Spectral dependence of the atmospheric aerosol optical depth in the wavelength range from 0.37 to 4 μm

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We present results of many-year studies of the spectral dependence of the atmospheric aerosol optical thickness (AOT) in the spectral region from 0.37–4 μm obtained near Tomsk. In the analysis of the AOT spectral dependence in the short-wave range (< 1 μm), parameters α and β of the Angström formula are used while in four spectral intervals between 1.2 and 4 μm of the long-wave range we used the mean value of AOT (τ_c). Statistical characteristics of α and β variations, as well as of $\tau_{0.5}$ and τ_c in different seasons and under conditions of the atmosphere polluted with smoke from forest fires are discussed. Mean values of α, β, $\tau_{0.5}$, and τ_c for the observation period were 1.33, 0.06, 0.153, and 0.055, respectively. Maxima of the aerosol turbidity and selectivity for AOT are observed in spring and during fires, and minima during the fall. Mean value of the wavelength AOT deviations within 1.2–4 μm is 0.02, a small fall of the AOT (about 0.01) is commonly observed within 1–2.2 μm region at increasing wavelength, and then in the region (2–4 μm) a spectrally neutral behavior of the annually mean AOT takes place.

Introduction

Investigations of the aerosol optical thickness (AOT) of the atmosphere and development of new instruments for measuring the spectral transmission of the atmosphere have been active in the past decade (see, for example, materials of WMO/GAW Expert Workshop[1]). Recently organized AERONET[2] system intended for global aerosol monitoring has become an important addition to the national networks for observation of AOT. Regular measurements of the atmospheric transmission over different regions of the planet are important for a more accurate determination of the quantitative characteristics of the aerosol climate forcing and their variation. At the same time, practically all data of AOT observations in the atmosphere were obtained in a relatively narrow wavelength range from 0.34 to 1 μm, where aerosol effect on radiative processes is more significant in comparison with the molecular absorption.

Examples of investigations of AOT at longer wavelengths can be found in Refs. 3 to 5, where the data of short-term observations in the south of France at the wavelengths up to 2.2 μm were considered along with the observations in the wavelength range up to 3.7–4 μm in Portugal and USA (Kansas). More measurements in IR range were carried out over ocean,[6,7] but analysis of data here was rather qualitative. For completeness, one can also mention the earlier results generalized in Ref. 8, in which molecular absorption was not subtracted in calculating the AOT. The main reasons for that small number of studies of AOT in the “atmospheric transmission windows” in the long-wave range are the difficulty of taking into account molecular absorption and lower extinction of radiation by aerosol.

We suppose that the problem of more accurate determination of the climatic role of different components of the atmosphere requires obtaining new data on the characteristics of radiative impact of aerosol not only in different regions of the planet, but also in a wider wavelength range of the incoming radiation.

In this paper we discuss the results of the studies of AOT of the atmosphere near Tomsk in two wavelength ranges – in traditional (short-wave) range from 0.37 to 1 μm and in the wavelength range from 1 to 4 μm. In the first case, statistics of the Angström exponent is analyzed, which is widely used as a quantitative characteristic of the spectral behavior of AOT in the short-wave range[8–10]

$$\tau^a(\lambda) = \beta\lambda^{-\alpha}, \qquad (1)$$

where α is the Angström parameter (exponent) of selectivity, β is the turbidity coefficient.

The second problem is spectral behavior of $\tau^a(\lambda)$ in the range from 1 to 4 μm. It is analyzed practically for the first time (only individual, statistically unrepresentative data were obtained earlier). Taking into account novelty of the results, the model estimates of the spectral dependences of the IR radiation extinction by aerosol are presented in the paper, which are physically possible under typical conditions of the earth’s atmosphere.

1. Model estimates of the spectral behavior

According to Mie theory of scattering, the dependence of AOT of the atmosphere on the aerosol disperse composition has the form

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$$\tau^{a}(\lambda,r) = \int_h \varepsilon_\lambda(h)\,\mathrm{d}h = \int_h\int_r \pi r^2 K_\varepsilon(\rho) f(r,h)\,\mathrm{d}h\mathrm{d}r, \quad (2)$$

where ε_λ is the aerosol extinction coefficient, $K_\varepsilon(\rho)$ is the extinction efficiency factor depending on the complex refractive index $m = (n - i\kappa)$ and the Mie parameter $\rho = 2\pi r/\lambda$; r is the particle radius, $f(r,h)$ is the particle size distribution function at different heights h.

Dividing the optical contribution of aerosol into fractions (in the radius range Δr_i), one can present Eq. (2) in the form of the sum of integrals[11]:

$$\tau^{a}(\lambda) = \sum_i \tau_i(\lambda) = \sum_i \int_{\Delta r_i} \pi r^2 K_\varepsilon f_i(r)\left[\int_h g_i(h)\,\mathrm{d}h\right]\mathrm{d}r = \sum_i H_i \varepsilon_i(\lambda), \quad (3)$$

where

$$\varepsilon_i(\lambda) = \int_{\Delta r_i} \pi r^2 K_\varepsilon f_i(r)\,\mathrm{d}r; \quad (4)$$

$g_i(h)$ are the functions of vertical distribution of the fractions; $H_i = \int_{h=0}^{\infty} g_i(h)\,\mathrm{d}h$ is the height of a homogeneous layer for each of the aerosol fractions (H_i varies from 300–500 m to 1.5–2 km).[12]

It follows from Eq. (3) that $\tau^a(\lambda)$ is the result of summing the spectral dependences of the extinction coefficients of different aerosol fractions, $\varepsilon_i(\lambda)$, taking into account the weighting factor H_i that depends on the vertical distribution of particles. Hence, for simplification of calculations of the possible spectral distributions $\tau^a(\lambda)$ one can consider only modeling $\varepsilon_i(\lambda)$ for different aerosol fractions (4).

