Temporal variability of atmospheric aerosol optical depth over European territory of Russia according to data of the ground-based and satellite observations: tendency of aerosol “enlightenment”

Temporal variability of atmospheric aerosol optical depth over European territory of Russia according to data of the ground-based and satellite observations: tendency of aerosol "enlightenment"

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Abstract. The results of studies of atmospheric aerosol over the territory of Russia are of great interest from the point of view of ecological and climatic problems. The paper presents the results of spatial and temporal variability of Aerosol Optical Depth (AOD) over the European territory of the Russian Federation in the period 1999 – 2016 yy. The assessments were carried out using the original AOD extraction method based on ground-based observations of the Russian actinometric network, and also on the satellite observations of MODIS. The general regularities of spatial variations in the aerosol optical depth over Russia are revealed: 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. The AOT increase in spring and summer is associated with a seasonal increase in temperature and humidity and with changes in the underlying surface. "Purification" of the atmosphere from aerosol is caused by the absence of large volcanic eruptions and by industrial "calm" conditions during the last decade. Negative tendencies are less pronounced in the fall than in spring and summer. To compare the atmospheric AOT values obtained from the MODIS, AERONET and GMS data, we have compiled a combined archive of daily AOT values synchronized in pairs for the 3 types of observations (GMS, MODIS and AERONET): "Aerosol optical thickness of the atmosphere by satellite and ground observations ". The data of the comparison of terrestrial and satellite data for AOD are presented only in averaged form and need further consideration.

1. Introduction

The aerosol optical thickness of the atmosphere (AOD) is an important parameter in assessing climatic changes: changes in the temperature of the underlying surface and changes in the incoming total solar radiation [1-3]. The factors causing the space-time variations of AOD are diverse both in terms of the degree of impact and the sign of the changes they make to the flux of solar radiation coming to the Earth's surface: volcanic stratospheric sulfate aerosol, anthropogenic industrial and heating aerosol, black and red carbon entering atmosphere due to forest, tundra and marsh fires, and finally, a mineral aerosol of desert and steppe regions, carried along with the air mass, depending on the type of atmospheric circulation, characteristic for this region. At present, work is under way to analyze the possibilities of using satellite data to estimate the spatio-temporal distribution of aerosol, when satellite data (for example, MODIS) and ground observations (AERONET networks and/or actinometric networks of the Russian Federation) are considered spatially over 10-year time intervals changes in AOD of a regional nature and the causal factors of these changes are identified [4-20]. Ultimately, the variability of AOT is used to simulate the temporal evolution and regional changes in the radiation effects of an aerosol in the atmosphere, radiative forcing at the Earth's surface [21-26].

2. Research objective

The aim of the work in the framework of the above problems is to analyze the systematic spatial and long-term temporal changes of AOT over the European territory of Russia with the characteristic features of the variations and the sources of aerosol. At the same time, we used both data from network ground-based actinometric observations of ROSHYDROMET (GMS) [27] and satellite data (http://modis.gsfc.nasa.gov), examples of which are given in [28-31].

3. Analysis of AOD observations over ETP

Network observation stations system and empirical data will be described now. A map showing the location of 18 actinometric stations of the Russian network for which the AOD of vertical atmospheric column were estimating for a wavelength of 0.55 μ is presented in Figure 1. These stations cover a large part of European territory of Russia and are located outside the zones of direct local anthropogenic sources of industrial and municipal aerosol emissions (suburbs, rural areas, uplands, etc.). An analysis of the AOD of a vertical atmospheric column can be made 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 time variations. The integral air transparency:

$$P = (S/S_0)^{1/2} \qquad (1)$$

where S is the direct solar radiation to the normal to flux surface, reduced to the average distance between the Earth and the Sun and a solar altitude of 30°; S_0 is the solar constant equal to 1.367 kW/m2. On the basis of 1) 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, 2) some semi-empirical approximations, 3) evaluations of the integral (total) and aerosol transparency, it is possible to analyze variations in the AOD of a vertical atmosphere. The procedure for extracting AOD and subsequent estimates is presented in [4-5]. So now we shall analyze variations in the AOD of a vertical atmosphere on the basis of the 1999–2016 y.y. observational data obtained at 18 actinometric stations.

