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Variations in the Atmospheric Aerosol Optical Depth from the Data Obtained at the Russian Actinometric Network in 1976–2006

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Abstract—The results of an analysis of variations in the optical depth of a vertical atmospheric column on the basis of a 30-year (1976–2006) series of observations obtained by the Russian actinometric network are generalized. This analysis is based on the Atmosphere Transparency special-purpose database created at the Voeikov Main Geophysical Observatory on the basis of observational data obtained at the actinometric stations of the Russian Hydrometeorological Research Center. The general regularities of spatial variations in the atmospheric optical depth (AOD) over Russia are revealed: there is a monotonic decrease from the southwest to the northeast, with localized areas having different aerosol loads due to the global and regional factors of their formation. A spatiotemporal structure of the anomalies of AOD annual values within the time interval under consideration, including the El Chichon (1982) and Pinatubo (1991) eruptions, is studied.

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The relationship between the increases in the global surface air temperature and in the atmospheric content of greenhouse gases has been proven. The warming over the past 50 years has mainly been related to human activities [1, 2]. Along with the anthropogenic factor, climate is affected by such natural factors as variations in the solar constant, cyclic interactions between the atmosphere and the ocean, and atmospheric aerosol; these factors are pronounced within time intervals of several years to several decades. The sign of aerosol forcing may be different: the stratospheric aerosol layer causes the reflection of solar radiation incident upon the atmospheric upper boundary and, thus, decreases the warming of the underlying air layers. For example, the sulfate aerosol which formed in the stratosphere after the Pinatubo eruption (June 1991) caused "short" (in 1993) global cooling [3]. Tropospheric aerosol can increase or decrease the surface air temperature, and its influence on the ecological state of the air is well understood [4]. Therefore, monitoring the atmospheric aerosol component is important now and necessary from the standpoints of its climatic forcing and ecology. The study of current spatiotemporal variations in the atmospheric aerosol component is of scientific interest and presents a problem. Current ground-based networks of monitoring (in particular, AERONET) are the results of such interest [5–7]. There are eight AERONET stations in Russia; seven of them are located in Siberia [8].

The maps, which show a global distribution of the sources of different (anthropogenic, natural, organic, mineral, marine, and volcanic) aerosols arriving in the atmosphere, the total aerosol optical depth in the atmospheric thickness according to model data [1], and the aerosol optical depth according to satellite (MODIS) monitoring [2], show Russia as a territory of decreasing aerosol optical depth (AOD) going from south to north. At the same time, Russia occupies the entire northeastern part of Eurasia (30° E–180° E; 50° N–80° N) and includes different climatic zones which differ in water content, air temperature, cloudiness, solar radiation flux incident upon the land surface, underlying surface, and air-mass circulation. In addition, the density of population and the degree of industrialization of different Russian regions are very inhomogeneous in space.

In the studies [9, 10] published by the authors of this paper, it has been shown that an analysis of the AOD of a vertical atmospheric column can be made on the basis of observational data obtained at the Russian actinometric network, in particular, on the basis of data on the integral atmosphere transparency (P), because P variations are, to a great extent, determined by the aerosol component of the attenuation of direct solar radiation; other components of the attenuation (water vapor and other gases) have little effect on its

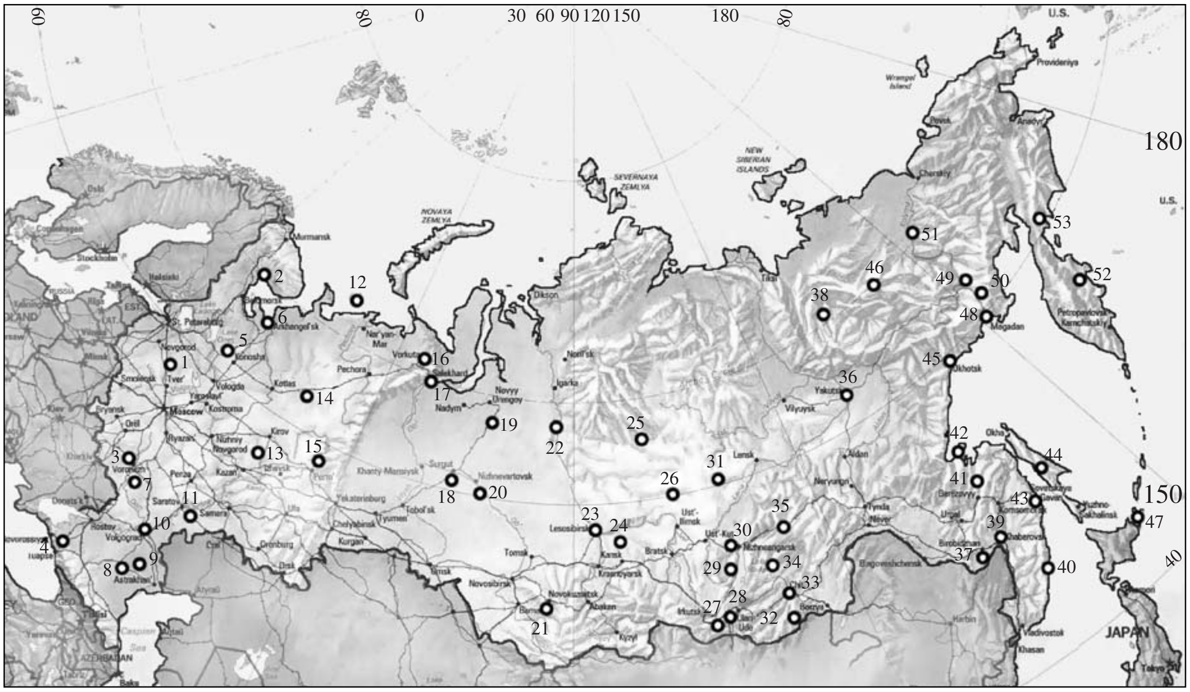

Fig. 1. Layout of 53 actinometric stations (Table 1) whose data have been analyzed in this paper.

