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Investigation of temporal-spatial parameters of an urban heat island on the basis of passive microwave remote sensing

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With 7 Figures

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Summary

Quantitative measurements of the impact of an urban environment on the thermal state of the atmospheric boundary layer are presented. Temperature profiles up to the height of 600 m were obtained in a continuous series of measurements by three microwave profilers MTP-5 located in different areas of Moscow. The influence of this large city on urban heat island (UHI) parameters was estimated on occasions with stationary atmospheric processes and during cases with frontal passage. Two types of UHI were identified: one with a dome of urban warmth at all levels, and another with a low warm dome in combination with a lens of cold air above.

1. Introduction

In recent years the number of research studies dedicated to the urban heat island has substantially increased. These investigations show that anthropogenic stress in the form of the powerful sources of gaseous and aerosol pollutants as well as water vapour and supplemental heat sources can greatly influence the intensity and the form of the environmental modification in large industrial cities and megalopolises. Many papers have been published on quantitative aspects of this phenomenon mainly based on *in situ* measurements of temperature and humidity. As a result the fundamental factors of the urban heat island formation are known (Duckworth and Sandberg, 1954; Oke, 1973; Oke, 1977). Nevertheless it is understood that the heat island is one the atmospheric phenomena which requires further study. The main lack of information is connected to the absence of representative data on the three-dimensional temperature structure over cities.

Thermal stratification controls both the turbulence intensity and the thickness of the mixing layer and hence the replacement of polluted air by purer air from upper layers. The atmospheric boundary layer (ABL) plays the role of a buffer zone accumulating heat, moisture, and pollutants. The state of the ABL determines the vertical exchange intensity. An unstable ABL is favourable for the removal of pollutants from the lowest atmospheric layer whilst when the ABL is stable exchange is suppressed creating the conditions for the growth of pollutant concentrations.

In large cities these processes are affected by factors different from those observed in the countryside. The main reasons for these differences are the higher water vapour content, greater concentrations of anthropogenic gases and aerosols as well as strong variations of the underlying surface parameters in the city.

Regular measurements of the temperature profile in the lowest 600-meter layer of the atmosphere have been carried out in the Moscow region since 2000. The measurements are conducted at three points in Moscow by means of microwave remote temperature profilers (MTP-5). The MTP-5 instrument is an angular scanning, single channel, microwave radiometer that can provide temperature profile measurements every 5 minutes within the altitude range of 0–600 m with an accuracy of 0.5 °C (Kadygrov and Pick, 1998; Viazankin et al., 2001). This is the first time such an extended set of observations of the vertical structure of the ABL in a large city and in its suburbs has been obtained. Preliminary analysis of the data from these measurements was undertaken by Golitsyn et al. (2002). They showed that two types of heat island are observed over Moscow. The first type is characterized by higher temperature over the city compared with the suburbs throughout the entire 600 m layer. The second one is characterized by higher temperatures over the city in the lowest 300 m whilst at higher altitude the temperature is lower over the city.

The prime aim of this work is to obtain quantitative estimates of the influence of the city environment on the thermal structure of the ABL and on atmospheric mixing conditions. For this analysis the temperature profile measurements obtained during the spring and summer months of 2001–2002 were used.

2. Measurement procedure and data processing

The data used in the analysis were obtained in synchronous measurements by MTP-5 instrument systems at three locations, namely: the centre of Moscow, the nearest suburb which is 20 km from the centre to the north (Dolgoprudny) and a location in the countryside about 50 km from the centre of Moscow to the west (Zvenigorod). The town of Zvenigorod has little industry, a small volume of traffic and topography that is conductive to good ventilation of the town. For these reasons Zvenigorod can be considered to be a relatively undisturbed rural site. Dolgoprudny situated at the northern border of Moscow can be considered as a site that is partly disturbed by the influence of Moscow.

Temperature profiles were obtained "around-the-clock", every 5 minutes, up to altitude of 600 m with a 50 meter grid (Westwater et al., 1999; Cadeddu et al., 2002).

To study features of the thermal field of the megalopolis and its suburbs the following parameters were calculated:

- temperatures normalized by the daily minimum temperature $Tn_h(t)$ according to the equation

  $$Tn_h(t) = T_h(t) - T_{min},$$

  where t is local time (Moscow); $T_h(t)$ the temperature at the following levels: h = 0, 100, 200, 300, 400, 500 and 600 m; T_{min} the daily minimum temperature
- differences of normalized temperatures $Tn_h(t)$ between Zvenigorod and Moscow

  $$dTn_h(t) = Tn_{h\,Zv}(t) - Tn_{h\,M}(t)$$
- the averaged value of $dTn_h(t)$ for stationary weather conditions $\langle dTn_h(t)\rangle$. In calculating the average value time was scaled by the time of sunrise
- intradiurnal temperature changes $\Delta T_h(t_i)$ according to the equation

