STATISTICAL RELATIONS BETWEEN THE OPTICAL AND MICROPHYSICAL CHARACTERISTICS OF AEROSOL IN ARID ZONE

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Statistical relations between the spectral extinction coefficient $\alpha(\lambda)$ *(*$\lambda = 0.4$–$11.5\ \mu$m*) of aerosol in an arid zone measured along a horizontal path and aureole portions of scattering phase function* β *and size–distribution function* $f(r)$ *are studied. A possibility of reconstructing* $\alpha(\lambda)$ *in the entire spectral region using a few parameter models with input parameters obtained from in situ measurements is estimated.*

A knowledge of aerosol extinction coefficients $\alpha(\lambda)$ in the visible and IR spectral ranges is very important for a number of scientific and applied problems. At the same time, direct measurements of $\alpha(\lambda)$ in a wide spectral range even near the ground are not always feasible since they need a costly and sophisticated instrumentation. In this case the spectral extinction coefficients are estimated using few–parameters models with optical or microphysical characteristics served as input parameters which are measured with a more readily accessible method.[1,3] These models, are inherently statistical and are based on known or established earlier relations between $\alpha(\lambda)$ and other parameters.

When the aerosol extinction coefficients measured at a single or several wavelengths using a long path method are employed, the problem on the accuracy of reconstruction of spectral behavior $\alpha(\lambda)$ depends on an information content (sensitivity) of a given spectral interval to the entire particle size spectrum which is responsible for extinction over the entire spectral range under study.

The use of the other input parameters, e.g., nephelometric or microstructural ones, is, as a rule, connected with measurements in much smaller volumes of air as compared to those in the long path method. This factor gives rise to additional errors caused by heterogeneity of the objects under study, difference in their scales, and different information contents of the measured characteristics concerning the entire size spectrum of active (from the optical point of view) particles.

Because the dependence of the variability of aerosol characteristics on geophysical, synoptic, meteorological, and other factors (sources, sinks, etc.) is very complicated, the construction of such few–parameter models cannot be based on theoretical calculations but requires some specific experiments to be conducted. Similar studies have been made earlier for Podmoskovnyi region[1,2] and under conditions of a coastal haze.[3]

In this paper we deal with statistical relations between spectral coefficients of aerosol extinction $\alpha(\lambda)$ in the wavelength range from 0.4 to 11.5 μm measured along a horizontal path and the results of *in situ* measurements of optical and microphysical characteristics of aerosol in an arid zone. An aureole portion of the scattering phase function $\beta(\theta)$ at $\lambda = 0.6328$ μm and $\theta = 20'$–$10°$ and the particle size distribution function in the range of radii $a = 0.2$–5.0 μm were selected for optical and microphysical parameters of aerosol.

The measurements of optical and microphysical characteristics accompanied by standard meteorological observations were performed in October 1986 in a Kazakhstan semidesert region. A distinguishing feature of the measurement conditions was high transmission of the atmosphere. The meteorological visibility range S_m was, on the average, 60 km.

The spectral transmission of the atmosphere was measured along a 4630–m–long horizontal path using the instrumentation described in Refs. 4 and 5.

A specially designed aureole photometer[6] operating along the 105–m path was used for measuring an aureole portion of the scattering phase function. A 50–mm–diameter quasiparallel laser beam formed with a collimator propagated at a 2.5–m height above the ground surface.

The particle size–distribution function of the aerosol was measured using an AZ–5 particle counter.

Because the aureole photometer could be operated only at night, synchronous measurements of other parameters were made from 20 p.m. to 8 a.m. An interval between measurements was 1 h 15 min. The measured parameters were averaged over 30 min interval.

The statistical processing carried out used 44 spectra of the aerosol extinction coefficient α_λ, the particle size–distribution function $N(a)$, an aureole portion of the scattering phase function $\beta(\theta)$, relative humidity r, partial pressure of water vapor e, air temperature t, and wind velocity v. From these measurement data we obtained the following mean values (the rms deviations are given in parentheses) of the meteorological parameters: $\overline{e} = 5.7\ (1)$ mB, $\overline{t} = 2.5\ (2.1)$°C, $\overline{r} = 77.3\ (10)$ %, and $\overline{v} = 3.6\ (1.6)$ m/s.