Calculations of the dependences $\varepsilon_i(\lambda)$ in the wavelength range 0.34 to 4 μm were carried out using a standard computer code[13] for two aerosol fractions, namely, the fine (or submicron) ε_f and coarse ε_c. The functions $f(r)$ were set in the form of the lognormal distribution with two parameters, the modal radius r_m and $\ln\sigma$ characterizing the mode width. The content of separate fractions was selected based so that the corresponding extinction coefficients in the range $\lambda = 0.5$ μm would have the values $\varepsilon_f \approx 0.1$ and $\varepsilon_c \approx 0.05$ km^{-1}. Main attention was paid to the model estimates of the optical manifestation of large particles, which, in fact, determine the spectral dependence of the aerosol extinction in the wavelength range above 1 μm. Setting of the aerosol microphysical characteristics was based on the model data,[14,15] near which the specific values of the input parameters n, κ, r_m, and $\ln\sigma$ varied (Table 1).

As was noted by many authors, extinction of radiation by small particles $r < \lambda$ manifests itself as a power law decrease of $\varepsilon_f(\lambda)$, the characteristics of which depend on m and $f(r)$. One of such dependences $\varepsilon_f(\lambda)$ is shown in Fig. 1*a*. Under average conditions significant effect of fine particles on the extinction extends to the wavelengths of 1 to 1.5 μm.

Table 1. Aerosol characteristics used in calculations of $\varepsilon_i(\lambda)$

Fraction	Refractive index		Distribution function	
	n	κ	r_m, μm	$\ln\sigma$
f	1.45	0.002	0.1	0.5
c_1	1.65	0.0025	7.2	0.3
c_2	1.65	0.0025	6	0.7
c_3	1.65	0.0025	3.6	0.3

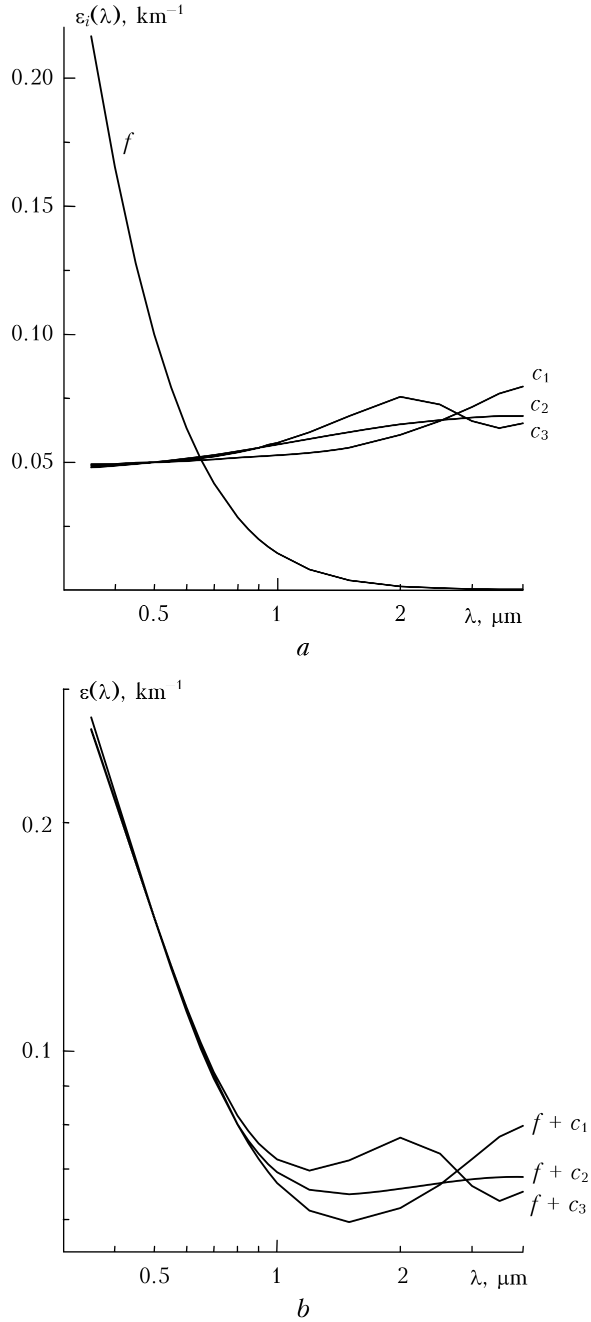

Fig. 1. Spectral dependences $\varepsilon(\lambda)$ for different models of atmospheric aerosol (see notations in Table 1).

