MEASUREMENTS OF BACKSCATTERING PHASE MATRICES OF CRYSTALLINE CLOUDS WITH A POLARIZATION LIDAR

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Backscattering phase matrices on four states of polarization of laser radiation were derived from the measured Stokes parameters of scattered radiation. It is shown that anisotropy of scattering is frequently observed in high–altitude clouds and is manifested in the nonzero values of the nondiagonal elements of the backscattering phase matrix.

The study of the ozone cycle in the atmosphere involves the study of the ozone interactions with other atmospheric constituents, in particular, with aerosol which strongly affects the equilibrium concentration of ozone. This effect is manifested, first, in the dependence of the solar radiation flux on the aerosol content. Second, primary substance of aerosol particles or gas molecules adsorbed on them can react with ozone. In this case a state of aggregation of a substance (droplets, regular crystals or conglomerates being formed as a result of particle coagulation) can be important. The effective means of routine monitoring of the aerosol content in the atmosphere capable of obtaining the information about the particle shape is the lidar in which the method of the Stokes parameter measurements has been implemented. The study of high–altitude clouds including the possible manifestations of stratospheric Polar clouds is the most interesting application of this lidar.

The technique based on measurements of the parallel $I_{||}$ and cross–polarized $I_{\perp}$ components of the scattered radiation intensity is frequently used in lidar investigations of aerosols. Their ratio $I_{\perp}/I_{||}$ can be interpreted as a certain measure of particle asphericity and is not absolutely correctly referred to as depolarization, since this term was introduced previously in Ref. 1 as:

$$d = 1 - p,$$

where p is the polarization degree given in terms of the Stokes parameters by the following relation:

$$p = \sqrt{Q^2 + U^2 + V^2}/I .$$

In fact, the Stokes parameter $Q = I_{||} - I_{\perp}$ can be determined from the measurements of $I_{\perp}$ and $I_{||}$ and under condition when

$$U = V = 0 \qquad (1)$$

the depolarization is given by the relation

$$d = 2\, I_{\perp}/(I_{||} + I_{\perp}) . \qquad (2)$$

Condition (1) is valid for aerosol ensembles consisting of randomly oriented particles of irregular shapes. The situation is quite different for the ensembles of crystalline particles, in particular, for cirrus. The failure of condition (1) was noted in Refs. 2 and 3. In 1988 we began the new run of measurements of the Stokes parameters of lidar returns upon exposure of a medium to a linearly polarized light. Our lidar parameters were listed in the catalog given in Ref. 4. The measurements performed in 1988–1990 were classified into five scattering ensembles which differ in combinations of the Stokes parameters.[5,6]

During 1990–91 we carried out the run of measurements in which the Stokes parameters were measured for the following four normalized Stokes vectors of the incident laser radiation ($\mathbf{S}^0 = \{1, q^\circ, u^\circ, v^\circ\}$):

$$\mathbf{S}_1^0 = \{1, 1, 0, 0\} , \ \mathbf{S}_2^0 = \{1, -1, 0, 0\} .$$

$$\mathbf{S}_3^0 = \{1, 0, 1, 0\} , \ \mathbf{S}_4^0 = \{1, 0, 0, 1\} .$$

Thus, we succeeded in measurements of the total backscattering phase matrices for most of the previously classified scattering ensembles. In this paper we present some preliminary results.

We classified 21 cases from 39 investigated manifestations of aerosol layers within the 7–11 km altitude ranges into the first (4 cases) scattering pattern and into the second (17 cases) scattering pattern. For them condition (1) holds and relation (2) is valid. Other 14 cases we classified into the fourth and fifth types of scattering pattern in which either the parameter v or u and v were nonzero. We note that the classification was made according to the Stokes parameters which were obtained when the sounding radiation corresponding to the vector $\mathbf{S}_1^0$ was polarized.

Figure 1 shows the example of a run of measurements carried out on July 11, 1991 in order to determine the backscattering phase matrix. The layer of crystal particles was located at the altitudes between 7 and 8 km. In the figures the scattering ratio $R = (\sigma_R + \sigma_a)/\sigma_R$ is shown on the right. Its average value is equal to 10. The profiles of the Stokes parameters normalized to the radiation intensity ($q = Q/I$, $u = U/I$, and $v = V/I$) are shown on the left. According to Fig. 1 *a* the layer is classified into the fourth type of previously introduced scattering pattern ($u = 0$ and $v \neq 0$). The difference between the fourth and fifth types of scattering pattern is quite arbitrary and depends on the orientation of the polarization basis of the lidar as can be seen from the analysis of the subsequent figures.

The backscattering phase aerosol matrix a_{ij} normalized to the element A_{11} has the following elements:

$$a_{ij} = \begin{pmatrix} 1 & -0.12 & -0.01 & 0.06 \\ -0.12 & 0.40 & -0.02 & 0.10 \\ 0.01 & 0.02 & -0.21 & 0.20 \\ 0.06 & 0.10 & -0.20 & -0.20 \end{pmatrix} .$$

