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Variations of Aerosol Optical Thickness of the Atmosphere in Russia in 1976–2003

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Abstract—Space-time variations of aerosol optical thickness of the atmospheric column are analyzed on the basis of observational data of the Russian actinometric network in 1976–2003. From the measured direct solar radiation flux and air humidity for 44 stations in European and Asian Russia, spectral aerosol optical thickness (AOT) of the atmosphere is estimated for a wavelength $\lambda = 0.55$ μm. Interannual, seasonal, and space variations of AOT are estimated. Effects of eruptions of the volcanoes El Chichon (April 1982) and Pinatubo (June 1991) are considered. For most stations, a negative tendency is found in the AOT interannual changes, which is more pronounced in spring and summer. It is shown that the period after the Pinatubo eruption is characterized by "purification" of the atmosphere from aerosol.

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INTRODUCTION

The aerosol radiative forcing (ARF) is a component of regional climate modeling. A special feature of estimates of the atmospheric aerosol radiative effect is its large space inhomogeneity and time variability as compared, for example, with the greenhouse gases. For ARF modeling, information is necessary on space and time variations of aerosol optical thickness (AOT) of the vertical column of the atmosphere; AOT, along with angular dependence of diffusion and with single-scattering albedo, is an input parameter for calculations of the aerosol effect in the equation of radiation transfer in the atmosphere. The international AERONET network (2 stations in Russia) for more than 10 years carries out monitoring of atmospheric aerosol parameters, including AOT [17, 29]. On the basis of regional observations (from several months to several years), AOT and ARF are being estimated in the mountainous areas [25–27], in the polar regions of the Earth [9, 10, 24], and in "significant" areas, from the point of view of the magnitude and composition of aerosol loading: South China, Southeast Asia, Italy, the Arabian Peninsula, and the east coast of the United States [18, 20–22, 28, 31]. Mutual agreement of model, satellite, and surface data on AOT and ARF is analyzed in [16, 19, 23, 30]. The studies should be mentioned of the Institute of Atmospheric Physics, Russian Academy of Sciences, concerning ARF during forest fires in the Moscow region in 2002 [12, 21] and investigations of interannual regional variability of AOT and transparency carried out at the Meteorological Observatory of Moscow State University, the Main Geophysical Observatory, and the Arctic and Antarctic Research Institute [1, 4, 5, 14, 15, 24]. The paper presents estimates of space and time variations of AOT in Russia on the basis of extensive use of long-period observations of actinometric network.

EMPIRICAL DATA

At the Main Geophysical Observatory, an information-reference system called "Transparency of the Atmosphere" has been developed which provides a user with a wide set of characteristics of atmospheric transparency and allows monitoring the integral and aerosol transparency of the atmosphere in Russia. As an addition to the system, a special archive of data on transparency characteristics and associated meteorological information with a 1-day resolution is produced. For analysis, the data from 44 stations are selected, including 15 and 29 stations in European and Asian Russia, respectively (Table 1). The stations are selected taking into account the quality of the series of instrumental observations [8].

