The Influence of High Aerosol Concentration on Atmospheric Boundary Layer Temperature Stratification

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Introduction

Investigations of the changing in the atmospheric boundary layer (ABL) radiation balance as cased by natural and anthropogenic reasons is an important topic of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program. The influence of aerosol on temperature stratification of ABL while its concentration was extremely high within a long period of time was studied experimentally. The case was observed in Moscow region (Russia) with the transport of combustion products from peat-bog and forest fires in July-September, 2002. At this time the visibility was some times at about 100-300 m. Aerosol concentration measured by Moscow University Observatory and A.M. Obukhov Institute of Atmospheric Physics field station in Zvenigorod (55.7 N; 36.6 E) for several days was in 50-100 times more than background one (Gorchakov at al 2003). The high aerosol concentration can change the radiation balance at ABL, and so to change thermal stratification in ABL above the megalopolis. For the analysis the data were used of synchronous measurements by MTP-5 (Microwave Temperature Profiler operating at wavelength 5 mm) in two locations, namely: downtown Moscow and country-side which is 50 km apart to the West (Zvenigorod station). (Kadygrov and Pick 1998; Westwater at al 1999; Kadygrov at al 2002). Zvenigorod station is located in strongly continental climate zone which is in between of the climates of ARM sites (NSA-North Slope of Alaska and SGP-Southern Great Plains). The town of Zvenigorod has little industry, small traffic volume and topography conductive to a good air ventilation of the town. For these reasons Zvenigorod can be considered as an undisturbed rural site. For the analysis some days were chosen with close meteorological parameters (average temperature, humidity, wind, pressure and cloud form) but strongly differing in aerosol concentration level.

The average values of mass concentration, minimum and maximum average-hourly ground temperature in Moscow, surface relative humidity, wind speed change in the layer 0-600 m, cloudiness and cloud form for the selected "clear" and "polluted" days are given in Tables 1 and 2. The values of relative humidity and wind speed were obtained on radiosonde data launched in the town Dolgoprudny (20 km from the center of Moscow to the north). Temperature profiles were measured synchronously in Moscow and Zvenigorod every 5 minutes.

Table 1. Relatively clear air

Date	Tmax/Tmin [degree,C]	H [%] Morning/Day	V [m/s] Morning/Day	M [mkg/m^3]	Cloudiness [%]	Cloud form
19.07.02	26.8/15.5	74/30	0-6/1-3	10-40	30	Ci
20.07.02	29.5/19.4	72/29	0-4/0-4	20-30	10	Ci
21.07.02	30.9/21.0	59/29	0-3/2-7	20-40	10	Ci
26.07.02	24.8/17.2	68/-	2-6/-	10-30	40-100	As, Cu
27.07.02	25.7/18.4	68/44	1-2/1-2	10-30	50	Cu
04.08.02	23.0/13.8	91/38	2-7/2-3	10-40	50	Ci, Cc
05.08.02	20.7/13.9	79/37	2-7/2-6	20-40	50	Cs

Table 2. Polluted air

Date	Tmax/Tmin [degree,C]	H [%] Morning/Day	V [m/s] Morning/Day	M [mkg/m^3]	Cloudiness [%]	Cloud form
01.08.02	31.6/22.1	60/29	0-5/0-4	60-220	60	Ci
15.08.02	24.5/13.8	59/39	1-7/3	150-300	40	As, Ci
16.08.02	25.9/16.1	74/34	2-3/-	100-250	20	Ci
04.09.02	23.4/13.4	71/50	0-4/3-4	400-500	30	Ci
05.09.02	23.2/14.4	79/41	0-7/2-6	220-250	40	Ci
07.09.02	23.5/15.7	79/50	0-5/2	500-2000	60	Ci
08.09.02	21.3/14.7	89/41	0-4/0-2	100-250	60	Ci, Ns

As can be seen in tables 1 and 2 wind speed did not exceed 7 m/s in the layer 0-600 m for all selected days. At some days was observed calm near the ground. In the daytime relative humidity did not exceed 50%. The range of temperature change was from $13^{O}C$ to $32^{O}C$. High-level clouds were observed as a rule. Cloudiness did not exceed 60%.

