Observation of the submicron aerosol content in the atmosphere over Russia in the TROICA international experiments

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Received February 1, 2008

The results of measurements of the submicron aerosol mass concentration M_a by means of the car-laboratory at 5 expeditions TROICA (Trans-Siberian Observations Into the Chemistry of the Atmosphere) along the Trans-Siberian Railway and Moscow Circuit Railroad are presented. Observations of the seasonal behavior of the aerosol content have shown its maximum in the autumn–winter period (39.6–73.6 μg/m^3) and minimum in spring and summer (10.7–31.1 μg/m^3), respectively. An excess of the aerosol content in the populated areas as compared to areas free of population was equal to 50–250 μg/m^3 in unfavorable meteorological conditions. During forest fires, peatbog ignitions, and grass burning, M_a increased up to 50–516 μg/m^3 at along Railway sections from 4 to 2000 km. In polluted air plumes at the Moscow Circular Railway, the "urban addition" varied from zero to 110 μg/m^3, depending on the meteorological conditions in Moscow.

Introduction

In the last two decades, the human activity strongly affects the content of gas admixtures and aerosol particles in the atmosphere, their natural cycles and sources. The air quality in cities and industrial regions essentially decreased. As a result of the changed atmospheric composition, the stratospheric ozone layer weakens, the near-ground ozone concentration increases, and the climate becomes warmer. Under these conditions the atmospheric aerosol plays an important role in radiative processes.[1,2]

The Global Atmosphere Service of the World Meteorological Organization (GAS WMO), created by developed countries, includes 54 observatories and more than 350 regional background stations. Unfortunately, there are no stations at the territory of Russia, included in the network of GAS WMO. The Russian state network of the environmental monitoring, based on observational agencies of the State Hydrometeorological Service carries out observations of the atmosphere of the following types: 1) the state of the air pollution in cities and industrial centers (629 stationary sites in 229 cities); 2) the trans-boundary transfer of pollutants (four sites); 3) the background pollution of the atmosphere (four sites in the European part of Russia and one in Altai)[3].

Regular measurements of the submicron aerosol content in the European part of Russia are carried out at stationary sites of the Institute of Atmospheric Physics RAS [Zvenigorod Scientific station (ZSS) and Kislovodsk High-Mountain Scientific Station (KHSS)]. The system of the atmospheric aerosol monitoring is organized in Siberia, which covers the territory of the Western and Eastern Siberia. In the majority of cases, stationary sites of Institutes of SB RAS are used for these purposes[4]. Measurements of aerosol characteristics are regularly carried out at the observation site of the Tomsk Akademgorodok at V.E. Zuev Institute of Atmospheric Optics SB RAS.[5] The Integration project "Siberian Aerosols" has been developed in the beginning of the 90s.

The TROICA mobile laboratory for observation of gas and aerosol composition of the atmosphere designed at the Institute of Atmospheric Physics RAS and All-Russian Scientific-research Institute of Railway Transport is capable of measuring spatial-temporal variability of atmospheric aerosol over the territory of Russia. One of the simple methods for the study the mass concentration of near-ground aerosol variability is nephelometry. The stationary observational sites, at which this method was used, and mean concentrations of submicron aerosol measured at them are shown in Table 1. Dates of continuous nephelometric measurements, carried out with the aerosol complex of IAP RAS in five TROICA expeditions, are shown in Table 2. The aerosol measurement complex, designed at the L.Ya. Karpov State Scientific Center of Russian Federation Scientific-research Physical-Chemical Institute,[6] is used since 1998.