Table 1. Numbers and coordinates of the actinometric stations

Number	Station	Coordinates		Number	Station	Coordinates	
		°N	°E			°N	°E
1	Valdai	58.0	33.3	23	Babushkin	51.7	105.9
2	Umba	66.7	34.3	24	Ivolginsk	51.8	107.3
3	Nizhnedevitsk	51.6	38.4	25	Yerbogachen	61.3	107.9
4	Krasnodar, Kruglik	45.1	39.0	26	Chita	52.1	113.5
5	Kargopol	61.5	39.0	27	Mangut	49.7	112.7
6	Arkhangelsk	64.6	40.5	28	Bogdarin	54.5	113.6
7	Kamennaya Step	51.1	40.7	29	Yekaterino-Nikolskoe	47.7	131.0
8	Gigant	46.5	41.3	30	Verkhoyansk	67.6	133.4
9	Tsymlyansk	47.7	42.1	31	Khabarovsk	48.5	135.1
10	Volgograd	48.7	44.4	32	Rudnaya Pristan	44.4	135.9
11	Bugrino	68.8	49.3	33	Im. Poliny Osipenko	52.4	136.5
12	Nolinsk	57.6	49.9	34	Bolshoy Shantar	54.8	137.5
13	Ust-Vym	62.2	50.4	35	Sovetskaya Gavan	49.0	140.3
14	Chermoz	58.8	56.2	36	Tymovskoe	50.7	142.7
15	Yeletskaya	67.1	64.1	37	Okhotsk	59.4	143.2
16	Tarko-Sale	64.9	77.8	38	Ust-Moma	66.5	143.2
17	Aleksandrovskoe	60.4	77.9	39	Yuzhno-Kurilsk	44.0	145.8
18	Kuzedeevo	53.3	87.2	40	Magadan	59.5	150.7
19	Kosh-Agach	50.0	88.7	41	Srednekan	62.4	152.3
20	Yeniseysk	58.4	92.2	42	Talaya	61.1	152.4
21	Tura	64.3	100.3	43	Srednekolymsk	67.5	153.7
22	Vanavara	60.3	102.3	44	Klyuchi	56.3	160.8

The technique for calculation of AOT (that is, of spectral aerosol optical thickness at the wavelength $\lambda = 0.55$ μm) from network measurements of direct solar radiation near the surface, including estimation of integral humidity from surface partial pressure of water vapor, is suggested and described in [2, 13], with indicated limitations and estimate errors. Preliminary data on estimates of integral transparency and turbidity of the atmosphere from the network measurements during recent decades were presented in [7], where, in particular, zoning of the area has been carried out and quasi-homogeneous regions have been identified from the point of view of atmospheric turbidity conditions. Within the regions, separate stations can characterize urban (mainly with increased turbidity), rural (relatively pure), and background (pure) conditions of observations. Rural stations are situated outside the urban areas, but are subject to their effects or to the influence of point sources of pollution. Stations situated far from urban areas, with little or no anthropogenic influence, are typical of the natural background of turbidity in the region. The stations considered in the paper are situated mainly in the cities or suburbs.

The AOT estimation error caused by location of some stations (Kosh-Agach, Chita, Bogdarin, and so on) at elevations of 600 to 1700 m was determined in a numerical experiment simulating the effect of elevation on integral humidity w (in mm of precipitated water):

$$w = ae + b,$$

where e is the vapor pressure near the surface, a and b are empirical coefficients [2]. In the experiment, using standard vertical profiles of humidity, the calculations were carried out for the station elevations of 1.0 to 1.5 km. The values of AOT practically coincide with those determined using the technique of [13]; the difference for monthly mean values does not exceed 0.02, which is not higher than the error of AOT estimation from the direct solar radiation flux.

SEASONAL VARIATIONS OF MONTHLY MEAN AOT

Figure 1 shows an average annual cycle of monthly mean AOT (for the period of 1976–2003) for the stations with different levels of atmospheric turbidity: from the highest (stations of Kosh-Agach, Bogdarin) to the lowest transparency (Krasnodar, Tsymlyansk, Volgograd). For Moscow, the data on the annual cycle are taken from [11] for the period of 1961–2000. At the urban (Krasnodar, Tsymlyansk, Volgograd) and rural (Kamennaya Step, Gigant) stations, the AOT maxima occur in spring (April–May) and summer (August). In spring and summer, respectively, AOT is 60–65% and 75–85% higher than the minimum