time variations. Thus, on the basis of data on the homogeneous (calibrated against a single standard and obtained with a unified method) observational series of direct solar-radiation fluxes at the land surface and estimates of the integral (total and aerosol) transparency, it is possible to analyze variations in the AOD of a vertical atmosphere, which is what we did in [9, 10] on the basis of the 1976–2003 observational data obtained at 44 actinometric stations. The character of multiyear seasonal variations in AOD was studied, the simplest statistical parameters (means, extrema, and variation coefficients) of spatial variations in AOD annual means were assessed, and the "purification" of the atmosphere from aerosol over the past decade of observations was quantitatively estimated.

In this work, we continue this analysis on the basis of an extended database (the number of stations has been increased by nine, and the period of observations has been extended to 2006), we generalize the results obtained before, and we compare the effects of the two natural factors (the global factor—the powerful volcanic eruptions in the latter half of the 20th century which resulted in the formation of a stratospheric aerosol layer—and the regional tropospheric factor—for example, the arrival of aerosol in the atmosphere due to tundra and forest fires) on AOD.

Figure 1 gives a map showing the location of 53 actinometric stations of the Russian network [11, 12] for which the AODs of vertical atmospheric columns were estimated for a wavelength of 0.55 μm from the measured fluxes of direct solar radiation at land surface. These stations cover a large part of Russia and are located outside the zones of direct local anthropogenic sources of industrial and municipal aerosol emissions (suburbs, rural areas, uplands, etc.). In other words, the considered spatiotemporal variations in AOD are formed under the influence of natural factors: the advection of air masses from the regions with an increased or decreased aerosol load, volcanic eruptions, and forest and tundra fires. In analyzing the 1976–2006 observational data, our goal was to obtain an averaged pattern of the spatial distribution of atmospheric aerosol over Russia and to compare this pattern with that of the global aerosol distribution which is presented in the IPCC third (modeling) and fourth (satellite data, MODIS) reports [1, 2]. In this case, the estimates obtained with our method supplement the international data on the model approximations and satellite monitoring of AOD. The advantages of our estimates are the great length of the series of actinometric observations under consideration (31 years), the universal methods of measurements and data treatment for all the stations, and the vast coverage area of Russia's large territory. Our analysis is within the scope of works by Russian scientists [13–21] studying the regional multiyear variability of the aerosol component of the attenuation of direct solar-radiation flux incident upon the land surface as an ecological and climatic factor.

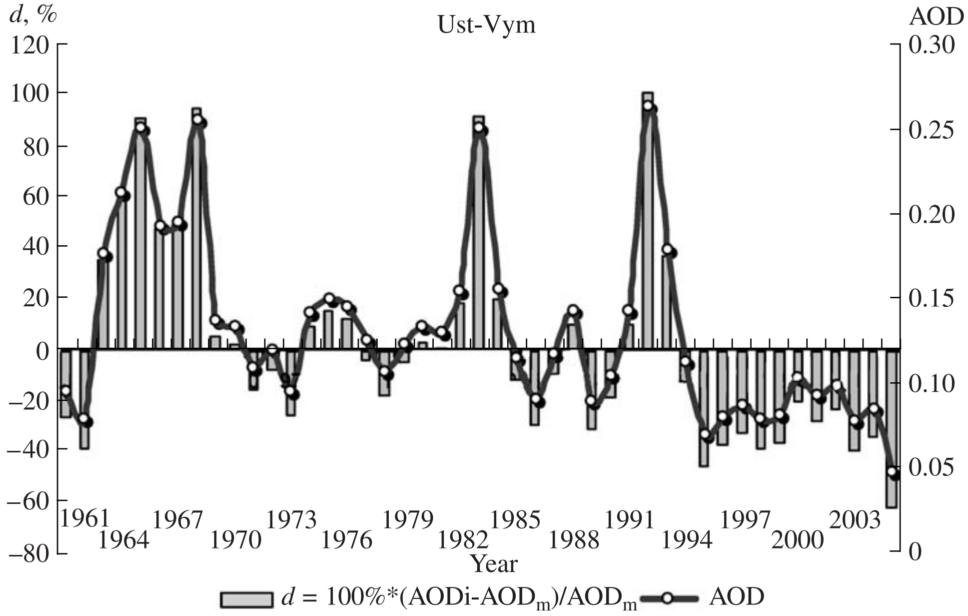

Fig. 2. Example of multiyear variations in the annual means of AOD and their deviations from the average *d* (%).

EMPIRICAL DATA AND ANALYSIS PROCEDURE

The special-purpose Atmosphere Transparency database formed at the Main Geophysical Observatory makes it possible to analyze both the integral and aerosol transparencies of the atmosphere [11, 12]. The stations given in Fig. 1 were selected with consideration for the quality and completeness of the instrumental series. The AOD of the vertical atmosphere was calculated with a method specially developed and used at the Moscow State University meteorological observatory [13–15] with consideration for its limitations and errors:

$$\frac{\ln S - [0.1886w^{-0.1830} + (0.8799w^{-0.0094} - 1)/\sin h]}{0.8129w^{-0.0021} - 1 + (0.4347w^{-0.0321} - 1)/\sin h} = \text{AOD}. \quad (1)$$

AOD—an index of the Angström spectral attenuation which depends on the size distribution of particles and on the coefficient of particle reflection—is assumed to be equal to 1; S is the direct solar radiation reduced to the average distance between the Earth and the Sun, W/m^2; and w is the water content of the atmosphere, g/cm^2. The conditions of observations at the stations, as a rule, correspond to the weather of an anticyclonic type (clear or slightly cloudy) when the Sun is not blocked by clouds.