  $$\Delta T_h(t_i) = T_h(t_i + 1) - T_h(t_i),$$

  where $i = 0, 1, 2, \ldots, 23$ are hour number; $t = 0{:}30, 1{:}30, 2{:}30, \ldots, 23{:}30$ local time. $T_h(t_i)$ is the hourly averaged temperature at the i-th hour at the level h = 0, 100, 200, 300, 400, 500 and 600 m
- hourly averaged laps rate in the layers 0–100, 0–200, 0–300, 0–400, 0–500 and 0–600 m $\gamma_{h1-h2}(t_i)$ according to the equations

  $$\gamma_{h1-h2}(t_i) = T_{h2}(t_i) - T_{h1}(t_i)$$
- monthly averaged value of the hourly averaged lapse rate $\langle\gamma_{h1-h2}(t_i)\rangle$
- monthly averaged value of the intradiurnal temperature change $\langle\Delta T_h(t_i)\rangle$. A correction for changes in the time of sunrise was not provided in this case because hourly average temperature was used
- differences of the hourly averaged temperatures between Moscow and Zvenigorod $\Delta T_{h\,M-Zv}(t_i)$ and Moscow and Dolgoprudny $\Delta T_{h\,M-Dl}(t_i)$ according to the equation:

  $$\Delta T_{h\,M-Zv(Dl)}(t_i) = T_{h\,M}(t_i) - T_{h\,Zv(Dl)}(t_i),$$

where $i = 0, 1, 2, \ldots, 23$ are hours; $t_i = 0{:}30; 1{:}30; 2{:}30, \ldots, 23{:}30$. $T_{h\,M}(t_i)$ is the mean temperature at the i-th hour at the level h in Moscow; $T_{h\,Zv(Dl)}(t_i)$ is the mean temperature at the i-th hour at the level h in Zvenigorod (Dolgoprudny); $h = 0$, 100, 200, 300, 400, 500 and 600 m.

3. Results

Differences between the normalized temperature $dTn_h(t)$ in the large city and in its suburb are a clear illustration of the urban impact on the thermal conditions of the ABL. Figure 1 shows the changes of $\langle dTn_h(t)\rangle$ and their range calculated for steady weather conditions in April–May, 2002 (13 days). The time of sunrise time used for the time correction is also shown.

The figure shows the strongest response of the temperature to the urban influence that was observed in the near surface layer of the atmosphere. At this level there was a significant diurnal variation of differences of normalized temperatures $Tn_h(t)$ and the largest range of $\langle dTn_h(t)\rangle$. An increase of difference was observed up to 12:30. The temperature in the lower layer rises faster in the suburb than in the city. The rate of increase of $\langle dnT_h(t)\rangle$ was about $2.8\,^{\circ}\mathrm{C\,h^{-1}}$. The value of $\langle dnT_h(t)\rangle$ changed little from 12:00 up to 20:00. At this time the measurements show the whole 600 m layer was convectively unstable. In the evening the stability of the ABL leads to an increase in pollution and moisture in Moscow and retards cooling in the

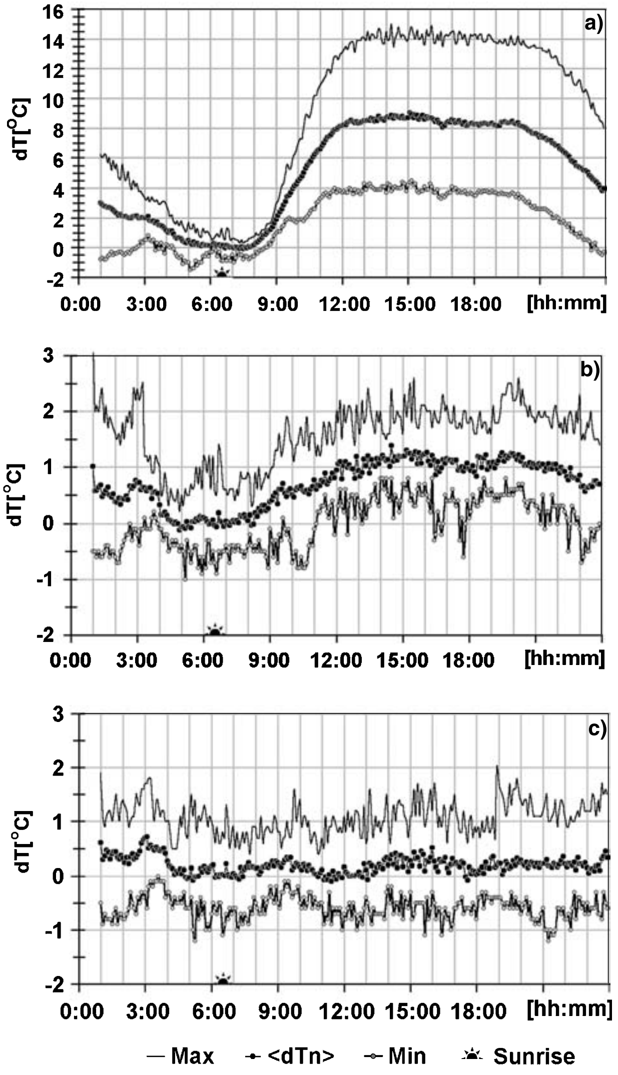

Fig. 1. Changes of $\langle dTn_h(t)\rangle$ in the **a**) 0 m; **b**) 300 m and **c**) 600 m layers for the steady weather conditions in April–May, 2002

