Studies of ice crystal clouds through lidar measurements of backscattering matrices

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The paper presents some results of statistical processing of experimental data on the backscattering phase matrices (BSPMs) of the ice crystal clouds. Using a sample of 463 matrices, we have determined the relative frequencies of elements of normalized reduced BSPMs, the parameter χ characterizing the degree of orientation preference of cloud particles about some azimuth direction Φ_0, and the frequencies of occurrence of that or other Φ_0 values. The term reduced BSPM is taken to emphasize that the matrix is defined in the coordinate system whose reference plane xOz coincides with the direction Φ_0. Thus, the BSPMs turn out to be expressed through parameters independent of random Φ_0 values, so that all BSPMs can be compared. It is concluded that in almost all situations observed, the particles have more or less preferred orientations about certain azimuth direction and about the horizontal plane. The particle orientation is nearly random in 70% of cases, and has essentially pronounced preferred direction in the other cases. It is suggested that the preferred particle orientation along some azimuth direction may be due to wind velocity variations. Generally, the particles are oriented with their long axis perpendicular to the wind velocity vector, i.e., normal to the Φ_0 direction.

Introduction

Since 1990, the Institute of Atmospheric Optics, SB RAS, periodically performed measurements of backscattering phase matrices (BSPMs) using a polarization lidar. Starting from 1994, this research is carried out in collaboration with the Department of Optical-Electronic Devices and Remote Sensing at Tomsk State University using lidar "Stratosfera," owned by the department. Some results of these studies, such as obtained by Kaul et al.,[1] have been published earlier in the *Atmospheric and Oceanic Optics*. During time elapsed from onset of observations, we accumulated statistically significant experimental material on the BSPMs, sufficient to make some generalizing conclusions about particle orientation and associated optical anisotropy. This information is difficult to obtain by *in situ* methods of cloud study, and so there is a gap in this part of knowledge on ice crystal clouds. At the same time, consideration of anisotropy of optical characteristics of high level clouds is required for more precise radiative flux calculations in radiation budget and climate studies. This is convincingly demonstrated, for example, by Feigelson[2] and by Khvorostyanov and Sassen.[3]

In this paper, we do not describe the instrumentation and measurement techniques, and only provide the required references,[1,9] also we present some notions concerning relationships of microphysical characteristics of ensemble of nonspherical particles and its BSPM, which will be required for discussion of the experimental results.

Parameters characterizing cloud particle orientation and their expression in terms of BSPM elements

In this paper, we consider only backscattering phase matrices and describe them in right handed coordinate system formed by three unit vectors $\mathbf{e}_x \times \mathbf{e}_y = \mathbf{e}_z$, with positive z direction chosen to coincide with the direction of wave vector of scattered radiation. The Stokes parameters of radiation of laser sensing are defined in the coordinate system $\mathbf{e}_x \times (-\mathbf{e}_y) = -\mathbf{e}_z$. If vector $\mathbf{E}$ varies in the plane xOz, then the Stokes vector, normalized by the intensity, has the components {1; 1; 0; 0}. The reference plane is chosen to be xOz plane. Its position is fixed by construction features of the lidar.[1] The azimuth angles Φ between the xOz plane and any arbitrary plane containing z axis are measured from the x axis. The sign is considered to be positive if a smallest rotation toward the positive y direction is to be done counterclockwise.

In the general case, the BSPM of an arbitrary particle is determined by 10 parameters, since for its off-diagonal elements the relation always holds

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$$M_{ij} = M_{ji} \text{ if either } i \text{ or } j \neq 3;$$

$$M_{ij} = -\,M_{ji} \text{ if either } i \text{ or } j = 3. \qquad (1)$$

In addition, we always have

$$M_{11} - M_{22} - M_{44} + M_{33} = 0. \qquad (2)$$

The derivation of these and other (used below) BSPM symmetries is presented in Refs. 4–7. Since cloud particles are independent scatterers, the BSPM of the scattering volume is the sum of BSPMs of all constituent particles; and for this BSPM, formulas (1) and (2) also hold.

Backscattering phase matrix of an ensemble of particles can be described by much fewer parameters if the ensemble possesses any symmetry.

