Monitoring of atmospheric aerosol in the Asian part of Russia in 2004 within the framework of AEROSIBNET program

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The problems in organization of the network of atmospheric aerosol observations with the use of automated solar photometers in the Asian part of Russia in the framework of AERONET program are described. Preliminary results of measurements of aerosol optical thickness, single-scattering albedo, and aerosol microstructure, obtained near Tomsk, Yakutsk, and Ekaterinburg, are discussed.

Introduction

Aerosol, together with greenhouse gases and cloudiness, play important role in radiative-climatic processes. One of the effective approaches to determining the atmospheric aerosol optical characteristics are the methods based on photometry of direct ("transmission method") and scattered solar radiation. Now the most developed, from the standpoint of automation of measurements, system is the network for aerosol observations AERONET (http://aeronet.gsfc.nasa.gov). To date, vast territories of Asian part of Russia were not covered by the network of aerosol monitoring system, in spite of the important role of the territory in aerosol–gas exchange and climate.

Investigations of the aerosol optical thickness (AOT) in Tomsk started in 1992, first in the regime of occasional cycles of observations, and then on a regular basis.[1,2] The restraining factor for extending the works was the absence of instrumentation and algorithmic basis providing for determination of the aerosol characteristics in the format compatible with that in other countries and regions. Such a possibility appeared upon concluding an Agreement with Goddard Space Flight Center (GSFC/NASA, USA) about installation of a few CE 318 photometers as a part of AERONET network in Siberia and carrying out joint investigations of atmospheric aerosol under conditions of boreal climatic zone.

In this paper we discuss some results obtained at the first stage of aerosol monitoring carried out under the AEROSIBNET program on the territory from Ural to the Far East, near the cities of Ekaterinburg, Tomsk, Yakutsk, Irkutsk, and Ussuriysk. The main attention is paid to discussion of the peculiarities in aerosol optical and microphysical characteristics in different regions observed in year 2004 as an example. Besides, the results are compared of determination of the AOT of the atmosphere by two types of photometers (CE 318 and SP–4)[2] and the problem is analyzed of distortion of the data obtained by the "residual effect of semi-transparent cloudiness."

1. Organization of regular observations

Organization of the network monitoring of the atmospheric aerosol characteristics on the territory of Siberia (AEROSIBNET) has been aimed at more accurate determination of the climatic effect of aerosol, revealing the peculiarities of its spatiotemporal variability, and in estimating the role of regional and global factors. To date, the sites are equipped and observations are organized in the following regions: Tomsk – from October 2003, Tory – from December 2003 (with a one-year break in 2004), near Yakutsk and Ekaterinburg – from June 2004, and near Ussuriysk – from November 2004. Let us present a

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brief climate and geographical characteristics of the observation sites.

1. Measurements in Tomsk are carried out in suburb forest zone to the east of city. The altitude of the photometer above sea level is ~120 m, and ~ 18 m above the ground surface. The region of observations is situated in the south-east of Western Siberia between rivers Ob' and Tom'. As in other regions of mid-latitudes, westerly transfer of air masses prevails here. According to Ref. 3, climate of Tomsk is intermediate between moderately wet warm climate of European part of Russia and strongly continental climate of Eastern Siberia. In cold seasons, the region is under the effect of the northern part of the Asian anticyclone and is characterized by stable temperature inversions. The mean temperature in December and January is –18°C. In summer, weak winds from south prevail (26%) and mean air temperature in July is +18°C. The dominance of air masses is as follows: 59% are mid-latitude continental air and 21% of Arctic air. Let us also note that forest fires are the characteristic peculiarity of this region in droughty periods (as in other regions of Siberia).

2. Second observation site was selected in village Tory (on the territory of geophysical observatory of ISTPh SB RAS) situated in Tunkinskaya valley (river Irkut), approximately 50 km to the west from Baikal. The height of installation of the photometer above the ground surface is 2.5 m, and ~ 670 m above sea level. Climate in the valley is strongly continental, Asian anticyclone prevails here in cold seasons. In winter, clear sky conditions prevail and temperature drops down to –50°C. As a rule, snow cover is thin here (30–35 cm). White snow cover causes intense reflection of solar radiation. Bad weather with frequent small snowfalls is characteristic of spring. The first half of summer is hot (temperature up to 40°C), and it often rains in the second half of summer. Fall is long, with clear warm days (the number of sunny days in the valley exceeds that in the south coast of Crimea).