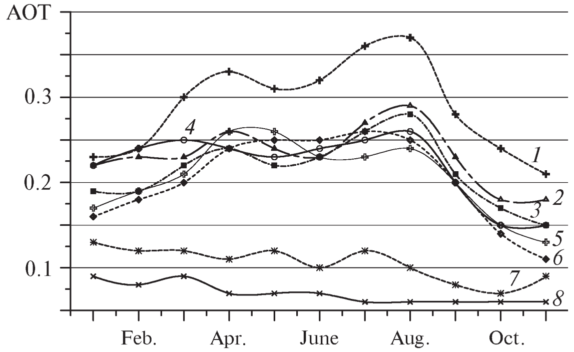

Fig. 1

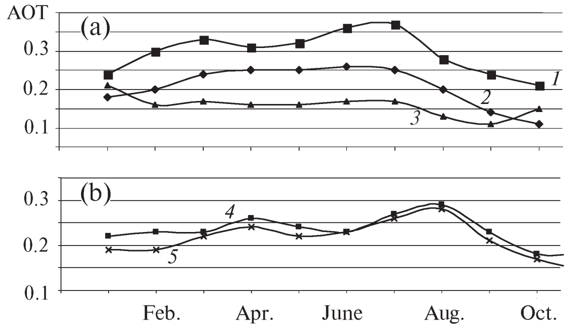

Fig. 2

Fig. 1. Long-period annual mean cycle of AOT for remote, rural, and urban stations. (*1*) Krasnodar; (*2*) Volgograd; (*3*) Gigant; (*4*) Tsimlyansk; (*5*) Moscow; (*6*) Kamennaya Step; (*7*) Bogdarin; (*8*) Kosh-Agach.

Fig. 2. Long-period annual mean cycle of AOT for stations situated (a) in different regions and (b) in the same region of European Russia. (*1*) Krasnodar; (*2*) Kamennaya Step; (*3*) Kargopol; (*4*) Volgograd; (*5*) Gigant.

monthly values observed in November–December. At the stations (Bogdarin, Kosh-Agach) situated in the areas of high and very high transparency, the seasonal variations of AOT practically vanish. The data shown in Fig. 1 cover the whole range of possible changes in monthly mean AOT in Russia: from the most turbid conditions in the south of European Russia (Krasnodar) up to the purest conditions (Kosh-Agach). The average annual cycles of AOT for the stations situated in the north (Kargopol), central (Kamennaya Step), and south (Krasnodar) parts of European Russia are displayed in Fig. 2a. In European Russia, turbidity growth from north to south is clearly seen. Both monthly values of AOT and annual cycle amplitudes are increasing. The space features of the AOT annual mean cycle are caused by a succession of climatic zones (seasonal synoptic processes determining temperature and humidity fields) and landscapes (the underlying surface structure), in conjunction with industrial loading of separate regions. Against the background of high turbidity of the atmosphere, differences in the AOT annual cycles for urban and rural stations can be minimal (Fig. 2b).

SPACE VARIABILITY OF AEROSOL OPTICAL THICKNESS

Figure 3 shows tendencies of changes in mean and average extreme AOT for the stations ranged from west to east and from north to south for the whole of Russia and for European Russia, respectively. Similar changes in aerosol optical thickness were observed during preceding decades, too [4, 6, 7, 14].

