Correlations between the parameters of Angström formula and aerosol optical thickness of the atmosphere in the wavelength range from 1 to 4 μm

S.M. Sakerin and D.M. Kabanov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received August 11, 2006

We continue to analyze the results of many-year studies of the atmospheric aerosol optical thickness (AOT) in the spectral region from 0.37–4 μm measured near Tomsk. Based on the information obtained under different atmospheric conditions (seasons, forest fire smokes), the interconnection between the parameters α and β of the Angström formula and AOT in the long-wave spectral range (1–4 μm) is discussed. It was found that β slightly differs from the AOT value at $\lambda > 1$ μm. Also, close linear relation between them has been revealed, as well as weak correlation between α and β. A possibility of assessing mean AOT level in the long-wave spectral range (1.2–4 μm) from measurements in the traditional range from 0.37 to 1 μm is shown. The procedure of dividing the atmospheric AOT into two components caused by extinction of light by fine and coarse aerosol is described and quantitative characteristics of their seasonal variability are presented.

Introduction

Peculiarities of the spectral behavior of the aerosol optical thickness (AOT) of the atmosphere $\tau^a(\lambda)$ in the wavelength range from 0.37 to 4 μm were considered[1,2] based on long-term measurements of atmospheric transmission near Tomsk. The spectral dependences $\tau^a(\lambda)$ in that wide spectral range have principle differences: monotonic decrease of AOT with the wavelength increasing up to ~1 μm (traditional range of investigations) and then (1.2–4 μm) practically neutral wavelength behavior. The parameters α and β of the empirical Angström formula[3–6,etc.]:

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

were used for quantitative characterization of the spectral behavior $\tau^a(\lambda)$.

Taking into account weak spectral variability of $\tau^a(\lambda)$ in the long-wave range, we used the mean values of AOT $\bar{\tau}_c$ in four intervals from 1.2 to 4 μm as the main characteristics. In discussing the variability of α, β, and $\bar{\tau}_c$,[1,2] we noted closeness of the values β to $\bar{\tau}_c$, as well as the decrease of the selectivity index α with the increase of β parameter. Relations between these parameters are considered in this paper in a more detail using the entire data array, separate seasons, and situations of forest fire smokes. Let us note that, because of small number of investigations of AOT in the IR wavelength range (there are no data on the value $\bar{\tau}_c$), the problem of joint variability of three parameters, α, β, and $\bar{\tau}_c$ was not discussed in the literature at all.

The peculiarities of instrumentation and technique for investigation of AOT of the atmosphere carried out near Tomsk were described earlier,[1,7,8] so let us consider here only minimum specifications. Analysis of the results was carried out for two data arrays obtained since 1995 until 2005 and during shorter period from 2001 to 2005, when measurements of AOT of the atmosphere were carried out in the extended wavelength range from 0.37 to 4 μm.

To calculate the parameters of the Angström formula (1), different authors use several approaches[9,10] and different wavelength regions in the range from 0.34 to 1.06 μm, that leads to some differences in the calculated values of α and β. In our case the parameters α and β were determined by the method of least squares after taking logarithm of the dependence (1) for hourly mean and daily mean dependences $\tau^a(\lambda)$. In order to compare the value α with the data of the global network (AERONET),[11] analogous wavelength range from 0.44 to 0.87 μm was used in our calculations.

1. Correlation between the Angström formula parameters

In spite of the long history of investigations of AOT, there are not so many papers where relations between the parameters α and β were considered.[12–15] In revealing the relations between the parameters of the Angström formula, among others, the possibility was considered of passing to single-parameter representation of the spectral dependence $\tau^a(\lambda)$.[16] The review of available data shows that for variety of atmospheric conditions correlation between these parameters is weak or is practically absent. One can expect some success only in analysis of the results in the frameworks of some regions or for the certain classes of situations.

0235-6880/07/03 200-07 $02.00

Regression relation between the Angström parameters obtained in Tomsk was considered for the entire data array collected since 1995 until 2005 (Fig. 1*a*) and separate seasons. The tendency toward decreasing α at increasing β is seen in correlation between the two parameters (it will be shown below that the change of β is closely related with AOT in the long-wave range or with the content of large particles). The correlation coefficient R for the entire data array is -0.29 at the level of significance of 0.06. The maximum α values (up to 2.5) are observed at $\beta < 0.02$ when the value of AOT in the IR range is minimum, and the mean values of the parameter α at $\beta > 0.16$ become less than 1. Analogous behavior of correlation between α and β was observed in Spain, China, USA,[13–15] and indirectly follows from the results obtained in other regions.