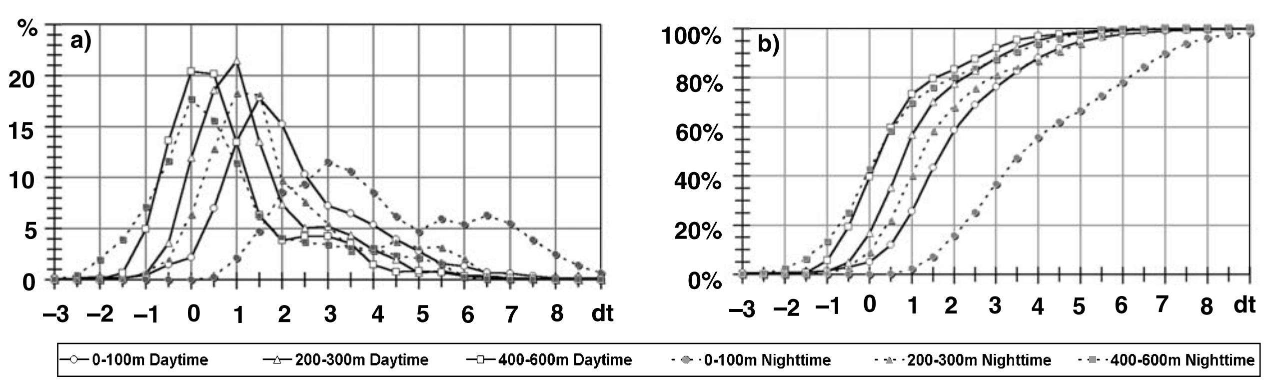

Fig. 2. a) Distribution, and **b**) cumulative distribution of the temperature difference between Moscow and Zvenigorod. In June, 2001. Daytime (6:00–21:00), nighttime (22:00–5:00)

evening. The heat absorbed by the buildings and asphalt roads also acts to retain warmth. As a result of these factors cooling in the suburbs happens faster. The decrease of $\langle dnT_h(t)\rangle$ begins at about 20:00 and continues up to sunrise. The rate of $\langle dnT_h(t)\rangle$ decrease was practically constant at about $1\,°C\,h^{-1}$.

The diurnal variation was not as significant at 300 m as near the surface. The value of $\langle dnT_h(t)\rangle$ increased up to 15:00 at the rate of about $0.2\,°C\,h^{-1}$. After 20:00 $\langle dnT_h(t)\rangle$ decreased to a rate of about $0.1\,°C\,h^{-1}$. No diurnal variation of $\langle dnT_h(t)\rangle$ was observed at the 600 m height.

In Fig. 2 shows the distributions of the temperature differences between Moscow and Zvenigorod obtained in June, 2001. City centre – suburb temperature difference distributions were calculated for the nighttime and daytime. In June since sunrise is close to 5:00 (4:53 – June 1, 4:48 – June, 30) and sunset is close to 22:00 (22:03 – June 1, 22:18 – June 30), nighttime was chosen to extend from 22:00 of the previous day up to 5:00 of the next day and daytime was chosen to be from 6:00 up to 21:00.

Figure 2a shows the maximum of the distribution in the layers below 400 m shifting to the right from day to night and from higher layers to the lower ones. The calculations show the lowest layer of the atmosphere (0–100 m) in the city was always warmer at night. The nocturnal city-suburb difference in this layer was greater than 2 °C on more than 85% of the observed cases and it can increase up to 9 °C. Differences of 10–12 °C were also observed (1.6% of observed time). Nocturnal city-suburb differences in the 0–300 m layer were greater than in the daytime. City-suburb differences were less than −0.5 °C in the 0–300 m layer in about 5%, and at the higher layers (400–600 m) in about 20%, of the observed cases as in the nighttime and in the daytime. City-suburb differences were greater than 1 °C in the 200–300 m layer in the daytime on at least 45%, and in the nighttime at least 60% of observed cases. In the 0–100 m layer these differences were observed in the daytime on more than 65%, and in the nighttime greater than 95%, of the observed cases. Nighttime and daytime city-suburb differences distributions differ insignificantly in the higher layer (400–600 m). Negative city-suburb differences were formed above the city in the 400–600 m layer as at night and in about 40% of observed daytime cases. The observed distributions of temperature differences between Moscow and Zvenigorod at the different levels show that thermal heterogeneity of the ABL caused by the large city can exist practically under any weather condition but with differences in the vertical structure and intensity.

