EPJ Web of Conferences **119**, 16001 (2016) DOI: 10.1051/epjconf/201611916001
ILRC 27

BACKSCATTERING PROPERTIES OF NONSPHERICAL ICE PARTICLES CALCULATED BY GEOMETRICAL-OPTICS-INTEGRAL-EQUATION METHOD

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ABSTRACT

Backscattering properties of ice crystal models (Voronoi aggregates (VA), hexagonal columns (COL), and six-branched bullet rosettes (BR6)) are calculated by using geometrical-optics-integral-equation (GOIE) method. Characteristics of depolarization ratio (δ) and lidar ratio (L) of the crystal models are examined. δ (L) values are 0.2~0.3 (4~50), 0.3~0.4 (10~25), and 0.5~0.6 (50~100) for COL, BR6, and VA, respectively, at wavelength λ=0.532μm. It is found that small deformation of COL model could produce significant changes in δ and L.

1. INTRODUCTION

Optical properties of nonspherical ice crystals influence the accuracy of retrieval of cirrus cloud information from remote sensing measurements. Improvements in modeling of ice crystal shapes and numerical calculation schemes are of increasing importance. Optical properties of three kinds of crystal models of VA (irregular particles), COL and BR6 (regular particles) have been investigated from visible to infrared wavelength regions by using the finite-difference time-domain (FDTD) and the GOIE methods [1]. In this work, the depolarization ratio (δ) and lidar ratio (L) for VA, BR6, and COL models are examined to study a feasibility for applying theoretical calculations to lidar measurements.

2. METHODOLOGY

Ice crystal models and computational scheme used in this work are described in [1]. A short summary is presented here. Size of ice crystals is expressed in terms of the radius of volume equivalent sphere (R_{eq}). Eleven (eight) kinds of R_{eq} is considered for VA and COL (BR6) from 2.8 μm (28.0 μm) to 202.0μm. The aspect ratio of COL and elements of BR6 are changed depending on the crystal size. Seven sizes of VA model are considered, for which the number of faces are changed from 92 to 2667. In GOIE, the reflected and refracted near fields are calculated by the ray-tracing technique, and then, the scattered far field can be obtained by integrating the near fields over the particle's surface [2]. Preliminary results of the backscattering phase function $F_{11}(\pi)$ and δ, defined by the perpendicular-to-parallel polarization components of backscattered light, have been presented in [1] with a note that "the values may include large errors". Note that, in [1], number of particle orientations is determined from the convergence check of average phase function, not from the convergence of backward radiation. In this respect, it is demonstrated that large numbers of random orientations (N_{ori}) are necessary to calculate the radiation of backward direction accurately [3-4]. After some trial and error, N_{ori} for COL and BR6 are chosen to be 24000~96000 and 48000, respectively, whereas N_{ori} for VA is changed from 500 to 24000 depending on the number of faces.

3. RESULTS

As a preliminary study, we compared, in Figure 1, the M_{11} element of Mueller matrix calculated by GOIE for quasi-horizontally oriented hexagonal plates with those calculated by the physical optics approximation method [5] that is essentially the same as GOIE. Except for some fluctuations at tilt angles less than 10 degree, GOIE calculation shows close agreement with the results by Borovoi et al. that is open to the public via World

Wide Web [5].

$F_{11}(\pi)$ and δ at λ=0.565μm are calculated in a similar manner to [1] except for using the above-mentioned N_{ori} values (Fig.2). Ice crystals are assumed to be randomly oriented in three-dimensional space. It has been confirmed that the fluctuations in $F_{11}(\pi)$ and δ with respect to size parameter X_{eq} are much reduced by increasing numbers of random orientations.