Spectral dependence of the extinction coefficient of coarse aerosol has different shape: the value ε_λ is practically constant up to ~ 1 μm, then deviations from neutral behavior can be observed. The dependences $\varepsilon_c(\lambda)$ with maximum in the range of 2 μm and monotonic increase up to 4 μm are shown in Fig. 1 (curves c_i). Realization of one or another dependence is determined by the first maximum of the extinction efficiency factor $K_\varepsilon(\rho; m)$ for the set particle size. The sharpness of the maximum of $\varepsilon_c(\lambda)$, or deviation from "neutral behavior" increases at narrowing the fraction and can be ~ 0.02, and the position of the maximum (at $n = 1.65$) is near the value $\lambda \approx 2r_m$.

2. Characteristics of instrumentation and techniques

Investigations of AOT of the atmosphere near Tomsk are carried out since 1992, mainly in summer.[11,12,16] Upon implementation of automated sun-photometers,[17] observations of the atmospheric transmission became all-the-year round. Besides, measurements of $\tau^a(\lambda)$ were extended to the wavelength range in the IR atmospheric transmission windows up to 4 μm. The wavelengths of transmission maxima of filters used to measure AOT with an SP-4 sun photometer[17] are presented in Table 2. Optical thicknesses of the molecular absorption τ^g and scattering τ^m contributing to the total thickness, as well as their variability limits ($\pm\Delta\tau$) under different atmospheric conditions in summer are also presented in Table 2.

Although positions of the maxima and the transmission contours of the filters were slightly different in different years, and, hence, the specific values of τ^g and τ^m changed, the presented data clearly show the ratio between the components of the extinction of radiation in different "transmission windows".

In passing to IR range, not only τ^g value becomes comparable with AOT, but also its variations under changing atmospheric conditions. Therefore a technique was developed[18] for retrieval of AOT of the atmosphere taking into account molecular absorption by gases and real variability of the water vapor content. The peculiarities of calculating AOT, as well as the technique for calibration were already considered in detail earlier,[7,17] so let us only note that the LOWTRAN-7 computer code was used in calculations of the gas transmission functions, and variability of the content of water vapor was taken into account using the extinction of radiation in the absorption band of 0.94 μm. According to our estimates, the error in determining AOT in the short-wave range is 0.01–0.02, and can reach 0.02–0.03 in the IR range.

Observations of the atmospheric transmission were carried out in the suburban zone of Tomsk at the specially equipped site on the roof of the building (at the height of ~18 m above ground). Before 2000, measurements were carried out as separate 5 to 30-min long series in the periods when no clouds screened the Sun. This fact was recorded by operators. After introducing the automated mode of all-the-year-round measurements, the aforementioned procedure was performed using special computer program.[17] Then, by analogy to Ref. 19, additional filtering of the obtained data from the effect of cloudiness was performed (cloud screening).

The data involved in analysis were either daily or hourly means with reference to the mean local time calculated using the coordinates of the observational site. Total number of the measurement days during the period from May 23, 1992 until October 4, 2005 is 1139, the number of hourly mean values is 6444. The number of measurement days in post-volcanic period (after 1995) is 1019, and 5708 hourly mean values. The longest series of observations was obtained in warm season in the wavelength range 0.37 to 1.06 μm. Distribution of the data over seasons is as follows: 6 winters (181 days of observations), 6 springs (155 days), 9 summers (542 days), 7 falls (131 days). Seasons were separated taking into account the peculiarities of the local climate in the region of observations[20]: summer since May 21 until September 9, fall since September 10 until October 26, winter since October 27 until March 23, and spring since March 24 until May 20. AOT of the atmosphere in the extended wavelength range were obtained in 2001–2005, the number of measurement days is 611, and 3479 hourly mean values.

3. Spectral dependence of AOT in the short-wave range

In spite of the variety of spectral behavior of $\tau^a(\lambda)$ under different atmospheric conditions (Fig. 2), the main regularity is the monotonic decrease of AOT with increasing λ. Even under conditions of enhanced or low atmospheric turbidity (which do not fall into 90% of the most probable values of AOT), the mean dependences remain the same. As was mentioned in the introduction, the most widespread form of description

Table 2. Spectral channels of the photometer and mean values of the optical thickness due to molecular scattering, τ^m, and absorption by gases, τ^g, in comparison with the mean spectrum τ^a_λ in Tomsk (2001–2005)

λ, μm	0.37	0.41	0.44	0.48	0.50	0.55	0.67	0.87	1.05	1.25	1.56	2.20	3.97
τ^g	–	–	0.002	0.005	0.01	0.026	0.030	0.075	0.038	0.051	0.053	0.165	0.207
$\pm\Delta\tau^g$	–	–	–	–	–	–	0.008	0.034	0.022	0.027	0.026	0.071	0.033
τ^m	0.496	0.326	0.244	0.171	0.145	0.098	0.044	0.015	0.007	0.003	0.001	–	–
$\pm\Delta\tau^m$	0.009	0.006	0.004	0.003	0.002	0.002	0.001	–	–	–	–	–	–
τ^a_λ	0.237	0.205	0.185	0.166	0.156	0.138	0.102	0.074	0.065	0.058	0.055	0.053	0.053