3. Measurements in Yakutsk are organized at the scientific field site WAS (wide atmospheric showers of cosmic rays of extra-high energy) situated in the valley of river Lena 50 km to the south-west from Yakutsk. The height of installation of the device is 8 m above the ground surface and ~110 m above sea level. Climate is strongly continental dry: temperature in July reaches +38°C, and in winter it decreases to –55°C. Westerly and northwesterly winds prevail here, mean annual amount of precipitation is 247 mm. Forest fires are frequent in summer, smoke of which covers the valley during days. In winter, especially at frost lower than –37°C, frosty fog appears and spreads along the valley. It is important to note that the WAS station is situated in sub-auroral latitudes, where polar lights and, almost always, diffuse background irradiance of the atmosphere are often observed during strong and moderate geomagnetic storms.

4. Observations on Ural are carried out on the territory of Kourovskaya astronomical observatory of Ural State University situated in the forested area near Sloboda village approximately 65 km to the north-east from Ekaterinburg. The height of installation of the photometer above the ground surface is ~7 m, and above sea level ~ 300 m. Climate of the region can be characterized as moderately continental, prevalent wind direction is from west to east. Winter is characterized by quite heavy snowfalls, thunderstorms are frequent in warm seasons, as well as fogs because of closeness to Chusovaya river. Although the region as whole can be characterized as "background," one can not ignore the influence of the nearby big industrial centers of metallurgical industry, first of all, plants in cities Pervoural'sk and Revda.

5. Observations in the Far East are carried out in a forested area on the territory of Ussuriysk astrophysical observatory (Gornotaezhnoe village) 80 km from Japan Sea shore and 25 km from the city of Ussuriysk in the region with a small technogenic effect on the atmosphere. The photometer is installed at the height of 280 m above sea level and 10 m above the ground surface. The observatory is situated near the boundary between zones of monsoon and continental climate. Air mass transfer in winter occurs mainly from north and north-west, and in summer from south and south-east. Mean temperature of January is –14.5°C, and that of July is +20.5°C. Large number of clear days is characteristic for winter, mean precipitation amount in January is 13 mm. The number of clear days in summer is lower, typhoons are frequent, which bring huge amount of precipitation (up to 340 mm per month).

The regions of observations cover quite big territory (Fig. 1) from 43.7° to 61.7°N and from 59.6° to 132.2°E. This enables to essentially decrease the deficiency of information on aerosol characteristics in the northern part of Asia.

Apart from IAO SB RAS and GSFC/NASA, the following institutions take part in the researches: Institute of Solar-Terrestrial Physics SB RAS, Institute of Cosmophysical Research and Aeronomy of SB RAS, Ussuriysk Astrophysical Observatory FEB RAS, Ural State University and Institute of Industrial Ecology UB RAS.

Let us also briefly characterize the AERONET network.[4] The automated network of aerosol observations consists now of more than 120 stations equipped with CE 318 Sun-Sky photometers on all continents of the planet. In addition to the above-mentioned regions, observations in Russia are carried out in Krasnoyarsk (earlier in Barnaul) and in Moscow. The basis version of the device measures the direct radiation (~ every 15 minutes) at the wavelengths of 0.34, 0.38, 0.44, 0.50, 0.67, 0.87, 0.94, and 1.02 μm. The data obtained are used for determination of AOT in seven spectral ranges and the columnar water vapor of the atmosphere (the channel of 0.94 μm). The error in determining AOT is ± 0.01–0.02.

Fig. 1. Map of sites equipped with the AERONET photometers on the territory of Siberia.

Measurements of the scattered radiation are carried out in the solar almucantar and in the main plane at four wavelengths of 0.44, 0.50, 0.67, and 0.87 μm once an hour, on the average.

The important advantage of the AERONET network is its high information capacity. The aerosol microstructure, refractive index, scattering phase function, asymmetry factor, and the aerosol single scattering albedo (SSA) are retrieved in addition to AOT and water vapor column density due to application of the modern methods for solving inverse problems. The SSA has the greatest uncertainty from the standpoint of the aerosol radiative forcing.