Figure 2 gives a “long” (45 years) series of annual means of AOD for the Ust Vym station (62.2° N, 50.4° E) which demonstrates a characteristic multiyear trend of variations in the annual values of AOD and its response to stratospheric disturbances. The four powerful volcanic episodes—Agung (8° S, 116° E, 1963), Fuego (14° N, 91° W, 1974), El Chichon (17° N, 93° W, 1982), and Pinatubo (15° N, 120° W, 1991)—are clearly pronounced and quantitatively estimated. In particular, the maximum effect observed a year after the eruptions is 100% (in deviations from the multiyear norm); throughout the year, its attenuation occurs with the dissipation and transformation of the stratospheric aerosol layer. A decrease in the AOD values for 1995–2006 is also clearly manifested. Such a character of multiyear variations in the annual values of AOD is characteristic of most stations and is, to a great extent, determined by the four powerful volcanic eruptions in the latter half of the 20th century, because seasonal and local disturbances caused by the effects of tropospheric aerosol, when annually averaged, become leveled and have almost no influence on the distribution of the multiyear values of AOD.

SPATIAL VARIATIONS IN AOD

Table 2 gives the multiyear means and extrema of the annual values of AOD and the standard deviations from these means, which are averaged over all the stations under consideration for the two periods. It is seen that the AOD mean over all the stations and the entire observation period is equal to 0.14 and varies from 0.30 to 0.07, which is in good agreement with the spatial range of the AOD variations obtained from the satellite and model data (for the Russian region) that are given in the IPCC third and fourth reports (0.30–0.05).

The annual values of AOD for each of the stations (multiyear means over 1976–2006, their standard deviations, and maximum and minimum values) are

Table 1. The actinometric stations whose observational data was used in this paper

Latitude	Longitude	Name and number of stations, height above sea level	Latitude	Longitude	Name and number of stations, height above sea level
58.0	33.3	Valdai, 1, 200	51.7	105.9	Babushkin, 27, 465
66.7	34.3	Umba, 2, 39	51.8	107.3	Ivolginsk, 28, 562
51.6	38.4	Nizhnedevitsk, 3, 186	53.2	107.3	Khuzhir, 29, 487
45.1	39.0	Krasnodar, 4, 28	56.3	107.7	Kazachinskoe, 30, 355
61.5	39.0	Kargopol, 5, 124	61.3	107.9	Erbogachen, 31, 284
64.6	40.5	Arkhangelsk, 6, 8	49.7	112.7	Mangut, 32, 807
51.1	40.7	Kamennaya Step, 7, 193	52.1	113.5	Chita, 33, 671
46.5	41.3	Gigant, 8, 79	54.5	113.6	Bogdarin, 34, 996
47.7	42.1	Tsimlyansk, 9, 64	57.8	114.0	Mamakan, 35, 244
48.7	44.4	Volgograd, 10, 118	62.0	129.7	Yakutsk, 36, 98
51.4	48.3	Ershov, 11, 110	47.7	131.0	Ekaterino-Nikolskoe, 37, 72
68.8	49.3	Bugrino, 12, 11	67.6	133.4	Verkhoyansk, 38, 137
57.6	49.9	Nolinsk, 13, 147	48.5	135.1	Khabarovsk, 39, 88
62.2	50.4	Ust-Vym, 14, 106	44.4	135.9	Rudnaya Pristan, 40, 26
58.8	56.2	Chermoz, 15, 122	52.4	136.5	Im. Poliny Osipenko, 41, 73
67.1	64.1	Eletskaya, 16, 113	54.8	137.5	Bolshoi Shantar, 42, 8
66.5	66.6	Salekhard, 17, 14	49.0	140.3	Sov. Gavan 43, 21
61.3	71.2	Sytomino, 18, 32	50.7	142.7	Tymovskoe, 44, 94
64.9	77.8	Tarko-Sale, 19, 26	59.4	143.2	Okhotsk, 45, 5
60.4	77.9	Aleksandrovskoe, 20, 47	66.5	143.2	Ust Moma, 46, 196
53.3	87.2	Kuzedeevo, 21, 293	44.0	145.8	Yuzhno-Kurilsk, 47, 49
65.8	87.9	Turukhansk, 22, 38	59.5	150.7	Magadan, 48, 115
58.4	92.2	Eniseisk, 23, 77	62.4	152.3	Srednekan, 49, 264
56.2	95.3	Solyanka, 24, 359	61.1	152.4	Talaya, 50, 703
64.3	100.3	Tura, 25, 188	67.5	153.7	Srednekolymsk, 51, 21
60.3	102.3	Vanavara, 26, 259	56.3	160.8	Klyuchi, 52, 28
			60.4	166.0	Korf, 53, 2

Table 2. Multiyear means, maxima, minima, and standard deviations of the annual means of AOD over all stations in absolute units

Period	AOD		σ	Trend of AOD variations in % over 10 years
1976–2006	Mean	0.14	0.04	–13
	Maximum	0.30		+21
	Minimum	0.07		–38
1995–2006	Mean AOT (σ)	0.12	0.04	
	Maximum	0.22		
	Minimum	0.06		