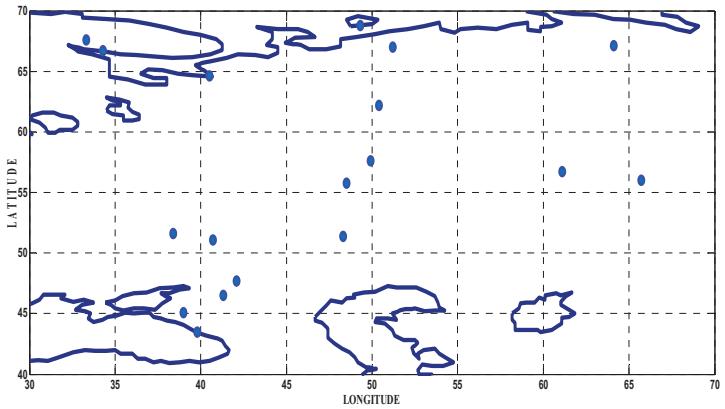

Figure 1. The map is a diagram of the location of 18 stations (SMS) on ETP: Sochi (43.5, 39.8), Krasnodar (45.1, 39.0), Gigant (46.5, 41.3), Tsimlyansk (47.7, 42.1), Kamennaya step (51.1, 40.7), Ershov (51.4, 48.3), Nizhnedevetsk (51.6, 38.4), Vyasovye (55.8, 48.5), Pamyatnya (56.0, 65.7), Verhnee Dubrovo (56.7, 61.1), Nolinsk (57.6, 49.9), Ust Vym (62.2, 50.4), Arkhangelsk (64.6, 40.5), Umba (66.7, 34.3); Kotkino (67.6, 51.2), Eletskaya (67.1, 64.1), Apatity (67.6, 33.3), Bugrino (68.8, 49.3).

