Peculiarities of many-year variations of atmospheric aerosol optical thickness and estimates of influence of different factors

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Data of many-year (1992–2007) observations of atmospheric transparency in the region of Tomsk city are used to analyze spectral features of the inter-annual variations of aerosol optical thickness (AOT) in the visible and near-IR spectral ranges. We present statistical characteristics of the spectral AOT and Angström parameters, as well as discuss the causes of their inter-annual variations. Results of comparison with data from other regions in the post-volcanic (after 1994) period have shown the absence of a significant trend and a small difference of AOT in three quite different regions of Russia (Moscow, Bugrino, and Tomsk). For the Moscow region, we discuss characteristics of the trend for a longer time period, from 1955 to 2007. It is shown that there is no direct significant relation to the cycles of the solar activity in many-year AOT variations in all considered regions.

Introduction

To reveal the reasons of recent changes in the climate, it is necessary to analyze the long-term variability of radiation-meaningful geosphere components in their relation to global factors, which can have certain impacts on the process. Aerosols occupy an important place among atmospheric components (along with greenhouse gases and cloudiness), and the main characteristic of their radiative interaction is the aerosol optical thickness (AOT) of the atmosphere.

Inter-annual variability of characteristics of the atmosphere aerosol turbidity over Russia has been analyzed by many specialists.[1–4] The longest series of AOT, retrieved from actinometric measurements at a wavelength of 0.55 μm [Ref. 5] were discussed earlier in detail.[6–8] There are several reasons to return to this problem. First, it is necessary to reveal spectral peculiarities in variations of AOT under conditions of a particular region; second, to determine more accurately quantitative characteristics of AOT variation, taking into account the recent data (up to 2007, inclusively), and third, to compare the data for typical regions of European and Asian parts of Russia.

Besides, it is necessary to discuss some publications,[9,10] authors of which relate the significant increase in the aerosol turbidity in the beginning of 80s and 90s with cycles of solar activity. This point of view continues to be the object of discussions at different conferences.

1. Inter-annual variability of spectral AOT in the Tomsk region

Measurements of the spectral transparency of the atmosphere within a wavelength range 0.37–1.06 μm were started in Tomsk in 1992 and regularly carried out in a series (2–3 months), mainly in the warm season. Since 2000, measurements became all-the-year-round, and the wavelength range was extended to 4 μm.[11] Specifications of the used sun photometers and the techniques of AOT (τ^a_λ) calculation are presented in Refs. 12 and 13.

To estimate the inter-annual variability of the spectral AOT of the atmosphere, we have used a longer series of summer observations. First, mean τ^a_λ values were calculated from the obtained data for individual days, then the monthly-average and summer-average values were calculated for each year. The AOT of the atmosphere was determined at many wavelengths; for brevity, we consider the following parameters: 1) values of τ^a_λ in three regions of the short-wave spectral range; 2) parameters α and β of the Angström formula $\tau^a(\lambda) = \beta\lambda^{-\alpha}$; 3) estimates of the coarse τ_c and fine τ_f (within 0.5 μm range) components of AOT. Let us explain the technique for determining two components of AOT.

It was shown earlier[14] that AOT of the atmosphere in 1–4 μm wavelength range, as well as the coarse component of AOT are close to the parameter β and connected with it by the linear dependence. For example, the magnitude of τ_c under summer conditions can be estimated by the formula $\tau_c = 0.01199 + 0.706\beta$. Correspondingly, the fine component τ_f is calculated as the residue of the total thickness at a given wavelength: $\tau_f = \tau^a_{0.5} - \tau_c$.

The long-term behavior of the aforementioned characteristics of AOT in the region of Tomsk is shown in Fig. 1.

Variations of the characteristics (decrease of AOT and increase of α in the first period (1992–

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1994) are related with cleaning of stratosphere from the products of Mt. Pinatubo eruption (see below for details). Instability of the data in the middle part is caused, to some extent, by irregularity of our observations at that time (missed measurements in 1996 and 1998).

Consider the characteristics of AOT during the last years in more detail, when measurements were carried out more regularly (all-the-year-round) and in all cases when the sky was free of clouds. Statistical characteristics for this period are presented in Table 1: mean values, root-mean-square deviation σ, and variation coefficients $V = (\sigma/\bar{x})$. Taking into account that the law of τ^a_λ distribution differs from the normal one (close to lognormal), the most probable (modal) values of all parameters were additionally determined. It is seen in Tables 1 and 2 that the distribution of AOT is asymmetrical: the probable values are approximately by 30% less than mean values.

The frequency distribution of the Angström exponent is more close to normal, the mean value α under summer conditions in Tomsk is equal to 1.45.