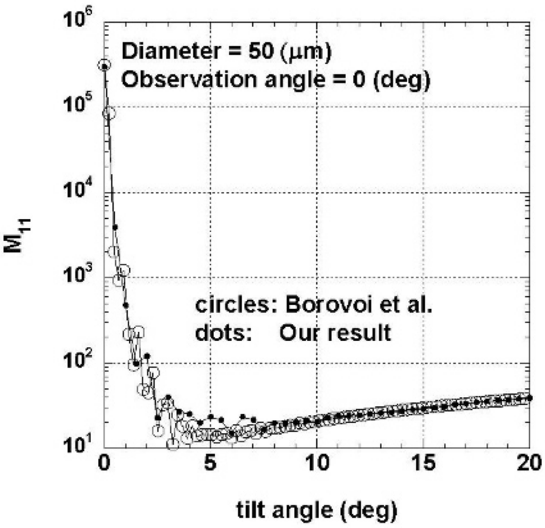
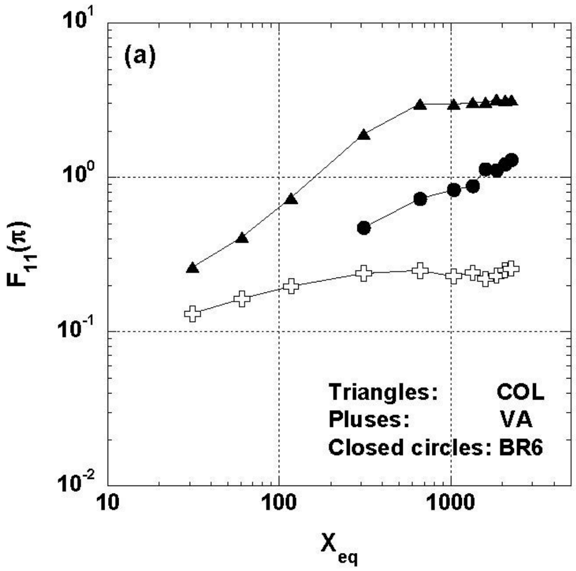


Fig. 1: Backscattering Mueller matrix element (M_{11}) at λ=0.532μm with observation angle of 0 degree for quasi-horizontally oriented ice plates of 50.0μm diameter and 11.7μm height as a function of plate tilt angle. M_{11} is defined as $F_{11}\sigma_{sca}/4\pi$, where F_{11} and σ_{sca} are the phase function and scattering cross section, respectively.



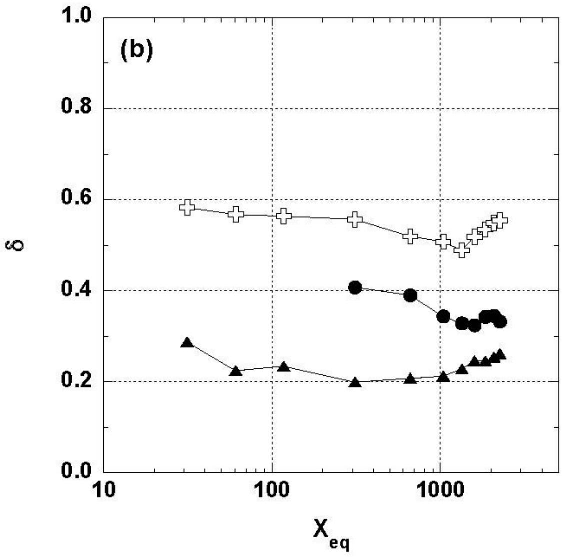


Fig. 2: Backscattering phase function $F_{11}(\pi)$, (a) and depolarization ratio δ, (b) with respect to the size parameters at wavelength λ=0.565μm for the Voronoi aggregates (VA), hexagonal columns (COL), and six-branched bullet rosettes (BR6).

Figure 3 shows the relation between δ and L predicted from theoretical calculations at λ= 0.532μm. L is defined as σ_e/σ_π where σ_e and σ_π are the extinction and backscatter cross sections, respectively. To examine a feasibility for applying theoretical calculations to lidar measurements, the range of (L, δ) for upper clouds over Tsukuba, Japan observed with the lidar is also presented in Fig.3.