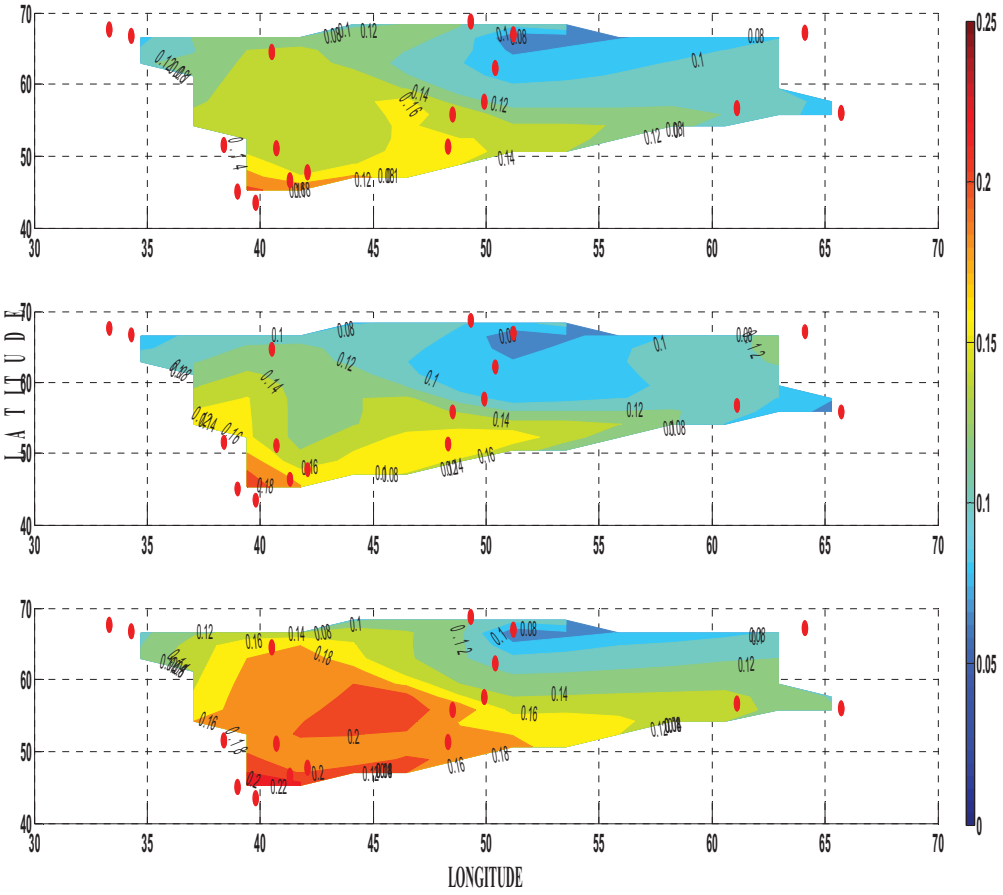

Figure 2. Spatial distribution of the values of Annual, April and July (from top to bottom) values of AOD over ETR; by the data of the actinometric terrestrial network of the Russian Federation. Observation period -- 1999-2016 yy.

The spatial variations of the AOT are shown in the diagrams in **Figure 2**. To interpolate the data of the stations shown in **Figure 1**. MATLAB package is used for the region under consideration: the option of creating a uniform grid for the ETR region in question, the option of performing bilinear interpolation (horizontally and vertically) of the data of 18 stations on the territory (40 ° -70 ° N, 30 °-70 °), the projection of the function T = F (φ, λ) onto the data grid, where φ and λ are the latitude and longitude respectively for each of the observation points. The spatial distribution of the mean values (for annual, April and July AOD) corresponds to the results obtained earlier [4-5] for the mean long-term values of the aerosol optical thickness of the atmosphere over the time interval 1976-2011 yy. In the post-volcanic period 1999-2016 yy. there is also a decrease in AOD from southwest to northeast, the localization of regional tropospheric sources of aerosol is not visible, except for Arkhangelsk, for which there is a summer increase in AOD. Perhaps there is a systematic local source of aerosol release into the atmosphere. The source may be due to both natural summer fires and anthropogenic industrial emissions in this area.

Long-term series of mean monthly values of AOT obtained from data of the terrestrial actinometric network of the Russian Federation (18 GMS stations) and time series of AOD based on the data of the MODIS (Moderate-resolution Imaging Spectroradiometer) satellite spectrometer for a wavelength of 550 nm with a resolution of 1 × 1 ° are also investigated here.

Spatial distributions of multi-year variability of aerosol optical depth (AOD) over ETR, tendencies of temporary changes, in Annual, April and July (from top to bottom) (in absolute values over 10 years) are presented in Figure 3.