The total range of AOT variability during nine years is rather noticeable: for example, $\tau^a_{0.5}$ changed from the minimum (0.107) in 2001 up to maximal value (0.19) in 2005. The undulatory oscillations with a period of about 3 years are seen in the temporal behavior of AOT, and there are no reasons yet to search for the trend component. Inter-annual variations of τ^a_λ are better pronounced in the short-wave spectral range and decrease as the wavelength increases. Minimal relative variability is characteristic of the coarse component τ_c, and maximal of the fine one τ_f, i.e., submicron aerosol plays the predominant role in the AOT variability. It should be also noted that the long-term τ^a_λ behavior is in agreement with variations of annual-average values of the submicron aerosol mass concentration in the near-ground layer[15]: maxima in 1999, 2003, 2005, and the minimum in 2001.

Main reasons of inter-annual AOT variation in post-volcanic period, in our opinion, are the following: 1) instability of circulations and synoptic conditions; 2) different repetitions and intensities of forest fires, characteristic of boreal zone. Data for the fire-dangerous seasons (May–September), kindly given us by the Tomsk Station of the Forest Protection Service ("Avialesookhrana") confirm the above-said: maxima of fires and burning areas were observed in 1999, 2003, and 2004, minima – in 2001, 2002, and 2007.

As for synoptic conditions, 2001 and 2003 years were anomalous for the region of Tomsk.[16] For example, the summer of 2001 can be considered as "cyclonic": the repetition of cyclones was twice greater than in neighboring years, and the quantity of anticyclones was noticeably lower than in the long-term period. Precipitations occur most often at the cyclonic weather; they wash-out aerosol, decrease the probability of forest fires, and, hence, increase the atmospheric transparency. The aforementioned peculiarities are in agreement with the character of AOT variations shown in Fig. 1.

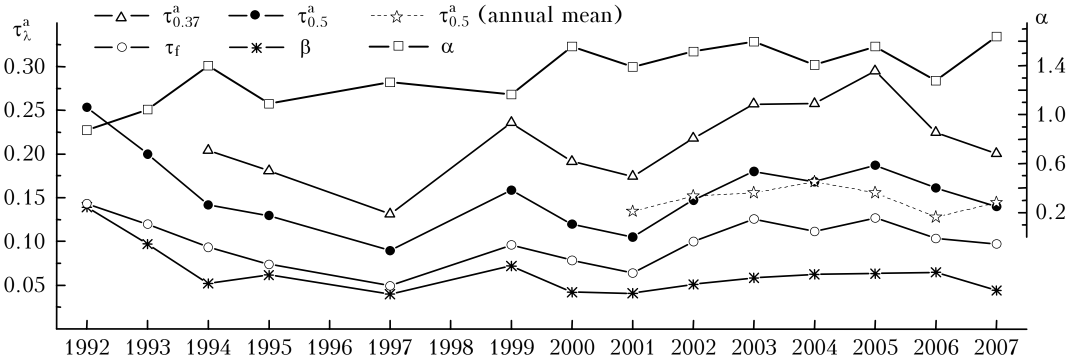

Fig. 1. Inter-annual variability of the AOT characteristics: $\tau^a_{0.37}$, $\tau^a_{0.5}$, α, β, and τ_f (dot line shows the change of inter-annual values of $\tau^a_{0.5}$).

Table 1. Statistical characteristics of AOT in the region of Tomsk in 1999–2007

Parameter	$\tau^a_{0.37}$	$\tau^a_{0.5}$	$\tau^a_{0.55}$	$\tau^a_{0.87}$	α	β	τ_c	τ_f
mean	0.229	0.152	0.133	0.068	1.45	0.056	0.052	0.10
σ	0.060	0.040	0.036	0.019	0.21	0.016	0.013	0.031
V	26.2	26.3	27	27.9	14.5	28.6	25	31
mode	0.17	0.11	0.09	0.045	1.50	0.035	0.038	0.05

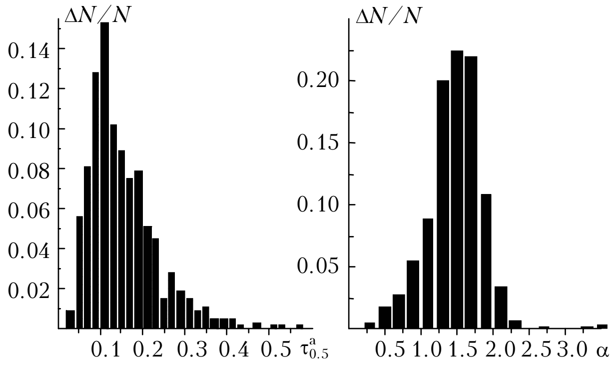

Fig. 2. Histograms of distributions of $\tau^a_{0.5}$ and α in summers of 1999–2007.