Van de Hulst defined a notion of rotational cloud symmetry; according to this notion, for any given particle orientation, there are many other orientations following from the original one by rotation about the direction of wave vector (z axis) through the angle Φ, and these angles are uniformly distributed over the interval from 0 to 2π. This definition is valid for an ensemble of quite many particles either oriented randomly in both polar Θ and azimuth Φ angles (to be called chaotic orientation below), or oriented randomly in Φ only and ordered in Θ in that or another way. In the latter case, the distribution will be called 2-D chaotic strictly if Θ is either 0 or $\pi/2$ only, and 2-D chaotic with flatter if otherwise.

Since any rotation about z axis recycles the chaotic ensemble into itself, the BSPM of such an ensemble must be invariant with respect to rotation of coordinate system, in which the matrix is described, by an arbitrary angle Φ. Mathematically, the BSPM invariance with respect to rotation is written as follows:

$$\mathbf{M}' = \mathbf{R}(\Phi)\ \mathbf{M}\ \mathbf{R}(\Phi) = \mathbf{M}, \qquad (3)$$

where $\mathbf{R}(\Phi)$ is the known operator of rotation of coordinate system about the z axis.[4]

Kaul[6] has shown that the only BSPM satisfying condition (3) is the matrix

$$\mathbf{M} = \begin{pmatrix} A & 0 & 0 & H \\ 0 & E & 0 & 0 \\ 0 & 0 & -E & 0 \\ H & 0 & 0 & C \end{pmatrix} \qquad (4)$$

or its particular case when $H = 0$.

Van de Hulst[4] defines such a matrix as a BSPM of an ensemble of asymmetric particles of one type with rotational symmetry, which depends on four parameters. In fact, there are three independent parameters since, as follows from Eq. (2), $E = (A - C)/2$. The requirement of a single particle type stems from the fact that the presence of particles with a different asymmetry may lead to the equality $M_{44} = -H$, so that Eq. (4) reduces to its particular case. The same is true if single-type particles and their mirror images occur in equal numbers, or if the particles are symmetric and are mirror images of themselves.

To proceed further, we should like to note that any deviation of a BSPM from form (4) or from its particular case means the rotational symmetry breakdown and existence of some preferred azimuth direction.

Kaul[6] has shown that, in the presence of preferred plane containing z axis, serving a mirror symmetry plane for an ensemble of particles, coincidence of reference plane with this plane allows the BSPM to be written in block-diagonal form:

$$\mathbf{M}_0 = \begin{pmatrix} A & B & 0 & 0 \\ B & E+F & 0 & 0 \\ 0 & 0 & -E+F & D \\ 0 & 0 & -D & C \end{pmatrix}, \qquad (5)$$

where $E = (A - C)/2$; $F = (A + C)/2$.

If we consider a mixed ensemble, in which some particles are oriented chaotically, then the parameters B, D, and F are determined only by a subensemble of oriented particles, while A, E, and C by the ensemble as a whole, and rotation operations are still invariant in this case. This BSPM is analogous in form to that obtained earlier in Ref. 7 for ensembles of axisymmetric elongated particles. However, as seen, the limitations due to particle shape are only minor. It is sufficient to require that the distribution over the orientation angles possesses mirror symmetry. For axisymmetric particles, it is fulfilled automatically.

If the reference plane does not coincide with the mirror symmetry plane and make an angle $\pm\,\Phi_0$ with it, and B and D are nonzero, then all elements but M_{14} and M_{41} are nonzero. However, the matrix $\mathbf{M}(\Phi_0)$ can be recast into the form (5) using the transformation

$$\mathbf{R}(\ \ \Phi_0)\ \mathbf{M}(\pm\Phi_0)\ \mathbf{R}(\ \ \Phi_0) = \mathbf{M}_0, \qquad (6)$$

with the angle Φ_0 determined from formula relating the BSPM elements

$$\Phi_0^{(1;2)} = \arctan\left(-\frac{M_{21}}{M_{31}} \pm \sqrt{\left(\frac{M_{21}}{M_{31}}\right)^2 + 1}\right), \qquad (7)$$

where the directions $\Phi_0^{(1)}$ and $\Phi_0^{(2)}$ are mutually orthogonal. The ambiguity in the angle is associated with the fact that, when reference plane is rotated ±90° away from the symmetry plane, the ensemble of particles becomes mirror symmetric about the plane of bisector, again leading to a block-diagonal matrix of the form (5), now with signs of B and D changed for the opposite ones.[4] An unambiguous choice of the angle is possible if the sign of parameter B is known when reference and mirror symmetry planes of the ensemble coincide. In our papers, we chosen minus sign over plus sign on the basis of the following model and experimental estimates.