It is easy to show that the considered tendency of mutual variations of the parameters of the Angström formula $\alpha(\beta)$ is the consequence of the peculiarities of Mie scattering by aerosol particles from two ranges of particle size. Investigations of different authors and model estimates (see for example, Ref. 1) show that aerosol extinction by coarse particles with the diameter larger than ~ 1 μm in the range $\lambda < 1$ μm has quasi-neutral spectral behavior, and power decrease of extinction is due to extinction by smaller aerosol particles. So one can present $\tau^a(\lambda)$ in the form of the sum of two components: the selective one due to extinction by fine aerosol $\tau_f(\lambda)$ and that due to extinction by coarse aerosol, τ_c:

$$\tau^a(\lambda) \approx \tau_f(\lambda) + \tau_c. \quad (2)$$

Taking into account small difference between β and τ_c (see details in the next section and Table 1), one can approximately assume that the parameter $\beta \approx \tau_c$ and that its value is proportional to the content of coarse particles. Then, taking into account Eq. (2), one can write for the component $\tau_f(\lambda)$ from Eq. (1):

$$\tau_f(\lambda) = \beta\lambda^{-\alpha} - \tau_c \approx \tau_c(\lambda^{-\alpha} - 1) \quad (3)$$

or

$$\alpha \approx -\frac{\ln\left[1 + \tau_f(\lambda)/\tau_c\right]}{\ln\lambda}. \quad (3a)$$

It is seen from Eq. (3a) that the α depends on the selective component τ_f (or microphysical characteristics of fine particles) and on the ratio of the optical contributions coming from two fractions τ_f/τ_c. That means that, at equal τ_f, the increase of the content of coarse aerosol fraction and the value τ_c will lead to a decrease of the selectivity parameter α.

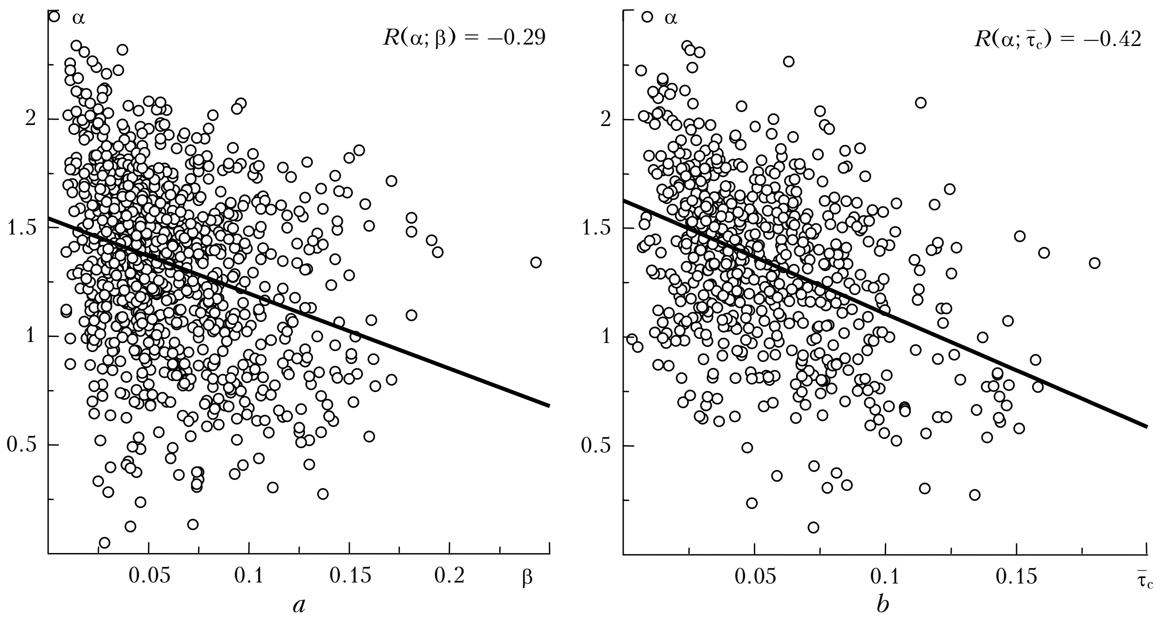

Fig. 1. Scatter diagrams: parameters α and β for the entire data array (1995–2005) (*a*), α and $\bar{\tau}_c$ for the data array compiled since 2001 until 2005 (*b*).