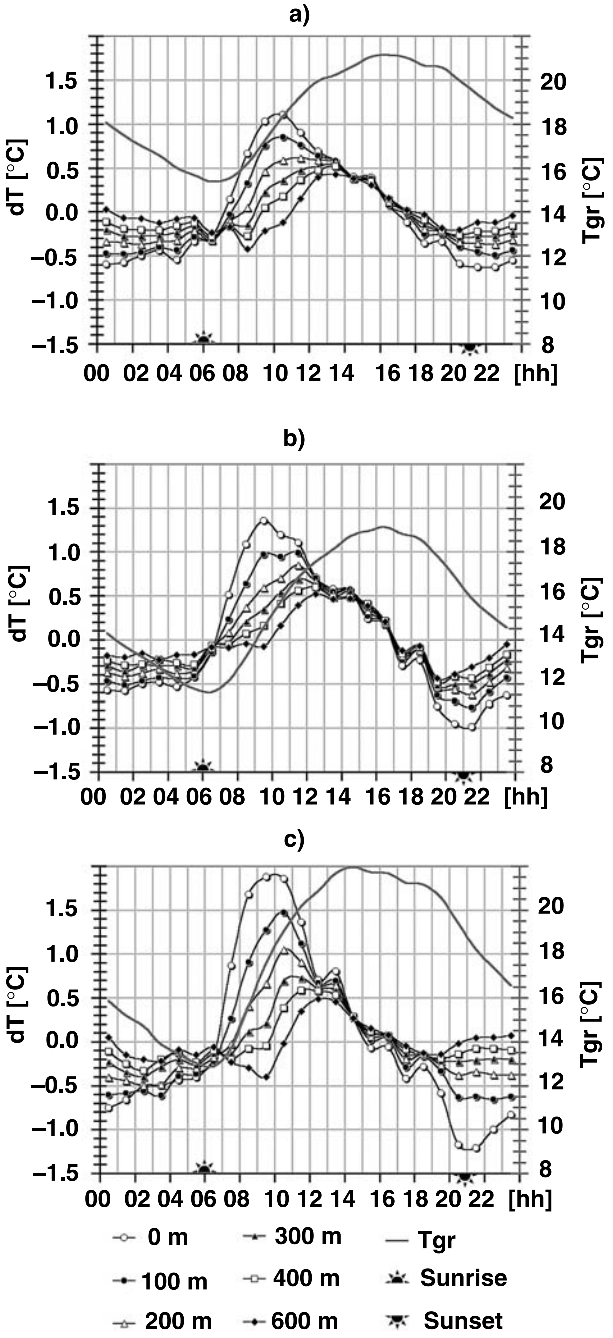

Fig. 3. Changes of $\langle \Delta T_h(t)\rangle$ for **a**) Moscow; **b**) Dolgoprudny; and **c**) Zvenigorod in August, 2001

Table 1. Heating rate at different locations. Changes of $\langle \Delta T_h(t) \rangle$ from 6:30 to 9:30 (heating rate) for different layers and the coefficient of linear approximation K [degrees km^{-1}] at three locations

Distance from Moscow [km]	Layer [m]						
	0	100	200	300	400	500	600
0 (Moscow)	1.3	1.0	0.8	0.5	0.3	0.2	0.4
20 (Dolgoprudny)	1.5	1.1	0.7	0.4	0.3	0.1	0.2
50 (Zvenigorod)	2.1	1.5	0.9	0.3	0.1	0.4	0.5
K linear approximation [degrees km^{-1}]	0.016	0.008	0.002	−0.004	−0.004	0.003	0.003

Figure 3 shows the variations of $\langle \Delta T_h(t) \rangle$ at three locations during August, 2001. The variations of hourly averaged temperature measured at $h = 0$ m (Tgr) is also given. There are a number of specific features of the daily variation of $\langle \Delta T_h(t) \rangle$, namely: the parts of curves with maximal divergence and convergence of $\langle \Delta T_h(t) \rangle$ are observed consecutively. These extremes are located inside ascending curves of the ground temperature and within the flat day maximum. The different signs of the trend of $\langle \Delta T_h(t) \rangle$ indicate that temperature is still decreasing in the layer above 300 m at the same time the lowest layer of the atmosphere are warming up under normal conditions in the morning (7:00–10:00 local time). The heating of the layer below 300 m in the urban ABL occurs slower than in the suburb.

In Table 1 the heating rate in the 0–100 m layer increases in proportion to distance from the city. Such dependence is not observed in the higher layers. The thermal wave in the city reaches the upper measurement levels almost 1 hour later. The beginning of the temperature increase at the 600 m height at all locations is observed at about 11 a.m., at the same time as the decrease of the temperature increment in the lowest layer (in Moscow and Dolgoprudny 0–100 m, in Zvenigorod 0–200 m).