0235-6880/08/11 848-06 $02.00

Table 1. Mean values of the mass concentration of submicron aerosol M_a (μg/m^3) measured by nephelometric method at stationary observational sites

Measurement site	Period of measurements	M_a	Reference
Moscow	June, 1990	32	[10]
	February, 1991	126	[10]
	October, 1993	37	[10]
	July–August, 2002	90	[10]
	September, 2002	250	[10]
ZSS	February, 1991	110	[12]
	January–December, 1991	39–113	[12]
	October, 1993	24	[13]
Kislovodsk	1985–1990	36	[10]
	April 12–28, 2000	35	[14]
	April 30 – May 12, 2000	10	[14]
	2001–2006	23–62	[17]
KHSS	1985–1990	21	[10]
Blue bay (Black Sea)	August 10–31, 2004	32	*
Island Chistaya Banka (Caspian Sea)	August, 2000	13	[15]
Lagan'	November, 2000	26	[15]
	May –June, 2001	13	[15]
River Ob' (Tomsk – Khanty-Mansiysk)	July 12–26, 1999	40	[16]
IAO, Tomsk	1997–2006	12–95	[5]
Alma-Ata	November, 1987	146	[10]
Beijing	November, 1996–1998	238–292	[18]
	July, 1999	153	[18]
	November, 2000	188	[18]

* Author's measurements.

Table 2. Dates of expeditions and mean values of the submicron aerosol mass concentration M_a, μg/m^3

Expedition	Moscow – Vladivostok		Vladivostok – Moscow	
	Period of measurements	M_a	Period of measurements	M_a
TROICA-3	April 1–7, 1997	29.3	April 8–14, 1997	31.1
TROICA-4	February 17–26, 1998	40.9	March 1–7, 1998	39.0
TROICA-8	March 19–25, 2004	30.5	March 26 – April 1, 2004	19.3
TROICA-9	October 4–11, 2005	73.7	October 11–18, 2005	53.3
TROICA-11	July 22–29, 2007	17.7	July 29 – August 5, 2007	28.3

Technique for measurements

The air to be analyzed was sampled at an altitude of 0.3 m above the railway car roof in its central part. The car-observatory immediately followed the electric locomotive. The complex of gas, aerosol, and meteorological instrumentation operated automatically with real-time recording of signals into a personal computer with the 10 s periodicity.

The nephelometry method was used for determination of the submicron aerosol concentration. It was shown[7] that the mass concentration of submicron aerosol M_a (μg/m^3) in finely dispersed hazes can be determined from the known value of the scattering coefficient σ (km^{-1}): $M_a = a\rho\sigma$, where ρ is the density of aerosol substance; a = 220 km.

The nephelometer "Dust Indicator and Tunnel System" designed by GRIMM Corporation (Germany) with the concentration measurement range from 0.01 to 15 μg/m^3 was used in expeditions in 2004–2007. The two-channel nephelometer designed at LOMA IAP RAS[8] and the nephelometer PhAN were used in expeditions of 1997–2000. Together with calibration of the instruments by self-designed calibration devices (of the PhAN-A – by the prism and pure air, the LOMA nephelometer – using the diffuse reflecting screen), regular joint calibrations were carried out both of our instruments and the nephelometers of observers participating in joint measurements.

Discussion of the measurement results

Observation of submicron aerosol at the Moscow Circular Railway

The expedition TROICA-10 was conducted on October 4–7, 2006. The railway length was 526 km (at a distance of approximately 50 km to the north-west and 100 km to the east from Moscow). The speed of movement of two cars of the observational complex by the individual electric locomotive was non-uniform because of frequent stops at stations. The submicron aerosol content in near-ground air during four measurement days strongly varied between 8 and 210 μg/m^3. In some cases, the values of the submicron aerosol mass concentration at railway stations reached 550 μg/m^3 because of the effect of emissions of locomotive exhausts (for example, at st. Orekhovo–Zuyevo on October 6, 2006 at 2:20–2:40). Figure 1 shows the measurement results of the submicron aerosol mass concentration during the total period of observations with 1-min averaging, except for the moments of air great pollution, caused by local sources (locomotives, opposite trains, stove smokes).

