LIDAR BACKSCATTERING BY QUASI-HORIZONTALLY ORIENTED HEXAGONAL ICE PLATES

Anatoli Borovoi[1], Alexander Konoshonkin[1], Natalia Kustova[1], Hajime Okamoto[2]

[1]*V.E. Zuev Institute of Atmospheric Optics, Rus. Acad. Sci., 1, Academician Zuev Sq., Tomsk 634021, Russia*
E-mail: borovoi@iao.ru
[2]*Kyushu University, Research Institute for Applied Mechanics, 6-1 Kasuga-koen Kasuga-city, Fukuoka 816-8580 Japan, E-mail: okamoto@riam.kyushu-u.ac.jp*

ABSTRACT

Three values measured by the spaceborne lidar CALIPSO, i.e. backscattering coefficient, color ratio and depolarization ratio, have been calculated within the framework of physical optics for quasi-horizontally oriented hexagonal ice plates. The dependence of these values on the effective deviation of crystal orientations is obtained for the case of normal incidence of light and axially symmetric distribution of crystal orientations. Such results are applicable for the data obtained by CALIPSO at the initial tilt of its axis at 0.3° from nadir.

1. INTRODUCTION

Lidars are the most effective instruments for retrieving microphysical parameters of clouds. In particular, for ice clouds, the microphysical parameters are sizes, habits and orientations of the ice crystals. At present, only the spaceborne lidar CALIPSO is capable to yield such information in global scale. It measures three quantities: the backscattering coefficient $\beta(0.532)$ at the wavelength of 0.532 μm, the color ratio

$$\chi = \beta(1.064)/\beta(0.532) \qquad (1)$$

and the depolarization ratio

$$\delta = \beta_{\perp}(0.532)/\beta_{\parallel}(0.532)\,. \qquad (2)$$

Therefore a lot of papers are devoted to a retrieval of the microphysical parameters of ice clouds from the CALIPSO data (e.g. [1-5]).

In such analyses, the case of quasi-horizontally oriented ice plates plays an important role since such crystals produce the specific lidar signals with anomalously large backscattering coefficient and small depolarization. This phenomenon has been widely studying by ground-based lidars for a long time (e.g. [6-10]). Also, this was the phenomenon that demanded to change the incidence angle of CALIPSO from the initial 0.3° to 3°.

A contribution of the horizontally oriented ice crystals to the lidar signals reflected from cirrus clouds for either spaceborne or ground-based lidars is a poorly investigated problem yet. The main reason of this is that the problem of light backscattering by such crystals has not been calculated theoretically in spite of a number of efforts [11-14].

In this paper we fill the gap by our numerical solution to the problem that is based on the physical-optics approximation described in [15].

2. BACKSCATTERING MUELLER MATRIX FOR QUASI-HORIZONTALLY ORIENTED PLATES

A hexagonal ice plate is determined by its diameter D and height h. Orientation of the plate is described by three Euler angles θ, φ, and γ. Here θ is the plate tilt, i.e. the angle between the normal to the upper facet of the plate and the vertical (zenith) upward direction; the azimuth angle φ corresponds to a rotation of the plate normal around the vertical; and γ determines a particle rotation around its normal. The plate orientations are mostly axially symmetric and gaussian, i.e. the orientations are uniformly distributed over the angles φ and γ, and only the probability density for tilts $p(\theta)$ is gaussian

$$p(\theta) = const \cdot \exp(-\theta^2 / 2\theta_{eff}^2)\,, \qquad (3)$$

where the standard deviation of the distribution will be called the effective tilt θ_{eff}.