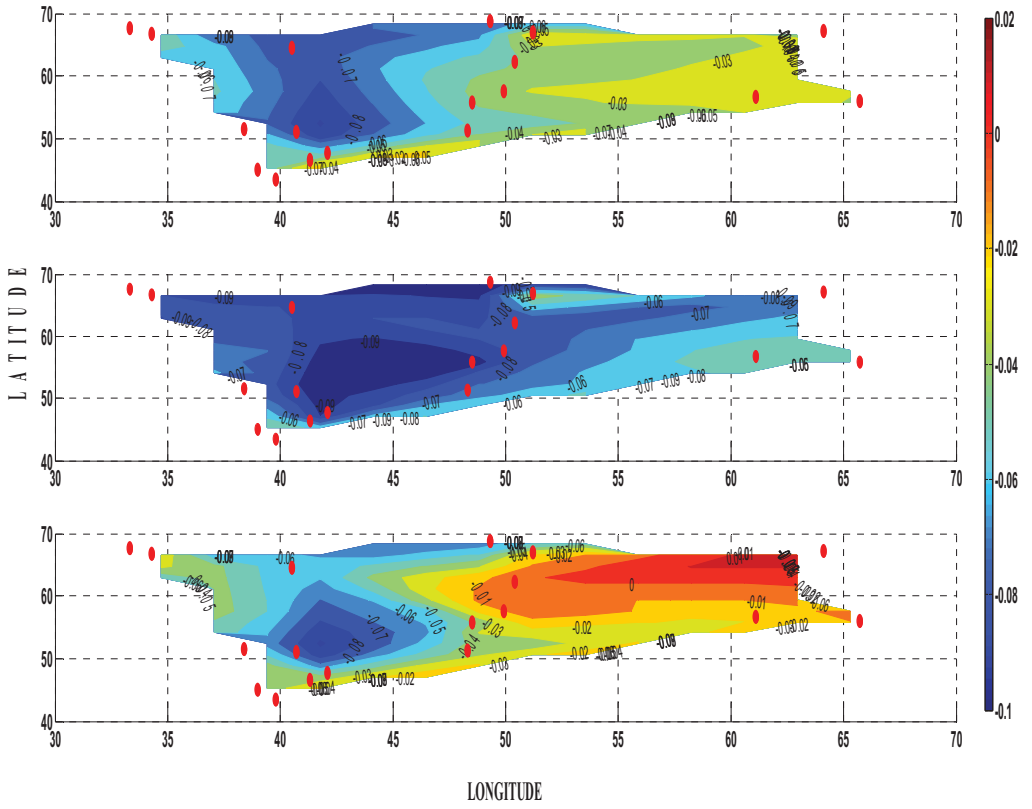

Figure 3. Spatial distributions over ETR of multi-year variability of aerosol optical depth (AOD): "trends" of temporary changes in Annual, April and July (from top to bottom) (in absolute values over 10 years). Observation period 1999-2016; data of the actinometric terrestrial network (GMS).

At the majority of observation points, the process of "purifying" the atmosphere from the aerosol occurs (see also [32-33]). In general, the trend of AOT changes is negative for the Russian region (Figure 3), while the value of the absolute value of the trend (over 10 years) varies from (-0.10) in the south-west of the ETP to (+ 0.02) in the north-east of the ETR, respectively. The average value of the absolute value of the annual AOT trend is -0.04 for 10 years, the maximum is 0.02 for 10 years, and the minimum value is -0.10 for 10 years, with a determinism coefficient of no more than 0.5. The average values of AOD for the region and the simplest statistics are given in Table 1.

Table 1. Average values of AOD and average tendencies of AOD changes over ETR for terrestrial (1999-2016 yy.) and satellite data MODIS (2002-2016 yy.)

AOD	Yearly values	April values	July Values
AOD (terrestrial GMS network) range of variation, standard deviation	0.13 (0.22-0.08); 0.04	0.13 (0.25-0.05); 0.04	0.16 (0.28-0.08); 0.05
Trend, referred to a 10-year interval (terrestrial GMS network)	-0.03 $R^2 = 0.50$	-0.07 $R^2 = 0.61$	-0.03 $R^2 = 0.50$
Trend (% per year)	-3.6	-6.1	-2.0
AOD (satellite data MODIS) range of variation, standard deviation	0.16 (0.23-0.12) 0.03	0.16 (0.31-0.07); 0.07	0.22 (0.35-0.14); 0.05
Trend, referred to a 10-year interval, (MODIS satellite data)	-0.0005 $R^2 <<$	-0.005 $R^2 = 0.41$	+0.002 $R^2 <<$

The latitudinal-temporal variations of the Annual, April and July AOD shown in Figure 4 are due to the following factors:

1. The obvious negative tendencies of AOD changes in time are manifested in all seasons of the year, which indicates the global processes of atmospheric purification from aerosol in the post-volcanic period. The average gradients over the past 18 years were 0.06 / 18 years (for annual values), 0.07 / 18 years (for April) and 0.04 / 18 years (for July);
2. The values of AOD as a whole decrease monotonically in all seasons in the direction from the south to the north: the spatial differences for the data presented by us are 0.08 (annual AOD), 0.08 (April AOD) and 0.12 (July AOD), 0.02 (February AOD), which indicates the circular nature of the formation of a spatial pattern of the distribution of AOD;
3. The growth of AOD in the spring-summer seasons is formed under the influence of seasonal changes in the nature of the transfer of air masses to the region (ETR) from the southeast regions with a high aerosol content, seasonal changes in temperature, humidity and the state of the underlying surface. This is especially apparent for southern stations, here in the summer, tropical air masses predominate, saturated with aerosol and moisture from the tropical and desert regions of Eurasia. Spring increases are due to the disappearance of the snow cover and the change in the dominant Arctic air masses to temperate or tropical ones;
4. In all seasons, especially in summer, aerosol inhomogeneities, localized in time and space are manifested and are more pronounced in summer seasons.

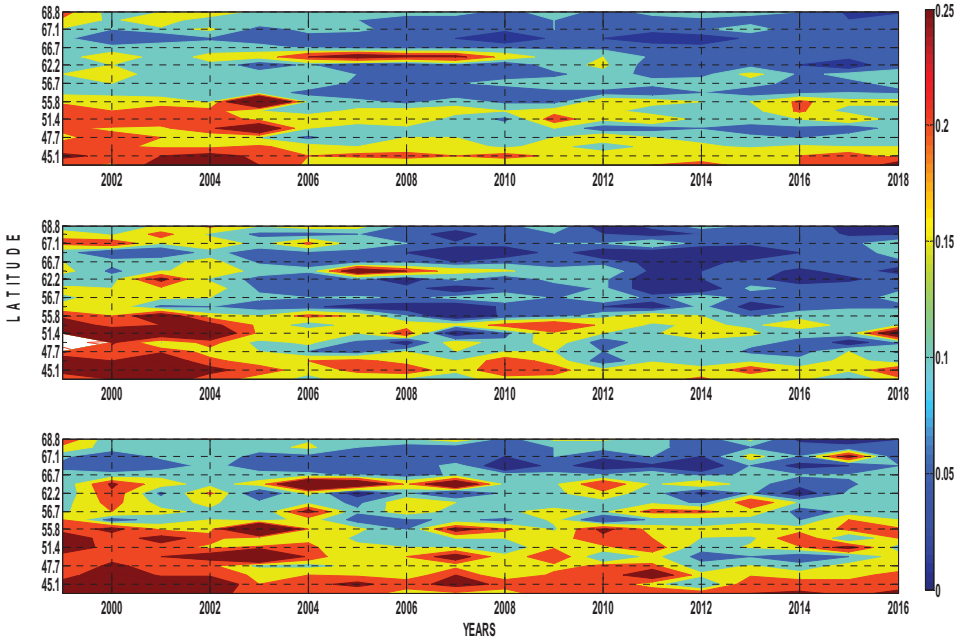

Figure 4. Spatio-temporal variations of Annual, April and July (from top to bottom) AOD on ETR; data (GMS) of the actinometric terrestrial network. Observation period -- 1999-2016 yy.

Table 1 summarizes the above ground network data. In addition, the satellite data that was downloaded via the specialized server Giovanni https://giovanni.gsfc.nasa.gov/giovanni, in particular, the time series of the average monthly values of AOD for MODIS TERRA (MOD08_M3_v.6) (personal communications) are given. In principle, a joint analysis of aerosol weakening by independent observing systems makes it possible to obtain more justified estimates of time trends and spatial changes in AOD, but in practice the analysis of data obtained by independent systems is a complex and ambiguous comparison problem in the absence of reference data. More detailed comparisons, as well as the reasons for the discrepancies, are necessary and will be carried out in the future.