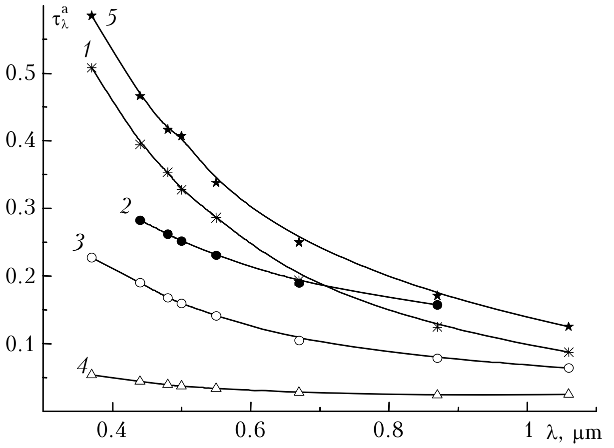

Fig. 2. Mean $\tau^a(\lambda)$ under different conditions: during fires (*1*); after Mt. Pinatubo eruption (summer 1992) (*2*); total data array (1992–2005) (*3*); under conditions of low and high atmospheric turbidities (which are not included into 90% of the most probable τ^a values) (*4*, *5*).

of the spectral behavior of AOT is Angström formula (1), in the majority of cases it well represents real dependences $\tau^a(\lambda)$, it is convenient for quantitative characterization and model calculations. At the same time, it is necessary to keep in mind that the empirical formula (1) has known restrictions: 1) it characterizes the mean component of the spectral behavior of AOT and usually it is applied to data acquired in the wavelength range ~0.4 to 1 μm; 2) it poorly describes the behavior of $\tau^a(\lambda)$ in the aerosol media with low content of fine fraction (for example, at anomalous transmission of the atmosphere[11]); the constant α can be different in different wavelength ranges as well as in techniques of calculation.

In our case, the parameters α and β were determined by the method of least squares after taking the logarithm of the dependence (1) for hourly mean (or daily mean) dependences $\tau^a(\lambda)$. The parameters of the Angström formula have some physical meanings. The parameter β, as will be shown below, is close to the AOT value in the long-wave range, which is determined by the content of coarse particles in the atmosphere. The index of selectivity α depends on both the characteristics of fine aerosol and the ratio of the optical contributions of two aerosol fractions, fine and coarse (for details see Ref. 21).

Figure 3 provides for general image of the interannual variability of AOT and the index α during the entire period of investigations.

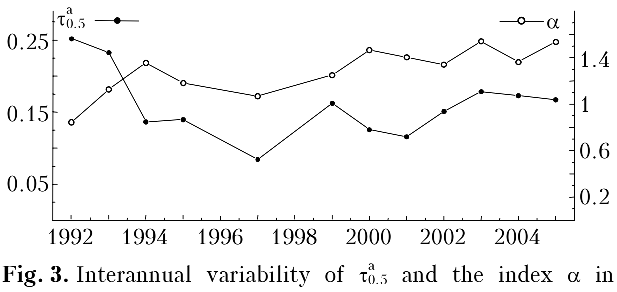

Fig. 3. Interannual variability of $\tau_{0.5}^a$ and the index α in summer.

The change of the characteristics in the initial period (1992–1994), as in other regions of the planet, was caused by the effluents from Mt. Pinatubo volcano, i.e., the decrease of AOT and increase of α. After self-cleaning of the stratosphere, the mean values $\tau_{0.5}^a$ varied from 0.08 to 0.18, while in the past three years in a narrower range from 0.016 to 0.018. Small decrease was first observed in the interannual variations of the Angström exponent in the after-volcano period, then α stabilized at the level of 1.3 to 1.5. It follows from histograms of the distribution for the ten-year period (Fig. 4) that the principal range, involving 90% of the values of the characteristics discussed, is in the limits: $\tau_{0.5}^a = 0.024–0.312$, $\alpha = 0.58–1.91$, $\beta = 0.018–0.123$. The mean and the most probable values (mode) of these characteristics are, respectively, 0.153 (0.12), 1.33 (1.55), and 0.06 (0.045).

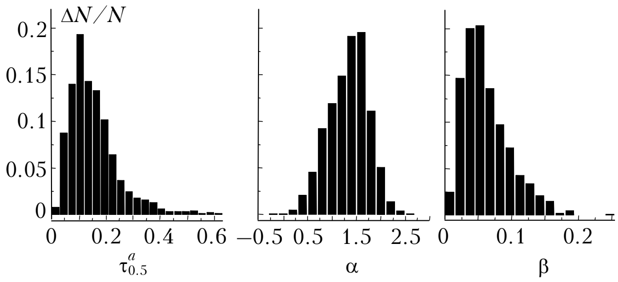

Fig. 4. Histograms of the distribution $\tau_{0.5}^a$, α, and β (1995–2005).

Wide variation of $\tau^a(\lambda)$ is an evidence of the variety of situations of the optical weather and different regularities of the variability of the aerosol fractions, i.e., classification of the data according to atmospheric conditions is necessary. Investigations[8,16,22–25] showed that change of seasons and air masses play the main role in variability of AOT (except for the volcanic eruptions). In this paper we consider the peculiarities of the characteristics of AOT in different seasons. Besides, the situations were selected as a separate class, when forest fire smokes were observed in the atmosphere. On the one hand, one can consider fires as episodic events occurring from time to time, including those caused be the human activity. However, on the other hand, reality is such that the forest fire smokes are typical and inevitable component of the atmospheric optical weather in the zone during warm seasons. Under unfavorable combination of meteorological conditions, the zone of the effect of smoke aerosol on the radiative characteristics of the atmosphere can cover several regions.[26,27]

Let us consider statistical characteristics of the Angström parameters and $\tau_{0.5}^a$ under different atmospheric conditions. It is seen in Table 3 that the maximum selectivity of AOT ($\alpha = 1.73$) is characteristic of situations of forest fires, and minimum is observed after Mt. Pinatubo eruption ($\alpha = 0.84$). The index α is characterized by the lower level of relative variability: the variation coefficient V_α is about 30%, while variations of the parameters β and $\tau^a_{0.5}$ are from 50 to 70% in the majority of cases.