2. Comparison of the results of measurements with two photometers

The quality of monitoring observations (especially long-term ones and on a network of stations) is determined by uniformity of the results obtained in different periods, sometimes by means of different measurement tools. To solve this problem, regular calibrations are necessary (usually every 6–12 months), as well as comparison of the data of different photometers taking into account the techniques used for calculation of the characteristics sought. As photometers of the SP-4 type were used for measurements in Tomsk until 2003, for justification of mutual comparability of the series of observations it was important to compare their data with the data obtained with a CE 318 photometer. Selective comparisons of two photometers (using a small data array) was carried out in 2003. In spite of the difference between the devices and the techniques for calculation of AOT, the results obtained are quite close. More complete comparison was carried out after one year of observations (1337 individual cycles). Figure 2 illustrates the results of comparison of AOT of the atmosphere τ_λ at one of the basis wavelengths recommended by WMO – 0.50 μm.

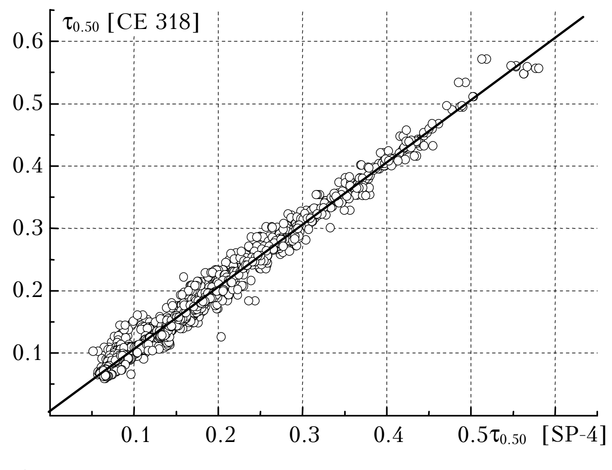

Fig. 2. Scatter diagram of τ_λ from the results of measurements with two photometers, CE 318 and SP-4.

The parameters *a* and *b* of the linear regression equation

$$\tau_\lambda^{\mathrm{CE318}} = (a \pm \Delta a) + (b \pm \Delta b)\,\tau_\lambda^{\mathrm{SP-4}}$$

were calculated for quantitative characterization of the differences between the data obtained with two devices, SP-4 and CE 318, as well as the rms deviations (RMSD) and correlation coefficients R. These characteristics at paired wavelengths of the photometers are presented in Table 1.

Table 1. Parameters of the regression equation between AOT measured with two photometers

$\lambda^{CE\text{-}318}$–$\lambda^{SP\text{-}4}$, μm	$a \pm \Delta a$	$b \pm \Delta b$	RMSD	R
0.38–0.371	0.026 ± 0.002	0.897 ± 0.005	0.033	0.976
0.44–0.438	$-6.019\cdot10^{-4} \pm 0.001$	0.987 ± 0.004	0.020	0.988
0.50–0.50	$0.007 \pm 8.666\cdot10^{-4}$	0.998 ± 0.004	0.015	0.990
0.67–0.675	$0.003 \pm 7.279\cdot10^{-4}$	1.057 ± 0.005	0.012	0.983
0.87–0.871	$0.003 \pm 7.644\cdot10^{-4}$	1.026 ± 0.007	0.012	0.967
1.02–1.047	−0.001 ± 0.001	1.007 ± 0.012	0.016	0.914

It follows from the obtained results that the values τ_λ are in a good agreement, and the value of the difference is approximately equal to the total error in AOT (it is estimated for each device as 0.01–0.02). Additional causes of the differences (apart from the measurement errors) are the following: a) the difference in the techniques used to take into account the gas absorption; b) incomplete coincidence of the transmission contours of the light filters used (see, for example, 0.38/0.371 μm and 1.02/1.047 μm); and c) different regimes and technique for rejecting cloudy situations.

3. The effect of semi-transparent cloudiness

The problem of taking into account the effect of cloudiness which has the optical thickness in the range of the real variability of AOT is important for realization in the algorithms for processing the data of automated sun photometers. Application of special filtration algorithms, "cloud screening"[7] makes it possible to reject the situations of dense lower cloudiness but is not effective in the cases of homogeneous and thin cirrus cloudiness.[8] Natural consequences are distortion of the statistical data on AOT of the atmosphere and the errors in interpretation. Another algorithm is used in measurements with the SP-4 photometer: "instrumental" algorithm for filtration of cloudiness (see details in Ref. 2), but the final result is the same: it is practically impossible to identify and completely reject the effect of homogeneous semi-transparent cloudiness in automated measurements. Application of additional procedures can only partially improve the algorithms of "cloud screening."

The results of continuous measurements of AOT of the atmosphere with a SP-4 photometer (Fig. 3) were used for estimation of the distortions related to the "residual effect of cloudiness."