If there are 2-D ensembles of strictly chaotically oriented hexagonal plates and columns, so that the hexagonal axes are vertical for the plates and horizontal for columns, for sensing along zenith direction the BSPM will have, due to rotational symmetry, the form (4) for zero H. If z axis in the xOz plane is tilted at an angle Θ, the rotational symmetry breaks down, however giving rise to preferred mirror symmetry plane coinciding with the xOz plane. In this case, the BSPM assumes the form (5), and the BSPM element $M_{12} = B$.

Kaul et al.[8] performed calculations and showed that, within this model of experiment, at angles $\Theta < 30°$ the M_{12} element monotonically decreases from 0 toward negative values, and for plates at a faster rate than for columns, possibly due in part to the geometric factor. For instance, circular plates will be projected onto the plane, perpendicular to the z axis, as ellipsoids oriented with their long axes across the mirror symmetry plane xOz; whereas hexagonal axes of the columns also will tend to shrink along a direction perpendicular to this plane. A similar behavior of the M_{12} element is also observed during sensing at different zenith angles. The choice of negative-valued parameter $B = M_{12}^{(0)}$ in determination of the angle Φ_0 means that the backscattering coefficient for linearly polarized radiation is minimum, if the vector of the electric field varies in the symmetry plane. As a likely hypothesis, it can be adopted that the cloud particles are oriented with their long axes across this plane.

If in formula (6) the $\mathbf{M}(\Phi_0)$ matrix is understood as an experimental BSPM, then the matrix $\mathbf{M}_0$, obtained as a result of transformation, in the following will be called the matrix reduced to the symmetry plane or, simpler, the “reduced BSPM”. The reduced BSPMs are more convenient for description of experimental results because they are expressed in terms of parameters that do not depend on the random Φ_0 values. Hence, BSPMs obtained in different experiments can be compared.

If particle ensemble consists of chaotically oriented particles of one type, or a few subensembles of chaotically oriented particles of different types, or one or a few particle subensembles subjected to the effect of some orienting factor, giving rise to a preferred mirror symmetry plane, then the measured BSPM can be presented as[6]:

$$\mathbf{M}^{(0)} = M_{11}^{(0)} \begin{pmatrix} 1 & m_{12}^{(0)} & 0 & m_{14}^{(0)} \\ m_{21}^{(0)} & m_{22}^{(0)} & 0 & 0 \\ 0 & 0 & m_{33}^{(0)} & m_{34}^{(0)} \\ m_{41}^{(0)} & 0 & m_{43}^{(0)} & m_{44}^{(0)} \end{pmatrix}. \quad (8)$$

As for any BSPM

$$m_{12}^{(0)} = m_{21}^{(0)};\ m_{34}^{(0)} = -\,m_{43}^{(0)};\ m_{14}^{(0)} = m_{41}^{(0)};$$

$$1 - m_{22}^{(0)} - m_{44}^{(0)} + m_{33}^{(0)} = 0.$$

The range of definition of normalized matrix elements m_{ij} is [−1; 1]. The algorithm of determination of experimental BSPMs is constructed in such a way that the normalization factor M_{11} – backscattering coefficient for unpolarized light – cancel out already at the stage of calculations of normalized non-reduced matrices **m**, the quantities immediately measured in experiment.[1,9] Then, reducing operation (6) is applied to **m** to produce the matrix $\mathbf{m}^{(0)}$ entering Eq. (8). To avoid misunderstanding, we note that $M_{11}^{(0)} = M_{11}$, since it is rotationally invariant. The element m_{44} is also invariant under transformation (3) and, together with $m_{11} \equiv 1$ and $m_{14} = m_{41}$, it constitutes the group of rotational invariants of normalized BSPM. Also, we can consider as a group member the related quantity $e = (1 - m_{44})/2$, representing the invariant part of moduli of the elements m_{22} and m_{33}.[6]

Based on the BSPM additivity with respect to scattering particles, we can easily prove the following statement. Suppose that the ensemble initially had rotational symmetry, and its BSPM had the form (4) with a determined element m_{44}. If now some particles are rotated about z axis and oriented along some preferred azimuth position, this will entail a change of BSPM. If, in particular, the particles are oriented in a position symmetrical about xOz plane, the BSPM will assume the form (5). However, after rotation of any number of particles through arbitrary angles Φ, the m_{44} value will remain unchanged. This proves the statement that the element m_{44} does not depend on particle azimuth position, and is determined by particle orientation relative to the plane perpendicular to the z axis. In our case, this is the horizontal plane.