Table 3. Statistics of the main characteristics (σ is the standard deviation, *V* is the variation coefficient)

Sample	Parameter	Mean value (mode)	σ (*V*, %)
Summer 1992 (Mt. Pinatubo)	$\tau^a_{0.5}$	0.252 (0.21)	0.082 (33)
	α	0.84 (0.90)	0.29 (34)
	β	0.139 (0.11)	0.035 (25)
Summer fires	$\tau^a_{0.5}$	0.328 (0.26)	0.113 (34)
	α	1.73 (1.75)	0.24 (14)
	β	0.10 (0.10)	0.041 (41)
	τ_c*	0.073 (0.065)	0.031 (43)
Summer without fires	$\tau^a_{0.5}$	0.146 (0.11)	0.072 (50)
	α	1.32 (1.50)	0.47 (35)
	β	0.06 (0.045)	0.035 (59)
	τ_c*	0.05 (0.035)	0.025 (50)
Summer (total)	$\tau^a_{0.5}$	0.151 (0.11)	0.085 (50)
	α	1.40 (1.60)	0.40 (28)
	β	0.056 (0.045)	0.029 (51)
	τ_c*	0.053 (0.035)	0.027 (51)
Fall	$\tau^a_{0.5}$	0.129 (0.075)	0.089 (69)
	α	1.31 (1.55)	0.43 (33)
	β	0.053 (0.03)	0.036 (68)
	τ_c*	0.04 (0.025)	0.025 (63)
Winter	$\tau^a_{0.5}$	0.145 (–)	0.069 (48)
	α	1.10 (0.90)	0.38 (34)
	β	0.071 (–)	0.038 (54)
	τ_c*	0.060 (–)	0.036 (60)
Spring	$\tau^a_{0.5}$	0.167 (0.11)	0.096 (58)
	α	1.38 (1.50)	0.37 (27)
	β	0.075 (0.05)	0.042 (56)
	τ_c*	0.066 (0.04)	0.037 (56)

* The characteristics of $\bar{\tau}_c$ are for smaller data array (2001–2005).

Analysis of annual variability of the characteristics of $\tau^a(\lambda)$ shows that transitional seasons are most different (Fig. 5): the maximum turbidity is observed in spring and minimum is in fall.

Each season is characterized by its own set of the values α, β, and $\tau^a_{0.5}$. Spring is characterized by high selectivity of AOT (α values) and the maximum values of the parameter β (i.e., the content of coarse aerosol). Minimum values of α and simultaneously large β values are observed in winter. The minimum β values are characteristic of the cleanest fall atmosphere, with α being close to the annual mean values. The mean summer spectrum $\tau^a(\lambda)$ is rather intermediate because of maximum α values and relatively small β values.

The characteristics of AOT (τ^a_λ, α, β) observed during forest fires are strongly different from other atmospheric situations in Siberia (Figs. 5*a* and 6).

It is seen from Fig. 6 that increase of the atmospheric turbidity occurs in the entire wavelength range, and the characteristic feature of smoke situations is in the values of the index of selectivity and the parameter β. As can be seen from the mean and modal values (see Table 3), the relative increase of β during fires is more significant in comparison with that of α. However, it is not an evidence of a smaller increase of fine aerosol, because α depends only on the relative particle size distribution, or on the ratio of the optical contributions of fine and coarse aerosol fractions.[21]

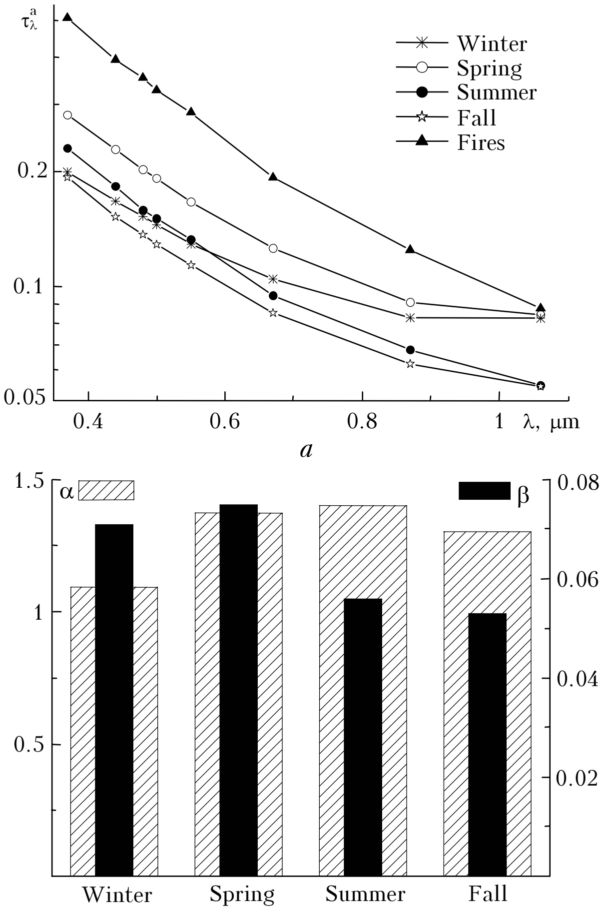

Fig. 5. Seasonal variations of the mean values $\tau^a(\lambda)$ (*a*) and the parameters α and β (*b*).