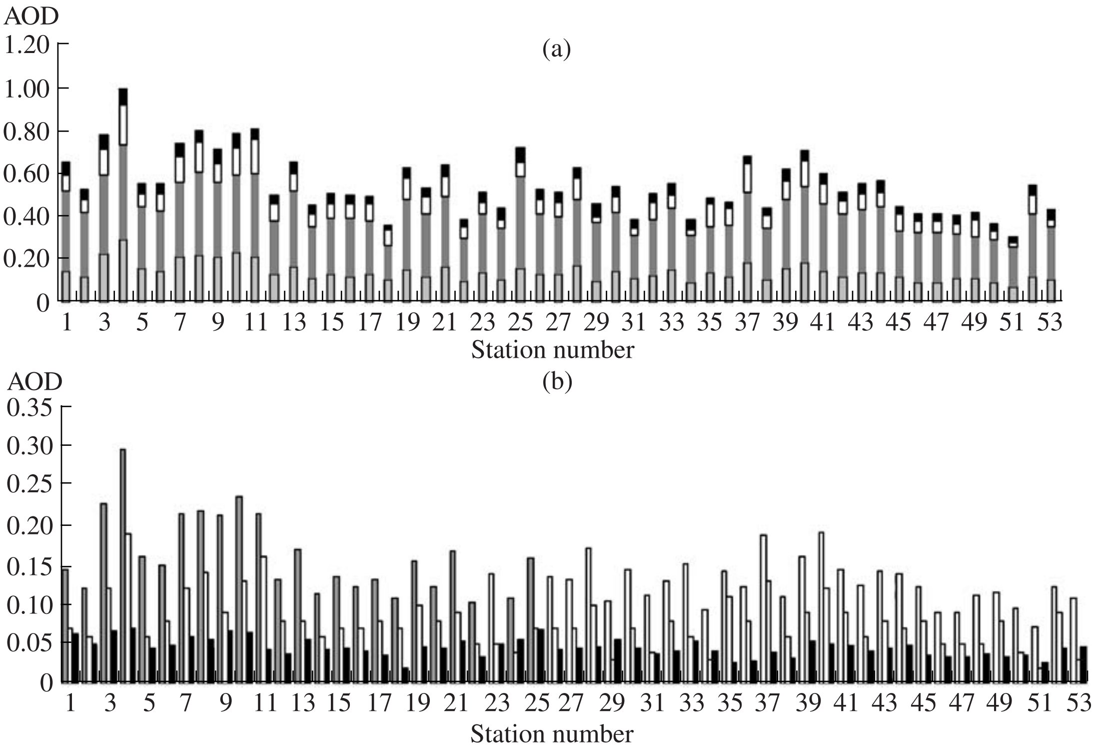

Fig. 3. Statistics of the annual means of AOD for each of the stations: (a) the ratio of the mean (light-grey) over the period 1976–2006, maximum (dark-grey), and minimum (white) values of AOD, as well as standard deviations (black) in the series of the annual values of AOD for each of the stations; and (b) the ratio of the AOD means (grey) over the period 1976–2006 and the AOD means (white) over the period 1995–2006 and the standard deviations (black) in the series of the annual values of AOD for each of the stations.

given in Fig. 3. Each column of the diagram corresponds to the number of the station in accordance with Table 1. The means of the AOD characteristics are denoted by different colors for each station: light-grey corresponds to the multiyear annual means of AOD, dark-grey corresponds to its annual maxima, white corresponds to its minima, and black corresponds to the standard deviations of the annual values of AOD from its mean for each station (Fig. 3a). In Fig. 3b, grey corresponds to the multiyear annual means of AOD for 1976–2006, white corresponds to the multiyear annual means of AOD for 1994–2006, and black corresponds to the standard deviations of the annual values of AOD from its mean for each station.

A spatial distribution of AOD is shown in more detail in the maps (Fig. 4) drawn by interpolating the data obtained at 53 stations to Russia's territory. For this interpolation, the technologies of the MATLAB 7.3.0. program package (R2006b) were used: there are options to create a uniform grid for the entire region, onto which the given functions $Z = F(x, y)$ were projected, where x and y are the latitude and longitude, respectively, for each of 53 observation points, and Z is the AOD mean. In addition, a bilinear interpolation of data was performed. Under bicubic and bisquare interpolations, the results, in principle, do not differ from those given in Fig. 4.

The spatial distribution of the AOD means over the 31-year period (Fig. 4a) is in a good agreement with the results of modeling a spatial atmospheric-aerosol distribution, which are given in the IPCC third report [2]. The model described in this report takes into account aerosols of different origins (anthropogenic and natural sulfates, organic particles, soot, mineral aerosol of natural origin, and marine saline particles) which have certain specific properties of distribution over the globe, and it yields a decrease in AOD over Eurasia from the southern to the northern latitudes in the presence of areas with increased atmospheric turbidity over southern Europe, the Middle East, southeastern Asia, Ukraine, and Kazakhstan. Figure 4 shows that the AOD over Russia decreases from the southwest to the northeast. The increased values of aerosol haziness in the southeast and southwest are most likely caused by an advective arrival of air masses from the regions with high aerosol content in the atmosphere: from Ukraine and Kazakhstan in the southwest and from southeastern Asia and China in the southeast. Figure 4a shows the localizations of regional tropospheric aerosol sources (western and eastern Siberia and Primorskii Krai). In the last decade (Fig. 4b), in the absence of powerful volcanic eruptions and under conditions the atmosphere being purified of the stratospheric aerosol layer, the sources

