

## STATISTICS OF AEROSOL LIGHT SCATTERING PHASE FUNCTIONS FROM MEASUREMENTS IN THE CENTRAL ARCTIC BASIN

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*From the measurements of the light scattering phase functions in the ground layer of the atmosphere at the drifting station SP-28 the aerosol scattering phase functions are calculated and statistically analyzed. Mean values, variances, angular correlations, and fundamental components of the covariance matrices are calculated for logarithms of the angular aerosol scattering coefficients at angles from 0 to 180°. It is shown that the variance of the aerosol scattering phase functions is much greater than that of the total scattering phase functions, especially at scattering angles between 80 and 140°. Autocorrelations between the measured angular scattering coefficients exceed a level of 0.5 for all angles of scattering.*

Regular measurements of light scattering phase functions were carried out in the ground layer of the atmosphere at the drifting station Severnyi Polyus 28 (SP-28) on February–March 1987. As a result, a representative sample of 78 scattering phase functions was obtained that characterized the angular scattering spectra variations for stable meteorological visibility range in the ground layer of the atmosphere.

The results of statistical analysis of the obtained scattering phase functions were presented in Refs. 1–2. However, these works comprise the data only for total light scattering, including the scattering on particles of the atmospheric aerosol and on air molecules. At the same time, measurements can be useful in the system of ecological and climatic monitoring of the atmospheric aerosol component,<sup>3</sup> if we use the characteristics of light scattering only by the atmospheric aerosols. Therefore, the measured scattering phase functions were divided into two components: molecular and aerosol, with the aim of determining statistics of the aerosol light scattering phase function variation and then the dispersed composition of aerosols.

In the present paper, the results of calculation of the statistical characteristics of aerosol scattering phase functions from the measurements at the drifting station SP-28 are presented. The conditions under which the initial data sample was obtained that was subsequently used to calculate the aerosol scattering phase functions are given below.

### Characteristics of the experimental conditions

Sample length ..... 78 scattering phase functions  
Measurement period ..... 02.22–03.16.1987  
Coordinates of the region ..... 81°00'–81°40'N

Ranges of variations of the meteorological parameters:

Air temperature ..... –46.3°C – –26.3°C  
Atmospheric pressure ..... 1000.8–1039.8 mbar  
Relative humidity ..... 52–79%  
Meteorological visibility range<sup>4</sup> ..... 12–52 km.

Measurements were carried out with an IF-14 visual nephelometer. The instrumentation and procedure of outdoor measurements of the total atmospheric scattering phase functions were described in detail in Refs. 4–5.

Effective spectral sensitivity of the instrumentation corresponds to the spectral sensitivity of eye. The measurements were carried out for the scattering angles from 16 to 164°. Time of measurement of the individual scattering phase function was about 3 min. The error in measuring the scattering coefficients was 5–10% (see Ref. 4).

Statistic analysis was performed in Refs. 1 and 2 for variations of the total scattering phase functions at angles from 0 to 180° with an angular step of 10°. In so doing, the experimental data were extrapolated toward 0 and 180° on cosine scale by the method described in Ref. 4.

The aerosol scattering phase functions  $\rho_a(\varphi)$  were calculated from the total scattering phase functions according to the formula

$$\rho_a(\varphi) = \rho(\varphi) - \frac{P}{T} \frac{T_0}{P_0} \rho_m^*(\varphi) \int_{\lambda} V(\lambda) \beta_m(\lambda) d\lambda, \quad (1)$$

where  $\rho(\varphi)$  is the total light scattering coefficient at the angle  $\varphi$  ( $\varphi = 0^\circ$  is the direction of an incident beam),  $P$  is the atmospheric pressure,  $T$  is the air temperature ( $P_0$

and  $T_0$  are the pressure and temperature for the standard atmosphere),  $V(\lambda)$  is the spectral sensitivity of photopic vision normalized by the condition

$$\int_{\lambda} V(\lambda) d\lambda = 1, \beta_m(\lambda)$$

is the coefficient of the molecular scattering at air temperature  $T_0$  and atmospheric pressure  $P_0$ , and  $\rho_m^*(\varphi)$  is the normalized Rayleigh scattering phase function

$$\rho_m^*(\varphi) = \frac{1}{4\pi} 0.7629 (1 + 0.9324 \cos^2 \varphi). \quad (2)$$

In numerical calculations, the parameters  $\beta_m(\lambda)$  and  $V(\lambda)$  were borrowed from Ref. 6. The concrete values of the atmospheric pressure and air temperature were specified with accuracies of 1 mbar and 1°C, respectively. For vivid illustration of the real relation between the aerosol and total scattering phase functions, in Fig. 1 the calculation results are shown for three typical scattering phase functions, measured for meteorological visibilities 16, 30, and 51 km.