Romashov and Rakhimov[7] introduced the parameter $i_2(k)$, which relates the parameter k (of Mizes distribution, *a priori* assumed for orientation of elongated axisymmetric particles) to the following combination of elements of non-reduced and non-normalized BSPM

$$i_2(k) = (M_{22} + M_{33})/(M_{11} + M_{44}) \cos\Phi_0;$$

$$i_2(k) = I_2(k)/I_0(k),$$

where $I_2(k)$ and $I_0(k)$ are modified second- and zero-order Bessel functions (for Mizes distribution see Ref. 7). After $i_2(k)$ is determined, it is possible to evaluate k and thereby to estimate the directional preference of particle axes around Φ_0 direction.

In interpretation of experimental data we assume that cloud particles have different shapes, and that some of them may be subject to the effect of a factor leading to a preferred particle orientation and the other may not. Therefore, for such mixed ensembles, this same unique qualitative measure of directional preference as introduced in Ref. 7 is unusable. Nevertheless, Kaul[6] introduced “preference parameter” χ, expressed in terms of the elements of the normalized reduced BSPM:

$$\chi = (m_{22}^{(0)} + m_{33}^{(0)})/(1 + m_{44}^{(0)}). \quad (9)$$

This parameter has maximum value of unity for the case when all particles are symmetric and their axes are oriented strictly parallel or perpendicular to the symmetry plane. In the other cases and, in particular, when strictly oriented symmetric particles are part of a mixed ensemble, this parameter is less than unity. For chaotic particle orientation, this parameter equals zero.

Description and discussion of the experimental results

The compiled measurement data on the BSPM, including early measurements, were reprocessed by the method based on calibration of instrumental vectors of the receiving system of lidar against the BSPM of the atmospheric molecular constituent and on statistical approach to solution of equation system from which elements of experimental BSPM were determined.[9] The latter has made it possible to obtain an error matrix for each measured matrix and, thus, to reject the matrices measured with large errors. The main sources of error were either instability of the cloud field during measurements, or minor predominance of aerosol component of BSPM over the molecular one. We excluded from consideration the BSPMs for which square root of weighted mean variance exceeded the prescribed threshold $\sigma_{th} = 0.05$.

Overall, the compiled experimental material contains about 600 matrices pertaining to high-level clouds. After data reduction according to σ_{th} criterion, 463 BSPMs left, defining the volume of the sample for determination of the statistical characteristics of BSPMs of the ice clouds.

All matrices included into the sample were subject to operation of reducing. However, the use of formula (7) for small values of element m_{31} in the presence of experimental uncertainty may lead to large errors in determination of the reducing angle Φ_0. Therefore, the argument of the operator $\mathbf{R}(\Phi_0)$, defined by the transformation (6), was determined using the property of reduced BSPM (8):

$$m_{13}^{(0)} = m_{23}^{(0)} = m_{24}^{(0)} = 0, \qquad (10)$$

approximate in character because of the experimental error. Additional conditions for Φ_0 determination is the above-justified relation:

$$m_{12}^{(0)} \text{ and } (m_{22}^{(0)} + m_{33}^{(0)}) \geq 0. \qquad (11)$$

The second inequality is the condition of nonnegative value of the parameter χ.

Using transformation (6), as well as condition (10), it is possible to write three equations for random values of argument of transformation (6) $Y_i = 2\hat{\Phi}_i$:

$$Y_1 = \arctan(-m_{13}/m_{12}) + l\pi,\ l = -1;\ 0;\ 1,$$

$$Y_2 = \frac{1}{2}\arctan[-2\,m_{23}/(m_{22} + m_{33}^{(0)})] + k\pi/2,$$

$$k = -2;\ -1;\ 0;\ 1;\ 2, \qquad (12)$$

$$Y_3 = \arctan(-m_{24}/m_{34}) + n\pi,\ n = -1;\ 0;\ 1,$$

where m_{ij} are elements of the normalized experimental BSPM; and Φ_i is a random estimate of the angle Φ_0. Values of l, k, and n were additionally defined by conditions (11) and the condition of the least divergence between Y_i. The variance $\hat{D}[Y_i]$ was estimated as a linear transformation of errors in the vicinity of the mean value using first term of expansion in Tailor series. Because of random and independent character of errors, the matrix $\mathbf{D}(Y)$ is diagonal. On account of this, the system (12) is considered as a linear-regression problem and represents the solution by the least squares method

