 m as well, but at 300–305 m the air temperature is probably the same at all three locations. The equal T values were observed also in Ostankino and in Dolgoprudny at the level of 385–400 m. The difference on the highest level of 500–503 m may be a result both of erroneous instrumental correction coefficient to a tower sensor and of radiosonde radiation cooling. It should be noted that T difference between Ostankino and Dolgoprudny at this level for separate years is ranged from +0.3 °C to –0.3 °C whereas its standard deviation σ = 0.2 °C for the whole period of eight years. Thus, this difference strongly depends on selected period of time.

Thus, any significant and constant in time spatial air temperature differences do not exist since the 300 m level above a big city. Average daily air temperature is close at all three places everywhere above because the effects of diurnal 'heat island' and nocturnal 'cool island' mutually compensate each other. It should be noted that the same estimation – about 300 m – was received for New York city using helicopter sounding (Bornstein, 1968).

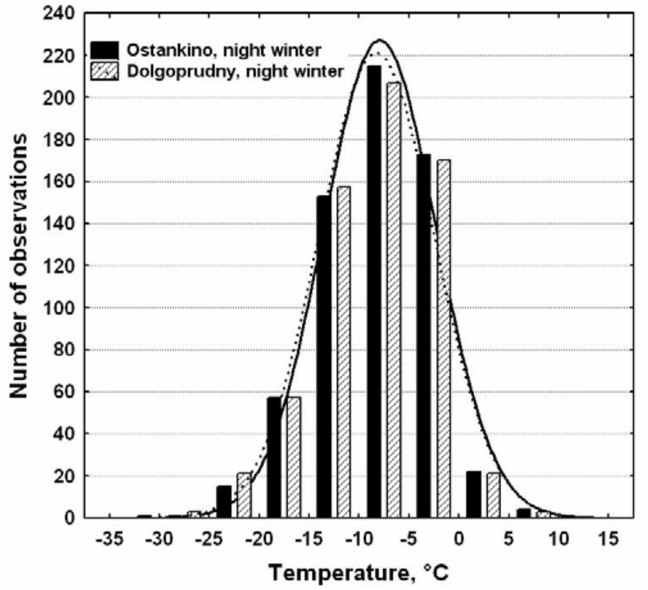

Figure 3. Statistical distributions of the air temperature values on 500-503 m height by the data of simultaneous measurements in Ostankino TV tower and by radiosondes in Dolgoprudny at 3:30 a.m. in winter for the period since 2006 till 2013. Solid lines represent the normal law distributions for both places.

Table 1. Average daily air temperature at heights from 2 to 500-503 m by the data of Ostankino TV tower in Moscow, radiosondes in Dolgoprudny and high mast in Obninsk for the period 2006–2013.

Height, m	**City centre (Ostankino TV tower)**	**City periphery (Dolgoprudny)**	**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 has been interpolated between 128 and 385 m.*

***Obninsk data are probably shifted on +0.3˚C in the comparison with other two locations.*

4. Case studying.

Let us discuss, besides averaged air temperature profiles over Moscow, some separate examples of them. As one knows the whole range of T possible values on the ground level (2 m) in conditions of Moscow climate is equal to about 80 ˚C (Lokoshchenko, 2012): from –42.1 ˚C on January 17th, 1940 to +38.1 ˚C on July 29th, 2010 (and even up to +39.0 ˚C in the city centre). However during last decade the air temperature varied in less range because the minimal value since 2004 was equal only to –30.1 ˚C (on January 18th, 2006). Unfortunately daily radiosonde wasn't launched on July the 29th of 2010, but four days later, on August the 02nd, maximal T at the University on South-Western urban periphery became only a bit less: +38.0 ˚C. Thus, the vertical structure of the urban 'heat island' for these extreme events is presented on Figure 4. As it is seen on January the 18th, 2006 (upper part) in conditions of extremely cold continental Arctic air mass invasion into Moscow region the surface inversion which is quite usual phenomenon at nocturnal time was absent. Evidently it was a consequence of strong cold advection. Moreover, it should be noted that the air temperature daily course in winter is comparatively weak. That's why the nocturnal and daily profiles of T by the data of mast in Obninsk coincide at the upper point (301 m height). In general, as it is seen, profiles of T at all three places are close to each other due to strong advection.