The whole array of points in Fig. 3 corresponds to the values of τ_λ and the Angström exponent α obtained in the standard regime of observations and rejecting the cloudy situations. The above-mentioned data array undergone additional filtration of cloudiness by taking into account two conditions: 1) real change of AOT of the atmosphere is not uneven but it occurs monotonically during a few tens of minutes (faster variations of τ_λ correspond to cloudiness); 2) measurements "through clouds" lead to approximately equal increase of the optical thickness at all wavelengths. Resulting from such selection, the data corresponding to cloudiness were chosen (dark points).

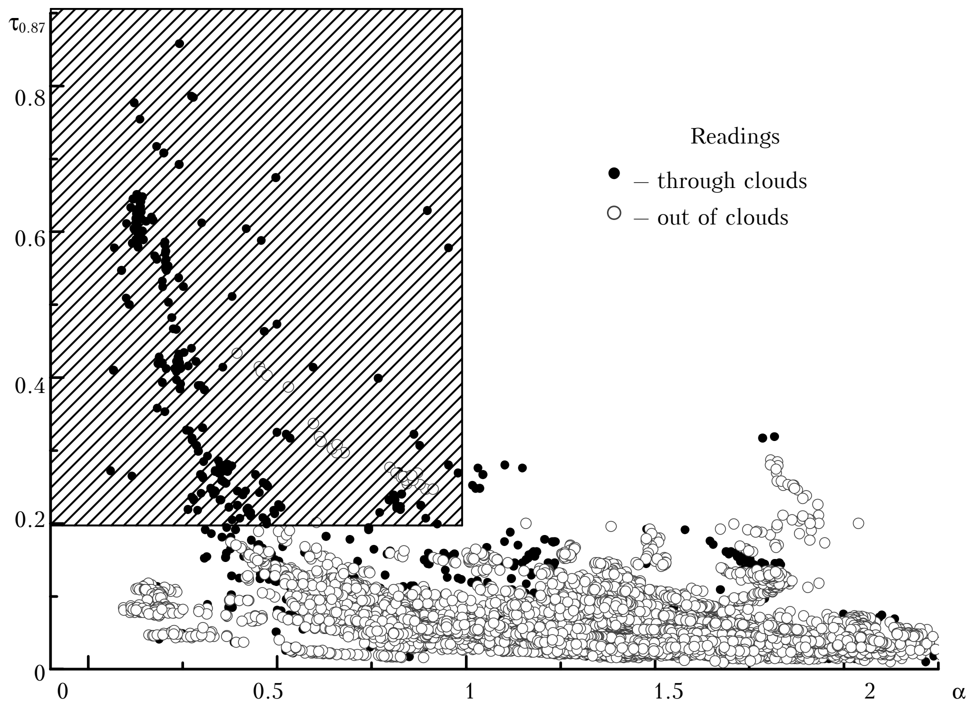

Fig. 3. Illustration of the values τ_λ and α before and after additional "filtration of cloudiness."

Analysis of the results has shown that the greatest part of "false" points leading to overestimation of τ_λ values is in the combined range of values $\{\tau_{0.87} > 0.2;\ \alpha < 1\}$. That means, that this criterion can be used as an additional procedure for filtration of the results of automated CE 318 or SP-4 photometers. The cloudy situations in the specific example were correctly identified in 92.6% of events, 0.2% of data were rejected by mistake, and 7.2% were not distinguished and left.

4. AOT and aerosol SSA in different regions of Siberia

Estimation of seasonal variability

Let us present preliminary analysis of annual variability of AOT only for Tomsk (although one can consider the quantitative estimates of these characteristics as tentative), because duration of observations in other regions is insufficient. Figures 4 and 5 and Table 2 give the generalized idea of seasonal variability of the parameter α and τ_λ.

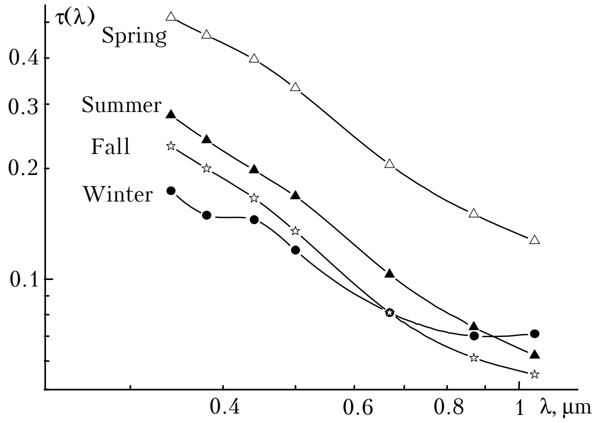

Fig. 4. Mean characteristic $\tau(\lambda)$ in different seasons (Tomsk).