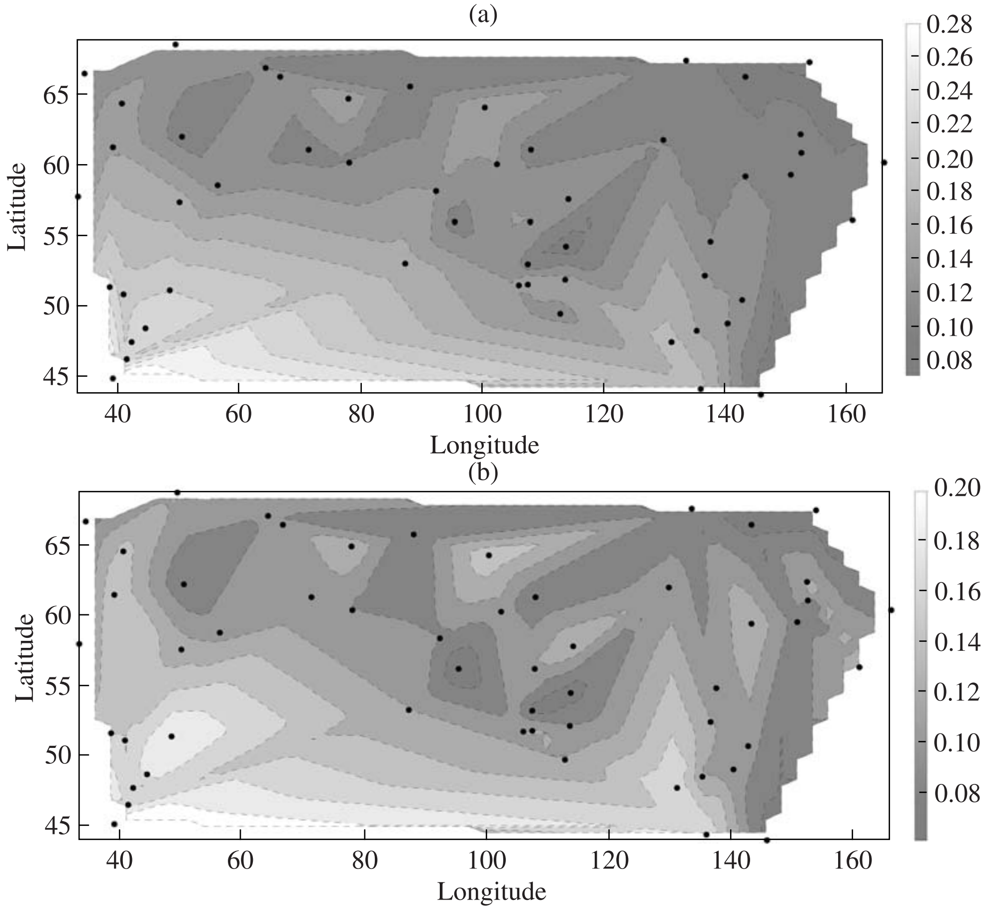

Fig. 4. Spatial distributions of the multiyear means of AOD over the observation periods (a) 1976–2006 and (b) 1995–2006.

of aerosol arriving in the troposphere have become more pronounced. In addition, in the last decade, the AOD has noticeably increased for a few stations in the Far East, which is probably due to increased volcanic activity on Kamchatka [22].

The spatiotemporal inhomogeneities of the AOD annual values clearly reflect their causes (Fig. 5a): the peaks of the volcanic eruptions (El Chichon, 1982, and Pinatubo, 1991) and the tundra fires of the last decade in eastern Siberia, the frequency and intensity of which have increased due to climate changes [3]. Figure 5b shows variations in the mean annual cycle of AOD. The features of the AOD mean annual cycle for each concrete station are formed under the influence of seasonal variations in the character of air-mass transport to a given point from regions with different aerosol contents (synoptic processes) and seasonal variations in air temperature, humidity, and in the state of the underlying surface, in combination with an industrial load of some regions. The AOD maxima are, as a rule, observed in April and July–August, but the summer maximum is more pronounced at stations (Nos. 4, 8, 9, 10, and 11) located in the south of European Russia. First of all, this is related to the fact that, in summer, tropical air masses dominate here which are characterized by high contents of moisture and aerosol. The spring maximum is caused by snow-cover melting and the replacement of the dominating arctic air masses by temperate or tropical air masses.

TIME VARIATIONS

Figure 6a gives some examples of time variations in the annual means of AOD for stations with negative and positive trends. In Fig. 6b, the examples of the time trends of the AOD annual values are supplemented by the corresponding variations in the flux of direct solar radiation (for the Sun's height $h = 30°$), which reach 100 W/m^2 over the course of 31 years (3 W/m^2 per year); estimates were obtained for two stations with the maximum and minimum means of AOD. Thus, the influence of a decreased aerosol load on the flux of direct solar radiation incident upon the land surface under clear skies is empirically estimated. For total radiation, this influence is less pronounced. And our estimate of the rate of a decrease in direct solar radiation does not contradict the satellite data [23] on the rate of a decrease in the flux of the total reflected (upward) solar radiation (-0.18 ± 0.11) W/m^2 per