$$2\hat{\Phi}_0 = (\mathbf{A}^{\mathrm{T}}\,\mathbf{D}^{-1}\,\mathbf{A})^{-1}\,\mathbf{A}^{\mathrm{T}}\,\mathbf{D}^{-1}\,\mathbf{Y} \qquad (13)$$

with the error estimate

$$D(2\Phi_0) = (\mathbf{A}^{\mathrm{T}}\,\mathbf{D}^{-1}\,\mathbf{A})^{-1},$$

where $\mathbf{A}^{\mathrm{T}} = (1\ 1\ 1)$; $\mathbf{Y}$ is the column vector with the components Y_i; and T indicates the transposition.

The procedure of Φ_0 calculation had made it possible to estimate the root mean square error $\sigma[\Phi_0]$ for each specific BSPM. For different matrices, the $\sigma[\Phi_0]$ estimate ranges from 0.5 to 6.5°. The orientation order parameter χ was determined from formula (10). At $\sigma_{th} = 0.05$ and model values of BSPM elements (which determine this parameter), $\hat{\sigma}[\chi]$ is estimated to be ±0.06.

In the following we deal only with quantities related just to the considered matrices; so the superscript (0) will be omitted.

The results of statistical processing are presented in Figs. 1–3; shown are the relative frequencies of occurrence of that or other values of BSPM elements and of orientation parameters. Below we present two matrices: one with modal values of frequency distribution, and the other one with the mean values:

$$\mathbf{m}_{\mathrm{mod}} = \begin{pmatrix} 1 & -0.1 & 0 & 0 \\ -0.1 & 0.6 & 0 & 0 \\ 0 & 0 & -0.4 & 0 \\ 0 & 0 & 0 & 0.1 \end{pmatrix},$$

$$\chi_{\mathrm{mod}} = 0.1;$$

$$\langle\mathbf{m}\rangle = \begin{pmatrix} 1 & -0.22 & -0.01 & 0.01 \\ -0.22 & 0.59 & 0.00 & -0.03 \\ 0.01 & 0.00 & -0.40 & 0.02 \\ 0.01 & -0.03 & -0.02 & -0.01 \end{pmatrix},$$