Table I gives mean values, rms deviations, and coefficients of variations for the observed optical and microphysical characteristics, *viz.*, aerosol particle concentrations $N_i(a > a_i)$, aerosol extinction coefficients $\overline{\alpha}(\lambda)$, and an aureole portion of the scattering phase function $\overline{\beta}(\theta_i)$ at $\lambda = 0.63$ μm.

TABLE I. Mean values, variation coefficients, and rms errors in measured parameters.

i	a_i,	$\bar{N}_i(a > a_i)$	V_{N_i}	σ_{N_i}	λ_i,	$\bar{\alpha}_i$	V_{α_i}	σ_{α_i}	θ_i	$\bar{\beta}_i(\theta_i)$	V_{β_i}	σ_{β_i}
	μm	$cm^{-3}\cdot 10^3$			μm	$km^{-1}\cdot 10^3$				$km^{-1}\cdot sr^{-1}\cdot 10^3$		
1	0.2	4846	0.59	2840	0.44	70	0.76	53	20′	1166	1.35	1576
2	0.25	1946	0.68	1324	0.55	61	0.70	43	30′	888	1.30	1150
3	0.3	958	0.78	749	0.87	52	0.62	32	40′	678	1.17	793
4	0.35	602	0.72	433	1.06	52	0.60	31	50′	560	1.05	588
5	0.4	412	0.75	308	1.60	55	0.51	28	1°	477	0.98	469
6	0.45	299	0.74	222	3.97	54	0.54	29	1.5°	344	0.89	305
7	0.5	230	0.77	177	9.20	68	0.56	38	2°	275	0.83	228
8	0.75	136	0.74	101	10.6	65	0.52	34	3°	185	0.79	146
9	1.0	85	0.72	61	11.5	69	0.57	39	4°	153	0.70	107
10	2	10	0.90	9	–	–	–	–	5°	110	0.72	79
11	3.5	1	1.00	1	–	–	–	–	10°	38	0.39	15

The results given in Table I indicate that the variation coefficients V_N and V_β increase with an increase in the particle radius a_i and a decrease in the scattering angle θ_i. Variations V_α are much smaller in value and have practically neutral spectral behavior.

It is clear that variations of the measured parameters are determined by the variability of the medium under study and errors in the measuring channels of the instrumenttation used. In our case relative instrumental error of measurements for all of the three installations is approximately the same $\delta \sim 5$–7%. The main contribution to the variance is mainly due to the variability of aerosol medium.

In turn, variations in aerosol characteristics are caused by the following basic processes: change of total concentration of aerosol particles; transformation of the particle size–distribution function (these two processes are determined by the effect of external geophysical, synoptic, and meteorological factors); natural fluctuations of the number of particles N_i in measurement volumes. Obviously, the variations of the total content of particles in the atmosphere do not violate the autocorrelations $\alpha(\lambda_\kappa, \lambda_j)$, $\beta(\theta_\kappa, \theta_j)$, and $N(a_\kappa, a_j)$.

Specific effect of variations in the particle size spectrum can be estimated from the normalized autocorrelation matrices of the parameters represented in Tables II and III.

TABLE II. Normalized autocorrelation matrices of an aureole portion of the scattering phase function and aerosol extinction coefficients (the level of correlation significance is 0.31*).*

i	$\rho(\beta_{\theta_i}\,\beta_{\theta_k})\cdot 10^2$											
	20′	30′	40′	50′	1°	1.5°	2°	3°	4°	5°	10°	θ
0.44	100	98	96	91	88	78	74	69	65	62	42	20′
0.55	99	100	97	95	94	86	84	79	75	73	54	30′
0.87	96	96	100	98	96	88	83	77	72	69	50	40′
1.06	92	92	95	100	99	95	91	86	82	79	62	50′
1.60	87	85	91	97	100	97	94	89	86	83	67	1°
3.97	82	80	86	93	97	100	99	96	94	91	76	1.5°
9.20	78	77	82	92	94	94	100	99	97	95	82	2°
10.6	81	80	85	93	96	95	99	100	99	98	87	3°
11.5	78	77	82	91	93	91	99	98	100	99	89	4°
λ, μm	0.44	0.55	0.87	1.06	1.60	3.97	9.20	10.6	11.5	100	91	5°
$\rho(\alpha_{\lambda_i}\,\alpha_{\lambda_k})\cdot 10^2$											100	10°