A study of the influence of aerosol high concentrations on the thermal regime of ABL is complicated by the large variability of temperature stratification from day to day. Therefore the straight comparisons of the profiles obtained for “clear” and “polluted” days do not allow to determine an effect. As showed the investigations [Khaikine at al 2002], a difference of hourly average temperature profiles measured in two points is more stable parameter.

The influence of aerosol high concentrations on the temperature stratification of ABL were carried out for the stationary weather conditions, i.e., in the absence of atmospheric fronts and an advection of new air masses. Therefore it is possible to consider both measuring points were located in the common air mass and a change of profile difference measured in clear and polluted air is caused by aerosol influence.

Hourly averaged temperature difference between Moscow and Zvenigorod $\mathbf{\Delta T_{h\ M\text{-}Zv}\ (t_i)}$**,** was calculated according to the equation:

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

where i=0,1,2... 23 - the number of hour; t_i = 0:30; 1:30; 2:30... 23:30. $T_{h\ M}(t_i)$ - mean temperature in the i-th hour at the level h in Moscow; $\mathbf{T_{h\ Zv}(t_i)}$ - mean temperature in the i-th hour at the level h in Zvenigorod; h=0, 50, 100, … 600 m.

$\mathbf{\langle \Delta T_{h\ M\text{-}Zv}(t_i) \rangle}$ **-** averaged value of $\Delta T_{h\ M\text{-}Zv}(t_i)$ for “clear” and “polluted” days;

For evaluating aerosol influence on the rate of temperature change at different levels intradiurnal temperature changes $\mathbf{dT_{h\ M(Zv)}(t_i)}$ was calculated for Moscow (Zvenigorod) according to the equation:
$\mathbf{dT_{h\ M(Zv)}(t_i) = T_{h\ M(Zv)}(t_{i+1}) - T_{h\ M(Zv)}(t_i)}$**,**
$\mathbf{\langle dT_{h\ M(Zv)}(t_i) \rangle}$ **-** averaged value of $dT_{h\ M(Zv)}(t_i)$ for “clear” and “polluted” days**.**

Results and discussion

The distributions of $\Delta T_{h\ M\text{-}Zv}(t_i)$ obtained for “clear” and “polluted” days are shown in the Figure 1. The distribution of $\Delta T_{h\ M\text{-}Zv}$ obtained for June 2001 is shown in this figure also. Temperature and humidity observed in June 2001 was close to those observed in July-August 2002. Pollution concentration was also close to background concentration. It can be seen in the Figure 1 the position of distribution maximum and the value of negative differences are the same for distributions obtained for “clear” days and for June 2001.