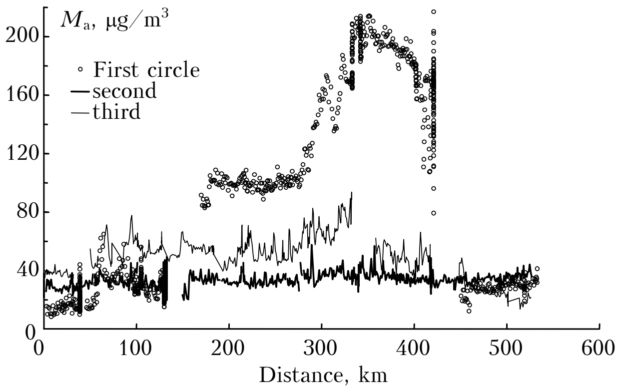

Fig. 1. Variations of the submicron aerosol mass concentration M_a at Moscow Circular Railway on October 4–7, 2006.

The mean value of the submicron aerosol mass concentration at the first circle of observations (October 4, 14:20 – October 5, 16:14) is equal to 185.6 μg/m^3, at the second one (October 5, 16:40 – October 6, 7:25) to 33.7 μg/m^3, and at the third circle (October 6, 7:25 – October 7, 10:28) to 49.5 μg/m^3. Periods of measurement at the station Iksha, accepted by us as a zero point, and the mean values of the mass concentration of submicron aerosol M_a in the circle sections with different aerosol contents for the first and the third circles are presented in Table 3. The M_a varies significantly at the first circle, weakly at the second circle, at the third circle it does not exceed 80 μg/m^3.

Earlier investigations at stationary observational sites in Moscow and at Zonal Scientific Station, located close to the Circular Railway, have shown that the extremely high values of the aerosol concentrations are observed in winter, mainly at easterly and south-easterly wind directions, while winds of the northern sector corresponds to lower values of M_a both in Moscow region and in the Moscow center. It is shown[9] that in October, 1993, the "urban addition," i.e., the excess of the aerosol content in Moscow as compared to the Moscow region was maximal in daytime, reaching approximately 30 μg/m^3.

Thus, we obtained 24-hour forward and back trajectories of air masses transfer at a height of 500 m at intervals of 2 hours (Fig. 2) for Moscow for October 4–7, 2006, using the data from Internet (www.arl.NOAA.gov). Analogous trajectories constructed by the Russian Hydrometeorological Service are in good agreement with ours. Comparing the periods of observation of different aerosol contents in the near-ground air, presented in Table 3, and the back trajectories of air mass transfer (Figs. 2*a* and *c*), we can state that the great values of M_a at the first circle from 03.50 to 12.00 LT on October 5 correspond to air mass transfer from the south-west direction, and the low M_a from 15.00 to 22.00 LT on October 4 and from 14.50 to 16.20 LT on October 5 are connected with the air mass transfer from the west direction. Back trajectories of air masses related to the travel along the second circle (Fig. 2*c*); and all air masses transfered from the west direction are connected with travel along the third circle.

To determine the period of "urban addition" incoming to the Circle Railway in the near-ground air plume, we have constructed the 24-hour forward trajectories of air mass transfer for a height of 500 m with 2-hour intervals from 4 a.m. on October 5 to 2 a.m. on October 7 (Figs. 2*b* and *d*). The intervals of observation at the first circle from 6 a.m. to the noon on October 5 and at the third circle from 7 p.m. to 9 p.m. on October 6 correspond to measurements in the plume of emissions from Moscow. The anthropogenic addition of the mass concentration of the submicron aerosol, found as the difference between M_a in the plume and M_a before incoming to the plume, is great (70–110 μg/m^3) in the first case (between Voskresensk and Aleksandrovo); in the second case (between stations Myakinino and Orekhovo-Zuyevo) it is approximately 17 μg/m^3. We did not observe some increase of M_a in the interval of the supposed plume coming at the second circle from 0 a.m. to 3 a.m. on October 7, determined from the forward trajectories. This is the evidence of small anthropogenic pollution of the atmospheric air in Moscow at this time due to favorable conditions for spread of atmospheric pollutions, which is confirmed by low values (1.7 μg/m^3) of the soot aerosol concentration at the observational site in the center of Moscow. For comparison, at the moment of recording high M_a in the plume at the first circle, the soot aerosol concentration in the center of Moscow was 5.8 μg/m^3.