The considered long-term variability of AOT is related to summer measurement period, therefore, it was of interest to estimate the degree of the difference between the summer-average and annual-average values of AOT. Such a comparison was carried out for the period of all-the-year-round observations (Table 2).

Table 2. Comparison of the annual-average and summer-average data in the Tomsk region (2001–2007)

Mean characteristics	$\tau^a_{0.37}$	$\tau^a_{0.55}$	$\tau^a_{0.87}$	α
year	0.217±0.020	0.128±0.023	0.073±0.009	1.31±0.17
summer	0.233±0.040	0.136±0.023	0.068±0.012	1.49±0.12
difference (year–summer), %	–7.12	–5.75	7.27	–13.1

It follows from the presented data that the difference in AOT is better pronounced at edges of the spectral range due to seasonal variability of selectivity of the AOT spectral behavior (see variations of α). The difference of summer AOT from annual one in the middle of the visible spectral range is small: more often, summer values are greater that the annual (see dot curve in Fig. 1), and the mean increase is less than 6%. Hence, the summer-mean AOT over Tomsk can serve as an estimate of annual mean (with accounting for the correction by 6%).

At the same time, due to the less scale of averaging, summer data undergo the effect of different factors (for example, forest fires) and show greater inter-annual variations. Note that the difference between summer and annual AOT values in Moscow is quite significant: 27%, in average, for the last years. This is caused by the fact that the amplitude of seasonal variations in large cities, as well as summer values of AOT (in comparison with annual ones) is larger than in clearer regions at the south-west of European part of Russia and in the central regions of Siberia.[4,8]

2. Comparison of the AOT variability in different regions in 1990–2007

Let us compare, to what degree the data on variability of AOT in Tomsk (56.5°N, 85°E), representing the typical region of Siberia, are in agreement with the data for other regions. In our experiments, we did not plan to analyze spatial nonhomogeneities of the aerosol turbidity, which were considered in detail in Refs. 4, 8, and 17. So, we bounded ourselves by comparison of the results only for three typical regions located in different climatic zones, namely 1) Meteorological Observatory of the Moscow State University, 55.7°N, 37.5°E; 2) Actinometric Station in Bugrino, 68.8°N, 49.3°E, [Ref. 8]; 3) Antarctic Station Mirnyi, 66.3°S, 93°E [Refs. 18 and 19]. The selection of the high-latitude station Burgino (island Kolguev) as an example is caused by the fact that correlation of AOT with solar activity was noted by authors of Ref. 9 just for high latitudes.

Temporal behavior of AOT of the atmosphere in the aforementioned regions together with data on solar activity – Wolf numbers R http://sidc.oma.be/html/sunspot.html), are shown in Fig. 3.

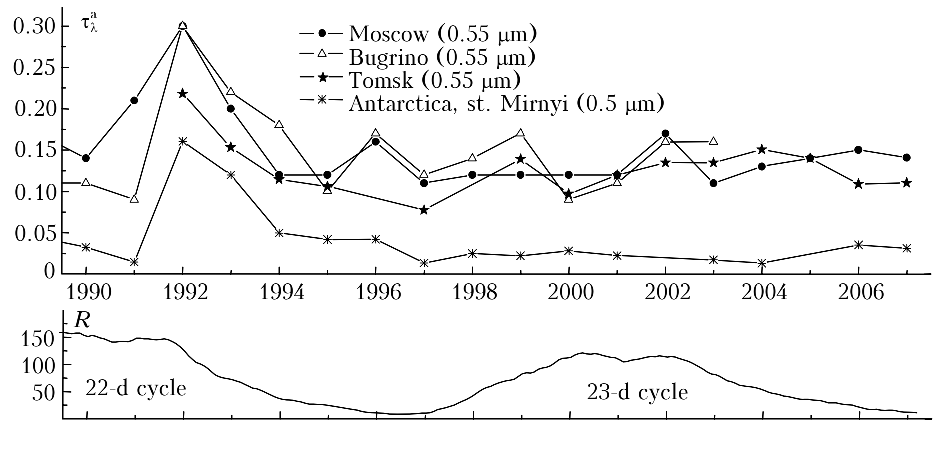

Fig. 3. Temporal behavior of AOT of the atmosphere in different regions and the solar activity R.