In the simplest case of vertical incidence of lidar light on a plate with axially symmetric orientations, the backscattering Mueller matrix is analogous to the case of randomly oriented particles [16], i.e. we have

$$M(\theta_{eff}) = \sigma(\theta_{eff})\times \times diag\left\{1, 1-d(\theta_{eff}), d(\theta_{eff})-1, 2d(\theta_{eff})-1\right\}. \qquad (4)$$

Here $\sigma(\theta_{eff})$ is the backscattering cross section reduced for the horizontally oriented plate to the well known equation [17]

$$\sigma(0) = \left[K^2 + K^2(1-K^2)^2\right]S^2/\lambda^2\,, \qquad (5)$$

where $K = (n-1)/(n+1)$, n is the refractive index of ice at the incident wavelength λ and S is the area of the upper plate facet. The value $d(\theta_{eff})$ is the backscattering depolarization that is connected with the depolarization ratio of Eq. (2) by the simple equation

$$\delta(\theta_{eff}) = d(\theta_{eff}) / [2 - d(\theta_{eff})]. \quad (6)$$

The color ratio of Eq. (1) is determined by the equation

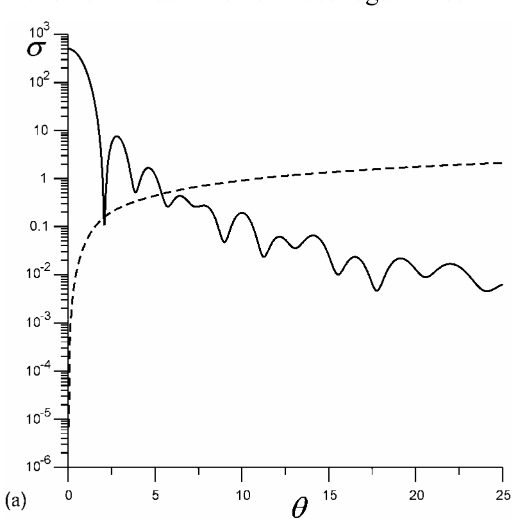
$$\chi(\theta_{eff}) = \sigma_{1.064}(\theta_{eff}) / \sigma_{0.532}(\theta_{eff}). \quad (7)$$

In this contribution, we have calculated the values $\delta(\theta_{eff})$ and $\chi(\theta_{eff})$ for three fixed plate diameters D, where the diameters of 10 μm, 100 μm, and 1000 μm were chosen to represent the small, mediate, and large sizes of the quasi-horizontally oriented plates. Their heights were taken from the well-known equation

$$h = 2.020241791 \cdot D^{0.449} \text{ (in microns)} \quad (8)$$

3. THE SPECULAR AND CORNER-REFLECTION TERMS

The specific feature of the problem of light scattering by quasi-horizontally oriented plates is that the scattered field consists of two components differing qualitatively from each other. The first is the specular term associated with light reflection by a plane-parallel plate truncated by the hexagonal facets. The second is the corner-reflection term where the angle of 90° between the hexagonal and rectangular facets transforms the plate into a 2D corner reflector at a specific value of the rotation angle γ [18, 19]. So while the specular term decreases with the plate tilt θ because of the diffraction pattern on the hexagonal facet, the corner-reflection term, on the contrary, increases because of the increasing projection of the plate height. Fig. 1 shows an illustration of these regularities.



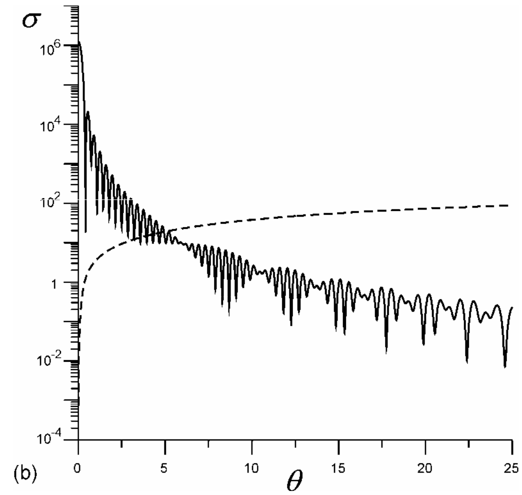


Figure 1. The backscattering cross sections versus the plate tilts θ for the specular (solid line) and corner-reflection (dashed line) terms (1a: $D = 10\,\mu$m, $\lambda = 0.532\,\mu$m; 1b: $D = 100\,\mu$m, $\lambda = 1.064\,\mu$m).