The change of $\langle \gamma_{0-600}(t_i) \rangle$ in Moscow, Dolgoprudny and Zvenigorod is shown in Fig. 4. At about 12:00 the whole 600-meter layer becomes convectively unstable, i.e. the so called "breakup" of the ABL occurs. This effect exhibits itself through the alignment of the rate of heating in all layers (see Fig. 3). The same value and sign (positive) of $\langle \Delta T_h(t) \rangle$ is observed at all levels between 13:00 to 17:00 which demonstrates the intense convection and the predominance of this mechanism in the exchange of heat and mass inside the lowest part of the ABL. The maximum value of $\langle \gamma_{0-600}(t) \rangle$ was observed at the same time (see Fig. 4). The vertical temperature gradients in Moscow were super adiabatic from about 11:00 up to 21:00. The value of $\langle \gamma_{0-600}(t) \rangle$ changes from -1.0 up to $-1.2\,^{\circ}$C $100\,\mathrm{m}^{-1}$. Intensive air substitution near the ground leads to the removal of the pollutants from the urban air and an alignment of the underlying surface warm-up conditions in the city and in the suburbs.

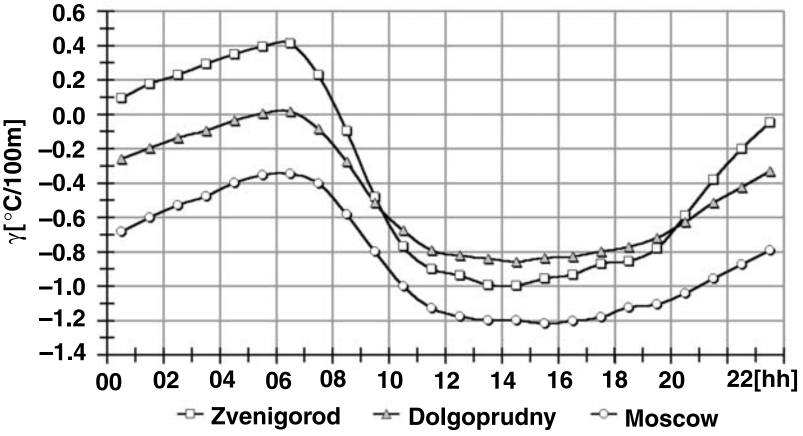

Fig. 4. The change of $\langle \gamma_{0-600}(t) \rangle$ in Zvenigorod, Dolgoprudny and Moscow

Figure 4 shows the temperature difference in the ABL between Moscow and Zvenigorod for situations that were accompanied by increased air pollution in Moscow and also for cases with relatively clean city air. This figure also gives the vertical profiles calculated using the hourly averaged temperature for the two different situations. On the 4th August, 2002 both relatively clean conditions and moderate air-mass transport from the north were observed. This ensures that any influence of Moscow pollution on Zvenigorod is excluded. The 20th July, 2002 case was selected as an example of a day with high urban pollution levels. The centre of an anticyclone was located near the Moscow on that day and weak wind was observed in the whole ABL. Thus one would not expect to observe the influence of urban pollution on the suburbs.

It is evident that at night and in the morning, even under the relatively clean conditions, the large city affects the thermal field, however, the depth of the urban heat dome is not great. The upper boundary of the dome extends up to approximately 300 m. The largest temperature gradients were found between the city and its suburb (1.5–3.5 °C) in the lowest atmospheric layer (0–100 m). In the afternoon (from 12:00 up to 18:00) the concentrations of pollutants and water vapour in the urban air decreased to give only weak influence on the thermal processes in ABL and the UHI decreased. The temperature difference between Moscow and Zvenigorod in the 0–100 m layer did not exceed 1 °C. Intensification of the UHI near the ground was observed after 18:00. An increase in the city-suburb difference was observed after 21:00 in the 0–100 m layer. The diurnal range of the temperature difference in the 300 m deep layer did not exceed 1.0 °C (0.1–1.0 °C). It equalled 0.7 °C in the 600 m layer (−0.5–+0.2 °C). Under highly polluted conditions (July 20, 2002) nocturnal and morning (0:00 to 9:00) city-suburb differences in