Table 3. Variations of the mean mass concentration of submicron aerosol M_a (μg/m^3) at different parts of the Moscow Circular Railway (2006)

	First circle				Third circle				
Date	October 4	October 5			October 6			October 7	
Time, hours	15–22	3.5–6	6–12	14.5–16.2	7.4–8	8–19	19–21	1–6	6–10
Distance, km	0–130	170–300	300–420	450–532	0–32	32–255	255–332	360–495	495–526
Sector, deg	270–290	210–230	230–270	270	250	270	270	270	250
M_a	18	100	170–210	25	40	60	70	40	20

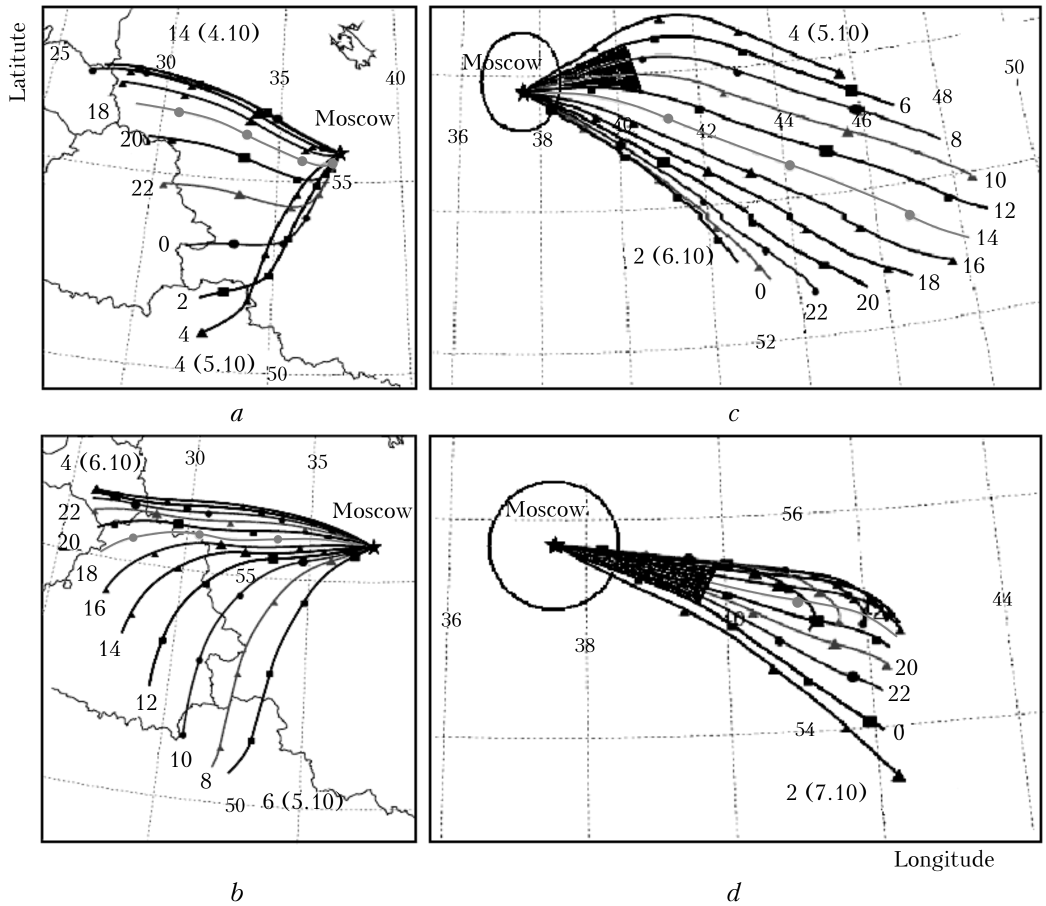

Fig. 2. 24-hour forward and back trajectories of air mass transfer at a height of 500 m at intervals of 2 hours for Moscow on October 4–7, 2006: forward (*a*, *b*), back (*c*, *d*).