4. THE CROSS SECTIONS AND THE COLOR RATIOS FOR FLUTTERING ICE PLATES

If orientations of the ice plates are determined statistically by means, for example, of the law of Eq. (3) we shall call the plate as fluttering for brevity where any motions of the plates are not inferred. For

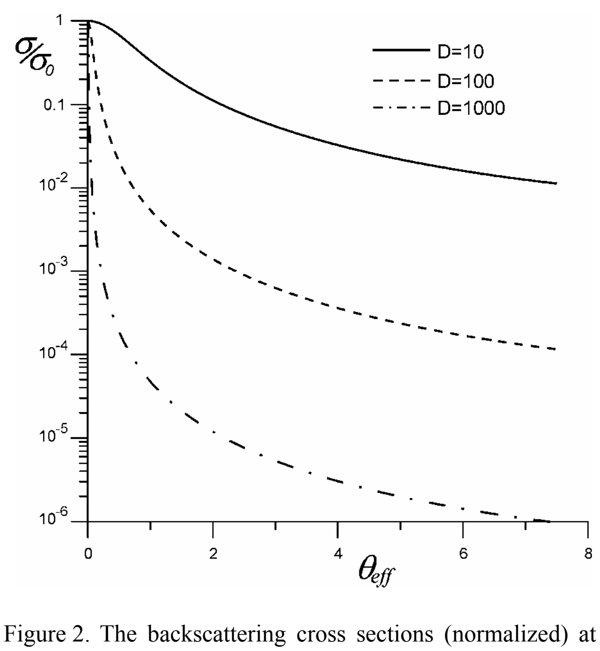


Figure 2. The backscattering cross sections (normalized) at the 0.532 μm wavelength for small, mediate and large plate sizes, respectively.

the fluttering plates, we have to average the backscattering cross sections like Fig. 1 over particle tilts according to the law of Eq. (3). As a result, we get the values $\sigma(\theta_{eff})/\sigma(0)$ presented in Fig. 2 at the wavelength of 0.532 μm that shows an impact of plate tilts on the backscattering. Fig. 3 shows the same value at the wavelength of 1.064 μm presented as their ratio that means the color ratio determined by Eq. (7).

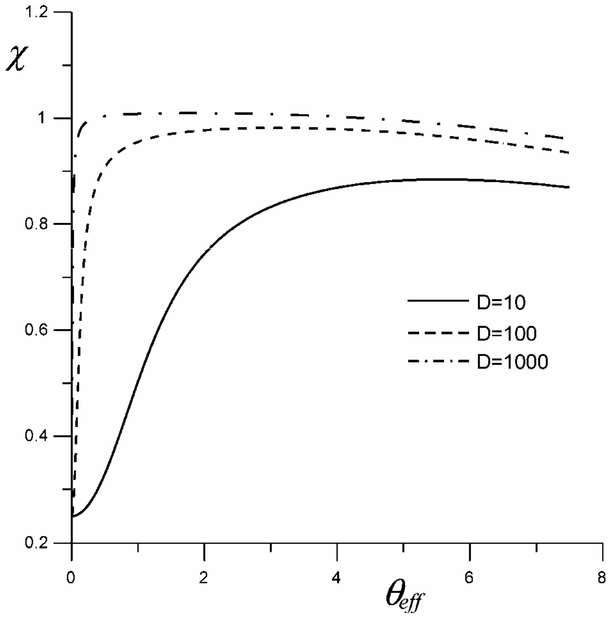
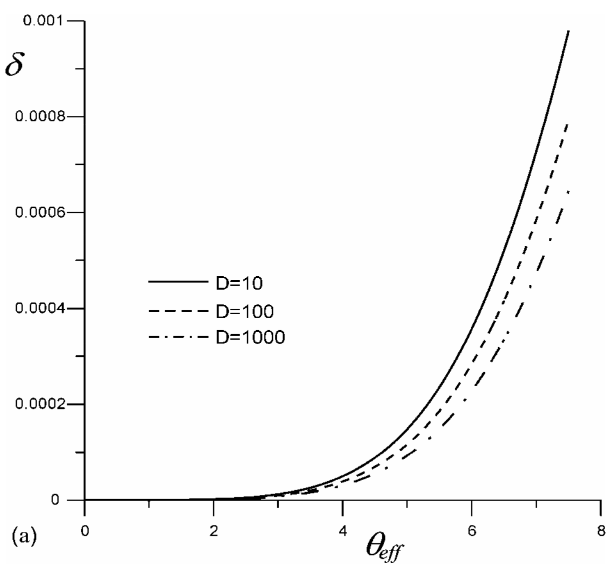