4. Database "Aerosol Optical Thickness of the Atmosphere from Satellite and Surface Observations"

Based on the presented estimates from observational data, the relevance of comparing the AOD values obtained from the data of independent observational systems is obvious. To compare the atmospheric AOD values obtained from the MODIS data, AERONET and GMS, we generated a combined archive [34] of daily AOD values synchronized in pairs for the 3 types of observations (GMS, MODIS and AERONET). Synchronized series of AOD were obtained mainly for the warm season (in the period from March-April to September-October) and practically absent in the winter months. About 15 pairs of comparison have been created. The data of the third level (daytime) for AOT (Optical_Depth_Land_And_Ocean) for a wavelength of 550 nm with a resolution of 1 × 1 ° were used. An example of a comparison of satellite and ground-based observations of AOD obtained at the some ETR stations is presented in Table 2. During the analysis, the "manual" culling of the AOD values was carried out, the situations when the AOD differed by more than 3 times were discarded.

Table 2. An example of comparing ground-based and satellite AOT values (2002-2016 y.y.) for six stations located on the ETR; stations are ranked in latitude from south to north; the row length and standard deviation from the average are also indicated

	AOD		AOD (pre-filtering)	
	GMS	MODIS	GMS	MODIS
Sochi (43.5, 39.8)	0.17 (0.13)	0.18 (0.14)	0.18 (0.11)	0.17 (0.10)
Number of days	2107	2107	1578	1578
Krasnodar (45.1, 39.0)	0.20 (0.11)	0.19 (0.14)	0.19 (0.10)	0.20 (0.12)
Number of days	2199	2199	1763	1763
Gigant (46.5, 41.3)	0.16 (0.11)	0.18 (0.14)	0.17 (0.11)	0.17 (0.12)
Number of days	1837	1837	1254	1254
Nolinsk (57.6, 49.9)	0.11 (0.09)	0.19 (0.23)	0.13 (0.09)	0.15 (0.11)
Number of days	921	921	573	573
Umba (66.7, 34.3)	0.08 (0.05)	0.14 (0.16)	0.09 (0.05)	0.11 (0.07)
Number of days	886	886	632	632
Bugrino (68.8, 49.3)	0.11 (0.07)	0.15 (0.16)	0.12 (0.06)	0.13 (0.08)
Number of days	837	837	594	594

As can be seen, the average AOT values for terrestrial and satellite data with a sample of a thousand or more days (for conventionally “southern” 3 observation points) turned out to be close both in terms of average values and in the range of variations (standard deviation from the average for synchronized series). The average discrepancies were 6% for synchronized rows and 0% for rows with pre-filtering. For conventionally “northern” observation stations, the corresponding values amounted to tens of percent, even in the case of preliminary filtering. It should be noted that averaging of several hundreds years and more is required for parameterization of models and validation of results in regional climatic schemes [1-3]. At the same time, the trend of temporary changes in the time interval 2002-2016 y.y. are negative, but statistically not significant.

5. Conclusion

1. The spatial distribution of AOD values, average for the 18-year-old post-volcanic review period, corresponds to the model of the global distribution of atmospheric aerosol over Eurasia, presented in the 3rd and 4th IPCC reports. This is manifested in the decrease of AOT from southwest to northeast by ETR in the presence of regions of constant high aerosol turbidity in the south-west of the ETR, due to the type of seasonal atmospheric circulation in these regions.
2. The trends of long-term changes in AOD over the past 18 years are steadily negative: the atmosphere clears the aerosol. Negative tendencies of AOD changes coincide with trends typical for developed countries of Europe and North America, they are caused both by stabilization of production facilities and by technologies of atmospheric purification from aerosol emissions.
3. The average daily values of AOT for terrestrial and satellite data with a length of rows of several hundred or a thousand days are quite close both in terms of average and in the range of variations (for example, 6 stations per ETR). Note that it is averaging over several years or more that is required for parameterization of models and validation of results in regional climatic schemes.

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