Observation of variations of submicron aerosol along the Trans-Siberian Railway

Continuous series of data on the submicron aerosol content in the atmosphere along the Trans-Siberian Railway were obtained in five expeditions TROICA. The measurement dates and mean values of the submicron aerosol concentration are given in Table 2. Seasonal behavior of the submicron aerosol concentration in the atmosphere above the territory of Russia is observed. The maximal values of M_a were recorded in autumn and winter, and minimal ones in spring and summer. The concentration of submicron aerosol in spring and summer was equal to 17.7–31.1 $\mu g/m^3$; in autumn and winter it was 39.0–73.7 $\mu g/m^3$.

The large-scale (500–1000 km) inhomogeneities of the submicron aerosol distribution were observed in the near-ground air along the Trans-Siberian Railway. They are connected with the effect of synoptic and meteorological processes, determining its transfer and accumulation. Earlier, analogous behavior of M_a was obtained at background stationary sites: at Zvenigorod Scientific Station of IAP RAS[9] from a series of observations of 1991–1998 and at the Aerosol monitoring station of IAO SB RAS[5] from data of 1997–2006.

Variations of the submicron aerosol concentration along the Trans-Siberian Railway, obtained with the nephelometer of GRIMM corporation for three seasons (spring, summer, and autumn) with 1-hour averaging are shown in Fig. 3.

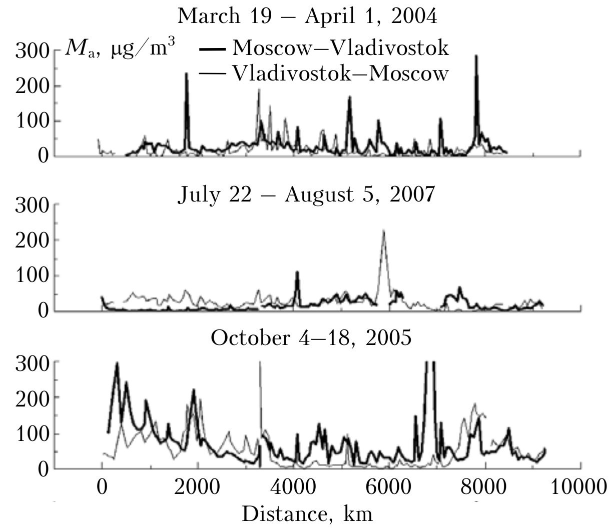

Fig. 3. Variations of the mass concentration of submicron aerosol M_a along the Trans-Siberian Railway in three seasons (spring, summer, and autumn) with hourly averaging.

It is seen in Fig. 3 that the submicron aerosol concentration in big cities (Ekaterinburg, Novosibirsk, Krasnoyarsk, Irkutsk, situated at distances of 1760, 3286, 4048, and 5136 km from Moscow, respectively) is greater than its concentration in rural area. However, the "urban addition" of submicron aerosol in these cities is greater only under unfavorable meteorological conditions (50–250 μg/m^3), but the submicron aerosol content in the urban atmosphere in spring and summer often weakly differs from that in the rural atmospheres. In spring, as different from other seasons, the "urban addition" M_a is observed in a greater number of cities.

Forest and peatbog fires, as well as grass burning often occur in warm season both in Europen and Asian parts on fields along the Trans-Siberian Railway.

The densest smoking originated from the 1700 km long peatbog fire between Moscow and Ural was observed on October 4–5, 2005, which caused the increase of the submicron aerosol content up to 50–100 μg/m^3. The Russian Hydrometeorological Center calculated the three-day back trajectories of air mass transfer at a height of 700 m for 17 stations of the Trans-Siberian Railway for 5 expeditions. The trajectories for the section Moscow – Tyumen on October 4–5 (Fig. 4*a*) correspond to westerly transfer of air masses, which favored the propagation of the smoke to Tyumen.