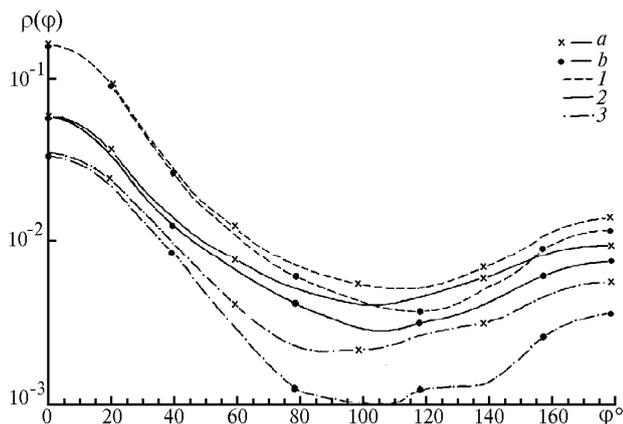


FIG. 1. Total (a) and aerosol (b) light scattering phase functions for different meteorological visibilities: 1) 16 km, 2) 30 km, and 3) 51 km.

For all three cases, the aerosol and total scattering phase functions are close to each other at small angles of scattering, because at these angles the contribution of the molecular scattering is small in comparison with the aerosol scattering. The largest difference is observed at scattering angles larger than 60°. In so doing, with the increase of the meteorological visibility the relative contribution from the molecular scattering is increased and the difference between the aerosol and total scattering phase functions is also increased.

For adequate description of variation statistics of the aerosol scattering coefficients, the scattering phase functions (as was proposed in Ref. 7) were represented in logarithmic scale. First, this is caused by the fact that the sample distribution of the aerosol scattering coefficients is close to the lognormal one. Second, application of the logarithmic scale to an analysis of the variation structure of the entire scattering phase

function, as a whole, permits one to adjust the variation levels at different angles, differed by their absolute values by several orders of magnitude, and to illustrate vividly the variations of the scattering phase function shape as a whole. In addition, when the scattering phase functions are expressed in the logarithmic scale with the use of the regression equations or expanded into the proper orthogonal components,<sup>8,9</sup> the positive determinacy of the scattering coefficients and uniform relative error for the entire range of angles are ensured.

Statistics of variations of the logarithms of aerosol scattering phase functions was calculated by direct taking logarithms of the angular scattering coefficients determined from formula (1), because the errors in measuring the scattering phase function and calculating the molecular scattering contribution, comprising the total error of aerosol scattering estimation, were comparatively small for the examined sample.

Let us consider some peculiarities of the main characteristics of statistic analysis. In Fig. 2, the results of calculations are shown in the form of the average total and aerosol scattering coefficients and the range of variations of the total and aerosol scattering coefficients, determined on the level  $\pm 3\sigma$  from the mean value ( $\sigma$  is the standard deviation from the mean for sample values of logarithms of the scattering coefficients).

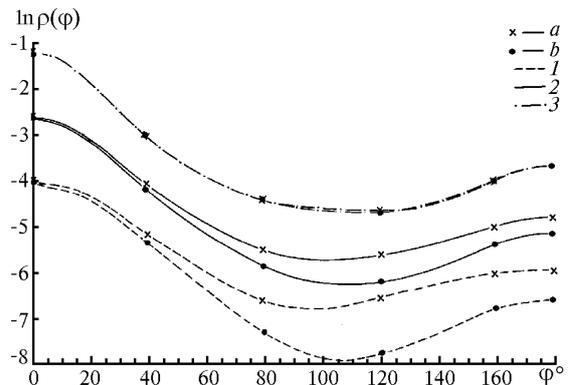


FIG. 2. Average (curve 1) light scattering phase functions and range of their variations at the level  $\pm 3\sigma(\varphi)$  (2, 3): a) total scattering phase function, b) aerosol scattering phase function.

The mean values of the aerosol scattering coefficients are always somewhat lower than total ones, and their difference fully agrees with the behavior of the scattering phase function for individual realizations shown in Fig. 1. The maximum coefficients of aerosol and total scattering practically coincide, which should be expected, because at high values of the total scattering coefficients and hence low values of the atmospheric transparency practically all scattering is determined by the aerosol component. The minimum values, corresponding to the conditions of weakly turbid atmosphere, are essentially smaller for the aerosol component than for the total scattering

coefficients, with the exception of the scattering angles smaller than  $40^\circ$ , at which the aerosol scattering is of primary importance in the examined experiment. Therefore, the variance of the aerosol scattering component is much greater than that of the total scattering, especially at scattering angles  $100\text{--}150^\circ$ .

In Fig. 3, the angular dependence of the standard deviations  $\sigma_a(\varphi)$  of the aerosol scattering coefficients is shown along with the plots of the first four eigenvectors of the covariance matrix for logarithms of the aerosol scattering phase function.