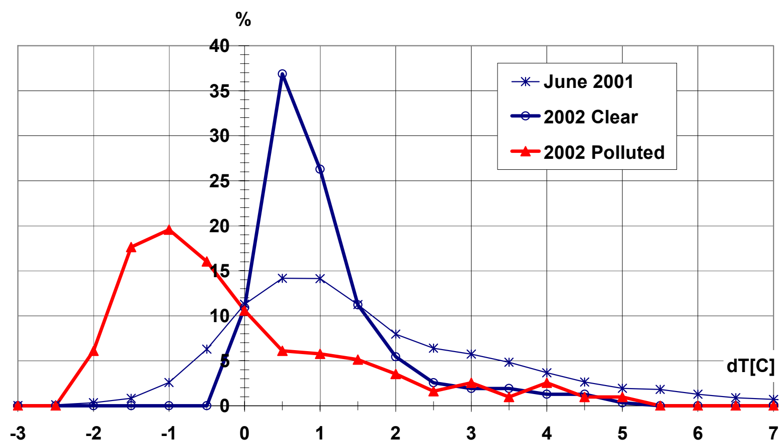
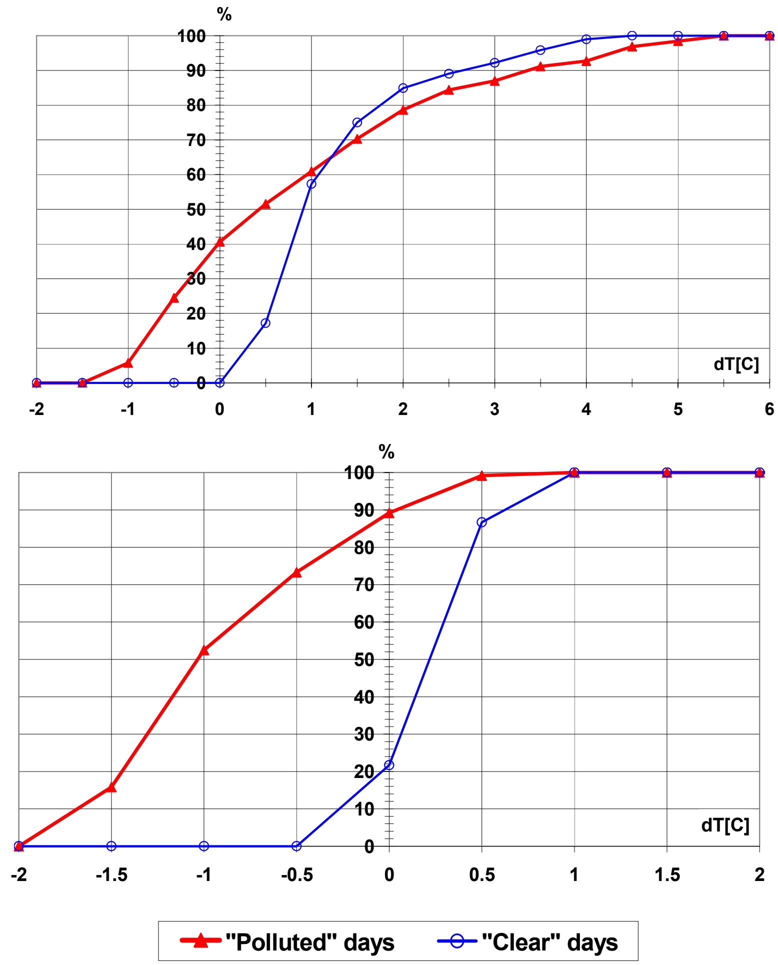


Figure 1. The distribution of $\Delta T_{h\ M\text{-}Zv}$ for “clear” and “polluted” days of 2002 Year and June 2001.

Figure 1 shows an increase of aerosol concentration leads to a shift of the distribution of $\Delta T_{h\ M\text{-}Zv}$ maximum in the region of negative values. The contribution of pollution into the temperature difference change increased with height as analysis showed. This effect can be seen well on cumulative distribution of $\Delta T_{h\ M\text{-}Zv}$, calculated for the levels 0-350 m and 400-600 m and shown in Figure 2.



a) b)

Figure 2. Cumulative distributions of $\Delta T_{h\ M\text{-}Zv}$ for “clear” and “polluted” days. a) - The layer 0-350 m; b) - The layer 400-600 m.

The lower 350 m layer was always warmer in Moscow than in the suburb under the conditions of relative clear atmosphere. The temperature was higher in the layer 400-600 m in Zvenigorod than in Moscow in 22% of the observed cases. That is the zones of colder air were observed above the city. But value of $\Delta T_{h\ M\text{-}Zv}$ was not less than -0.5°C. The layer 0-350 m was warmer in Moscow only in the morning and evening time (60% of cases) for the “polluted” days. In 40% of the observed cases the suburb was warmer than the city. This excess reached 1 degree. The layer 400-600 m in Moscow was almost always colder than in the suburb for the “polluted” days (90% of the cases). The layer 400-600 m was warmer in Moscow only in 10% of the observed cases, but not more than 0.5 degree.