Analysis of the results shows that, independently of the regions and methods for determining AOT (from spectral[12] and total direct radiation[15]), the main regularity in variations of the aerosol turbidity over the considered period is the same: the peak of AOT in 1991–1994 followed by its weak variations during next years. Underline that this regularity was observed at all latitudes and in all regions of the globe. Temporal behavior of $\tau^a_{0.5}$ in the Antarctic evidences this fact.

The data of numerous investigations (photometric, lidar, airborne, balloon-borne[20–23]) show that AOT increases due to aerosol generation in stratosphere (total mass of 20–30 Mt) after Mt. Pinatubo eruption, when the maximal increase reached 0.01–0.02 [Refs. 21–24]. Chemical composition and the total mass of aerosol, as well as dates and chronology of development of the stratospheric layer do not allow one to attribute this event to the direct effect of the solar activity. Besides, the apparent "correlation" in 22-d cycle of the solar activity was not explicitly pronounced in the 23-d cycle, therefore, the analysis of a longer observation series is necessary for the proof.

During next period (after 1994) the AOT in the considered regions varied near its mean value, and no significant trend was observed. The characteristic of this period is a small difference between aerosol turbidity in three quite different regions of Russia (Moscow, st. Bugrino, and Tomsk). Mean values of rms deviations of AOT in the post-volcanic period were as follows: 0.131 ± 0.019 in Moscow, 0.14 ± 0.033 at st. Bugrino (1994–2003), and 0.126 ± 0.025 in Tomsk in summer (annual values were 0.119 ± 0.021). Synchronic variations of AOT at two of three sites of observation were observed in some years, for example, a coincidence of the turbidity maxima in 1996, 1999, and 2002.

3. Peculiarities of the many-year variability

At present, the explosive volcanic eruptions[25,26], are considered as the most powerful and thoroughly proved factors of the long-term AOT variability. During these eruptions, tropopause breaks, and tens of megatons of the aerosol-producing substance (mainly, sulfur dioxide) are emitted into stratosphere.

Weaker volcanic eruptions lead to increase of the aerosol turbidity at the regional scale and for shorter periods. Among other possible reasons of inter-annual variations and trends of AOT the following can be noted: instability of the general circulation of the atmosphere, El-Nino phenomenon, variations of the anthropogenic loading, cycles of solar activity, and others. When revealing correlation with these factors, the contribution of the volcanic aerosol is undoubtedly first. Temporal behavior of $\tau^a_{0.55}$ in Moscow in 1955–2007 is shown in Fig. 4, which is the longest observation series at the territory of Russia.

The peaks of AOT after three most powerful volcanic eruptions are well seen in the inter-annual behavior (marked by dot lines): Agung, 1963; El-Chichon, 1982; Pinatubo, 1991. The effect of volcanoes can be simply taken into account through replacing the enhanced turbidities observed for about 3 years by the mean values of AOT for the neighboring undisturbed period before eruption and 2–3 years after. (The corrected values $\tau^a_{0.55}$ are marked by asterisks in Fig. 4).

We excluded the volcanic addition only for two most obvious events – Mt. Pinatubo and Mt. El-Chichon. It was difficult to unambiguously take into account the effect of Mt. Agung, followed by eruptions of other volcanoes – Fernandina, Fuego, Sent-Helens, and Alaid.

The obtained series of $\tau^a_{0.55}$ values was compared with the data on solar activity. The correlation coefficient between $\tau^a_{0.55}$ and R is small (0.034), and even lower than the level of a significant correlation of 0.269 with a confidence probability of 0.95.

However, the correlation coefficient between these two parameters even without the exclusion of the volcanic addition does not exceed 0.04.

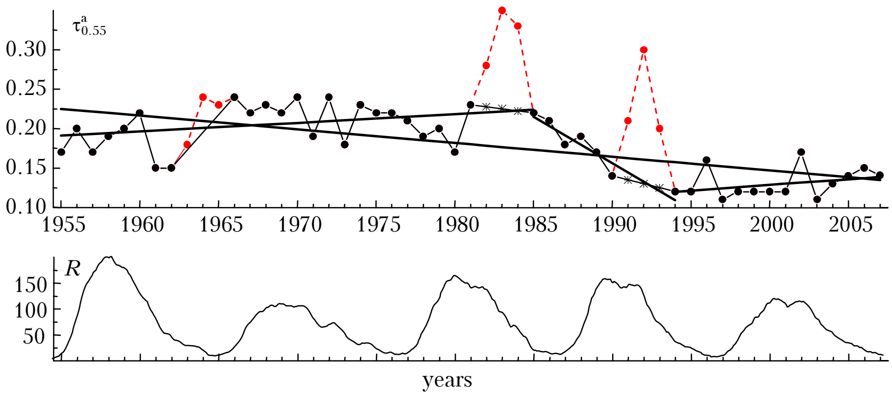

Fig. 4. Long-term variability of $\tau^a_{0.55}$ (Moscow, 1955–2007) and solar activity R (solid lines show the linear trends for individual periods).