Table 1. Characteristics of correlations of α and β with $\bar{\tau}_c$ (2001–2005)

Situation	Mean value			$\alpha - \beta$; $\alpha - \bar{\tau}_c$				$\beta - \bar{\tau}_c$			
	α	β	$\bar{\tau}_c$	$R(\alpha;\beta)$	γ	$\sigma(\alpha;\beta)$	$R(\alpha;\bar{\tau}_c)$	$R(\beta;\bar{\tau}_c)$	a	b	$\sigma_{u/p}$
Total array	1.34	0.062	0.055	−0.35	−3.76	0.366	−0.42	0.84	0.892	0.737	0.017
Fall	1.35	0.047	0.040	−0.23	−3.26	0.419	−0.46	0.89	0.496	0.749	0.012
Winter	1.09	0.071	0.060	−0.54	−5.39	0.347	−0.61	0.84	0.796	0.729	0.019
Spring	1.35	0.077	0.066	−0.39	−3.55	0.359	−0.48	0.87	0.797	0.756	0.018
Summer	1.44	0.058	0.053	−0.21	−2.29	0.317	−0.27	0.79	1.199	0.706	0.016
Summer without fires	1.42	0.052	0.050	−0.42	−5.88	0.304	−0.35	0.82	0.486	0.871	0.014
Forest fires	1.66	0.110	0.073	−0.45	−2.37	0.178	−0.57	0.61	1.693	0.510	0.025

Let us consider in a more detail the quantitative characteristics of the relation between α and β using the data array collected since 2001 until 2005, in which the data on the wavelength range and seasons are most complete. The correlation coefficients $R(\alpha; \beta)$, standard deviation $\sigma(\alpha; \beta)$, and the tangent of the slope of the regression line γ are presented in Table 1. It follows from the data obtained that, at the same general tendency toward a decrease of α at increase of β, the correlation between them under different atmospheric conditions (seasons, fire events) is slightly different: 1) the closest correlation is observed in winter and in situations of forest fire smokes (the characteristics for fire events were calculated using the hourly mean values); 2) maximum slope of the regression line is observed in winter and in summer (without fires), situations of forest fires break this correlation – $R(\alpha; \beta)$ and γ dramatically decrease. Comparative analysis of the characteristics of AOT in fire situations is considered in detail in Ref. 17, and these data are presented here only for comparison with seasonal variations.

Correlation of α with the mean value of AOT in the long-wave range $\bar{\tau}_c$ was additionally considered (Fig. 1*b*). Analysis of the data has shown that characteristics of that regression are similar to interaction of (α; β) and the correlation coefficients $R(\alpha; \bar{\tau}_c)$ are somewhat higher. For example, $R(\alpha, \beta)$ for the entire data array is –0.42, and in winter it is –0.61.

2. Correlation between parameters β and τ_c

The data, which are evidence of closeness of the values AOT in the long-wave range and the parameter β were already presented in our previous paper.[1] It is seen from Table 1 that the difference $\beta - \bar{\tau}_c$ (on average, –0.007) doesn't exceed the error in determining AOT, and the relative value of the difference is about 10%. That means that the value of the parameter β is mainly determined by the optical contribution of coarse particles.

Let us consider correlation between β and τ_c in a more detail. First, it is interesting to obtain the formula for approximate estimation of AOT in the long-wave range (1.2–4 μm) using the value of the parameter β, i.e., in the case when measurements of $\tau^a(\lambda)$ have been carried out only in the short-wave range (from ~ 0.4 to ~ 1 μm). Second, the use of correlation between β and τ_c will enable one to separate the optical contribution of two aerosol fractions without solving the inverse problem (this issue will be considered in the next section).

To solve the first problem (estimation of τ_c in the long-wave range), as earlier,[1] one can use the value $\bar{\tau}_c$, which is the mean value of AOT in four wavelength regions ("transmission windows" of the atmosphere) from 1.2 to 4 μm. It is seen from the results shown in Fig. 2 that close correlation is observed between β and $\bar{\tau}_c$, which can be presented in the form of linear dependence:

$$\bar{\tau}_c = a10^{-2} + b\beta. \qquad (4)$$

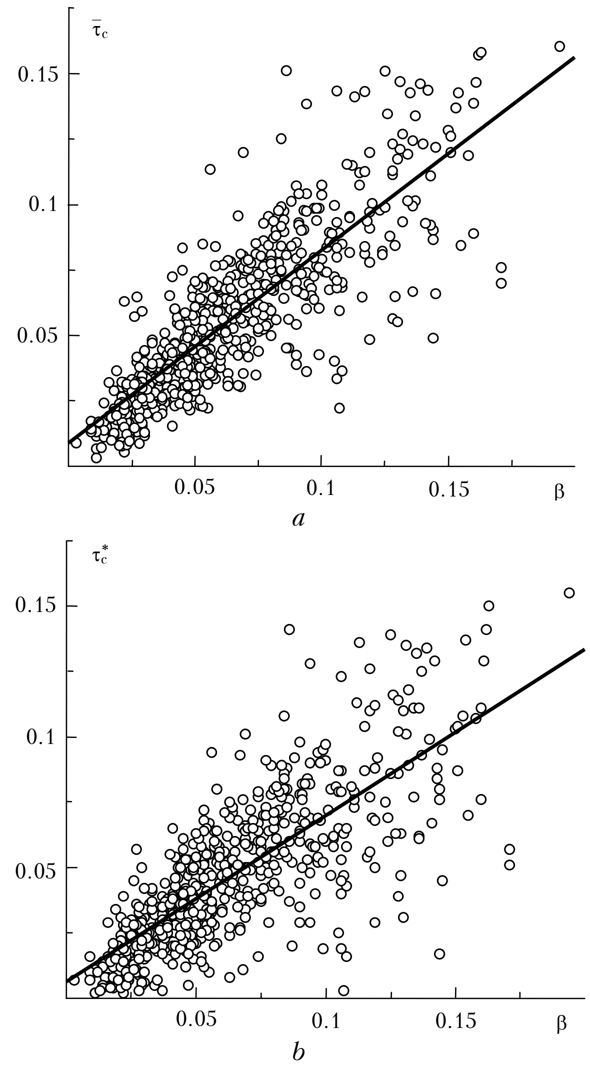

Fig. 2. Correlations of the parameter β with $\bar{\tau}_c$ (*a*) and τ_c^* (*b*).

The correlation coefficients $R(\beta; \bar{\tau}_c)$, the parameters *a* and *b* of the regression equation (4) for different data arrays are presented in the right-hand part of Table 1. Maximum correlation $R(\beta; \bar{\tau}_c)$ is observed in fall, minimum is in summer (because of the presence of smoke situations with other characteristics of correlation in this data subarrays). Comparison of the measured $\bar{\tau}_c$ values and those calculated from the value β by Eq. (4) has shown that the standard deviation of their difference is small being less than 0.02 (see $\sigma_{u/p}$ in Table 1). Thus, one can draw a conclusion about the possibility of estimating of the mean level of AOT in the wavelength range 1.2–4 μm from the value β with a tolerable error comparable with the error of measurements. Naturally, the presented characteristics (including the values of the parameters *a* and *b*) were obtained only under conditions of specific region, and can be different under other conditions.

Let us note that the problem of estimation of aerosol extinction of radiation in the long-wave range from the measurement data in the visible wavelength range has already been considered. For example, in the technique for calculation,[18] the measured results on the extinction at two wavelengths 0.48 and 0.69 μm are used as input parameters for solving the problem, as well as two empirical adjustment parameters and the model data on the spectral behavior of coarse particles. As applied to AOT of the atmosphere, our approach (the value β is used as input parameter) has, at least, two advantages. First, the Angström parameters are the standard characteristics, which are determined in investigations of AOT, i.e., it is not necessary to calculate the adjustment parameters for one or another wavelengths. Second, the parameter β is calculated using the set of values $\tau^a(\lambda_i)$ by the method of the least squares, with the result that the errors in determining AOT at individual wavelengths are smoothed (decrease). As a result, all other factors being equal, the error in calculating AOT in the long-wave range also decreases.

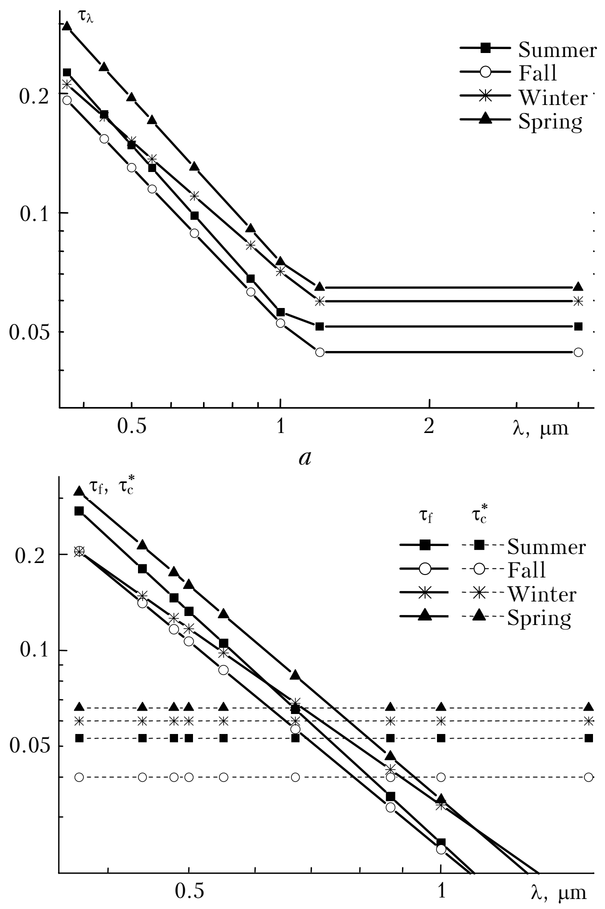

Fig. 3. Model spectra of AOT: calculated from the mean values α, β, and $\bar{\tau}_c$ (β) for 1995–2005 (*a*); AOT components due to extinction by fine and coarse aerosol as retrieved from *m*, *n*, and τ_c^* (2001–2005) (*b*).