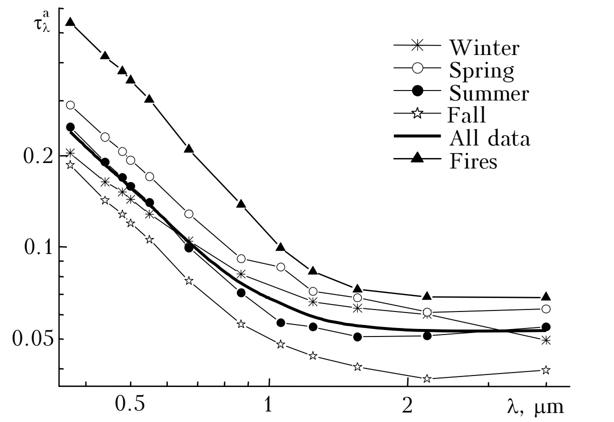

Fig. 6. Mean $\tau^a(\lambda)$ in the extended wavelength range.

The obtained results on the value and behavior of the Angström exponent well agree with the data obtained in other regions of midlatitudes[8,28–33]: the annual mean α usually is in the range 1.2 to 1.6, and the higher summer values in comparison with winter ones are more often observed in seasonal behavior. Agreement with other regions is also observed in the annual mean values of AOT. For example, according to data of AERONET[28] the mean $\tau^a_{0.5}$ values in "clean" regions are the following: in Mongolia $\tau^a_{0.5} = 0.13$, in Sherbrook (Canada) $\tau^a_{0.5} = 0.12$, in Oklahoma (USA) $\tau^a_{0.5} = 0.17$. Aerosol turbidity in the regions of Washington, Paris, and Moscow[28–30] is a bit higher, i.e., the mean values $\tau^a_{0.5}$ are about 0.2, i.e., the data obtained in Tomsk (annual mean $\tau^a_{0.5} = 0.15$) are closer to that in the regions with small anthropogenic impact. Comparison of the relative frequencies of occurrence of aerosol turbidities with the values lower than the "background aerosol threshold" $\tau^a_{0.5} < 0.1$ shows the same result.[28] There are 31% of such situations in Tomsk and 26.4% in Moscow.[29]

The main difference of our data is in seasonal behavior of AOT: a) as a rule, the spring–summer maximum and fall–winter minimum are observed in industrially developed regions of Europe and North America; b) the winter values of AOT in Tomsk are quite large, that better agrees with the results obtained in some clean regions of Siberia.[23,33] On the whole, one should note that the seasonal amplitude of $\tau^a_{0.5}$ (from max to min) in Tomsk is not that large (~25%), as is observed in the regions with higher turbidity. For this reason, another distribution of the characteristics of AOT over seasons can be observed in Tomsk some years. For example, in 2003 with anomalous circulation conditions[34] the mean value of AOT in winter was at the level of the minimum fall values.[35] Some differences between the results can also appear[36] if seasons have been divided ignoring the climatic conditions of the region, but according to calendar dates.

Analysis of the histograms of the distributions (Fig. 4) showed that they are identical both for the total data array and for separate classes of situations. In the majority of cases (except of winter) the histograms are asymmetric and have single mode. The modal values of all parameters are presented in Table 3. The view of the obtained distributions of $\tau^a_{0.5}$, α, and β do agree with those obtained in other regions,[28,31,32] confirming the general regularity that a) the distribution function of the parameter β (the same as $\tau^a_{0.5}$) is close to the lognormal dependence with asymmetry to the side of larger values, b) the histogram of the Angström exponent is closer to the lognormal distribution, and asymmetry is observed as more dramatic decrease of larger α values.

4. Spectral dependence of AOT in the long-wave range

Not very numerous studies of AOT in the "atmospheric transmission windows" in the IR range[3–6] are evidence of the possibility of realization of both neutral dependence $\tau^a(\lambda)$ and deviations from it at some wavelengths. Let us note that the obtained results significantly depend on how exactly the molecular scattering by gages has been taken into account, which is comparable or exceeds the τ^a value sought (see Table 2).

The results of investigations in Tomsk have shown that the mean dependence $\tau^a(\lambda)$ for the entire data array is smooth: the power decrease of AOT is gradually transformed (in the range from 0.8 to 1.5 μm) to neutral behavior with the value of 0.06 (Fig. 6). Let us remind that measurements of $\tau^a(\lambda)$ in the extended wavelength range (up to 4 μm) were carried out only in recent years, therefore the bulk of these data is small. Nevertheless, seasonal mean spectra $\tau^a(\lambda)$ in the range $\lambda < 1$ μm agree with the data of longer series of observations (see Figs. 5*a* and 6): maximum turbidity in spring, minimum in fall, and intermediate values in winter and summer. To estimate seasonal differences in the long-wave range, the mean AOT were calculated: $\bar{\tau}_c$ in the range from 1.2 to 4 μm (in four wavelength intervals). The statistical characteristics of $\bar{\tau}_c$ under different conditions are shown in Tables 3 and 4.