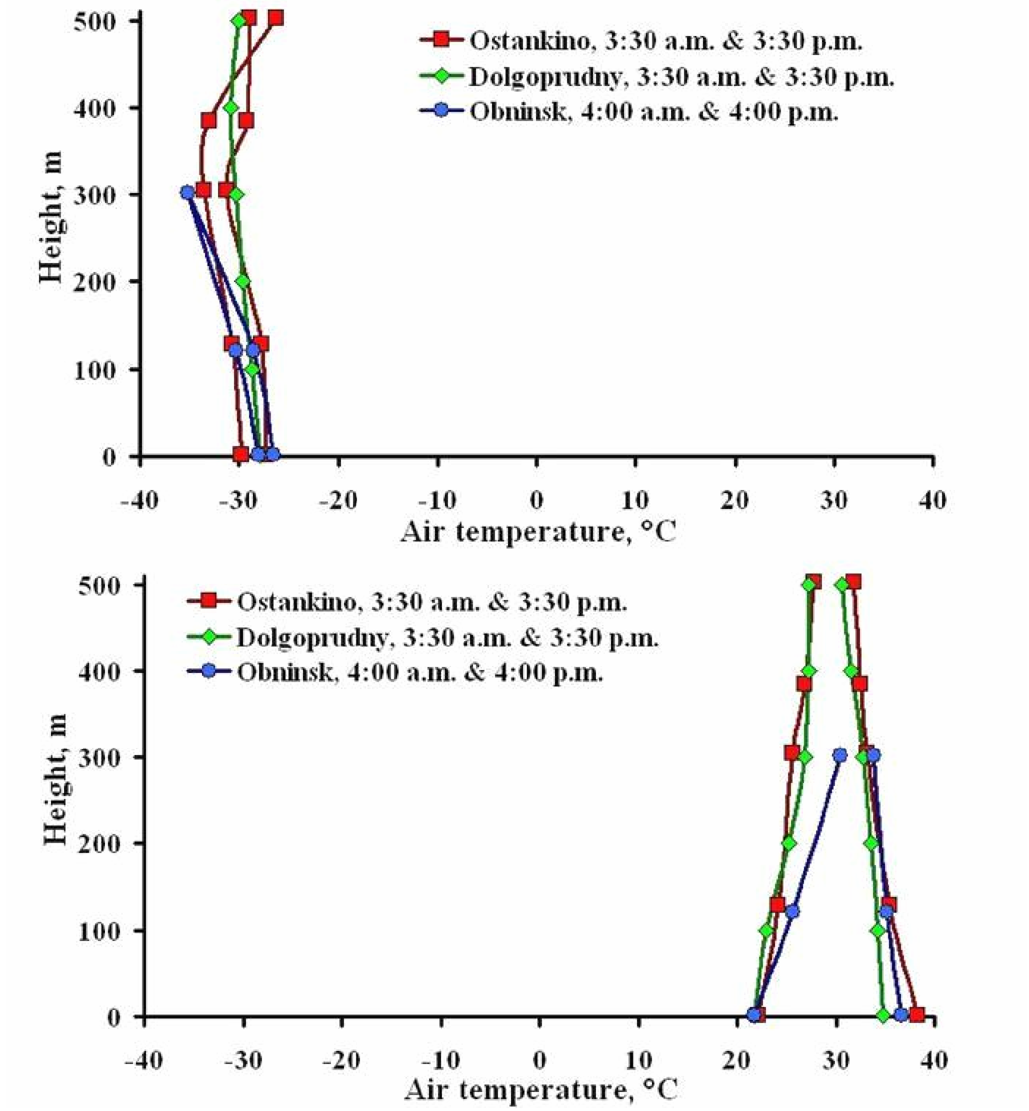

Figure 4. Nocturnal (3:30–4:00 a.m.) and diurnal (3:30–4:00 p.m.) air temperature profiles by the data of Ostankino TV tower in Moscow, radiosondes in Dolgoprudny and high mast in Obninsk on January 18th, 2006 (upper) and on August 02nd, 2010 (below). Summer-time is noted.

Unlike the first example, during extremely hot summer day August 2nd, 2010 (lower part of Fig.4) there is a large difference between nocturnal and daily T values accordingly to all three sources of data: on the ground level about 13 ˚C in Dolgoprudny, 15 ˚C in Obninsk and 16 ˚C in Ostankino. Besides, due to strong daily course of T, its values at night and in the afternoon are different at any height up to 500 m. In the middle of the day the vertical thermal gradient in the ground air layer (below 100 m) was equal to 1.2 ˚C in Obninsk, 0.6 ˚C in Dolgoprudny and 2.2 ˚C in Ostankino. It is not a surprise that in the city diurnal lapse rate of the air temperature at that day was super-adiabatic unlike close rural area (Dolgoprudny). It should be noted as well that the nocturnal surface inversion existed at all three sites as a result of strong anticyclone conditions, i.e. cloudless sky and light wind (in Dolgoprudny – even calm). This inversion was very strong (its intensity was 5.6 ˚C in Dolgoprudny, not less than 5.7 ˚C in Ostankino and evidently more than 8.7 ˚C in Obninsk because its top was higher than 300 m) and high (its thickness was 400 m in Dolgoprudny, ≥ 500 m in Ostankino and > 300 m in Obninsk). Evidently, surface inversion was enhanced by strong warm advection of continental Tropic air mass into Moscow region from Caspian Sea and Central Asia. As one can see an intensity of the surface inversion at rural zone (in Obninsk) is higher than in the city: in the lowest 100 m air layer a value of the vertical thermal gradient $\gamma = -\partial T/\partial z = -3.2$ ˚C/100 m in Obninsk, –1.7 ˚C/100 m in Ostankino and –1.3 ˚C/100 m in Dolgoprudny. Evidently, an overestimation of Obninsk data due to geographic zoning must be accounted here so that T values by the mast for the comparison with two other sources are lower. Thus, the urban ‘heat island’ may be seen on daily T profiles in conditions of strong heat wave as the highest values of the air temperature in the city (Ostankino TV tower) in the comparison with two other locations.