To illustrate application of the proposed approach, let us present the results of retrieval of the spectral dependences of AOT in the range from 0.37 to 4 μm for the entire period, starting from 1995, when measurements were carried out only in the short-wave range. Figure 3*a* shows the stylized spectral dependences $\tau^a(\lambda)$ calculated from two parameters: α and β in the range up to 1 μm, and ($\bar{\tau}_c$) from the value β [Eq. (4)] in the long-wave range. Comparison of calculated and real (Fig. 5*a* in Refs. 1 and 7) spectra $\tau^a(\lambda)$ has shown their good agreement in different seasons. In particular, it follows from this fact that the main seasonal peculiarities are the same in the short (2001–2005) and long (1995–2005) periods of observations.

In principle, it is easy to determine the range of τ_c in the long-wave range in addition to the mean level of AOT, or the values in each spectral channel based on the mean spectral dependence of AOT in the range from 1 to 4 μm.[1] However, we thought it to be expedient to present such specifications after additional research.

3. Estimation of the optical contribution of two aerosol fractions to AOT

In the problem of separation of the optical contributions of two aerosol fractions [Eq. (2)] it is necessary to take into account that, strictly speaking, the component τ_c also has spectral dependence. According to model estimates (see, for example, Fig. 1*c* in Ref. 1), the most probable is a small increase of τ_c from visible to IR wavelength range. So, to separate the contribution of two components $\tau^a(\lambda)$ in the range less than 1 μm, it is better to take not the mean value $\bar{\tau}_c$ as its component $\tau_c(\lambda < 1\ \mu m)$ caused by the coarse aerosol, but the minimum of the AOT values in the range 1.2–4 μm τ_c^*, i.e., let us assume that $\tau_c(\lambda < 1\ \mu m) \approx \tau_c^*$.

To determine τ_c^*, one can use measured values $\tau^a(\lambda)$ in the range from 1.2 to 4 μm or to calculate them from the parameter β using the regression relationship identical to Eq. (4). Let us consider such a possibility of estimating $\tau_c^*(\beta)$ from the data array obtained in 2001–2005 (see Fig. 2*b*). The correlation coefficients $R(\beta; \tau_c^*)$ and the parameters of the regression formula a^* and b^* are presented in Table 2 for different atmospheric conditions.

Analysis of the characteristics of regression is evidence of the possibility of estimating τ_c^* from the value β: the correlation coefficients are about 0.8 (except the fire situations), and the mean error of the regression is about 0.02. It is seen from comparison of β, $\bar{\tau}_c$, and τ_c^* (columns 2–4 in Table 2) that the component of AOT due to extinction by the coarse aerosol makes the main contribution to β value. Let us also pay attention to the fact that τ_c^* is, on the average, less than $\bar{\tau}_c$ by 0.01, that agrees with the model estimates.[1]

Table 2. Characteristics of correlation (β; τ_c^*) and the parameters of two components of AOT (τ_c^*, m, n) for the short-wave range (2001–2005)

Situation	Mean β, τ_c			Correlation $\beta - \tau_c^*$				m		n	
	β	$\bar{\tau}_c$	τ_c^*	$R(\beta; \tau_c^*)$	a^*	b^*	$\sigma(\beta; \tau_c^*)$	Mean	σ_m	Mean	σ_n
1	2	3	4	5	6	7	8	9	10	11	12
Total array	0.062	0.055	0.046	0.79	0.628	0.634	0.018	0.028	0.021	2.23	0.56
Fall	0.047	0.040	0.034	0.85	0.119	0.698	0.013	0.024	0.016	2.17	0.45
Winter	0.071	0.060	0.047	0.75	0.399	0.608	0.022	0.033	0.025	1.84	0.53
Spring	0.077	0.066	0.054	0.80	0.624	0.620	0.020	0.034	0.024	2.24	0.51
Summer	0.058	0.053	0.045	0.77	0.734	0.660	0.017	0.025	0.018	2.41	0.54
Summer without fires	0.052	0.050	0.043	0.81	0.0006	0.826	0.014	0.021	0.011	2.41	0.55
Forest fires	0.110	0.073	0.062	0.49	1.736	0.407	0.027	0.059	0.032	2.36	0.39

The component of AOT $\tau_f(\lambda)$ caused by extinction of light by fine aerosol can be obtained accurate to the estimate of the value $\tau_c(\lambda < 1\ \mu m)$. It is logical to present it in the form of a power law dependence:

$$\tau_f(\lambda) \approx \tau^a(\lambda) - \tau_c^* = m\lambda^{-n}. \quad (5)$$

The mean values and the standard deviations of the parameters of approximation (5) for different atmospheric conditions are presented in columns 9–12 of Table 2. The parameter n, on the contrary to α in the Angström formula (see Eqs. (1) and (3a)) depends only on the microphysical characteristics of the fine aerosol forming the component τ_f, and the value m is close to its value in the range of 1 μm: $m \approx \tau_f$ (1 μm). The parameter m is approximately twice as low as the analogous parameters β in the Angström formula.