$$\langle\chi\rangle = 0.125.$$

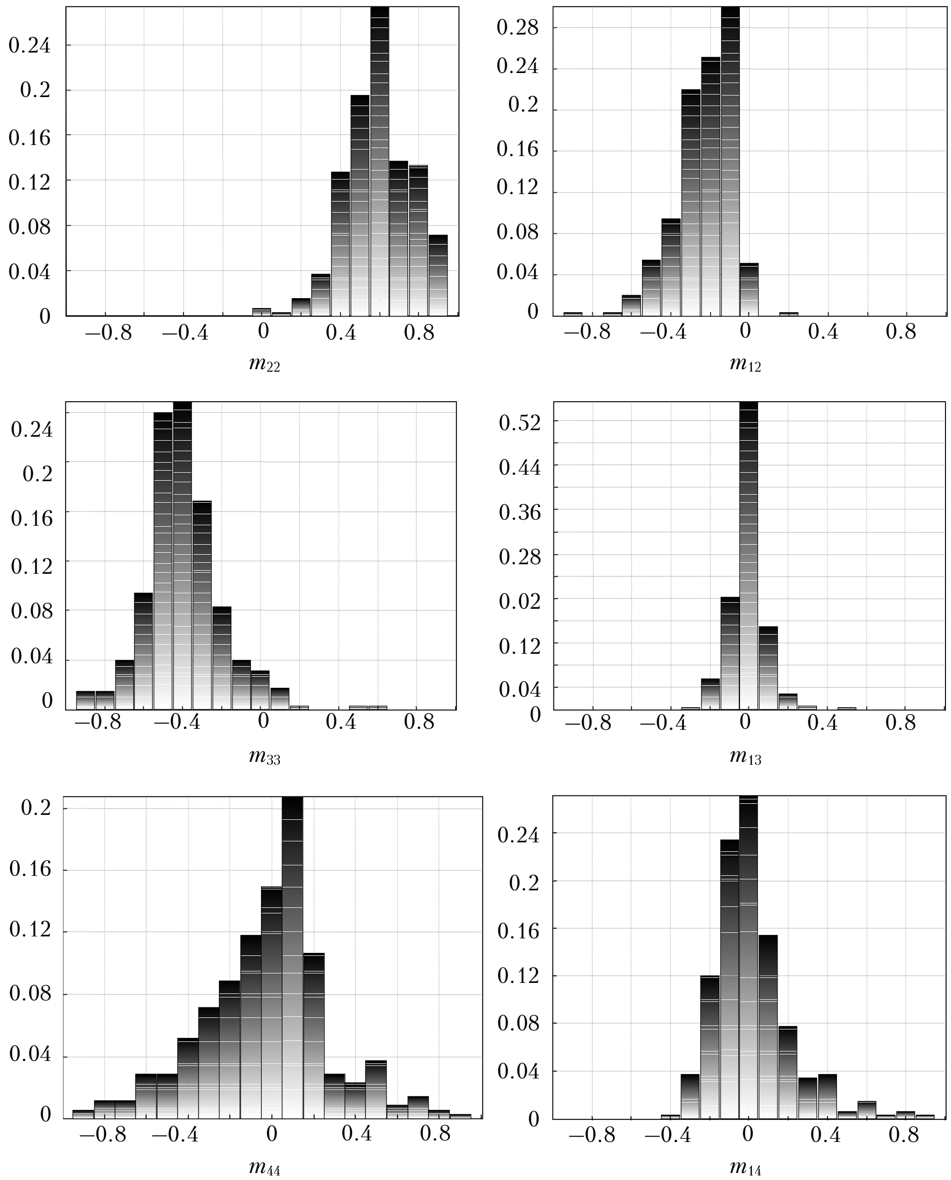

Fig. 1. Relative frequencies of values of elements m_{ij} of normalized reduced backscattering phase matrices for ice clouds.

The first of them should not be considered physically meaningful, because this is just a compact representation of modal values of the corresponding elements. The second matrix can be interpreted as a normalized BSPM of hypothetical ensemble of particles, composed of subensembles representing equal fractions of all ensembles making up the sample. Here, the equality of fractions is understood as the equality of backscattering coefficients for natural light (of course, assuming that all subensembles are reduced to a single symmetry plane using rotations at the corresponding angles). Thus, the BSPMs of subensembles are by definition independent of random values of the orientation angle.

Form the above material we can conclude and speculate the following:

1. The state of ice crystal cloud, at which rotational symmetry breaks down, is more probable than the state with no symmetry breakdown. This statement follows from the fact that the mode of the distribution of the element m_{12} is shifted from zero to −0.1 (Fig. 1). The probability of this and larger (in absolute value) negative m_{12} value is estimated at 0.95. From the aforesaid it follows that, at sensing along zenith with a linearly polarized radiation, it is highly probable to obtain an uncertainty in the backscattering coefficient, because it will depend on orientation of polarization plane of laser radiation.

2. The mode of the χ parameter distribution (Fig. 2) does not coincide with zero, but the majority of cases concentrates in the region 0–0.15. Comparison of this result with that presented in section 1 enables us to conclude that the particles oriented along some preferred azimuth direction are usually only a part of the cloud ensemble. Most particles are unaffected by the orientating factor. In other words, most probable are

mixed ensembles in which some particles are chaotically oriented, and the other have preferred orientation. However, $\chi \geq 0.2$ in about 30% of cases that may reach 0.6 or higher in some other cases suggests quite marked orientation preference. Presumably, in such situations the cloud is largely composed of quite large, similar, and essentially anisometric particles such as hexagonal columns or needles.

3. From results presented in Fig. 3 we can see that the center of distribution of positions of symmetry plane, defined by condition (11), is shifted toward west-east direction, i.e., toward dominating wind direction at ice cloud heights. Considering this in the framework of an earlier argument that particles are oriented with their long axes perpendicular to the symmetry plane, we can hypothesize that wind velocity variations may serve as orientation factor. The inertial forces, arising in this case and acting for a long time, may lead to partial orientation ordering along azimuth direction such as occurs during gravitational settling of particles, with their long axes in horizontal position. Also the orientation effect of the electric fields is not ruled out.