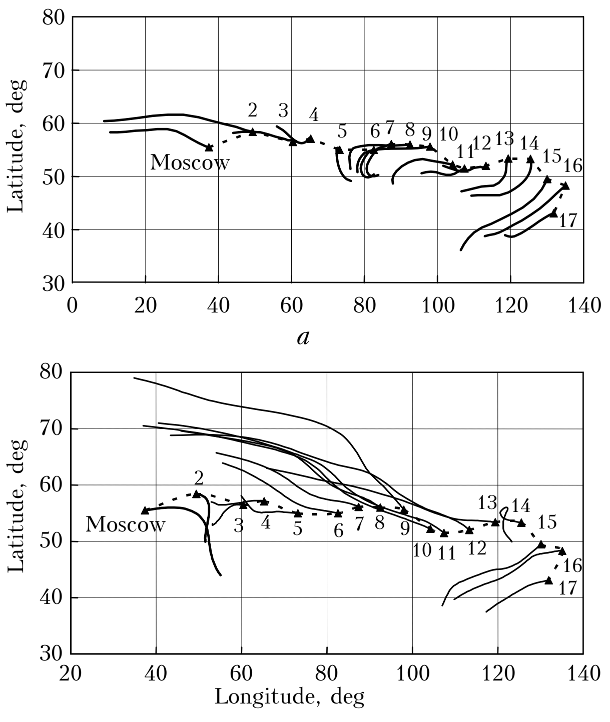

Fig. 4. Three-day back trajectories of air mass transfer at a height of 700 m for 17 stations of Trans-Siberian Railway: October 4–11 (*a*) and October 11–18, 2005 (*b*). Vyatka (2), Ekaterinburg (3), Tyumen (4), Omsk (5), Novosibirsk (6), Krasnoyarsk (8), Taishet (9), Irkutsk (10), Ulan-Ude (11), Chita (12), Mogocha (13), Magdagacha (14), Bureya (15), Khabarovsk (16), and Vladivostok (17).

Somewhat less extension of smoke from forest fires, approximately 100 km long, yielding however an aerosol concentration of 150–510 μg/m^3 was observed on October 9, 2005 at the railway section between 6831 and 6927 km.

Two sources of smoke with aerosol concentration of 800 μg/m^3 at the distance of 4 km were observed at 4–5 p.m. on October 15, 2005 approximately 100 km before Novosibirsk (3412 and 3353 km), while the great values of M_a in Yurga (3415 km) and Novosibirsk (3287 km), 500 and 700 μg/m^3, respectively, evidenced unfavorable meteorological conditions for spread of pollutants. The 40 km long plume of submicron aerosol from Novosibirsk, according to the trajectory analysis, was caused by westerly transfer of air masses with a velocity of 4 m/s.

The smoke in the region of st. Mysovaya (5428–5456 km) on July 26, 2007 insignificantly increased the content of submicron aerosol. The addition M_a did not exceed 20 μg/m^3.

Strong smoking from forest fires within 6010–5830 km at 6–9 a.m. on August 1, 2007, which had a submicron aerosol maximum concentration of 420 μg/m^3 at 5960 km (880 m above see level) decreased by 7 times to the initial and final boundaries of smoking along the train route. The dense 170 km long smoke layer with M_a of 140–420 μg/m^3 was situated at a height of 810–920 m ASL (probably, the forest fire origin was also situated here). Upper boundary of the smoke was situated at a height of 950–920 m, and the lower boundary was at 810–760 m. Their M_a was equal to 40–140 μg/m^3.