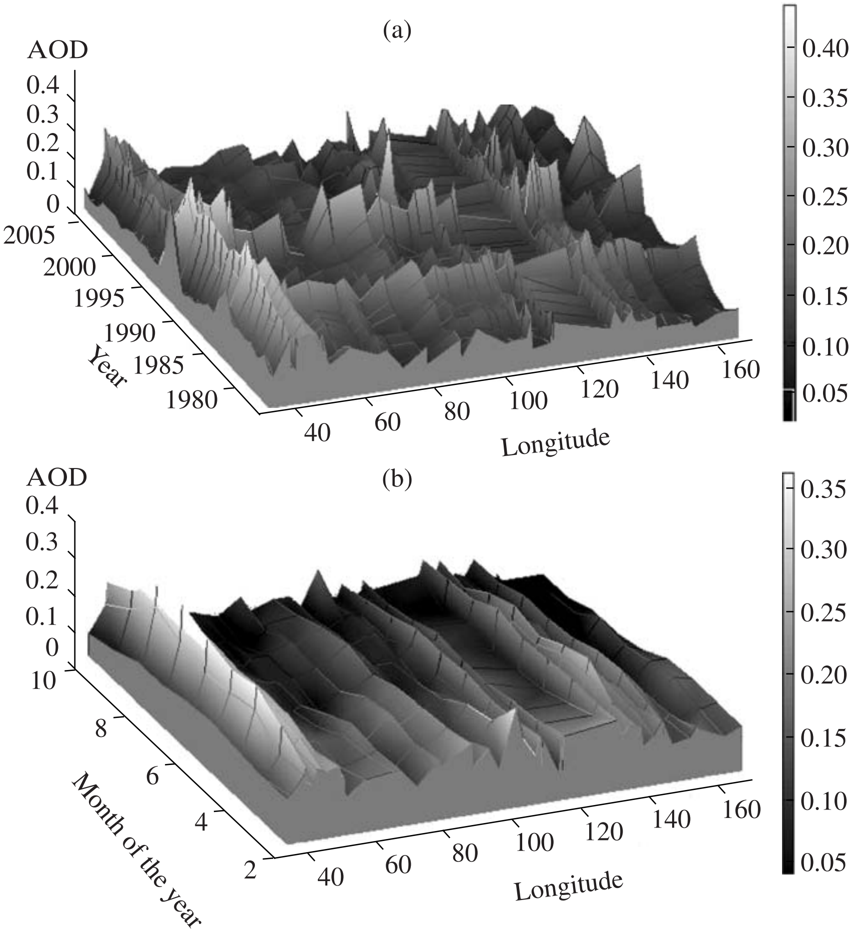

Fig. 5. Spatiotemporal variations in AOD: (a) multiyear variations in the annual values of AOD for all stations under consideration and (b) mean seasonal variations in AOD for all stations under consideration.

year (the ISCCP project) and (–0.13 ± 0.08) W/m^2 per year (the ERBS project)) over the course of 1984–1999 and the assumption made in [23] that this is caused by a global decrease in stratospheric aerosol (the so-called phenomenon of "aerosol dimming").

At most observation sites, the atmosphere was purified of aerosol within the period under consideration. On the whole, for Russia, the trend of AOD variations is negative (Fig. 7a); the absolute value of the trend (over 10 years) varies from (–0.05) to (+ 0.01) and increases generally from the southwest to the northeast of Russia. The mean of the relative trend accounts for (–13%) over 10 years, its maximum is 21% over 10 years, and its minimum is (–38%) over 10 years at a determination coefficient of no more than 0.5. It is evident that, in this case, a decrease in the AOD mean must be observed during the last decade for the whole region (Table 2). The largest negative trends are observed at the Solyanka station (in the south of the Krasnoyarsk Krai), in Chita (Transbaikalia), Khabarovsk (Primorskii Krai), and in the south of European Russia. The combination of the two factors—global purification of the atmosphere from transformed volcanic aerosol and decreased anthropogenic forcing—forms the negative trends in these regions. Positive trends are observed in Arkhangelsk and the Far East (Kamchatka and Okhotsk), and almost zero trends are observed in western (station nos. 18, 19, and 90) and eastern (Tura, station no. 25) Siberia. The positive (Arkhangelsk) and decreased negative (the indicated Siberian stations) trends may be caused by increased industrial emissions in these regions, an increase in the number and intensity of fires, and comparatively low-power volcanic eruptions (for example, in Kamchatka). The estimates of the AOD trends and integral transparency obtained by other authors [14, 17–21] were compared with our estimates earlier in [9]. This comparison shows an agreement with the results presented in this paper.

The results of ground-based and satellite (from aboard the TOMS and TOVS platforms in the framework of the SAGE and SAM projects) observations of the evolution and optical properties of the stratospheric layer formed in the Earth's atmosphere due to

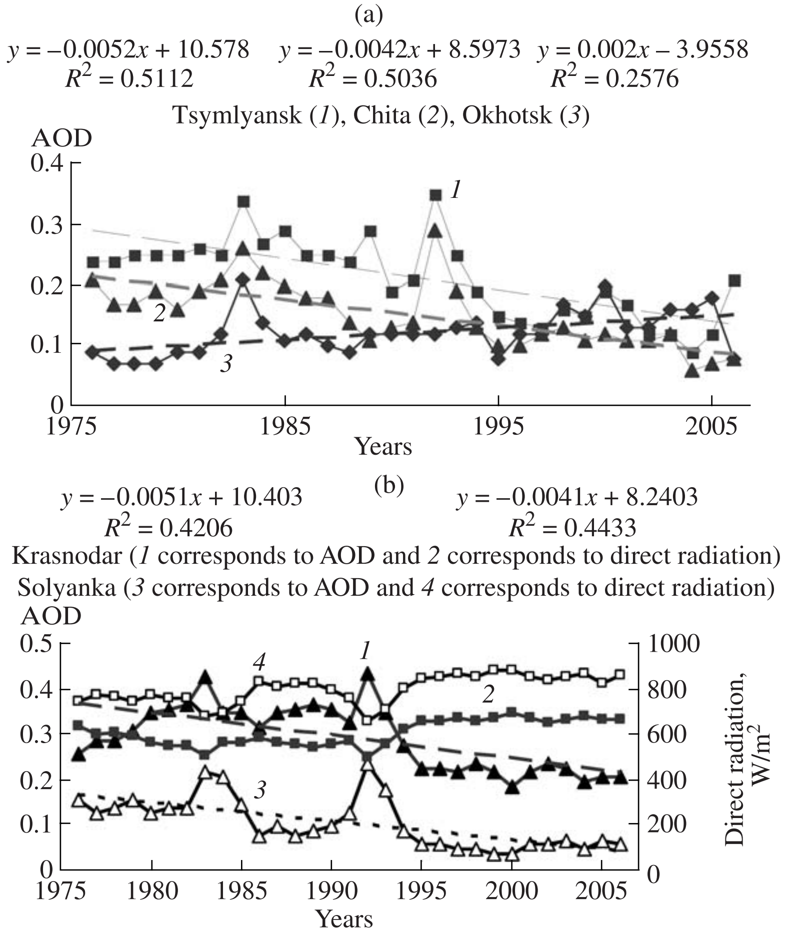

Fig. 6. Time variations in the annual values of AOD and in the flux of direct solar radiation for the Sun's height 30°: (a) multiyear variations in the annual values of AOD for three stations (Tsymlyansk, Chita, and Okhotsk) and (b) multiyear variations in the annual values of AOD and in the annual mean of direct solar radiation flux at the Sun's height 30° for the two stations with the maximum and minimum means of AOD. For both graphs, the period under analysis is 1976–2006.