Annual mean values for 1976–2003 are presented in Fig. 3a, along with average extreme values; the stations are arranged in longitude (with latitude neglected). The AOT values typical of Russia as a whole and of European and Asian Russia separately are given in Table 2. The AOT value averaged over all stations and over the whole period is 0.15 with a variation rate of 20%, maximum annual mean of 0.29 is reached in Krasnodar, and a minimum of 0.07 is observed at the “aerosol pure” station of Kosh-Agach (Altai, 1758 m a.s.l.). The average maximum annual AOT is 0.33 with variations of 15% (maximum annual AOT values vary from 0.47 in Krasnodar to 0.19 in Kosh-Agach). For the minimum annual AOT, the value averaged over all the stations under consideration is 0.06, with variations of 30% (minimum annual AOT values vary from 0.15 in Krasnodar to 0.01 in Kosh-Agach, Fig. 3a). As can be seen from Table 2, AOT standard deviations for averaging over 1976–2003 for each station are 0.03–0.04 and are close to the standard deviations of AOT averaged over the whole area (0.02–0.03). From Fig. 3a it can be seen that high-turbidity regions in European Russia are represented by the stations of Nizhnedevitsk, Krasnodar, Tsymlyansk, and Volgograd, for which the annual mean AOT exceeds 0.20 during the whole period and 0.40 in the years with anomalous high turbidity. In Asian Russia, high AOT values (0.20 and 0.30, respectively) are found for a number of cities in eastern Siberia, for example, at the station of Chita. The stations corresponding to the regions with high transparency can be clearly determined in Fig. 3a from analysis of the long-period mean and annual minimum AOT. The mean AOT below 0.15 and minimum AOT below 0.05 can be accepted as threshold values for conditions of high transparency. In Russia, these conditions are fulfilled at a number of stations, for example, Umba, Arkhangelsk, Ust-Vym, Yeletskaya, Kosh-Agach, Bogdarin, Ust-Moma, Verkhoyansk, Magadan, and so on. As follows from Table 2, average annual minimum values of AOT in Russia as a whole and separately for European and Asian Russia are,

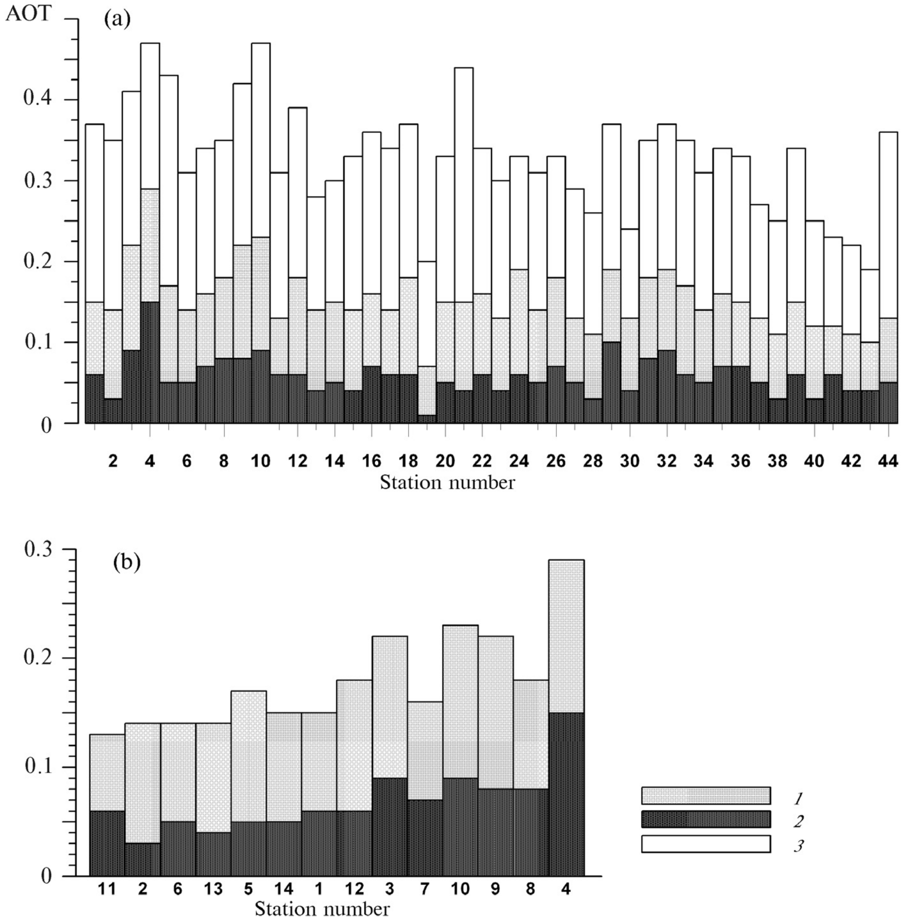

Fig. 3. Mean (*1*), mean minimum (*2*) and mean maximum (*3*) AOT for all stations arranged in (*a*) longitude (from in west to east European Russia) and (*b*) latitude (from north to south). Station numbers are given in Table 1.

respectively, 0.06, 0.07, and 0.05. For European Russia, the mean and extreme AOT values are typically higher than for Asian Russia.