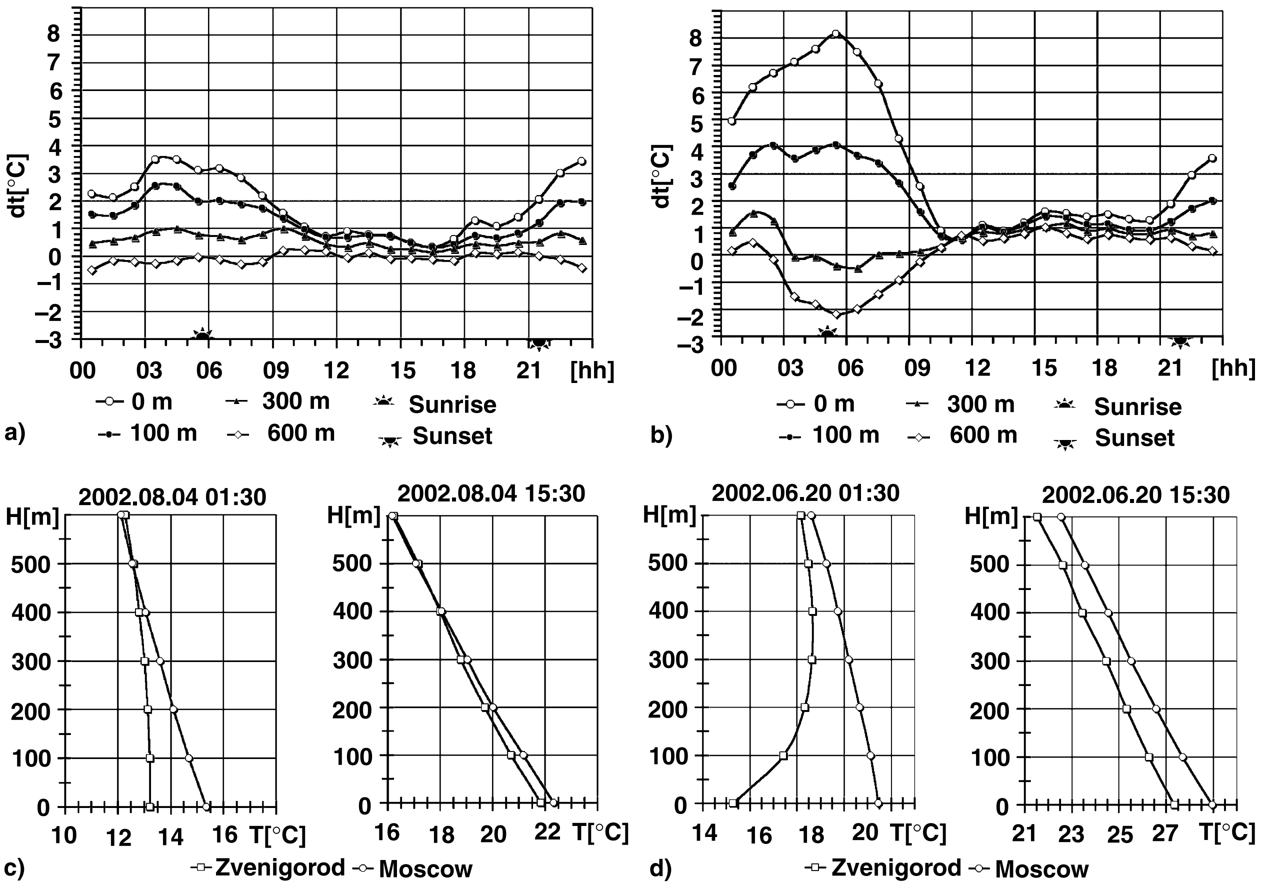

Fig. 5. The difference of the hourly average temperatures between Moscow and Zvenigorod. **a**) August 4, 2002; **b**) July 20, 2002 and hourly averaged temperature profiles at two locations for **c**) August 4, 2002; **d**) July 20, 2002

the 0–100 m layer were from 2.6 to 8.2 °C. The UHI was conserved and its top reached up to 600 m in the afternoon, but its intensity even in the lowest layer of the atmosphere, rarely exceeded 1–2 °C.

Our studies confirm that the UHI is generally observed at night. This thermal heterogeneity usually disappears in the afternoon. We identified two types of UHI. The type when the air in the heat dome is warmer than the air in the suburb at all levels (Fig. 5a, c), and the second type when there is a low warm dome in combination with a lens of cold air aloft (Fig. 5b, d). The lens of colder air placed under the dome (negative difference in the 300–600 m layer) is a result of the altered radiation balance in the more humid and polluted urban air. An inversion up to 8 °C with its upper boundary at 500–600 m was observed under calm conditions in the suburb from 4:00 up to 5:00, but in Moscow no inversion was observed at the same time. The difference is due to the accumulation of anthropogenic heat during the day (under hot and dry weather conditions), and reduced heat losses at night because of the weak turbulent exchange. There are also substantial discrepancies between the daytime temperature differences obtained for August, 4 (Fig. 5a) and for July, 20 (Fig. 5b). On July 20 in the morning (about 11:00), when high pollution levels were observed, the cold lens disappeared completely due to the absorption of the solar radiation by aerosols. The 0–600 m layer was warmer in the city than in the suburb after 11:00.

The influence of the megalopolis on the thermal structure of the ABL is well illustrated by changes in the lapse rates of the different layers. Figure 6 shows the temporal dependence of the hourly averaged lapse rate in the different layers, calculated for the relatively clean day of