the two most powerful volcanic eruptions are described in detail in [23–26]. The use of both satellite and ground-based empirical data has made it possible to create a database and then build models of the zonal and global distributions of volcanic sulfate aerosol with a vertical averaging on the basis of simplified parametric schemes of atmospheric transport [27–32].

In conclusion, we think it is reasonable to give quantitative estimates of the time evolution of AOD anomalies over the period 1976–2006 that we obtained for all the stations of the Russian actinometric network. Figure 8a shows the spatiotemporal variations in the normalized anomalies of the annual values of AOD for Russia; the AOD means were chosen as a norm for the series (with the exception of 1983–1984 and 1992–1993). The anomalies were normalized to a standard deviation of the time series for each station:

$$(\tau_{\text{year}} - \tau_{\text{aver}})/\sigma_\tau = \text{an}\tau, \qquad (2)$$

where τ_{year} is the annual mean of AOD for a given station; τ_{aver} is the multiyear mean of AOD for a given station; σ_τ is the standard deviation of the series of AOD annual values for a given station; and anτ is a normalized AOD anomaly (in parts of σ_τ).

From Fig. 8a, one can estimate the AOD anomalies in the year of eruption and, after it, the time that the maximum effect (anτ = 7–8 parts of σ_τ for 1983 and 1992) and the spatial distribution of anτ over Russia were manifested. Since 1994, the purification of the stratosphere has proceeded with the subsequent transition of the effect to the region of negative anomalies characteristic of the last decade. However, for some stations in Siberia, Transbaikalia, and the Far East (Tura, Mangut, Rudnaya Pristan, Okhotsk, and Klyuchi), positive anomalies are observed even after 1995 that are less pronounced (4–2 parts of σ_τ) and shorter than those during volcanic episodes.

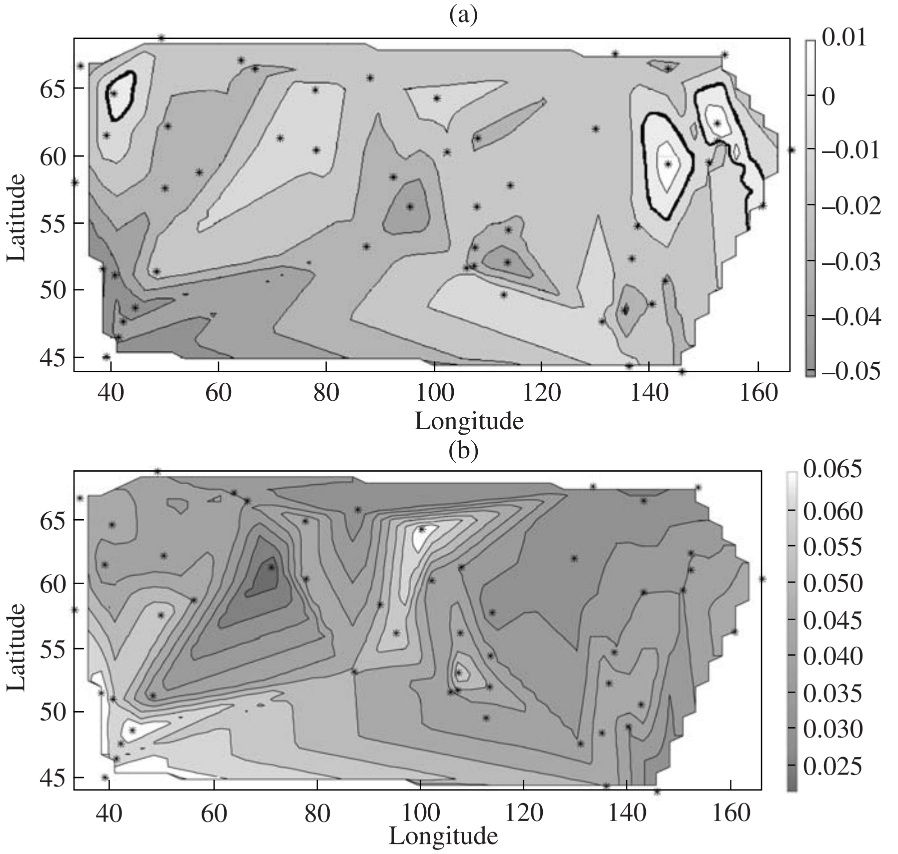

Fig. 7. Spatial distributions of the multiyear variability of AOD: (a) trends of the time variations over the past 30 years (in absolute values over 10 years) and (b) the absolute value of the standard deviation of the annual values of AOD over the entire observation period 1976–2006.

The anomalies of the annual means of surface air temperature were calculated:

$$(t_{\text{year}} - t_{\text{aver}})/\sigma_t = \text{an}\,t, \qquad (3)$$

where t_{year} is the annual mean of surface air temperature for a given station, t_{aver} is the multiyear mean of the surface air temperature for a given station, σ_t is the standard deviation of the series of the annual values of surface air temperature for a given station, and an$t$ is the normalized anomaly of t (in parts of σ_t).