The time dependence of $<\Delta T_{h\ M\text{-}Zv}>$ for the “clear” and “polluted” days at different levels is shown in the color fields in Figure 3. Sunrise for the “clear” days was in the time from 4:00 to 5:00. Sunset occurred in the time from 20:00 to 21:00. For the “polluted” days sunrise was in the time from 5:00 to 6:00 and sunset was from 19:00 to 20:00.

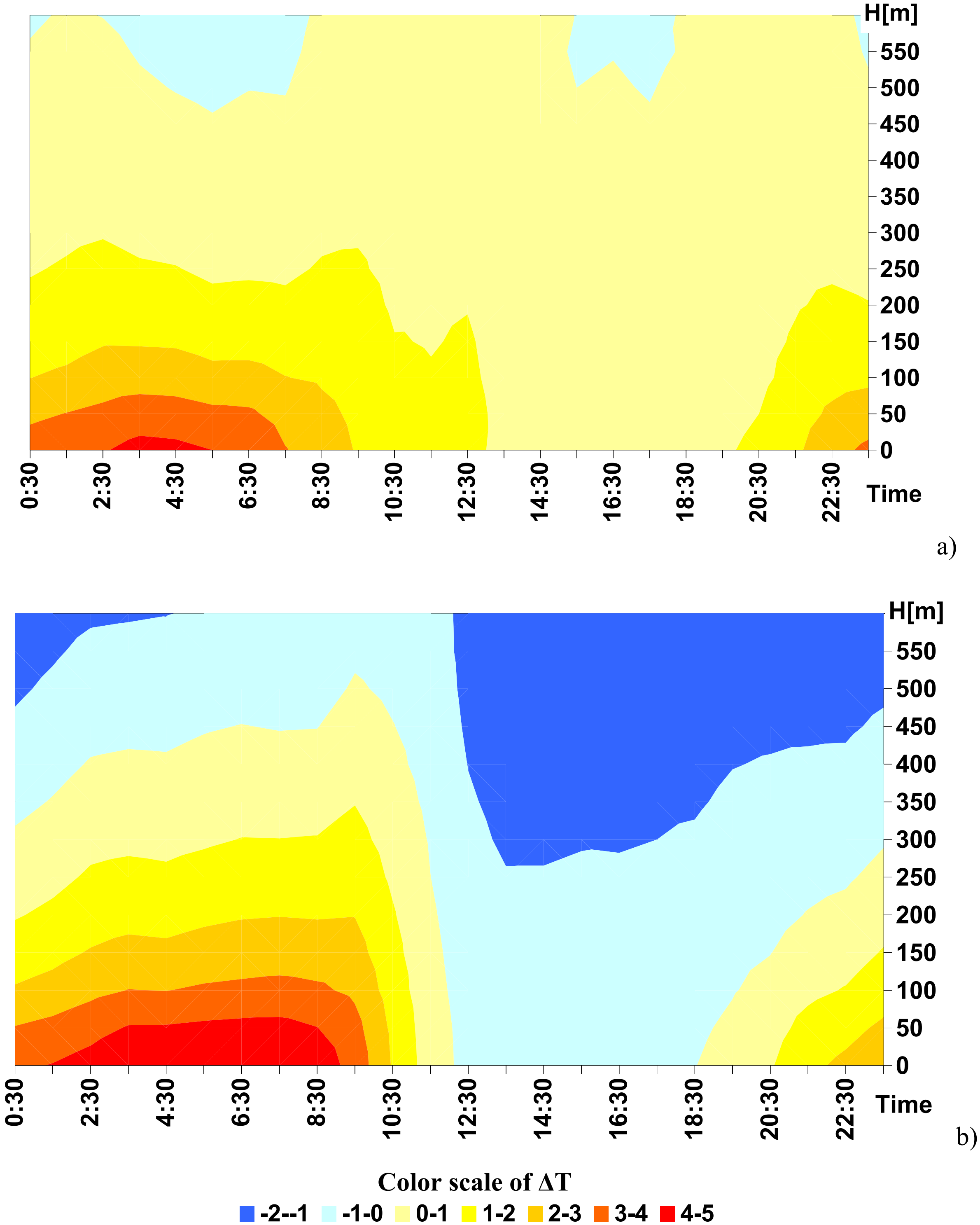


Figure 3. Color field of $<\Delta T_{h\ M\text{-}Zv>}$ for "clear" – a) and "polluted" – b) days.