Figure 3. The color ratio versus the effective particle tilts for large (upper), middle, and small (lower) plate sizes.

5. THE DEPOLARIZATION FOR FLUTTERING PLATES

The depolarization ratio of Eq. (2) is shown in Fig. 4a while the same value for the wavelength of 1.064µm is presented in Fig. 4b for a comparison .



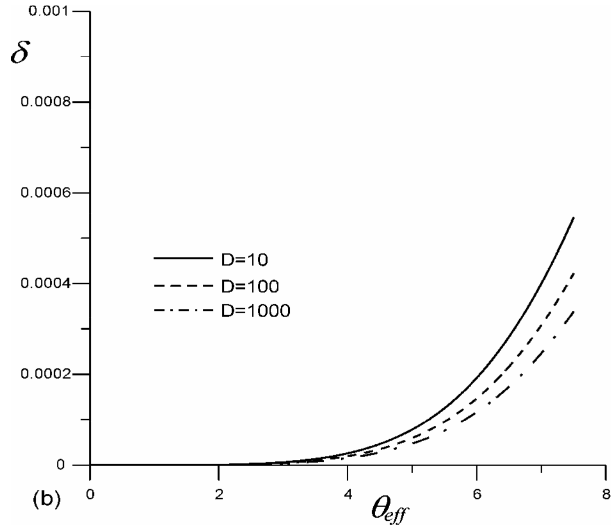


Figure 4. The depolarization ratio versus the effective particle tilts at the wavelengths of 0.532µm (4a) and 1.064 µm (4b).

6. CONCLUSIONS

Three values obtained, i.e. the backscattering cross section, the color ratio and the depolarization ratio are just the full set of parameters that are needed to incorporate the quasi-horizontally oriented plates in any light backscattering model for both ice and mixed clouds.

The data of this paper concern only the case of normal incidence of light. Nevertheless, as seen from the figures obtained, an additional tilt of the particles on the angle of 0.3° corresponding to the initial tilt of the axis of CALIPSO does not crucially change the values calculated. Therefore, the data of this paper are applicable to the CALIPSO data with the tilt of 0.3°. However, an additional tilt of the particles on the present tilt of CALIPSO of 3° essentially changes the values of interest. So the case of slant incidence of light should be further calculated.

ACKNOWLEDGMENTS

A. Borovoi is acknowledged to Kyushu University where he was affiliated with as a visiting researcher. A. Borovoi, A. Konoshonkin and N. Kustova thank the Russian Foundation for Basic Research supporting this work under the grant No. 12-05-00675a. H. Okamoto is supported by the Ministry of Education, Culture, Sports, Science, and Technology of Japan through Grants-in-Aid for Scientific Research B (22340133).

REFERENCES

1. Hu Y., M. Vaughan, Z. Liu, B. Lin, P. Yang, D. Flittner, B. Hunt, R. Kuehn, J. Huang, D. Wu, S. Rodier, K. Powell, C. Trepte, D. Winker, 2007: The depolarization-attenuated backscatter relation: CALIPSO lidar measurements vs. theory, *Optics Express,* **15**, pp. 5327-5332.

2. Cho H.-M., P. Yang, G. W. Kattawar, S. L. Nasiri, Y. Hu, P. Minnis, C. Trepte, D. Winker, 2008: Depolarization ratio and attenuated backscatter for nine cloud types: analyses based on collocated CALIPSO lidar and MODIS measurements, *Optics Express,* **16**, pp. 3931-3948.