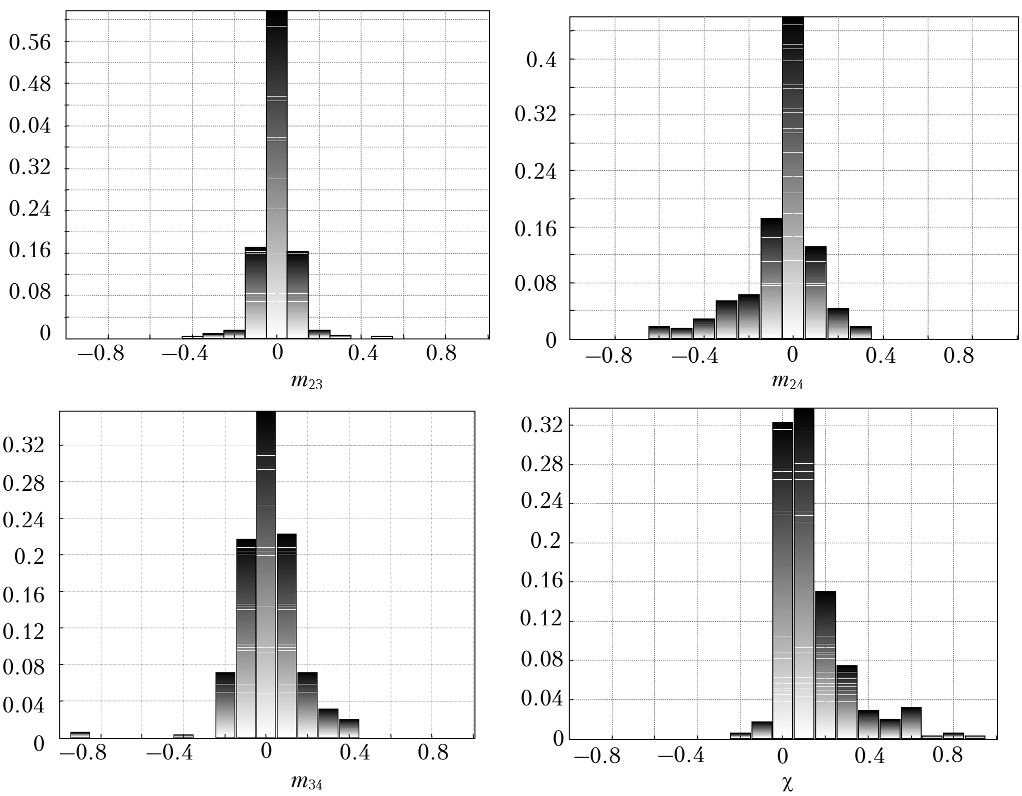

Fig. 2. Relative frequencies of values of elements m_{ij} of normalized reduced backscattering phase matrices for ice clouds as well as parameter of degree of orientation preference along azimuth direction χ.

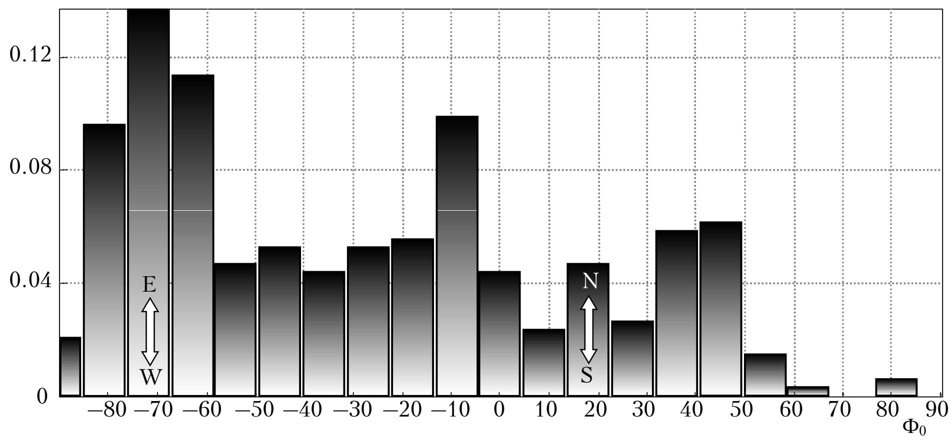

Fig. 3. Relative frequencies of occurrence of angles of symmetry plane orientation of cloud particle ensemble Φ_0 about reference plane xOz of coordinate system associated with lidar receiving system. The angle is measured from positive direction of x direction, oriented horizontally at an azimuth angle 342° during sensing along the zenith.

4. As it has already been shown above, the value of the element m_{44} is related to particle orientation relative to the horizontal plane. This relation depends on the particle shape. For mixed ensembles, such as ice clouds, the exact quantitative estimation of the orientation preference is difficult to find. The numerical simulations of BSPM ensembles of hexagonal ice plates and columns[8,10] make it possible to develop some qualitative or semi-quantitative judgements.