Air in Moscow was warmer than in the suburb all time up to the height 400 m in relatively clear atmosphere. Negative values of $<\Delta T_{h\ M\text{-}Zv}>$ in the range from 0 up to –0.5 degree were observed in the morning from 3:00 up to 7:00, in the daytime from 14:00 up to 19:00 and only at the levels higher than 400 m.

The phenomenon of temperature increase in the in the city in comparison with the suburb is known as the urban heat island (UHI) [Oke 1973]. One of the main reasons of the UHI formation is the higher pollution concentration and moisture content in urban air, than in the suburb. The condition of ABL changed from the unstable to the indifferent or steady state after sunset [Garrat 1992]. The stability of ABL leads to the accumulation of moisture and pollution in the lower layer and blocks cooling in the evening. The heat absorbed by buildings and asphalt roads also decreases the cooling. All these processes lead to ΔT increase. The presence of pollution and water vapor in urban air decreases the air heating rate in the city in comparison with that in the suburb after sunrise. As a result ΔT begins to decrease. The influence of moisture and pollution decreases with the height and a difference in the air heating rates in the city and the suburb decreases. The intensive vertical mixing of air leads to the clearing of urban air from the pollution during the daytime and the conditions of warming up in the suburb and in the city are equalized. The typical picture of the diurnal variation of temperature difference city-suburb is shown in Figure 3a.

A sharp increase of aerosol concentration changed the thermal regime of ABL (Figure 3b). The lower 400 m layer was warmer in Moscow within 0:00 up to 12:00 for “polluted” days. The whole 600 m layer in Moscow was colder than in Zvenigorod from 12:00 up to 18:00. The value of ΔT decreased at the height of 600 m up to -4°C for some days. The sign of ΔT degrees changed after 18:00 to the positive and it was observed an increase of ΔT up to the height 300 m. The layer above 400 m was in Moscow always colder.

The profiles of temperature change rate were calculated for an estimate of aerosol influence on the thermal regime of ABL, i.e. the height dependence of values $dT_{h\ M}$ and $dT_{h\ Zv}$. Figure 4 shows the profiles of averaged values of $dT_{h\ M}$ and $dT_{h\ Zv}$, calculated for the “clear” and “polluted” days and for three characteristic times.

The first time corresponded to the time of sunrise. The second time was selected four hours after sunrise and corresponded to the maximum of the heating rate. The third time was selected the one hour after sunset. Values of $< dT_{h\ M} >$ and $< dT_{h\ Zv} >$ calculated for three selected times and for heights 0, 300 and 600 m are presented in Table 3.