Thus, the considered procedure of separation of individual characteristics includes: 1) determination of τ_c^* from the parameter β (Eq. 4) or based on measurements of the real values $\tau_c(\lambda > 1\ \mu m)$; 2) calculation of the parameters m and n by Eq. (5). As a result, individual optical characteristics of two components of AOT are obtained, which can be used further for estimation of the contents of fine and coarse aerosol.

One should clarify that some data were partially rejected from calculation of the parameters m and n. The matter is that, the selectivity parameter n has logarithmic dependence on $\tau_f(\lambda)$ and is most sensitive to the values AOT at the long-wave boundary of the used range (in this case, at the wavelength of 0.87 μm). As a result, the calculated values of the $\tau_f(0.87\ \mu m)$ component can occur underestimated, at close values of τ_c^* and $\tau^a(0.87\ \mu m)$ (or even negative), because of the error in determining AOT, and the parameter n in these cases exceeds the maximum possible value for aerosol scattering $n = 4$. So the initial data array was "filtered": only the realizations of $\tau^a(\lambda)$ were used for further processing, in which the values $\tau^a(0.87\ \mu m)$ were greater than τ_c^* by the value of the error: $\tau^a(0.87\ \mu m) - \tau_c^* \geq 0.01$.

Analysis of the obtained values m, n, and τ_c^* has shown the following. Seasonal variations of m are small (from 0.024 to 0.034, i.e., 17%), but its day-to-day variations can reach 70% and higher. The selectivity parameter n is characterized by high stability: seasonal variations are 13%, and the coefficient of day-to-day variations is about 25%. The component τ_c^* has relatively high seasonal (±22%) and day-to-day (more than 50%) variability.

The frequency distributions of m, n, and τ_c^* in the total data array obtained in 2001–2005 are shown in Fig. 4. The distribution of the selectivity parameter n is close to normal – the mean and modal values are ~ 2.2, 85% of all values are concentrated in the range of n from 1.5 to 3. The distributions of m and τ_c^*, as well as of $\tau(\lambda)$ and β, are lognormal with the modal values less than the mean ones: about 0.025 and 0.015, respectively.

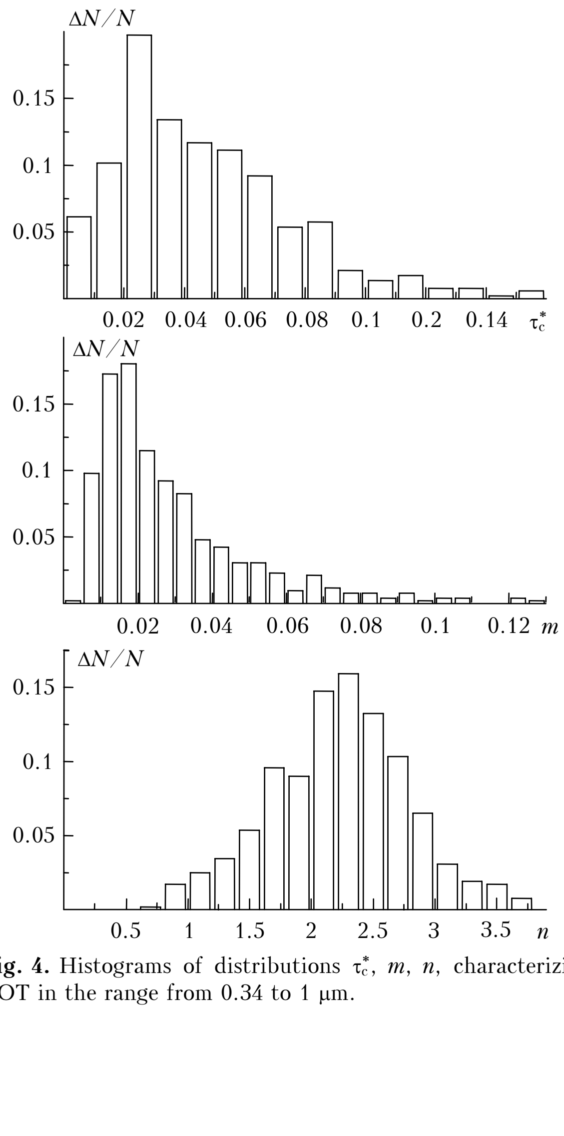

Fig. 4. Histograms of distributions τ_c^*, m, n, characterizing AOT in the range from 0.34 to 1 μm.