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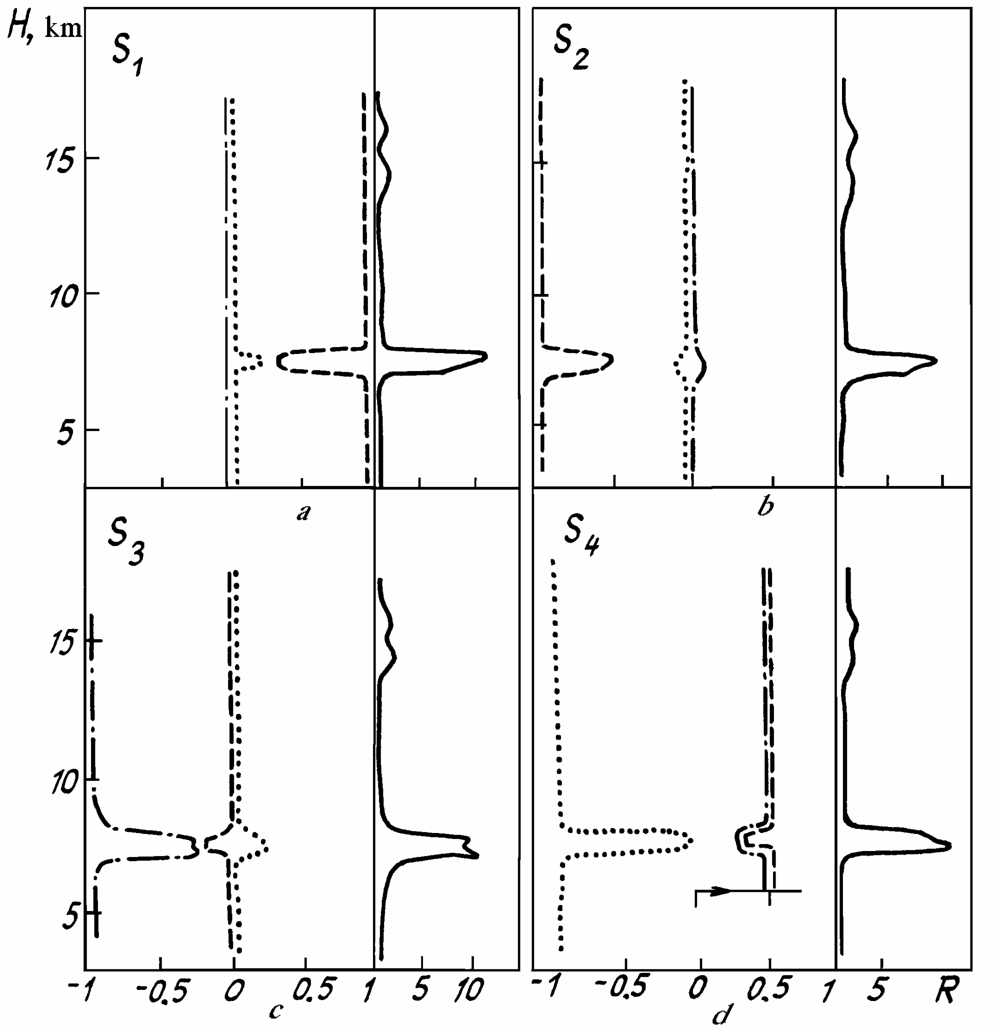

FIG. 1. The vertical profiles of the Stokes parameters q (dashed lines), u (dot–dash lines), and v (dotted lines) and the scattering ratio R (solid lines) obtained on July 11, 1991 on the polarization states of the incident laser radiation: a) $\mathbf{S}_1^0$, *b)* S_2^0, *c)* $\mathbf{S}_3^0$, *and d)* $\mathbf{S}_4^0$.

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The matrix elements are dimensionless. We estimate the absolute measurement error of the elements by a value of ± 0.04. In order to calculate the absolute values of the matrix elements, each of them should be multiplied by A_{11} given by the formula

$$A_{11} = \sigma_R(\bar{R} - 1) ,$$

where σ_R is the backscattering coefficient of the molecular constituent at the altitude of the layer maximum, $\bar{R}$ is the average experimental value of the above–defined scattering ratio.

The noticeable ellipticity of the linearly polarized radiation and almost complete depolarization of the circular polarized radiation are the salient features of the given example. It is of interest that such a scattering pattern was predicted in Ref. 7 for partially oriented cylinders of finite length whose transverse dimensions were comparable with wavelength. It is obvious that this scattering pattern can be extended to prisms of comparable dimensions. Then the data on the dimensions and orientations of crystals can be obtained which, in their turn, are associated with physical conditions in the layer containing the crystals. We intend to discuss this problem in more detail in the nearest future.

Sufficiently long–time manifestation of aerosol layers centered at the altitudes of 14.5 and 15.5 km is of a certain interest. They were firstly recorded on July 11, 1991. The preceding date when they were not yet observed is July 7, 1991. Then we were recording these layers till October. In addition, since August instead of two layers one layer was manifested within the 14–16 km altitude ranges. The scattering matrix remained diagonal all the time. The absolute values of the matrix elements a_{22}, a_{33}, and a_{44} retained at 0.95 and the scattering ratio was within the limits 1.5–2. Apparently, these were the droplet formations. Though the absolute values of the above–indicated elements must take the value 1.0, we could not separate them against the background of Rayleigh scattering. Another possible explanation is that the particles are aspherical but their dimensions are much smaller than the wavelength. Therefore, the scattering pattern remains Rayleigh scattering. Since the end of September we recorded occasionally (owing to the unfavourable conditions of observations) the stratospheric layer within the 19–22 km altitude ranges. The depolarization within the layer was also absent. The value of R was equal to 2.5–3. We noted a layer within the 15.5–21 km altitude ranges with two maxima at altitudes of 17.5 and 19 km on October 30 and 31, 1991. And the single stratospheric layer within the 20–23.5 km altitude ranges with the maximum $R = 3 - 3.5$ at an altitude of 21 km was noted on November 12, 1991.

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