It is a common feature for plates and columns that the element m_{44} tends to shift toward large negative values with increase of orientation preference about horizontal plane. As follows from simulated results in situations where up to 90% of ice column axes concentrate within ±10° of horizon, m_{44} values lie in the range [−0.45, −0.35]. Close values are found for ensembles of plates, for which 90% of hexagonal axes are within 30° about the vertical. As the orientation preference increases on, m_{44} asymptotically approaches −1. Ensembles of ice columns with chaotic orientation have m_{44} ranging from 0.3 to 0.4. Similarly oriented plates have near-zero values. However, near-zero m_{44} values are also found for ensembles of plates with weak to moderate orientation preference, i.e., with more than half (up to 90%) of axes lying within 45° of the vertical.

If the experimental results presented in Fig. 1 are interpreted in terms of available simulation results, then m_{44} values corresponding to the mode and average of the distribution can be considered to characterize both ensemble of columns with weak to moderate orientation preference and ensemble of plates with chaotic orientation or weak orientation preference. However, it would be more realistic to suggest that the cloud ensemble in such a case is represented by a mixture of quite large anisometric particles with a substantial orientation preference about horizontal plane of plates or columns or particles of some other shape, or, otherwise, both small and large (but isometric) particles not subjected to gravitational orientation.

It is noting the substantial skewness of the distribution of the element m_{44}. BSPM realizations have values $m_{44} \leq -0.2$ in about 30% of cases, and sometimes may reach near-asymptotic value $m_{44} = -0.9$. These should be considered as realizations with substantial, strong, and very strong orientation preference in the case of gravitationally settling particles. It should be natural to suggest that in such cases, the cloud layer is dominated by large (larger than 50 μm in characteristic size) and anisometric particles which, according to Volkovitskii,[11] have preferred orientation due to aerodynamic forces during gravitational settling.

A significant (up to 15%) percentage of realizations lies in the interval $0.2 \leq m_{44} \leq 0.4$ and can be interpreted as a BSPM of an ensemble of columns with weak to no orientation preference.

In the framework of models considered here, a small (up to 5%) percentage with $m_{44} \geq 0.5$ can be interpreted only as BSPMs of an ensemble of columns with strong orientation, but relative to a tilted plane. However, this is not the subject of the present work.

Conclusion

From measurements of BSPMs of ice crystal clouds we can conclude the following.

Large (up to 70%) percentage of clouds seems to be represented by ensembles of particles having different shapes within a wide size spectrum comprised of many small-sized particles. These latter, together with large but isometric particles are unaffected by orientation factors and mask the influence of large particles with preferred orientation on the form of the BSPM. Nonetheless, the preferred orientation almost always manifests itself in small but nonzero parameters χ and m_{12}, as well as in corresponding values of the m_{44} element. For a cloud with a set of parameters $0 \leq \chi < 0.2$; $m_{12} > -0.2$, and $m_{44} \cong 0$, the particle orientation, seemingly, can be considered quasi-chaotic and, therefore, the model of equivalent radius spheres can be used to calculate the extinction of solar radiation. However, for χ and m_{12} values, indicated above, the m_{44} value is shifted significantly toward negative values, a substantial orientation preference about horizontal plane can be expected. In such a case, the extinction of solar radiation will depend on the solar elevation angle. Here we note that Kaul et al.[8] demonstrated how the element m_{44} can be determined in a simple experiment with circularly polarized sounding radiation with a small probability of significant error, primarily because the distribution of the element m_{14} is quite closely concentrated about zero.

In many of the BSPM realizations, there is a significant anisotropy of optical properties of ice-crystal clouds, so that the extinction of solar radiation depends not only on the elevation but also on the azimuth position of the sun. In such a case, the distribution of scattered solar radiation has complex angular structure. Detection and treatment of such situations generally requires knowledge of the complete BSPM. However, if the hypothesis that wind velocity variations play an important role as the particle orientation factor will be justified, then the knowledge of wind velocity and direction and BSPM element m_{44} as prognostic parameters possibly would be sufficient to estimate the state of particle orientation in calculations of transmitted and scattered solar radiation; the latter parameter, as was noted above, is easily measured in experiment. The optimism about this possibility is based on the correlation between degrees of orientation preference in azimuth and horizontal directions, noted in Ref. 10. This correlation is easily explained if the azimuth orientation preference due to wind variations is assumed.

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