The view of seasonal distribution of m and n is analogous to those of the parameters α and β (see Table 1): maximum n values at small m values are observed in summer, minimum n and large m occur in winter, in the transitional seasons the values of the parameters are intermediate. The regression of the parameters m and n is analogous to α and β (see Figs. 1 and 5), although it has a little bit different meaning.

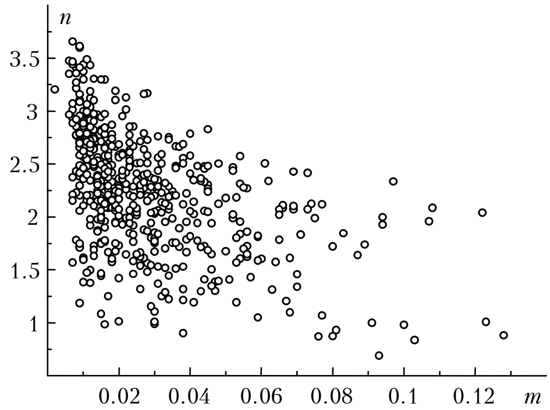

Fig. 5. Correlation between parameters m and n.

The parameters m and n characterize only τ_f and do not depend on the content of coarse aerosol fraction. Therefore, the observed tendency of n decreasing with the increase of m is the result of the inherent relation between these parameters depending on microphysical characteristics of small particles – concentration, refractive index, and effective size.

For explanation, let us consider Fig. 3*b*, where the stylized spectra $\tau_f(\lambda)$ are presented, which were calculated from seasonal mean values of m and n. It is seen that two extreme dependences $\tau_f(\lambda)$ have different level – minimum in fall and maximum in spring, but practically equal slope of the curves – the parameter n is ~ 2.2. Such a behavior of $\tau_f(\lambda)$ can be explained by different concentration of fine aerosol at the same efficiency of extinction, which depends on the refractive index and particle size. The difference in aerosol turbidity in spring and fall is the following: approximately 1.4 times in $\tau_f(\lambda)$ component and ~ 1.6 times in $\tau_c(\lambda)$ component. Principle differences in AOT in two other seasons, summer and winter, already are not related with the concentration but with the slope of the spectral dependence $\tau_f(\lambda)$: the selectivity parameter n is minimum in winter and maximum in summer. The change of n causes the change of the parameter m: the greater is the slope of the spectral dependence (or the value n), the less is the value m, which is equal to "residual value" of $\tau_f(\lambda)$ in the range of 1 μm.

It is interesting that dividing the summer season in situations with forest fires and "without fires" shows small change of the slope of the spectral dependence $\tau_f(\lambda)$ (see Table 2). The selectivity parameter n changes, on the average, from 2.41 to 2.36, and the main peculiarity of smoke situation is in higher content of fine and coarse aerosol particles: τ_f increases approximately by three times, and τ_c^* by 1.5 times.

One can follow the peculiarities of seasonal behavior of $\tau_a(\lambda)$, individually for its components, on the "trajectory" of the change of three parameters, m, n, and τ_c^* (Fig. 6):

– the main features, in passing from winter to spring, are essential increase of selectivity of the spectral behavior of τ_f (the parameter n) and in reaching the maximum of τ_c^* component;

– as summer comes, the value n additionally increases, reaching the maximum value of 2.41, and, simultaneously, the values m and τ_c^* decrease;

– the decrease of all parameters is observed in fall, m and τ_c^* become minimum;

– in passing to winter, the parameter n reaches its minimum value of 1.84, and m and τ_c^* increase.

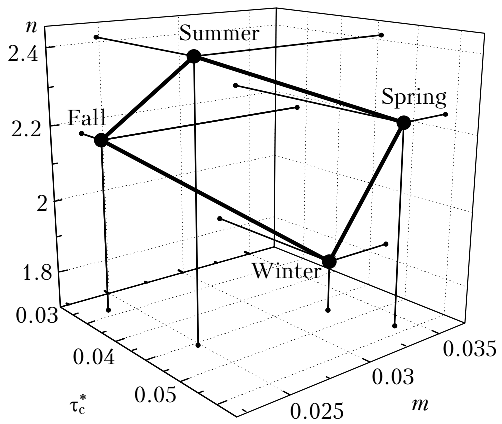

Fig. 6. Joint variations of m, n, and τ_c^*, characterizing of AOT in different seasons.

Conclusions

Analysis of the relations between the characteristics of AOT of the atmosphere in the extended wavelength range (0.34–4 μm) carried out using long-term measurement data in different seasons near Tomsk, enable us to draw the following conclusions:

1. Weak but significant correlation observed between the parameters α and β of the Angström formula. The correlation is caused by the dependence of α on the value of the component τ_c and on the value β, which is close to it.