Table 4. Characteristics of AOT in the long-wave range (2001–2005)

Array	$\beta \pm \sigma$	$\bar{\tau}_c \pm \sigma$	$\Delta_\lambda = \tau_{max} - \tau_{min}$
Summer fires	0.110 ± 0.038	0.073 ± 0.031	0.023
Summer without fires	0.052 ± 0.024	0.050 ± 0.025	0.015
Summer (total)	0.058 ± 0.030	0.053 ± 0.027	0.015
Fall	0.047 ± 0.030	0.040 ± 0.025	0.012
Winter	0.071 ± 0.041	0.060 ± 0.036	0.021
Spring	0.077 ± 0.042	0.066 ± 0.037	0.023
Total array	0.062 ± 0.036	0.055 ± 0.031	0.017

The seasonal variations of $\bar{\tau}_c$ occurred to be the same as that of the parameter β for a longer series of observations (1995–2005): the maximum level of $\bar{\tau}_c$ (and the content of coarse particles) is observed in spring and winter, and the minimum one in fall. Estimates obtained based on the Student criterion have shown that the differences in $\tau^a(\lambda)$ between different seasons are significant for no less that two parameters (Table 5). The amplitude of seasonal variations of $\bar{\tau}_c$ relative to the annual mean level is 47% at the day to day variation coefficient of 56%.

Frequency distributions of $\bar{\tau}_c$ are analogous to the histograms of AOT in the short-wave range and correspond to the lognormal dependence with the mode less than the mean values. For example, in the total data array of 2001–2005 the mean value $\bar{\tau}_c$ is 0.06, the modal value is 0.035, and the maximum is 0.16. The largest values of $\bar{\tau}_c$ are observed, as in the shortwave range, under conditions of forest fire smokes. Significant concentrations of fine particles are usually observed in smoke aerosol. The results of the extinction of radiation obtained in the IR range (see Table 4 and Fig. 6) are evidence of the increase of aerosol particles number density also in the size range of coarse fraction (by ~1.5 times).

Table 5. Reliability of seasonal differences in different parameters ($\tau^a_{0.5}$, α, β, $\bar{\tau}_c$)

Season	Parameter	Summer	Fall	Winter
Spring	$\tau^a_{0.5}$	0.997	0.997	0.997
	α	no	0.87	0.997
	β	0.997	0.997	no
	$\bar{\tau}_c$	0.997	0.997	no
Summer	$\tau^a_{0.5}$	–	0.997	0.78
	α	–	0.94	0.997
	β	–	0.90	0.997
	$\bar{\tau}_c$	–	0.997	0.98
Fall	$\tau^a_{0.5}$	–	–	0.90
	α	–	–	0.997
	β	–	–	0.997
	$\bar{\tau}_c$	–	–	0.997

Analysis of the "inter-wavelength" variations of AOT ($\Delta_\lambda = \tau_{max} - \tau_{min}$) in the wavelength range 1.2 to 4 μm has shown that the mean value of Δ_λ is about 0.02 (see Table 4). To determine the qualitative behavior of $\tau^a(\lambda)$ dependences in the IR range, the frequency of occurrence was calculated for different types of the spectral behavior in two wavelength intervals 1–2.2 and 2.2–4 μm (Fig. 7). The sign "–" indicates the decrease of AOT with increasing wavelength, "0" means neutral behavior, and "+" indicates the increase of AOT. For example, the column of the histogram with designation "+" means the frequency of occurrence of the cases when the increase of AOT is observed in the first and second wavelength intervals, "+0" means that AOT increases in the first interval and has neutral behavior in the second one.

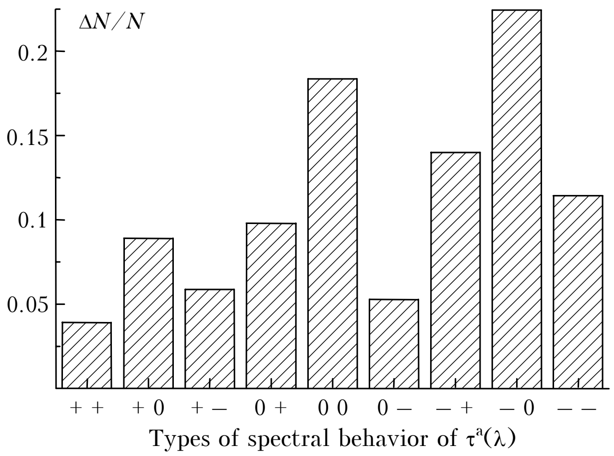

Fig. 7. Histograms of the distribution $\bar{\tau}_c$ and the types of spectral behavior of $\tau^a(\lambda)$ in the sections 1 to 2.2 μm (left-hand sign under the histogram) and 2.2–4 μm (right-hand sign).