Figure 8b gives the time dependences of the mean (over the stations in the south of European Russia) normalized annual anomalies of AOD (solid line) and the analogous normalized anomalies of surface air temperature (dashed line). Note that the maximum negative anomalies of air temperature were observed in 1985 and 1993, which corresponds to the years following episodes of volcanic eruptions (3 and 2 years after eruptions, respectively).

CONCLUSIONS

Our analysis has made it possible to formulate the following conclusions about the spatiotemporal distribution of AOD over Russia. The spatial distribution of the AOD values averaged over the 31-year period under consideration generally corresponds to the model of global aerosol distribution over Eurasia, which is represented in the IPCC third and fourth reports. This is manifested in the AOD decrease from the southwest to the northeast in the presence of regions with continuous increasing aerosol turbidity in southwestern and southeastern Russia. Against this background, regions with increased tropospheric aerosol loads are pronounced that have been more noticeable under the global purification of the atmosphere from the stratospheric aerosol layer that started in 1995. These tropospheric sources are related either to an anthropogenic load (cities in southern Russia, western Siberia, and Primorskii Krai) or to forest and tundra fires in Siberia, in particular, at the Tura station in the Evenki Area. One more cause of the decreased transparency in the atmosphere over eastern Russia, which is manifested in the annual means of AOD, is the volcanoes of Kamchatka. On the whole, for Russia, the trends of multiyear variations have been negative in the last decades. However, there are stations at which the AOD trends are positive; this is particularly true of the stations of Kamchatka and the Far East.

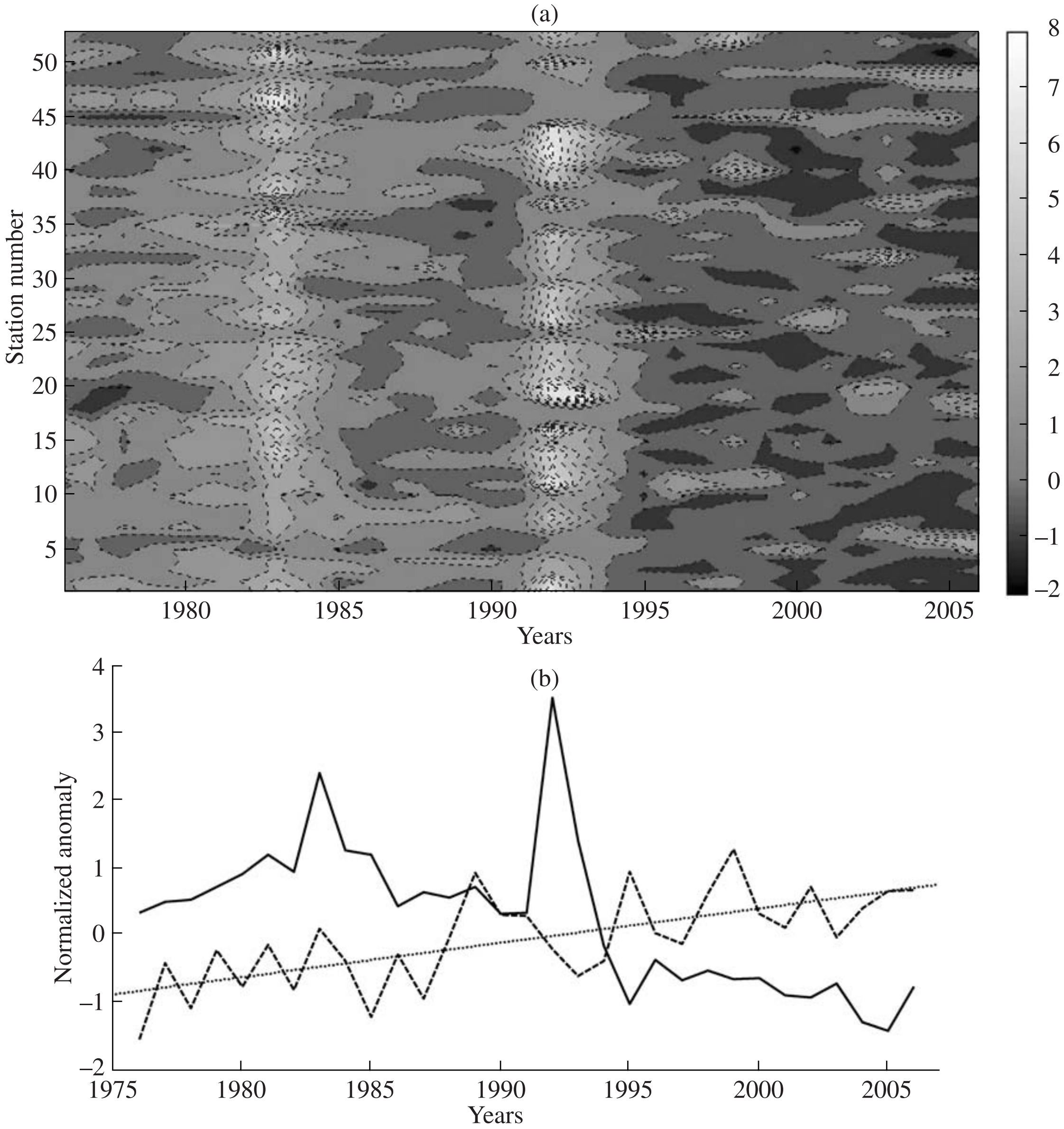

Fig. 8. (a) Spatiotemporal distributions of the normalized anomalies of the annual values of AOD over Russia during 1976–2006 and (b) the time dependences of the mean normalized annual anomalies of AOD (solid line) and surface air temperature (dashed line) for seven stations located in the south of European Russia.

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