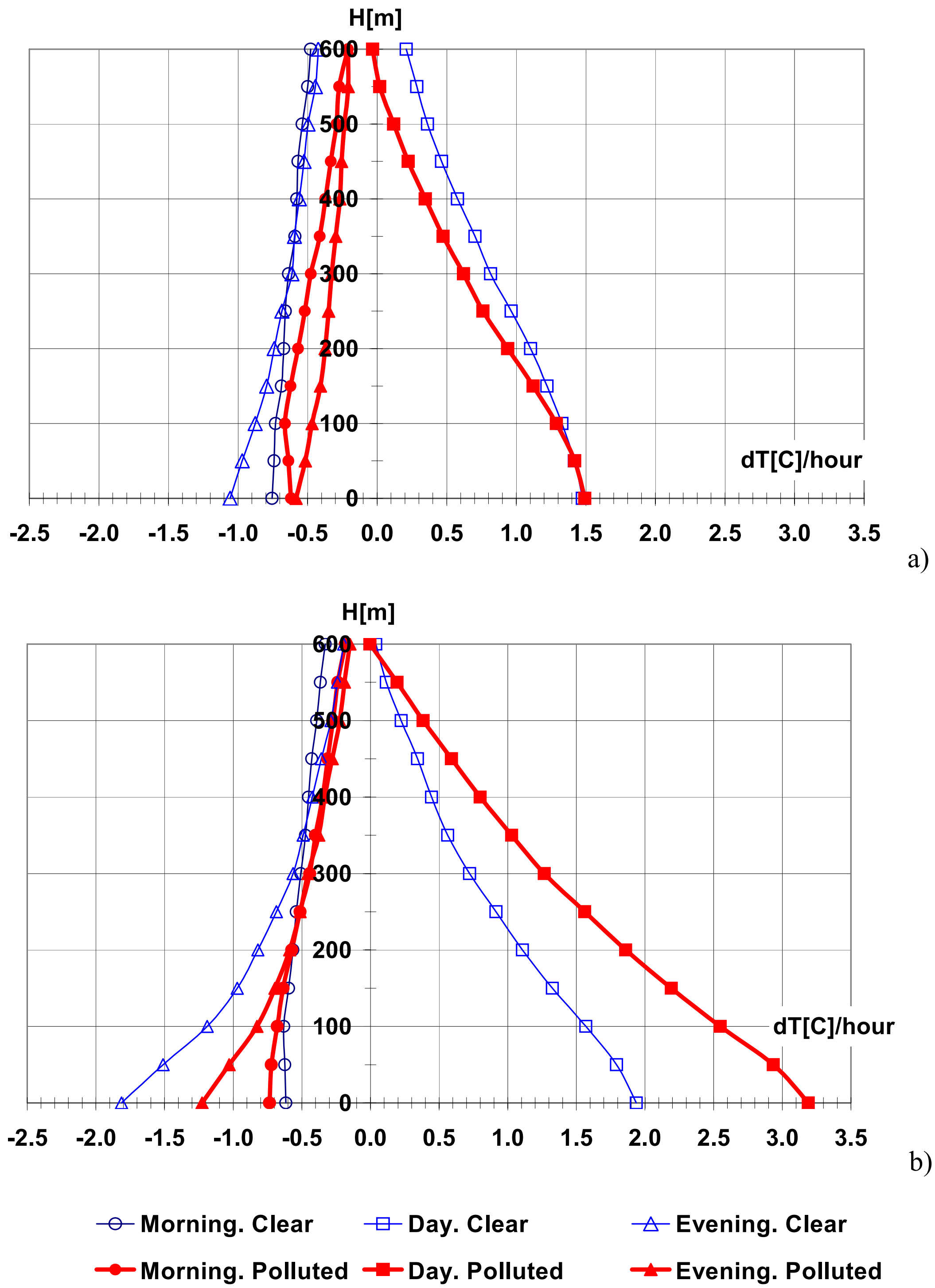


Figure 4. Profiles of temperature change rate for “clear” and “polluted” days in Moscow – a) and Zvenigorod – b).

Table 3. Temperature change rate dT_h [deg/hr] for clear and polluted air in Moscow and Zvenigorod for morning, day and evening time.

	0 m			300 m			600 m		
	Morning	Day	Evening	Morning	Day	Evening	Morning	Day	Evening
Moscow. "clear" air	-0.8	1.5	-1.1	-0.6	0.8	-0.6	-0.5	0.2	-0.4
Moscow "polluted" air	-0.6	1.5	-0.6	-0.3	0.6	-0.3	-0.1	0.0	-0.2
Zvenigorod "clear" air	-0.6	1.9	-1.8	-0.5	0.7	-0.6	-0.3	0.0	-0.2
Zvenigorod "polluted" air	-0.7	3.2	-1.2	-0.4	1.3	-0.5	-0.2	0.0	-0.2