It is seen in the histogram that the most probable (~20% of all cases) types of the dependences $\tau^a(\lambda)$ are the following: a) decrease in the first interval and then neutral behavior; b) neutral behavior in the entire wavelength range. The next type according to the frequency of occurrence (~14%) is the decrease of AOT up to 2.2 μm and then increase up to 4 μm. If the wavelength intervals are considered separately, the distribution of the spectral behavior is the following: the decrease of AOT (48%) or its neutral behavior (34%) are the most probable in the interval 1 to 2.2 μm and the neutral behavior (50%), or the increase of AOT (33%) are the most probable in the interval 2.2 to 4 μm. To obtain the quantitative estimates, the monthly mean differences of AOT were calculated in the same wavelength intervals: $\Delta_{1-2} = \tau^a_1 - \tau^a_{2.2}$ and $\Delta_{2-4} = \tau^a_{2.2} - \tau^a_4$. It is seen from Fig. 8 that the difference is always positive in the first wavelength interval, i.e., the decrease of AOT with the annual mean value of $\Delta_{1-2} \approx 0.01$ is observed. The annual mean dependence τ^a (1–4 μm) in the section 2.2–4 μm is neutral, but there are some seasonal differences. The decrease of AOT of the same magnitude, as the average over the range up to 2.2 μm (~0.01), is observed in cold season, and small increase of AOT up to 4 μm is observed since May until October.

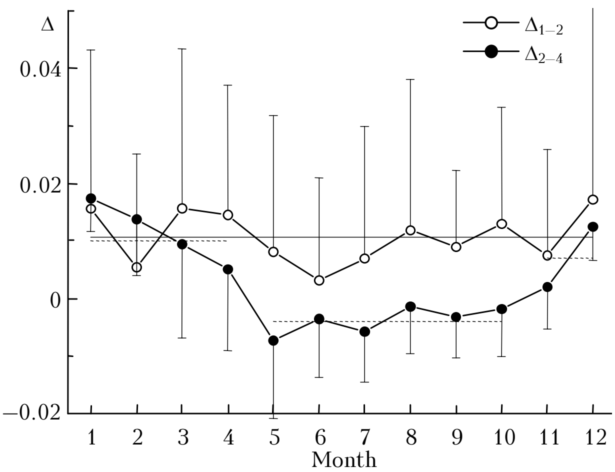

Fig. 8. Inter-month variations Δ_{1-2} and Δ_{2-4} (horizontal lines mark the annual mean level of Δ_{1-2} and seasonal mean values Δ_{2-4}).

For a comparison, let us present the results measured by other authors in the IR wavelength range: a) in Kansas (USA)[5] – the decrease of $\tau^a(\lambda)$ in the wavelength interval up to 1.6 μm and then neutral behavior at the level of 0.02–0.045; b) at the south of Portugal[4] – neutral behavior of $\tau^a(\lambda)$ in the interval up to 2.2 μm at the level of 0.05–0.1, and then decrease to 0.01–0.07; c) at the south of France under conditions of dust emissions from Sahara[3] – monotonic decrease of AOT in the interval 1 to 2.2 μm. Although the enumerated results were obtained during short periods of observations (4 days of measurements in each case) and in other regions, they agree with our data within the limits $\tau^a_\lambda \pm \sigma_\tau$.

For a conclusion, let us pay attention to the closeness of the values of the parameters β and $\bar{\tau}_c$. The problem of correlations among α, β, and $\bar{\tau}_c$ as well as determination of the optical contributions of two aerosol fractions are considered in Ref. 21 in a more detail. Let us consider here only the estimates of the difference of β from $\bar{\tau}_c$. It is seen in Table 4 that the maximum differences are observed during forest fire smokes, and the annual mean difference $(\beta - \bar{\tau}_c)$ is 0.007 (or 12%), i.e., it is less than the error in determining AOT. This means that the parameters β or τ^a (1 μm) can be used for approximate determination of $\bar{\tau}_c$ and the content of coarse aerosol.

Conclusions

1. Comparison of the results of long-term observations of AOT of the atmosphere with the data obtained in other regions of midlatitudes shows that one can consider Tomsk as typical region of boreal zone of Eurasia with weak anthropogenic impact. Mean values and the mode of the main characteristics (1995–2005) have the following values: $\tau^a_{0.5}$ is equal to 0.153 and 0.12, α is equal to 1.33 and 1.55, β is equal to 0.06 and 0.045, $\bar{\tau}_c$ (2001–2005) is equal to 0.06 and 0.035.

2. Spectral dependences $\tau^a(\lambda)$ in the short-wave range are well described by the Angström formula (parameters α and β), while in the IR range (1.2 to 4 μm) by the mean $\bar{\tau}_c$ value because of small "inter-wavelength" differences. The parameter β slightly differs from $\bar{\tau}_c$ being, on the average, 12% larger.

3. Statistical characteristics (mean values, rms deviations, mode) of the Angström parameters and $\bar{\tau}_c$, which determine the main peculiarities of the spectral dependence $\tau^a(\lambda)$ in different seasons are obtained:

– the maximum selectivity of AOT (parameter α) is observed under conditions of forest fires and in spring and summer, minimum is observed in winter; the parameter β and AOT in the IR range $\bar{\tau}_c$ have maximum values in spring and minimum in fall;

– seasonal differences in $\tau^a(\lambda)$ in Tomsk are not that large, but statistically significant at least for two parameters of the set α, β, $\tau^a_{0.5}$, and $\bar{\tau}_c$.

4. Mean value of "inter-wavelength" deviations of AOT in the range 1.2 to 4 μm is about 0.02, small decrease of AOT (~ 0.01) with the wavelength is usually observed in the first part (up to 2.2 μm), and then (from 2 to 4 μm) the annual mean dependence $\tau^a(\lambda)$ is neutral (small increase of AOT to 4 μm in warm season).

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