It seems reasonable that high values of the observed autocorrelation coefficient (the level of significant correlation is 0.31) for the aerosol extinction coefficient ($\rho \geq 0.77$), aureole portion of the scattering phase function ($\rho \geq 0.42$), and particle size distribution function ($\rho \geq 0.39$) are indicative of interrelations between the processes which govern the variability of the fine and coarse fractions of aerosol under this study.

High autocorrelation for $\alpha(\lambda)$ (Table II) makes it possible, within the framework of the equation of linear regression, to restore the values $\alpha(\lambda)$ over the entire spectral range using the values $\alpha(\lambda)$ for a single λ, used as an input parameter. In particular, based on such a single–parameter approach the values of the aerosol extinction coefficients $\alpha(\lambda = 10.6\ \mu m)$ are restored using an input parameter $\alpha(\lambda = 0.55\ \mu m)$ with the relative error $\delta = 31\%$. It is preferable from point of view of instrumentational realization to do the reference measurements in the visible spectral range in order to obtain an input parameter. Such a single–parameter model enables one to account for variations in a fine fraction of aerosol propertly. The variations in content of large particles are taken into account indirectly through the correlations. One can see from this that an additional parameter considering variations in content of large particles should be used to improve the accuracy of reconstructing $\alpha(\lambda)$ in the IR spectral range.

TABLE III. Normalized autocorrelation matrix of aerosol particles concentration.

i	$\Delta\alpha_i$, μm	$\rho_{N_K N_i}$				
		K=1	2	3	4	5
1	0.2–0.35	100	86	74	73	39
2	0.35–0.5		100	91	90	45
3	0.5–1			100	93	54
4	1–3.5				100	63
5	>3.5					100

The highest reconstruction accuracy can be achieved, if the value $\alpha(\lambda)$ in the IR is used as the second input parameter (see the correlation coefficients in Table II). At the same time, taking into account the instrumental difficulties of measuring the extinction coefficients in the IR it is desirable to select such an input parameter, from the characteristics measured, with *in situ* methods. To select the second input parameter we have determined the coefficients of conditional mutual correlation between $\alpha(\lambda_i)$ and N_i and between $\alpha(\lambda_i)$ and $\beta(\theta_i)$, respectively, provided that variations of $\alpha(\lambda = 0.55\ \mu\text{m})$ are equal to zero. The calculational results are presented in Figs. 1 and 2.

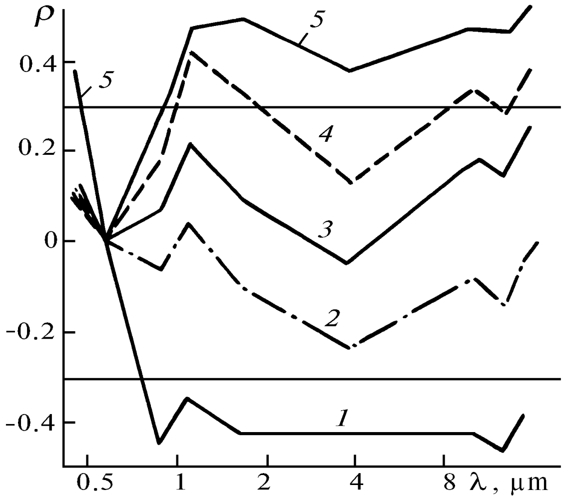

FIG. 1. Spectral behavior of coefficients of conditional correlation $\rho(N_i(\Delta a), \alpha_\lambda/\alpha_{0.55})$: *1)* Δa = 0.2–0.35, *2)* 0.35–0.5, *3)* 0.5–1, *4)* 1–3.5, *and 5)* a > 3.5 μm.