Table 2. Statistics of AOT in different seasons in Tomsk (October 2002 – September 2004)

Parameter	Mean	RMSD	Min	Max
Winter (N = 142)				
τ(0.34 μm)	0.174	0.066	0.070	0.343
τ(0.38 μm)	0.149	0.062	0.051	0.308
τ(0.44 μm)	0.145	0.056	0.054	0.296
τ(0.50 μm)	0.120	0.050	0.037	0.258
τ(0.67 μm)	0.081	0.041	0.016	0.195
τ(0.87 μm)	0.070	0.040	0.014	0.178
τ(1.02 μm)	0.071	0.040	0.020	0.190
α	1.241	0.496	0.115	2.074
W, g/cm^2	0.296	0.075	0.161	0.462
Spring (N = 1541)				
τ(0.34 μm)	0.516	0.477	0.064	2.434
τ(0.38 μm)	0.461	0.449	0.029	2.286
τ(0.44 μm)	0.397	0.368	0.054	1.896
τ(0.50 μm)	0.331	0.308	0.037	1.587
τ(0.67 μm)	0.205	0.186	0.014	0.904
τ(0.87 μm)	0.150	0.122	0.013	0.547
τ(1.02 μm)	0.127	0.095	0.017	0.471
α	1.387	0.338	0.141	2.554
W, g/cm^2	1.032	0.671	0.059	2.987
Summer (N = 3269)				
τ(0.34 μm)	0.279	0.158	0.065	1.299
τ(0.38 μm)	0.239	0.14	0.046	1.208
τ(0.44 μm)	0.198	0.116	0.044	1.08
τ(0.50 μm)	0.168	0.097	0.034	0.958
τ(0.67 μm)	0.103	0.062	0.011	0.686
τ(0.87 μm)	0.074	0.044	0.008	0.527
τ(1.02 μm)	0.062	0.037	0.009	0.46
α	1.483	0.360	0.230	2.674
W, g/cm^2	1.956	0.588	0.630	4.022
Fall (N = 593)				
τ(0.34 μm)	0.230	0.131	0.055	0.749
τ(0.38 μm)	0.200	0.117	0.041	0.656
τ(0.44 μm)	0.166	0.094	0.043	0.529
τ(0.50 μm)	0.135	0.081	0.024	0.433
τ(0.67 μm)	0.081	0.052	0.006	0.251
τ(0.87 μm)	0.061	0.038	0.005	0.199
τ(1.02 μm)	0.055	0.032	0.010	0.188
α	1.576	0.387	0.365	3.455
W, g/cm^2	1.234	0.746	0.199	2.914

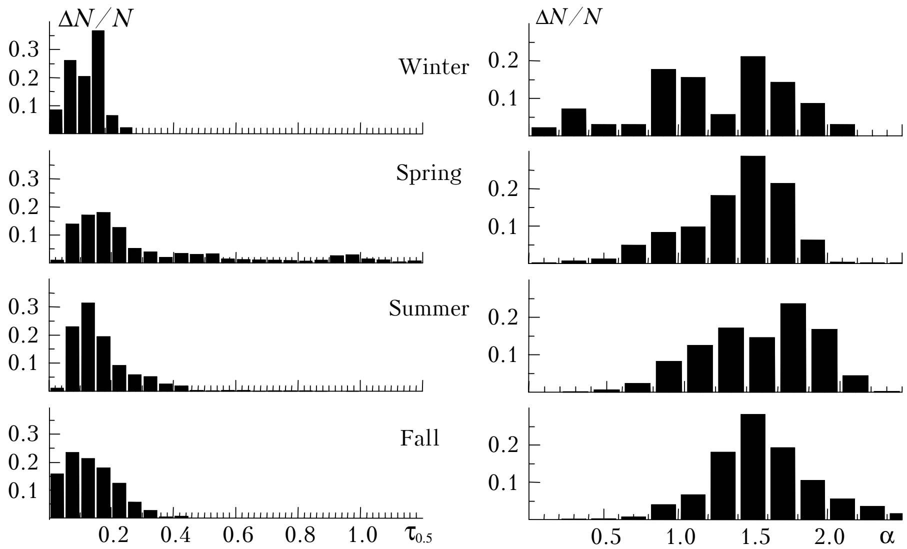

Fig. 5. Histograms of the frequency of occurrence of $\tau_{0.5}$ and the parameter α (Tomsk).