3. Noel V., H. Chepfer, 2010: A global view of horizontally oriented crystals in ice clouds from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), *Journal of Geophysical Reearch,* **115**, D00H23.

4. Okamoto, H., K. Sato, Y. Hagihara, 2010: Global analysis of ice microphysics from CloudSat and CALIPSO: Incorporation of specular reflection in lidar signals, *Journal of Geophysical Research,* **115**, D22209, doi:10.1029/2009JD013383.

5. Sato K., H. Okamoto, 2011: Refinement of global ice microphysics using spaceborne active sensors, *Journal of Geophysical Research*, **116**, D20202, doi:10.1029/2011JD015885

6. Platt C. M. R., N. L. Abshire,G. T. McNice, 1978: Lidar backscatter from horizontal ice crystal plates, *Journal of Applied Meteorology,* **17**, pp. 1220-1224.

7. Sassen K., S. Benson, 2001: A midlatitude cirrus cloud climatology from the Facility for Atmospheric Remote Sensing. Part II: Microphysical properties derived from lidar depolarization, *Journal of Atmospheric Sciences,* **58**, pp. 2103-2111.

8. Noel V., K. Sassen, 2005: Study of planar ice crystal orientations in ice clouds from scanning polarization lidar observations, *Journal of Applied Meteorology,* **44**, pp. 653-664.

9. Del Guasta M., E. Vallar, O. Riviere, F. Castagnoli, V. Venturi, M. Morandi, 2006: Use of polarimetric lidar for the study of oriented ice plates in clouds, *Applied Optics,* **45**, pp. 4878-4887.

10. Balin Y. S., B. V. Kaul, G. P. Kokhanenko, I. E. Penner, 2011: Observations of specular reflective particles and layers in crystal clouds, *Opt. Express,* **19**, pp. 6209-6214.

11. Yang P., Y. X. Hu, D. Winker, J. Zhao, C. A. Hostetler, L. Poole, B. A. Baum, M. I. Mishchenko, J. Reichardt, 2003: Enhanced lidar backscattering by quasi-horizontally oriented ice crystal plates in cirrus clouds, *Journal of Quantitative Spectroscopy and Radiative Transfer,* **79-80**, pp. 1139-1157.

12. Chen G., P. Yang, G. W. Kattawar, M. I. Mishchenko, 2006: Scattering phase functions of horizontally oriented hexagonal ice crystals, *Journal of Quantitative Spectroscopy and Radiative Transfer,* **100**, pp. 91-102.

13. Bi L., P. Yang, G. W. Kattawar, B. A. Baum, Y. X. Hu, D. M. Winker, R. S. Brock, J. Q. Lu, 2009: Simulation of the color ratio associated with the backscattering of radiation by ice particles at the wavelengths of 0.532 and 1.064 μm, *Journal of Geophysical Research,* **114**, D00H08.

14. Bi L., P. Yang, G. W. Kattawar, Y. Hu, B. A. Baum, 2011: Scattering and absorption of light by ice crystal particles: Solution by a new physical-geometric optics hybrid method, *Journal of Quantitative Spectroscopy and Radiative Transfer,* **112**, pp. 1492-1508.

15. Borovoi A., G., I. A. Grishin, 2003: Scattering matrices for large ice crystal particles, *Journal of the Optical Society of America,* **20A**, pp. 2071-2080.

16. Mishchenko M. I., J. W. Hovenier, 1995: Depolarization of light backscattered by randomly oriented nonspherical particles, *Optics Letters,* **20**, pp. 1356-1358.

17. Iwasaki S., H. Okamoto, 2001: Analysis of the enhancement of backscattering by nonspherical particles with flat surfaces, *Applied Optics,* **40**, pp. 6121-6129.

18. Borovoi A., I. Grishin, E. Naats, U. Oppel, 2000: Backscattering peak of hexagonal ice columns and plates, *Optics Letters,* **25**, pp. 1388-1390.

19. Del Guasta M., 2001: Simulation of lidar returns from ideal and deformed hexagonal ice prisms in cold cirrus by means of face tracing, *Journal of Geophysical Research,* **106**, D12, 12.589-12.602.