5. Conclusions.

1. Above big city (Moscow) a thermal anomaly exists, which is expressed in a ‘heat island’ effect in daytime at least up to 500 m height and in nighttime up to 100 m. Above 100 m height at night an urban atmosphere is characterized by a ‘cool island’ due to ‘cross-over’ effect, i.e. an intersection of the urban and rural air temperature nocturnal profiles.
2. The intensity both of diurnal ‘heat island’ and of nocturnal elevated ‘cool island’ gradually goes to zero with a height. Thus, at the levels of 400-500 m the spatial differences between nocturnal and diurnal air temperature are statistically insignificant.
3. In daily average the ‘heat island’ was registered at the ground level and at 100 m height. At the level of 300 m thermal anomaly above Moscow region already wasn’t detected. Thus, the level of 300 m can be considered as the vertical range of the urban thermal anomaly in average of a day.
4. The urban ‘heat island’ intensity strongly depends on weather conditions including thermal advection.

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References

Bornstein R.D., 1968: Observations of the urban heat island effect in New York City. *Journal of Applied Meteorology*, **Vol.7**, pp.575-582.
Duckworth F.S. and Sandberg J.S., 1954: The effect of cities upon horizontal and vertical temperature gradients. *Amer. Meteor. Soc. Bulletine*, **Vol. 35**, No. 5, pp.198-207.
Ivanov A., Katz A., Kurnosenko S, Nash N. and Zaitseva N., 1989: WMO International Radiosonde Comparison, Phase III, Instruments and Observing Methods, Report No.40. Dzambul, USSR, 172 p. WMO/TD-No.451, 1991.
Kadygrov E.N., Kuznetsova I.N. and Golitsyn G.S., 2002: Heat island in the boundary atmospheric layer over a large city: new results based on remote sensing data. Transactions (Doklady) of the Russian Academy of Sciences / Earth Sciences Section, **Vol.385**, No.6, pp.688.
Kobysheva N.V. (Ed.), 2001: The Climate of Russia. *Gidrometeoizdat Publ.,* St.Petersburg, 656 p. (in Russian).
Kokovin N.S., 1966. Radio telemetry of the atmospheric sounding. *Gidrometeoizdat Publ.,* Leningrad, 164 p. (in Russian).
Landsberg H.E., 1981: The Urban Climate. *Academic Press, New York.*
Lokoshchenko M.A. 2012: Catastrophic heat of 2010 in Moscow from data of ground-based meteorological measurements. *Izvestiya, Atmospheric and Oceanic Physics,* **Vol.48**, No.5, pp.463-475.
Lokoshchenko M.A., 2014: Urban ‘heat island’ in Moscow. *Urban Climate*, **Vol.10**, part 3, pp.550-562.
Lokoshchenko M.A., Isaev A.A., Kallistratova M.A., and Pekour M.S., 1993: Studies of the atmospheric boundary layer over Moscow by remote sensing and in situ methods. *Russian Meteorology and Hydrology*, **Vol.18**, No.9, pp.13-24.
Lokoshchenko M.A. and Korneva I.A., 2012: Underground urban ‘heat island’ below Moscow city and dynamics of the soil temperature. *Proceedings of the 8th International Conference on Urban Climate (ICUC8)*, Dublin, Ireland, 2012, paper index: 516.
Lokoshchenko M.A. and Korneva I.A., 2015: Underground Urban Heat Island below Moscow City. *Urban climate*, **Vol.13.**
Lokoshchenko M.A., Korneva I.A., Kochin A.V., Dubovetsky A.Z., Novitsky M.A. and Razin P.Ye., 2015: About vertical range of the urban heat island above Moscow. Transactions (Doklady) of the Russian Academy of Sciences / Earth Sciences Section, in print.