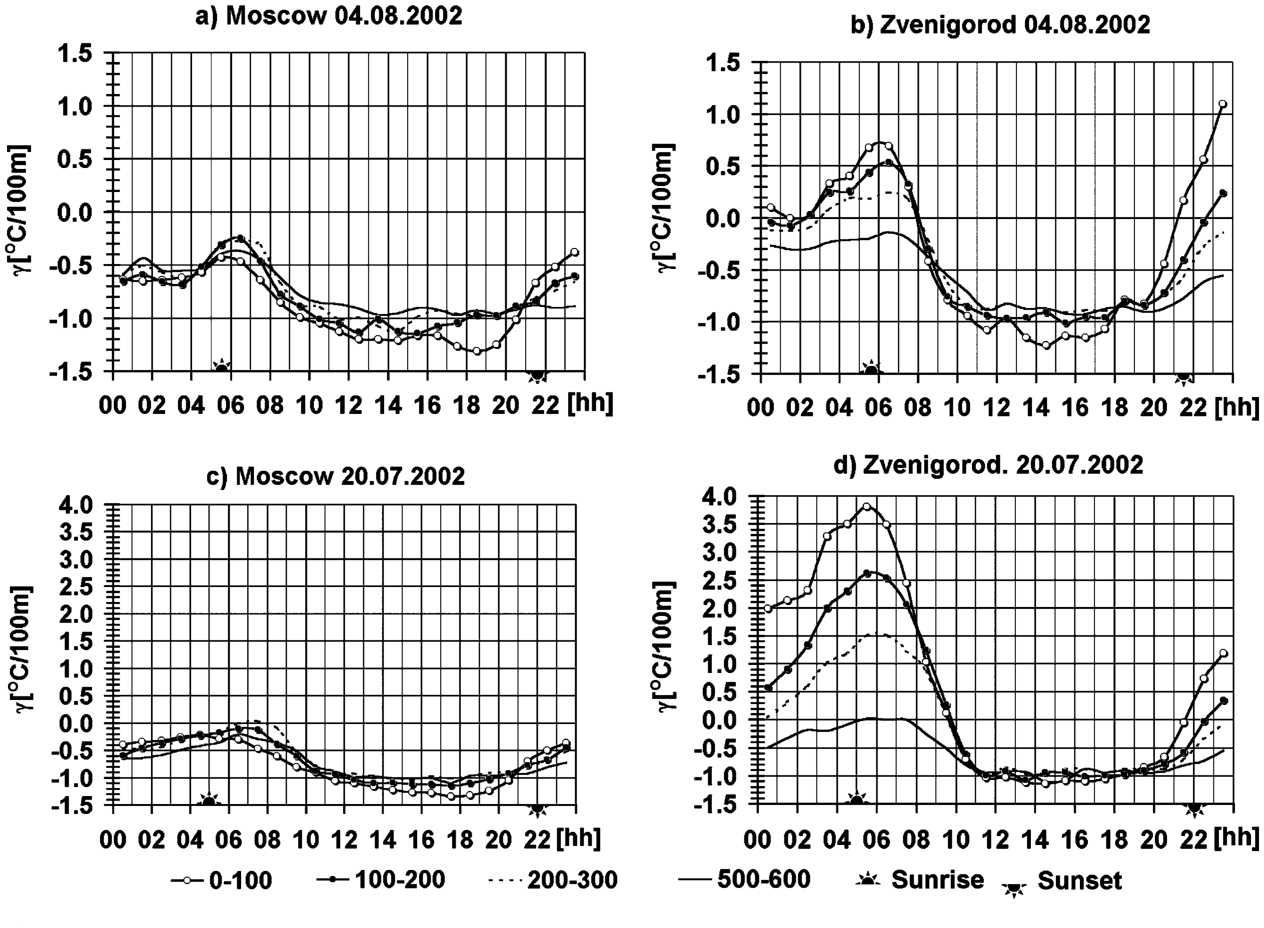

Fig. 6. Time dependence of the hourly average lapse rate for **a**) Moscow, August 4, 2002; **b**) Zvenigorod, August 4, 2002; **c**) Moscow, July 20, 2002; and **d**) Zvenigorod, July 20, 2002

August 4, 2002 and the day with high urban pollution level (July 20, 2002) in Moscow and Zvenigorod. In Moscow for August 4 the value of hourly averaged lapse rate changed weakly in the morning up to sunrise and was close to −0.6 °C 100 m^{-1} in the entire 600 m layer (Fig. 6). On the 20th August at 0:30 the value of the averaged lapse rate was −0.4 °C 100 m^{-1} and −0.7 °C 100 m^{-1} in the 0–100 m and 500–600 m layers, respectively. A small increase (about 0.3 °C 100 m^{-1}) of the average lapse rate occurred in all layers. After sunrise up to 12:00 the rate of lapse rate decrease was about the same for all layers for both days.

An increase of the average lapse rate was observed in Zvenigorod in the 0–300 m layer in the morning, up to sunrise (0.7 °C 100 m^{-1} and 1.5 °C 100 m^{-1} for August 4 and July 20, respectively). In the 500–600 m layer the morning change in the average lapse rate was about the same as in Moscow. After sunrise up to 11:00 the speed of the decrease in the lapse rate was not the same in all layers. For July 20 the rate of decrease was 0.8 °C 100 m^{-1} in the 0–100 m layer, 0.6 °C 100 m^{-1} in the 100–200 m, 0.4 °C 100 m^{-1} in the 200–300 m and 0.2 °C 100 m^{-1} in the 500–600 m layers. An increase of the average lapse rate in the 0–300 m layer was observed in Moscow after sunset and in Zvenigorod it was observed about one hour earlier.