Let us consider the large-scale spatial-temporal variability of the submicron aerosol content in the near-ground air for the cases, when different types of air masses come. Back north-westerly trajectories of the air mass transfer in autumn of 2005 at the section Mogocha–Mariinsk (6891–3660 km) were long (4000–6000 km), originated at 65–78N (Fig. 4*b*) and evidenced the coming of the clear Arctic air to this region. This explains the measured low values of M_a (10 μg/m^3). The trajectories at sections Ekaterinburg–Moscow (1760–0 km) and Vladivostok–Bureya (9242–7982 km) show that air masses came from south and south-west, respectively (Fig. 4*a*). This gave a contribution between 25 and 200 μg/m^3 into the observed content of aerosol in the near-ground air. The concentration of M_a from Tyumen to Vladivostok in autumn 2005 fell in the range from 25 to 150 μg/m^3, and the back trajectories of the air mass transfer also moved from south and south-west directions (Fig. 4*a*). Trajectories within Nizhny Novgorod–Chita in the expedition of 1997 (spring) were long and began from 60–70N; therefore, M_a was approximately equal to 20 μg/m^3. Then between Chita and Khabarovsk M_a increased to 60 μg/m^3, and the trajectories became short and moved from different directions. Cleaning ability of the atmosphere in the first case was predominantly connected with the cold Arctic air advection. The Arctic air transfer was not observed during expeditions of 2004 and 2007.

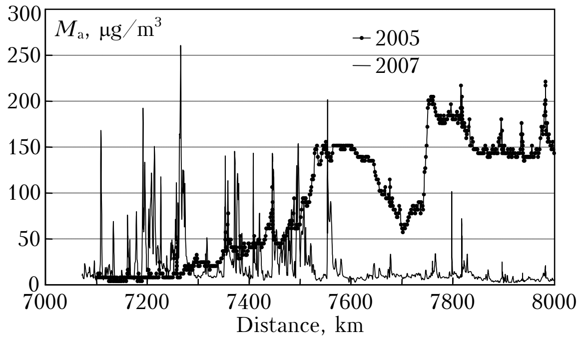

Fig. 5. Variations of M_a in expeditions of 2005 and 2007 at a route section of 7000–8000 km.

In order to distinguish the variability of M_a connected with the remote transfer and caused by the local sources (inhabited areas, opposite trains and locomotives), we used the series of M_a with the 10 s and 1 min averaging. Variations of M_a obtained in expeditions of 2005 and 2007 with the 1 min averaging at the same route section from 7000 to 8000 km are shown in Fig. 5. Variations of M_a in autumn of 2005 were small-scale and corresponded to location of 9 inhabited areas, being the local sources of anthropogenic aerosol. Variations of M_a in summer, 2007 with variability periods of approximately 200 km were caused by the remote transfer of aerosol.

Conclusions

Measurements of the submicron aerosol mass concentration in TROICA expeditions yielded the following results:

1. The seasonal behavior of the submicron aerosol content was observed over the territory of Russia with maximum in the fall-winter season and minimum in the spring–summer one. Mean aerosol concentrations were equal to 39.6–73.7 and 10.7–31.1 μg/m^3, respectively.

2. Exceeding of M_a by 50–250 μg/m^3 in inhabited areas in comparison with their vicinities was observed under meteorological conditions, unfavorable for spread of pollutions (weak wind, temperature inversions). However, in spring-summer season, the levels of the submicron aerosol content in inhabited areas and outside them did not differ.

3. The content of submicron aerosol increased during forest and peatbog fires and grass burning up to 50–800 μg/m^3 within 4–2000 km sections of the Trans-Siberian railway.

4. In spring and summer, M_a decreases approximately to 10 μg/m^3 with coming air masses from Arctic and reaches 25–200 μg/m^3 with coming continental air masses from the south.

5. Measurements at the Moscow Circular Railway have shown that M_a is maximum (85.6 μg/m^3) due to air masses from south-western directions and minimum (33.7 μg/m^3) in air mass of the western direction. "Urban addition" at the Circular Railway in the plume of Moscow anthropogenic pollution is maximal under unfavorable meteorological conditions in Moscow for spread of pollutions.

Acknowledgements

Author thanks T.Ya. Ponomareva for kindly presented data on trajectories of air mass transfer, A.A. Isakov and A.S. Emilenko for their help in preparation of the instrumentation, G.I. Gorchakov and M.A. Sviridenkov for their help in the work.

This work was supported in part by International Scientific – Research Center (Projects Nos. 2770, 2773) and Russian Foundation for Basic Research (Grant No. 07-05-01828).

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