It is seen from the figures that values N_i for large particles (e.g., with a > 3.5 μm) and $\beta(\theta)$ for $\theta = 20'$ can be used as the second parameter. The rms error in reconstructing $\alpha(\lambda = 10.6\ \mu\text{m})$, when using the second parameter $\beta(\theta = 20')$, was 28% and for $N(a > 3.5\ \mu\text{m})$ it was 27%. The formulas for calculating the rms error in reconstruction were taken from Ref. 7. It is also clear from these figures that introduction of additional information obtained in a local volume makes it possible to decrease the error in $\alpha(\lambda)$ reconstruction in the long wave spectral range by 3–4%.

The main obstacle in the improvement of the $\alpha(\lambda)$ reconstruction, when using characteristics determined in local volumes as input parameters, are variations of the measured parameters due to fluctuations of an aerosol medium closely related to the size and peculiarities of forming the volume used in measurements.

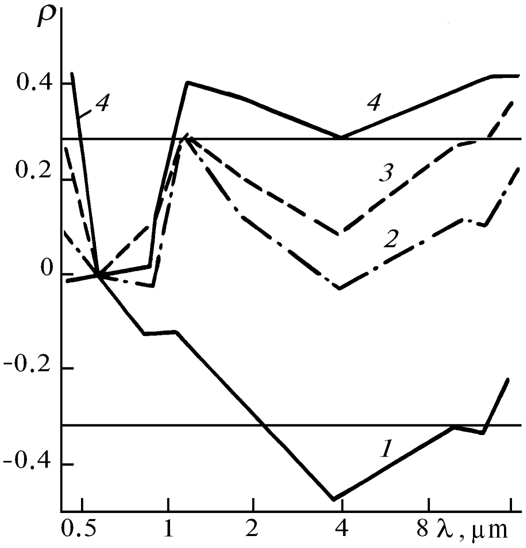

FIG. 2. Spectral behavior of coefficients of conditional correlation $\rho(\beta(\theta), \alpha_\lambda/\alpha_{0.55})$: *1)* θ = 10°, *2)* 5°, *3)* 1°, *and 4)* 20′.

In our experiments for long path measurements of $\alpha(\lambda)$ the working volume was about 4000 m^3, the maximum volume in measurements by the method of spatial scanning of an aureole portion of the scattering phase function $\beta(\theta)$ was 0.05 m^3 (for $\theta = 20'$) and the minimum one was $2.5\cdot10^{-4}$ m^3 (θ = 10°). The volume of air pumped through an AZ–5 photoelectric particle counter was 10^{-3} m^3 for fine particles and $5\cdot10^{-3}$ m^3 for large particles.

Fluctuations in concentration of aerosol particles of different size differently affect the variations in measured parameters depending on the value of a scattering volume. For aureole portions of the scattering phase function this effect also depends on a contribution particles of a given size to the total signal of light scattering along a preset direction. Thus, it follows from the analysis of the angular dependence $\beta(\theta)$ and from the form of the particle size–distribution function $N(a)$ that particles with $a \geq 20$ μm (concentration ~ 0.1 per liter) produce the main contribution to variations in $\beta(\theta)$ at the scattering angles $\theta < 1°$. To estimate the power of scattered radiation along a particular direction one should take into account the following facts: the overwhelming amount of energy of radiation scattered in the forward direction is concentrated in the region limited by the first diffraction minimum of the scattering phase function, the angular position of which can be approximately estimated as $\theta \sim \dfrac{180°}{\rho}$, where $\rho = \dfrac{2\pi a}{\lambda}$. At the same time, in the case of $\alpha(\lambda)$, variations in content of such particles make a contribution to the variance σ_α no more than 1% in the entire spectral range of measurements. The variation coefficient of aerosol particles content V_N, increases with the increase of the size a_i and reaches 100% for $a > 3.5$ μm, according to measurements with a photoelectric counter.