The average cooling rate of the layer 0-100 m (negative values of $< dT_{h\,M} >$) for the "clear" days was in Moscow in the morning up to sunrise little higher than for the "polluted" days. The difference equaled 0.2 deg/hr. This difference increases with the height. The value of $<dT_{h\,M}>$ changed on 0.3 deg/hr at the change of height from 0 up to 600 m for the "clear" days. This change was equaled to 0.5 deg/hr for the "polluted" days. That is the upper layers cooled more slowly for the "clear" days than for the "polluted" days. There was no appreciable difference in the heating rate of air in the lower 100 m layer for the "clear" and "polluted" days in the daytime. The difference of heating rate increased with the height. As one would expect the clear air was heated faster. The rate of "clear" air cooling was on 0.5 deg/hr higher than that for "polluted" air in the evening after sunset and this difference did not depend from the height. The rate of "clear" air cooling was sufficiently close in the morning and in the evening in the layer above 200 m. The rate of cooling of layer 0-100 m in Zvenigorod for the "clear" and "polluted" days was practically identical in the morning up to sunrise. The "polluted" air cooled somewhat slower than "clear" air in the layer above 300 m. The rate of "clear" air heating was lower on 1.3 deg/hr than that for "polluted" air in the daytime in contrast to Moscow. This difference decreased with the height up to 0.0 deg/hr. The rate of "clear" air cooling in the evening in the layer 0-400 m was higher than that for "polluted" air on 0.2-0.6 deg/hr. The rate of cooling of "polluted" and "clear" air coincided in the evening with the rate of "polluted" air cooling in the morning in the layer above 400 m.

The differences in the profiles of temperature change rate, which were observed in Moscow and Zvenigorod, make it possible to understand the reason of temperature difference field changing under influence of aerosol.

The formation of positive value of $\Delta T_{h\,M\text{-}Zv}$ in the lower 300 m layer begins in the evening after sunset through larger rate of air cooling in the suburb than that in the city. This process continues in the morning of the next day under the favorable weather conditions (anticyclone and the absence of air mass advection), since the rates of air cooling in the layer 0-400 m in Moscow and suburb are approximately identical in the morning up to sunrise. The heating rate of "polluted" air in the whole 600 m layer is higher in the suburb than in Moscow in the daytime. As a result the temperature in Zvenigorod becomes in the whole 600 m layer higher than in Moscow. The rates of temperature change are equalized gradually. The process of air cooling starts 2.0-2.5 hours prior to sunset. The rates of air cooling in

Moscow and Zvenigorod differed insignificantly in this time. The difference begins to be noticeable only after sunset.

Conclusions

The unique situation observed in July-September 2002 made it possible to carry out the studies of the influence of aerosol high concentration on the thermal regime of ABL in the large city and its suburb.

The investigations showed the additional aerosol particles injected into atmosphere of Moscow by combustion products had not caused the strong changes of temperature rate change in the layer 0-600 m in average in the morning time.

The greatest differences of air heating rate for the "clear" and "polluted" days were observed in the upper levels in the daytime. The rate of relative clear air cooling exceeded the rate of polluted air cooling in the whole 600 m layer in Moscow on 0.5 deg/hr in the evening after sunset.
An increase of aerosol concentration produced substantial changes of the profile of temperature change rate in the lower 400 m layer in Zvenigorod. Specially strong changes were observed during the maximum solar radiation in the daytime. The rate of air heating of the lower 100 m layer of "polluted" air exceeded more than one degree the heating rate of "clear" air in this time. The rate of "clear" air cooling was higher than the rate of "polluted" air cooling on 0.5-0.7 deg/h only in lower 300 m layer in the evening after sunset. The profiles of temperature change rate observed in relatively clear and contaminated by aerosol atmosphere were insignificant in the layers higher 300 m.

Distinctions in the field of temperature difference Moscow-Zvenigorod observed for the "clear" and "polluted" days were caused by changes of the radiation fluxes dynamics in the ABL of Zvenigorod.

The obtained results can be used in the simulation models of ABL radiation balance taking into account the anthropogenic factor influence

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