It follows from the data presented, that the atmosphere in fall and winter is most clean, from the standpoint of aerosol content, and spring is characterized by the maximum turbidity and variability of τ_λ. Lower selectivity of the spectral behavior and, simultaneously, maximum variability of α are observed in winter, because of a relatively higher content of coarse aerosol compared to that in other seasons. Fall season is characterized by the maximum α values. The presence of two maxima in the histograms of τ_λ and α in winter can be explained, evidently, by two types of weather, one of which is related to inversion situations favoring accumulation of "local" aerosol in the lower layer of the atmosphere. Second maximum of the parameter α in summer is related, probably, to the effect of vast forest fires which lead to enrichment of air with fine aerosol and the increase of selectivity of the spectral behavior $\tau(\lambda)$.

The study of the aerosol single scattering albedo Λ, which characterizes its absorption properties, is the most important problem for more accurate determination of the aerosol radiative forcing. Rapid development of the methods for solving inverse problems in the past decade made it possible to determine this parameter from the angular distributions of the scattered solar radiation. The algorithms for calculating Λ in the AERONET system, although have been developed to the level acceptable for routine use, continue to be improved. So, to estimate the variations of Λ under Siberian conditions, let us use the data of only 2004. It follows from the histograms of frequency of occurrence (Fig. 6) that the aerosol SSA in the region of Tomsk varies in the range from 0.5 to 1.

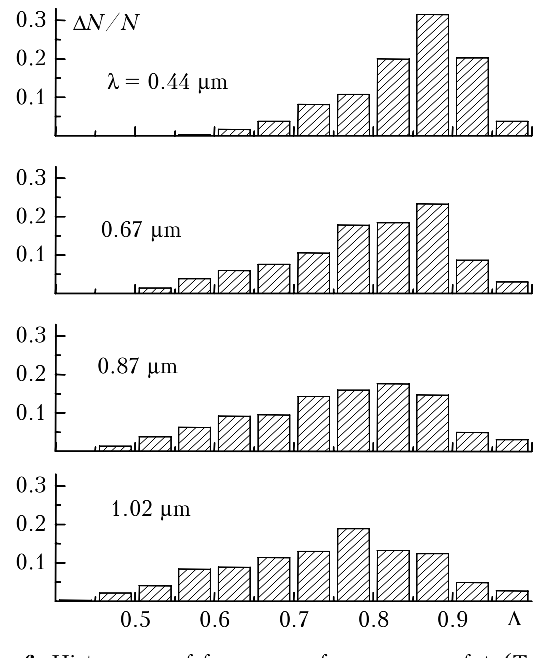

Fig. 6. Histograms of frequency of occurrence of Λ (Tomsk, May – September 2004).

Stronger absorption and smaller Λ are characteristic of the long-wave spectral range: the mean Λ value at the wavelength of 1.02 μm is 0.74, and in the range of 0.44 μm it is 0.84 (Fig. 7). Let us also note that variations of Λ increase with the wavelength and their relative variability is essentially lower compared to that of $\tau(\lambda)$. For example, the variation coefficients of Λ change from ~9% (0.44 μm) to ~ 16% (1.02 μm), and that of AOT of the atmosphere are, as a rule, 40–60%.