The total 1976–2003 mean AOT for Russia (0.15) agrees well with the annual mean global AOT (0.14), calculated in [30] from the ECHAM-HAM aerosol climate model, in which the evolution of microphysical properties of aerosol, its size distribution, and composition (sulfates, soot, organics, sea salt, and mineral aerosol) were taken into account. The averaged values obtained from the AERONET data and from satellite data are 0.14 and 0.16, respectively [17, 19, 29].

TENDENCIES OF LONG-PERIOD CHANGES IN AOT

In Fig. 4, time changes in April mean AOT during the whole period of observations (1976–2003) are shown for separate stations. Statistical characteristics of AOT time series for April and November for the stations with different aerosol "loading" are presented in Table 3. Time changes in AOT in July are close to those in April. For all stations, there is a tendency for AOT decrease during the last 28 years, equally well-defined at the remote, urban, and rural stations; this tendency is less pronounced in the fall (the trend not exceeding 0.04/10 years) than in spring and summer (to 0.07/10years). The long-period trends of AOT and of integral transparency *P* for the atmospheric column have been estimated before [1, 3, 14, 15] for other periods and have been found to be 0.04/10 years (1960–1986), 0.03/10 years (1955–1998), 1.2%*P*/10 years (1955–1986), and 2%*P*/10 years (1967–1986). The last two estimates correspond to an AOT increase of 0.03 during 10 years. Evidently, the tendency of long-period AOT variation has changed its sign during the last 10–12 years. It can be pointed out that in Russia, "purification" of the atmosphere from aerosol takes place which is associated with the absence of large volcanic eruptions and with anthropogenic (industrial) "calm" conditions during the last 10 years. Mean AOT values for Russia as a whole, with indications of their range of variation for the last decade and for preceding 18 years, are given in Table 2.

Table 2. Annual mean AOT averaged over the stations

AOT	Period	Characteristic	Russia as a whole	European part	Asian part
Long-period mean	1976—2003	Mean	0.15	0.18	0.14
		σ	0.03	0.03	0.20
		Maximum	0.29	0.29	0.19
		Minimum	0.07	0.13	0.07
	1976—1993	Mean	0.17		
		σ	0.04		
		Maximum	0.32		
		Minimum	0.07		
	1994—2003	Mean	0.12		
		σ	0.03		
		Maximum	0.21		
		Minimum	0.04		
Maximum annual mean	1976—2003	Mean	0.33	0.37	0.31
		σ	0.05	0.05	0.05
		Maximum	0.47	0.47	0.44
		Minimum	0.19	0.28	0.19
Minimum annual mean	1976—1993	Mean	0.06	0.07	0.05
		σ	0.02	0.02	0.01
		Maximum	0.15	0.15	0.10
		Minimum	0.01	0.03	0.01

Note: σ is the rms deviation.

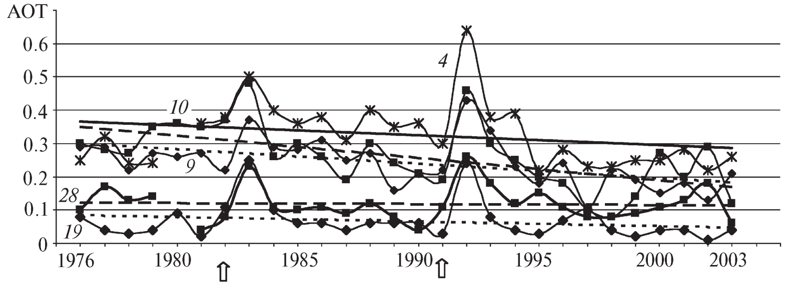

Fig. 4. Interannual changes in monthly mean AOT for April, 1976–2003. Digits near the curves denote station numbers from Table 1. The arrows show times of El Chichon and Pinatubo eruptions.