An example of the variation of the temperature field during the passage of an atmospheric fronts due to the influence of the megalopolis on the thermal structure of the ABL is shown in Fig. 7. It presents thermograms (temperature variations measured at different levels) obtained during the passage of an atmospheric front from the northeast through Moscow and Zvenigorod. The front passed Moscow at about 14:00 and Zvenigorod at 16:00. In the frontal zone the intense mixing of air led to thermal homogenization of the ABL. Temperature jumps were observed in both cases, i.e. when the front passed Moscow and the suburb. Partial restoration of the UHI behind the atmospheric front was observed in the city. Temperature gradients in the 0–600 m layer were equal to 1.3 degree 100 m^{-1} and 1.1 degree 100 m^{-1} in Moscow and Zvenigorod, respectively before passage of the front. In the half an hour after the atmospheric front passage the temperature gradient decreased 3.7-fold in Zvenigorod and to become 0.3 degree 100 m^{-1}.

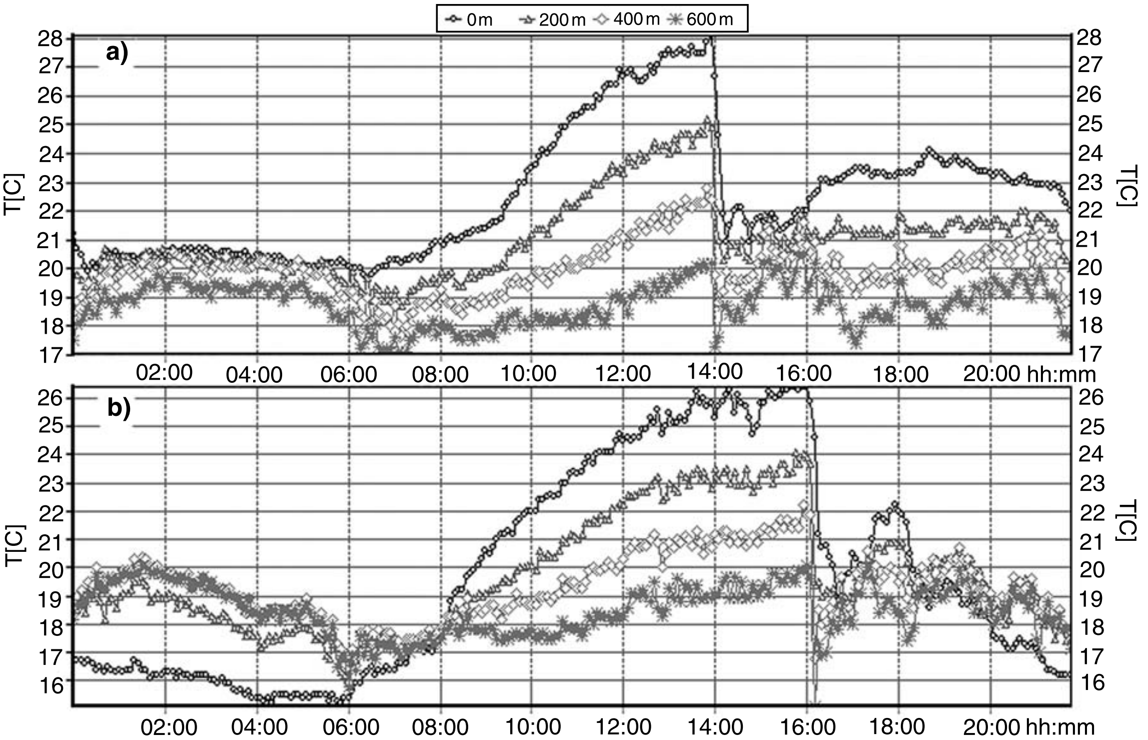

Fig. 7. Temperature variations at different heights during passage of a front at **a**) Moscow, and **b**) Zvenigorod, June 20, 2001

In Moscow the gradient decreased only 2-fold and it equalled the moist-adiabatic rate (0.6 degree $100\,\mathrm{m}^{-1}$).

4. Summary and conclusions

Measurements of atmospheric temperature profiles up to 600 m above ground were carried out by means of three MTP-5 profilers. Their locations made it possible to estimate the influences of the megalopolis on the thermal regime of the ABL.

Two types of UHI were identified from the temperature profile measurements: one with a warm urban heat dome at all levels, and another with a low warm dome in combination with a lens of cold air above. The case of a cold air lens placed under the dome is a result of both alteration of the radiation balance in more humid and polluted urban air and the more active mixing processes in the more unstable urban air.

A UHI exists not only under the conditions with elevated pollution levels, but also with relatively clear air. The most pronounced UHI are observed in the morning and at night. The accumulation of pollutants and water vapour in the urban air occurs at this time and the UHI reaches its maximum intensity. During the day the UHI breaks down or remains only in the lowest 300 metres.

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