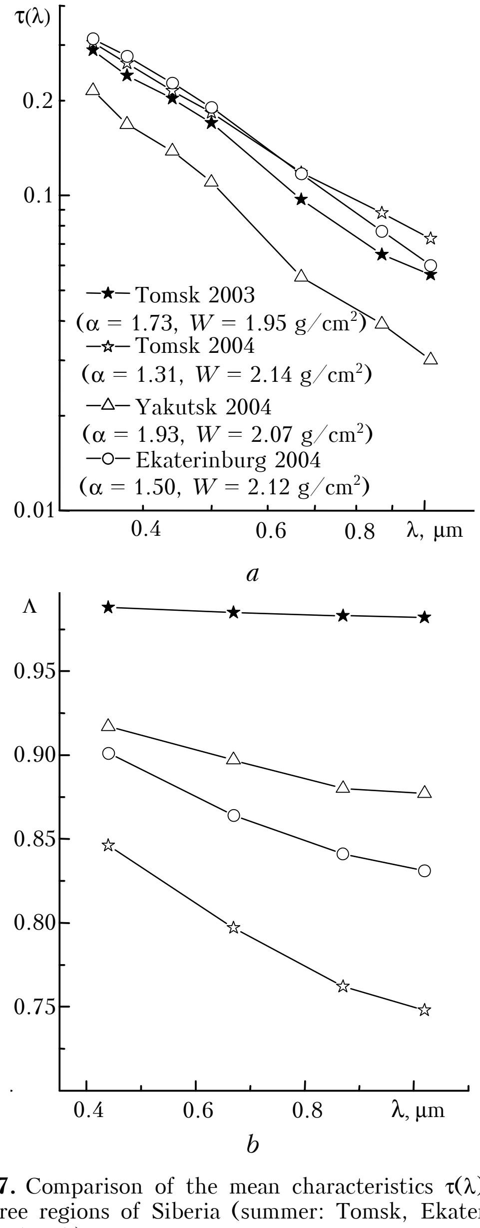

Fig. 7. Comparison of the mean characteristics $\tau(\lambda)$ and Λ in three regions of Siberia (summer: Tomsk, Ekaterinburg, and Yakutsk).

Spatial inhomogeneities

It is interesting to estimate spatial variability of the aerosol characteristics and water vapor column density in the atmosphere over the territory of Siberia. Let us remind that measurements near

Yakutsk and Ekaterinburg, contrary to Tomsk, started only in summer 2004, so for comparative estimation let us use the data only for June, which is the most completely represented in the three regions of observations (Fig. 7). Even superficial analysis shows that the monthly mean values of the water vapor column density in the atmosphere are close in different regions, but the aerosol characteristics show significant differences. Let us pay attention for the following peculiarities:

1) minimum turbidity of the atmosphere is observed in the region of Yakutsk, the value of AOT here is 1.5–2 times lower than in Ekaterinburg and Tomsk, τ_λ in the visible wavelength range in Tomsk is slightly lower than in Ekaterinburg, while in the IR range the situation is reverse.

2) Maximum selectivity of the spectral behavior of AOT is characteristic of Yakutsk (see parameter α), which is evidence of the relatively greater content of fine aerosol in the atmosphere.

3) Larger values of Λ are also characteristic of Yakutsk, i.e. the content of the absorbing substance in aerosol is lower.

5. Aerosol disperse composition

As was mentioned above, the use of the algorithms for inverting the optical data[4–6] makes it possible to retrieve and to analyze the columnar refractive index and the columnar characteristics of the aerosol disperse composition at different observation sites. Let us consider the estimates of geographical variability of the volume aerosol size distribution in summer 2004 (Fig. 8). As is seen, the content of practically all particles in Yakutsk is lower than in the regions of Tomsk and Ekaterinburg. The results obtained in Tomsk and Ekaterinburg for small particles (with the radius up to 4–5 μm) are practically the same, and there are more large particles in the region of Tomsk. Reliable differences for these geographical sites are, most likely, caused by different time of flowering and emission of pollen of herbs and trees. One should note that two fractions are most pronounced in the microstructure of aerosol obtained by inverting the optical data: fine and coarse fractions. At the same time, from the distribution curves one can judge on the presence of a hidden intermediate-size fraction of aerosol particles with the size from 0.6 to 1 μm. The presence of this fraction is also noticeable in the mean distribution curves in summer (Fig. 8).

Mean values of the microphysical characteristics of two main aerosol fractions are generalized in Table 3. It follows from the data presented that Yakutsk is characterized by minimum values of not only the particle number density, but also other characteristics like modal and effective radii and imaginary part of the refractive index. In the atmosphere of Tomsk, in contrast to Ekaterinburg, the content of aerosol is a bit higher and the particle size is larger (see also Figs. 7 and 8). However, this fact is not evidence of the same situation, for the case of industrial pollution. Let us remind that measurements in Tomsk are carried out in eastern suburb zone, and in the region of Ekaterinburg they are 65 km to the west from the city, i.e., in practically background area for this region. From the standpoint of the prevalent westerly transfer of air masses, arrangement of the observational sites in Ural is more favorable. Within the framework of an individual paper, for Tomsk it is necessary to more carefully analyze the effect of the city on the obtained aerosol characteristics.