The mean and maximum AOT decrease reaches an average of 30%. Quantitative estimates of the "aerosol purification" effect of the last 10 years are shown in Figs. 5 and 6. In Fig. 5, for each station, mean AOT values are presented for two time intervals: 1976–1993 and 1994–2003. Differences in AOT from one station to another vary from 0 to 0.10, decreasing from west to east, with an average of 0.05. In Fig. 6, differences of mean AOT values for 1976–1993 are displayed for the whole time series and for the series from which 18 months after volcanic eruptions were withdrawn. The difference values are of minimum significance (0.01–0.02). That is, whereas a local effect of the AOT increase can reach 100%, as can be seen from Fig. 4, the averaged effects, within our consideration, are minimal.

CONCLUSIONS

The aerosol optical thickness is an important characteristic of the atmospheric climate. The application of the AOT estimation technique for processing the results of observations at the actinometric network stations allows obtaining qualitatively new and detailed information on the level of aerosol pollution of the atmosphere in separate regions and in Russia as a whole. The analysis of AOT variations during the last 30 years shows the following results:

Table 3. Characteristics of AOT series in April and November 1976–2003

Station	$\overline{\text{AOT}}/\sigma$		Equation of linear trend, R^2	
	April	November	April	November
Krasnodar	0.33/0.07	0.21/0.05	$y = -0.003x + 0.369$ $R^2 = 0.10$	$y = -0.003x + 0.251$ $R^2 = 0.11$
Kamennaya Step	0.26/0.07	0.14/0.04	$y = -0.004x + 0.301$ $R^2 = 0.10$	$y = -0.003x + 0.175$ $R^2 = 0.16$
Gigant	0.25/0.06	0.15/0.06	$y = -0.001x + 0.263$ $R^2 = 0.02$	$y = -0.002x + 0.180$ $R^2 = 0.03$
Tsymlyansk	0.24/0.05	0.13/0.06	$y = -0.004x + 0.305$ $R^2 = 0.25$	$y = -0.004x + 0.200$ $R^2 = 0.21$
Volgograd	0.26/0.07	0.21/0.11	$y = -0.007x + 0.358$ $R^2 = 0.11$	$y = 0.004x + 0.150$ $R^2 = 0.03$
Kosh-Agach	0.07/0.04	0.05/0.03	$y = -0.001x + 0.087$ $R^2 = 0.04$	$y = -0.001x + 0.070$ $R^2 = 0.05$
Bogdarin	0.12/0.04	0.09/0.04	$y = -0.000x + 0.123$ $R^2 = 0.02$	$y = -0.003x + 0.134$ $R^2 = 0.16$

Note: $\overline{\text{AOT}}$ is the monthly mean value; R^2 is the determination coefficient.