To estimate the effect of correlation, the spectral analysis of inter-annual variations of AOT was additionally conducted. Harmonics with periods of 3, 5, and 8.7 years are observed in the obtained amplitude spectrum (Fig. 5), and the oscillations corresponding to the cycles of solar activity (11 years) are absent.

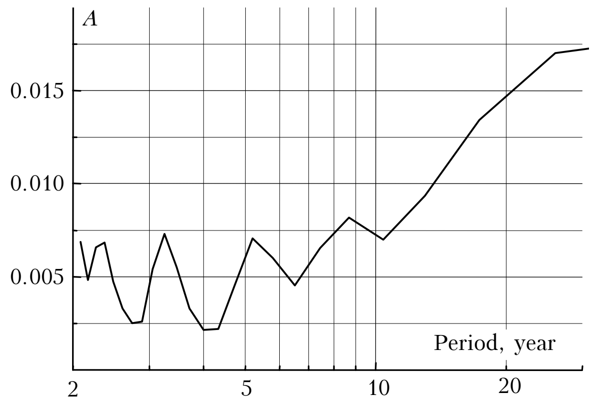

Fig. 5. Periodogram of inter-annual variations of $\tau^a_{0.55}$ in the Moscow region.

Interpretation of the characteristic periods of AOT oscillations is the subject of a special study. Note that the distinguished harmonics are in agreement with the known cycles of circulations in the ocean – atmosphere system.[27,28]

Thus, the conducted analysis has shown the absence of any significant correlation between AOT and cycles of solar activities in the last half-century period. At the same time, there are no reasons to negate an indirect effect of solar activity or cosmic rays on the aerosol component of the transparency, for example, through circulation.[28–30] "Solar" effect on transformation of circulations and cloudiness is under active discussion now along with other mechanisms.[27,31] In any case, this effect is lower than volcanic one and hidden by many factors including changes in regional conditions (fires, anthropogenic loading). Combined effect of all factors on the inter-annual variability of AOT can be characterized by the rms deviation, which was 0.035 during the considered period. Unfortunately, authors of the hypotheses of a significant effect of cosmophysical factors just on the atmospheric transparency[32–34] do not use the available long-term series of observations in their proofs, limiting themselves only by examples of individual events or indirect facts.

In conclusion, consider the trend component in the long-term AOT behavior, which was estimated for some periods.[4,7,8] If to exclude the volcanic effect, a significant negative trend of $\tau^a_{0.55}$ was observed in Moscow in 1955–2007. (The trend is considered as significant at the confidence probability $P \geq 95\%$). It is seen in Fig. 4 that the main decrease of AOT was observed in the period 1985–1994. Therefore, it is more correct to underline three periods in the behavior of the aerosol turbidity: 1) 1955–1985, the period of increasing anthropogenic loading in Moscow with the tendency of AOT increase; 2) 1985–1994, significant negative trend, mainly attributed to stagnation of industry not only in Moscow but in the region as a whole; 3) 1994–2007, the absence of significant trend (the AOT weak increase without a significant trend).

Quantitative characteristics of the trend for the aforementioned periods are presented in Table 3.

Thus, the aerosol turbidity in Moscow, other regions of Russia[4,8,17] and Tomsk during the last decade is characterized by the absence of significant trend, low values of AOT, approaching the values of AOT between urban and background regions to each other. Such behavior of AOT is associated with reduced anthropogenic emissions, the absence of large volcanic eruptions,[5] and favorable effect of other natural factors, which do not lead to increase of the total aerosol content at the regional and global scale.

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Table 3. Characteristics of the linear trend of $\tau^a_{0.55}$ in different periods of observations

Period	$\tau^a_{0.55}$	a	b	Δ	Δ, %	P	n
1955–2007	0.180	–0.0017	0.227	–0.089	–39	> 99	53
1955–1985	0.207	0.0011	0.190	0.033	17	> 95	31
1985–1994	0.162	–0.0118	0.227	–0.106	–49	> 99	10
1994–2007	0.131	0.00145	0.120	0.019	15,5	< 95	14

Footnote: a and b are the coefficients of the trend equation $y = ax + b$; $\Delta y = y_n - y_1$ is the total linear change of $\tau^a_{0.55}$; Δ, %, is the relative value of the trend, P is the confidence probability of the trend, n is the number of years.

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