Spectral behaviors of the coefficients of mutual correlation shown in Fig. 3 reveal that with the increase of a particle size and decrease of the scattering angle there occurs a tendency for a relative increase in the correlation coefficient in the long wave region as compared to that in the short wave region. As was noted above, difference in working volumes used in experimental devices resulting in different effects of large particles on variations of measured parameters can lead to a decrease of the absolute values of correlation coefficients for large particles with $a > 3.5$ μm and $\theta \sim 20'$ in the long wave region.

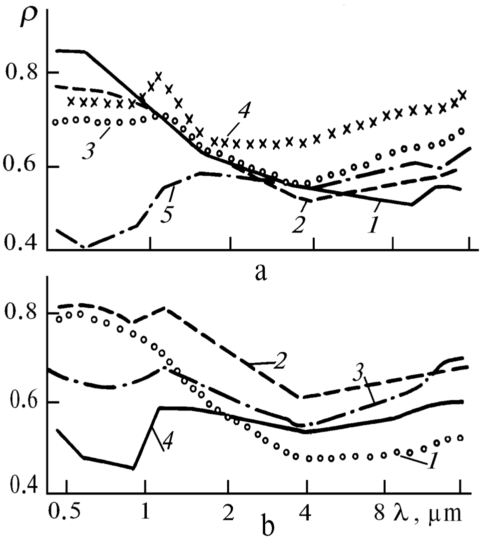

FIG. 3. Spectral behavior of the coefficients of mutual correlation. (a) Between concentration of aerosol particles of different fractions Δa *and spectral coefficients of aerosol extinction* α_λ: *1)* $\Delta a = 0.2–0.35$, *2)* 0.35–0.5, *3)* 0.5–1, *4)* 1–3.5, *and 5)* $a > 3.5$ μm. *(b) Between the aureole portion of the scattering phase function* $\beta(\lambda = 0.6328$ μm, $\theta)$ *and the spectral coefficient of aerosol extinction* α_λ: *1)* $\theta = 10°$, *2)* 5°, *3)* 1°, *and 4)* 20′.

Taking into account the above said let us try to assess the posibilities of the model of reconstructing the aerosol extinction coefficients which could be of the highest practicability provided that only the data of *in situ* measurements are used as input parameters.

Within the framework of a single–parameter representation the aerosol extinction coefficient $\alpha(\lambda = 10.6$ μm) is reconstructed using $N(a > 3.5$ μm) accurate to 36% mean relative error and using $\beta(\theta = 20')$ accurate to 42% error. It is clear that in the case of a two–parameter method of reconstructing $\alpha(\lambda)$ the most useful combination of pairs of input parameters should be chosen among $N(a > 0.2$ μm), $N(a > 3.5$ μm), $\beta(\theta = 20')$, and $\beta(\theta = 5°)$. To reconstruct $\alpha(\lambda)$ in the visible and near IR it is possible to use the parameters $\beta(\theta > 2°)$ and $N(a > 0.2$ μm), ($\delta \sim 32\%$).

The least relative error in reconstruction being, on the average, $\delta \sim 35\%$ for $\alpha(\lambda = 10.6$ μm) is provided by the pair of input parameters $\beta(\theta = 5^0)$ and $N(a > 3.5$ μm). The same pair gives satisfactory results for $\alpha(\lambda)$ at $\lambda = 0.55$, 1.06, and 3.9 μm ($\delta = 36\%$). Curve *4* in Fig. 3*a* and curve *2* in Fig. 3*b* show that these parameters are related to the largest values of the coefficients of correlation with $\alpha(\lambda)$.

The quality of reconstructing $\alpha(\lambda)$ can be improved by increasing the working volume used in a measurement device and a reasonable (not exceeding the periods of eigen rhythms of geophysical processes) increase of a set of data from local volumes to be averaged.

Thus the analysis of statistical relations between the optical and microphysical characteristics of aerosol in an arid zone shows that the use of small–parameter models makes it possible to reconstruct the aerosol extinction coefficients in a wide wavelength range 0.4–12 μm. It should be noted that not only the results of $\alpha(\lambda)$ measurements along a horizontal path in the visible spectral range but also those obtained in local volumes of an aureole portion of the scattering phase function and aerosol particles concentration can be used as input parameters for these models.

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