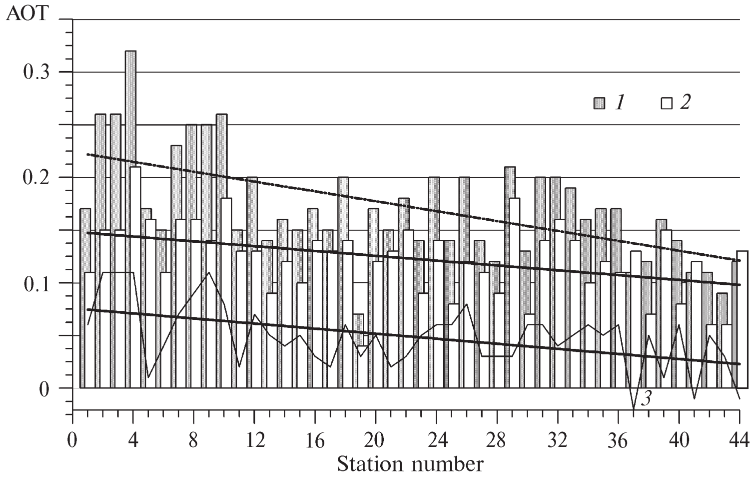

Fig. 5. Annual mean AOT for (*1*) 1976–1993 and (*2*) 1994–2003 and (*3*) their difference. Straight lines denote linear trends. (*1*) $y = -0.0023x + 0.2441$; $R^2 = 0.343$; (*2*) $y = -0.0012x + 0.1506$; $R^2 = 0.191$.

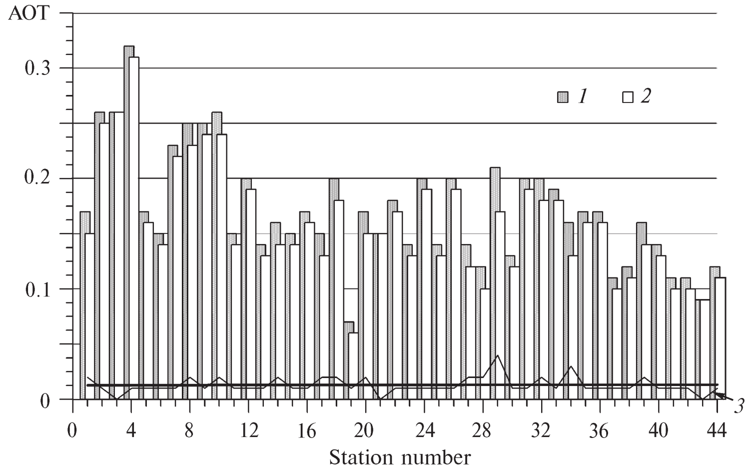

Fig. 6. Annual mean AOT for (*1*) 1976–1993 and (*2*) for the same period with removal of the years of the volcanic eruption influence and (*3*) their difference.

(1) The character of the long-period annual cycle of AOT did not change as compared with the preceding decades. For most stations, the AOT typically increases in spring and summer by 60–80% with respect to its minimum values in November–December. The AOT increase in spring and summer is associated with a seasonal increase in temperature and humidity and with changes in the underlying surface, as well as with a more intense photochemical and condensational generation of aerosol and with a flux of aerosol from the soil to the atmosphere;

(2) The main factors of space changes in the AOT annual cycle are a latitudinal succession of climatic and landscape zones, in combination with higher industrial loading of the southern regions of European Russia, as compared with the northern ones, and with higher industrial and urban development of European Russia as compared with Asian Russia;

(3) Total averaged AOT over all stations and the whole period under study (0.15) is very close to the annual mean global AOT value (0.14) calculated from the ECHAM-HAM model and to the estimates obtained from satellite data (0.16);

(4) Maximum annual mean AOT (0.29) is reached in Krasnodar, and the minimum one (0.07) is observed at the "aerosol pure" station of Kosh-Agach. The averaged time changes (standard deviations from the annual cycle for each station) are within 0.03–0.04 and are equal to mean space changes (standard deviations of mean AOT over all stations) which are found to be 0.02 to 0.03;

(5) Minimum annual mean AOT values for Russia as a whole and for its European and Asian parts are, respectively, 0.06, 0.07, and 0.05;

(6) Average and maximum annual AOT values increase at the stations located from north to south in European Russia and decrease from west to east in the whole of Russia;

(7) "Purification" of the atmosphere from aerosol is caused by the absence of large volcanic eruptions and by industrial "calm" conditions during the last decade. The mean AOT for the last decade is 30% lower than in the preceding 18 years, both for maximum and average values. Negative tendencies are almost similar for remote and urban (as well as for rural) stations; they are less pronounced in the fall than in spring and summer;

(8) Local effect of the AOT increase due to volcanic eruptions can reach 100%, while the average effects, within our consideration, are minimal.

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