Because the columnar particles with length of 80~150μm are dominant in the microscopic image of the cloud particles taken using the hydrometer videosonde over the lidar observational site [6], from now on, we concentrate on the analysis of lidar measurements by using COL model.

The (L, δ) calculations for COL of comparable sizes to the observational data are indicated with the symbols A and B. Although the results are within the observational range of (L, δ), most measurements of (L, δ) produced by the lidar are inconsistent with the calculations for COL model.

It should be noted that the COL model is assumed to be composed of perfect hexagonal ice crystals without any roughness or deformations. On the contrary, the microscopic image of the ice cloud particles shows deformation from the perfect hexagonal shapes to some extent. We did sensitivity tests to investigate the effect of deformation of COL on L and δ.

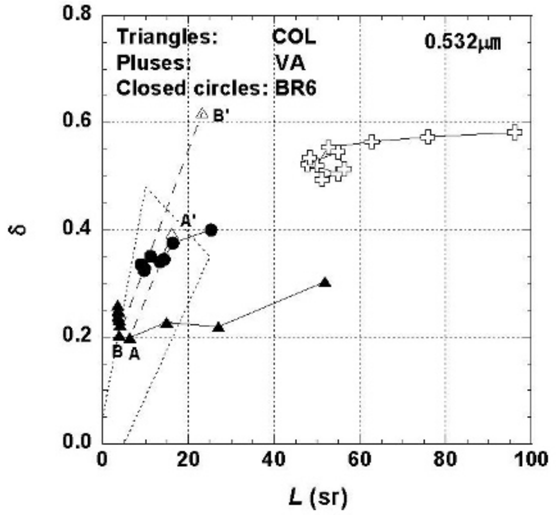


Fig. 3: Diagram showing the relation between the lidar ratio (L) and depolarization ratio (δ) for randomly oriented ice crystal models at wavelength λ=0.532μm calculated by GOIE. The area surrounded by dotted lines roughly shows (L, δ) of upper clouds measured with the lidar over Tsukuba, Japan on 29 March 2004 [6]. The symbol A shows the results for COL of R_{eq}=28.0μm with the radius (a) and length (l) of 23.1μm and 66.1μm, respectively; symbol B for R_{eq}=59.4μm, a=45.0μm, l=167.0μm. The symbols A' and B' indicate the results for modified COL models (See text in detail).

Center of each hexagonal face of COL is moved towards the column center by 0.5% of the column length. Thus, shallow hollows are created on the hexagonal faces. The (L, δ) for the modified COL model are shown by open triangles indicated with the symbols A' and B'. It is noted that L and δ values significantly changes by the small deformation of COL.

This changes in L and δ can be explained as follows. The backscattered light by hexagonal plates and columns are composed of specular and corner-reflection terms [7]. The corner-reflection term originates from refraction/reflection events at orthogonal faces of the hexagonal crystals. For particles randomly oriented in three-dimensional space, the corner-reflection term is dominant in backscattering radiations. Thus, the L and δ values could be significantly influenced by disturbing the orthogonality between neighboring faces, particularly for large sizes of particles.

4. CONCLUSIONS

Backscattering properties of nonspherical ice particles are calculated for three kinds of ice crystal models (VA, BR6, COL) by use of the GOIE method. Particularly, δ and L are examined for their applications to the lidar measurements. The calculated L and δ are compared with measurements by the lidar. It is difficult to explain all observed δ and L values by theoretical calculations with the above-mentioned crystal models. However, small deformation of the COL model produce significant changes in δ and L. In consequence, wide ranges of L and δ values observed by the lidar could be explained by some deformation of crystal models.

ACKNOWLEDGEMENT

This work was supported by the Global Change Observation Mission Climate (GCOM-C1) research project of Japan Aerospace Exploration Agency (JAXA). We thank Drs. Borovoi and Konoshonkin for valuable comments on calculation of backscattering radiation of quasi-horizontally oriented hexagonal plates.

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