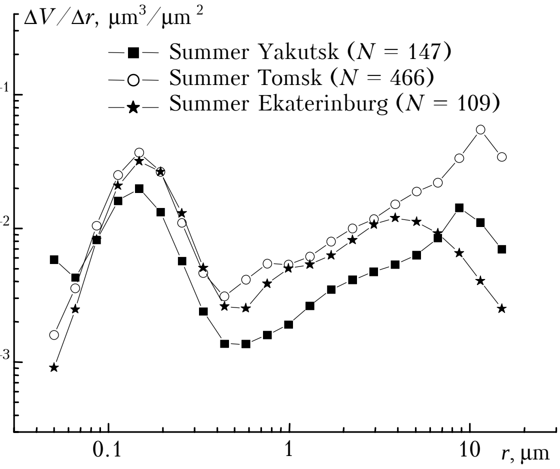

Fig. 8. Mean volume size distribution in summer.

Let us estimate seasonal variability of the aerosol disperse composition in Tomsk, where the relatively greater bulk of data has been obtained (Fig. 9). Similarly to the case with AOT of the atmosphere, it is the expected result that the aerosol concentration has spring maximum that is typical for the majority of the mid-latitude regions. At the same time, according to data of AERONET network and other papers,[8–11] maximum of the aerosol turbidity is observed not only in spring but also in summer, and minimum in fall and winter. The differences between seasons in the data obtained in the region of Tomsk are not that explicit (except in spring). Weak seasonal behavior of AOT in clean regions of Siberia and even slight excess of turbidity in winter over that in summer was noted earlier.[12,13]

Table 3. Mean aerosol microphysical characteristics (summer, λ = 0.87 μm)

Region	Total volume V_C, μm³/μm²	Effective radius r_{eff}, μm	Modal radii		Refractive index	
			r_m^c, μm	r_m^f, μm	n	χ
Tomsk	0.091	0.34	3.77	0.16	1.45	0.017
Yakutsk	0.038	0.22	3.55	0.14	1.45	0.013
Ekaterinburg	0.055	0.27	3.33	0.16	1.48	0.015

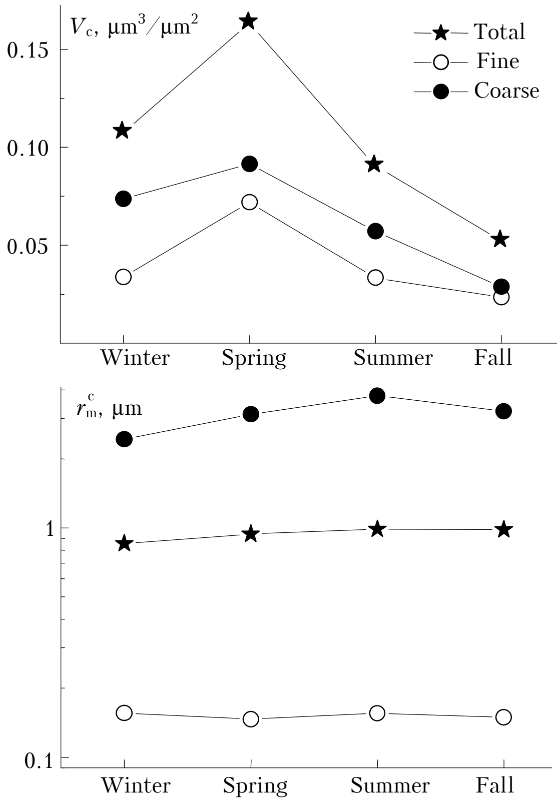

Fig. 9. Seasonal variability of the volume concentration and the modal radii of particles (Tomsk).

As for the modal radii of two aerosol fractions, the main peculiarity of annual variability is the presence of summer maximum in the size of coarse particles: in winter $r_m^c = 2.4$ μm, and it increases till summer up to 3.8 μm. No significant seasonal variability of fine particles is observed in the obtained results.

Let us emphasize once again, that the presented data on seasonal behavior of the aerosol characteristics and the peculiarities of their geographical distribution are preliminary due to the short period of observations. As long series of observations are accumulated and the data in "new" regions (where measurements started later) are available, the regularities in the variability of the optical and microphysical characteristics revealed will make it possible to propose empirical models and to estimate the role of global, regional, and local processes in the formation of aerosol. However, the preliminary consideration of the data even at this stage makes it possible to more rationally plan further development of the studies under the AERONET program.

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