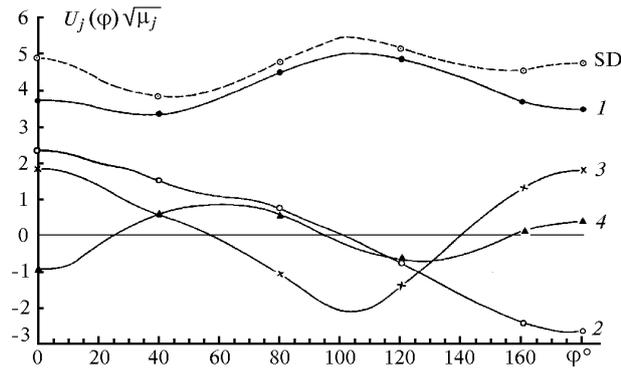


FIG. 3. Standard deviations (SD) of logarithms of the aerosol scattering coefficients and the first four (curves 1–4) eigenvectors  $U_j(\varphi)$  of their covariance matrix on the scale proportional to  $\sqrt{\mu_j}$ .

For vivid presentation of the significance of the contribution from each vector to the scattering phase function variation, the absolute values of the components of each vector  $U_j(\varphi)$  were multiplied by the square root of the corresponding eigenvalue  $\mu_j$ . In Fig. 3, the maxima of the aerosol scattering coefficient variations are clearly pronounced at scattering angles  $100\text{--}110^\circ$ , where the decisive role plays the first eigenvector that provides the main contribution to the formation of this maximum. Other vectors carry the information about the scattering phase function shape variations; in this case, with the increase of the serial vector number, the frequency of angular variations was also increased. The first four vectors, shown in Fig. 3, describe 99% of the total variance of variations of the angular scattering coefficients. Recall that the coefficients for angles  $0, 10, 170,$  and  $180^\circ$  were extrapolated. Therefore, the data presented here really characterize the variations at angles  $20\text{--}160^\circ$ , and asymptotic tendency of all vectors to the constant at angles between  $0$  and  $180^\circ$  is possibly determined by this very circumstance.

An important contribution from the total scattering variations (connected with the first vector, see Fig. 3) to the variation structure of the aerosol scattering coefficients determines the high level of angular correlation of the aerosol scattering phase functions.

In Fig. 4, curves show the numerical estimates of correlations of the aerosol scattering coefficients calculated for all 78 scattering phase functions. Correlation is positive for all angles of scattering and exceeds 0.5 between  $20$  and  $160^\circ$ . Smooth angular behavior is typical of the correlation coefficients and the bell-shaped maximum near the reference angle of scattering. It is remarkable that the behavior of angular correlation for the aerosol scattering coefficients is very similar to that of angular correlation for the total scattering coefficients. The reason for this is that the form of the second component of the total scattering phase function – molecular scattering phase function – remains unchanged whereas its absolute value varies only insignificantly.

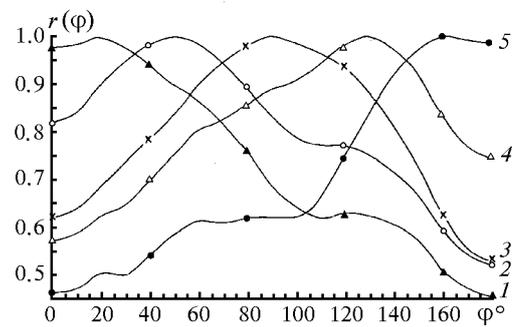


FIG. 4. Angular correlation of logarithms of the aerosol scattering coefficients at angles  $20$  (1),  $50$  (2),  $90$  (3),  $130$  (4), and  $160^\circ$  (5).

It also should be noted<sup>10</sup> that the correlation coefficients of logarithms of the scattering coefficients differ only slightly from that of the absolute coefficients of the aerosol scattering and hence characterize the level of correlation for the absolute aerosol scattering phase function as well.

## MAIN RESULTS

The data about the average coefficients of the aerosol scattering and their standard deviations shown in Figs. 2 and 3 show the range of variability of the aerosol scattering coefficients.

Shown in Fig. 3 are the eigenvectors on the scale proportional to  $\sqrt{\mu_i}$ . In numerical modeling of the parameters of the atmospheric scattering, they make it possible to use the four-parameter model of variations of the aerosol scattering phase functions that approximate these variations with the help of four eigenvectors with the error smaller than 1% of the total variance.

On the whole, the character of the obtained statistical regularities of the aerosol scattering phase function variations fully agrees with the physical processes governing not only aerosol, but also total scattering in the ground layer of the Arctic air under stable meteorological conditions in winter.

Comprehensive analysis of statistics of aerosol scattering phase function variations in connection with the microphysical characteristics of the aerosol calls for special further consideration.

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