2. Small difference of the parameter β from AOT in the wavelength range above 1 μm has been revealed, as well as the presence of linear correlation between them. For example, for the entire data array $R(\beta; \bar{\tau}_c) = 0.84$, and the mean difference $(\beta - \bar{\tau}_c)$ is 0.007. The possibility of estimating the mean level of AOT in the wavelength range 1.2–4 μm from the data of measurements in the traditional range from 0.37 to 1 μm has been shown based on the revealed correlation.

3. The procedure of dividing AOT in two components, τ_f and τ_c caused by the contributions of fine and coarse aerosol has been described, as well as presentation of $\tau_a(\lambda)$ in the form of three characteristics – the parameters *m* and *n* for the component caused by fine aerosol and by the value τ_c^*. It is shown that the value of the parameter β (known as the "coefficient of turbidity"[3,4]) is mainly determined by the optical contribution of coarse particles, and the effect of fine aerosol is 10–30%.

4. The mean and the most probable values of τ_c^*, *m*, and *n* under conditions of Tomsk in 2001–2005 are (mean/mode) 0.046/0.025, 0.028/0.015, and 2.23/2.2, respectively.

5. The following peculiarities of variations of τ_c^* and the parameters *m* and *n* revealed are as follows:

– in winter, the minimum selectivity of $\tau_f(\lambda)$ ($n = 1.84$) is observed and τ_c^* takes annual mean values;

– in summer, on the contrary, selectivity of $\tau_f(\lambda)$ becomes maximum ($n = 2.41$) at the same values τ_c^*;

– in transitional seasons (spring, fall), selectivity of the spectral behavior of $\tau_f(\lambda)$ is the same, on the average ($n \approx 2.2$) and the difference is in greater content of fine and coarse aerosol in spring (τ_c^* by 1.6 times, τ_f by ~ 1.4 times).

Acknowledgements

The study was supported in part by Russian Foundation for Basic Research (grant No. 05–05–64410).

References

1. S.M. Sakerin and D.M. Kabanov, Atmos. Oceanic Opt. **20**, No. 2, 141–149 (2007).
2. S.M. Sakerin and D.M. Kabanov, in: *Proc. of 16 ARM Science Team Meeting* 2006. (http://www.arm.gov/publications/proceedings/conf16/extended_abs/sakerin_sm.pdf).
3. A. Angstrom, Geogr. Ann., No. 11, 156–166 (1929).
4. A. Angstrom, Tellus **XVI**, No. 1, 64–75 (1964).
5. O.D. Barteneva, N.I. Nikitinskaya, G.G. Sakunov, and L.K. Veselova, *Transparency of the Atmosphere in Visible and IR Wavelength Range* (Gidrometeoizdat, Leningrad, 1991), 224 pp.
6. G.P. Gushchin, *Methods, Instruments, and Results of Measurements of the Spectral Transparency of the Atmosphere* (Gidrometeoizdat, Leningrad, 1988), 200 pp.
7. D.M. Kabanov, S.M. Sakerin, and S.A. Turchinovich, Atmos. Oceanic Opt. **14**, No. 12, 1067–1074 (2001).
8. D.M. Kabanov and S.M. Sakerin, Atmos. Oceanic Opt. **10**, No. 8, 540–545 (1997).
9. V.E. Cachorro, A.M. de Frutos, and J.L. Casanova, Appl. Opt. **26**, No. 15, 3069–3076 (1987).
10. V. Cuomo, F. Esposito, G. Pavese, and C. Serio, Aerosol Sci. and Technol. **18**, 59–69 (1993).
11. B.N. Holben, T.F. Eck, I. Slutsker, D. Tanre, J.P. Buis, A. Setzer, E. Vermote, J.A. Reagan, Y.J. Kaufman, T. Nakadjima, F. Lavenu, I. Jankowiak, and A. Smirnov, Remote Sens. Environ. **66**, 1–16 (1998).
12. V.E. Cachorro and A.M. Frutos, Atmos. Environ. **28**, No. 5, 963–971 (1994).
13. Zhao Bolin, Mao Jietai, Zhang Chengxiang, and Wang Qiang, in: *Aerosols and Climate* (A. DEEPAK Publishing, 1988), pp. 89–99.
14. R.N. Halthore, B.L. Markham, R.A. Ferrare, and T.O. Aro, J. Geophys. Res. D **97**, No. 17, 18769–18778 (1992).
15. V.E. Cachorro, P. Duran, R. Vergaz, and A.M. de Frutos, J. Aerosol Sci. **31**, No. 6, 687–702 (2000).
16. M. Shenermark, G. Zimmerman, B.I. Nizik, T. Waltzer, and R. Bishoff, Issled. Zemli iz Kosmosa, No. 2, 47–53 (1989).
17. D.M. Kabanov and S.M. Sakerin, Proc. SPIE **6522**, 65221J (2006), 6 pp.
18. N.N. Shchelkanov, Atmos. Oceanic Opt. **15**, No. 12, 1011–1014 (2002).