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Dependence of ice crystal optical properties on particle aspect ratio

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ABSTRACT

The single-scattering properties of randomly oriented hexagonal ice crystals have been extensively used to study the bulk radiative properties of ice clouds. It has been reported in the literature that the asymmetry factors of these particles vary with their aspect ratios in a "V-pattern" with the minimum at a unit aspect ratio. However, this phenomenon was not explained in the previous studies. The present paper reports on an in-depth analysis of the optical properties of hexagonal ice crystals. It is shown that the delta-transmission is primarily responsible for the aforementioned "V-pattern" variation of the asymmetry factor as a function of the aspect ratio. Additionally, the term $(1-f_\delta)g$ is also partially responsible for the large values of the total asymmetry factor in the case of small aspect ratios, where f_δ indicates the ratio of the amount of the energy associated with the delta-transmission rays to the total amount of the scattered energy and g is the asymmetry factor associated with the geometric optics rays.

1. Introduction

It is generally recognized that ice clouds are one of the highly uncertain climate components in quantitative climate studies. To improve our knowledge of the role of ice clouds in the energy budget of the earth-atmosphere system, considerable effort has been made in the past three decades to better understand the radiative effect and microphysical and optical properties of these clouds [1–7]. Particularly, a number of parameterization schemes for the bulk radiative properties of ice clouds, which are based on the optical properties of individual ice crystals, have been developed for applications to general climate models (GCMs). Although complex particle geometries, such as bullet rosettes, aggregates and polycrystals, have been considered in some parameterizations (e.g., [8,9]), several schemes [10–12] are based on the single-scattering properties of hexagonal ice crystals. Using ice water content and generalized effective size that conserves both total volume and projected area of nonspherical ice particles, a hexagonal-geometry-based scheme for parameterizing the extinction coefficient and single-scattering albedo can be a good approximation for applications to studying the radiative properties of cirrus clouds consisting of various nonspherical particles such as plates, columns, bullet rosettes, and aggregates. Recently, Fu [13] introduced a mean effective aspect ratio for an ensemble of ice crystals to generalize the applicability of the hexagonal-geometry-based parameterization of the asymmetry factor associated with the scattering of solar radiation by cirrus clouds.

Neshyba et al. [14], Grenfell et al. [15] and Fu [13] showed that the variation of the asymmetry factors for individual hexagonal ice crystals versus their aspect ratios presents a "V-pattern" as the aspect ratios vary from those for columns to their counterparts for plates. The minimum asymmetry factor occurs approximately at a unit aspect ratio. This interesting

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scattering feature, however, has not been explained from the perspective of a fundamental scattering process within the framework of the geometric optics method, although the scattering properties of hexagonal ice crystals have been extensively investigated [16–26]. This study is intended to provide an in-depth analysis of the dependence of the single-scattering properties of hexagonal ice crystals on their aspect ratios; particularly, an explanation of the aforementioned "V-pattern" variation of the asymmetry factor versus the aspect ratio is presented.

2. Geometric optics solution for the optical properties of ice crystals

The present study is limited to the optical properties of hexagonal ice crystals. Note that a comprehensive database of the single-scattering properties of hexagonal ice crystals has been developed by Hess and Wiegner [19]. Hexagonal geometry is the basic structure of ice crystals although it has been suggested that pristine hexagonal plates and columns are rare in cirrus clouds because halos are not often observed [27]. The physical dimension of a hexagonal ice crystal can be specified in terms of its length (L) and cross section width (D), which are indicated in panels (a) and (b) in Fig. 1, respectively. The aspect ratio (α) of the particle is defined in the form

$$\alpha = D/L. \tag{1}$$

The sizes of most ice crystals within cirrus clouds are on the order of several tens and hundreds of microns, and, thus, the corresponding size parameters in the solar spectral region are in the geometric optics regime. For this reason, we use the conventional ray-tracing technique to compute the single-scattering properties of hexagonal ice crystals. The technical details of the ray-tracing method are not reiterated here because they were thoroughly described in several previous studies (e.g., [16–18,20,21,25]). In this study, the scattered rays are categorized into different orders according to their histories. The zero-order scattered field is for the diffraction of the incident wave, which can be computed from a formula presented by Yang and Liou [26] for the entire 0°–180° scattering region. Note that the conventional diffraction formulation [16] can be applied only to the scattering angles ranging from 0° to 90°. As shown in panel (c) of Fig. 1, the first-order ($n = 1$) rays indicate externally reflected rays, the second-order ($n = 2$) rays indicate those that undergo two sequential refractions without undergoing an internal reflection, and the third-order ($n = 3$) rays indicate those that undergo one internal reflection and two refractions. The scattered field is the sum of the contributions from diffraction and geometric optics rays with orders from $n = 0$ to N. In theory, N is infinite; however, it is sufficient to only consider the rays of orders with $n < 14$ because the energy associated with the rays of higher orders is negligible.

An outcome inherent to the ray-tracing method is the delta-transmission associated with the collimated rays that transmit through two parallel faces of an ice crystal and propagate along the incident direction. Panel (d) in Fig. 1

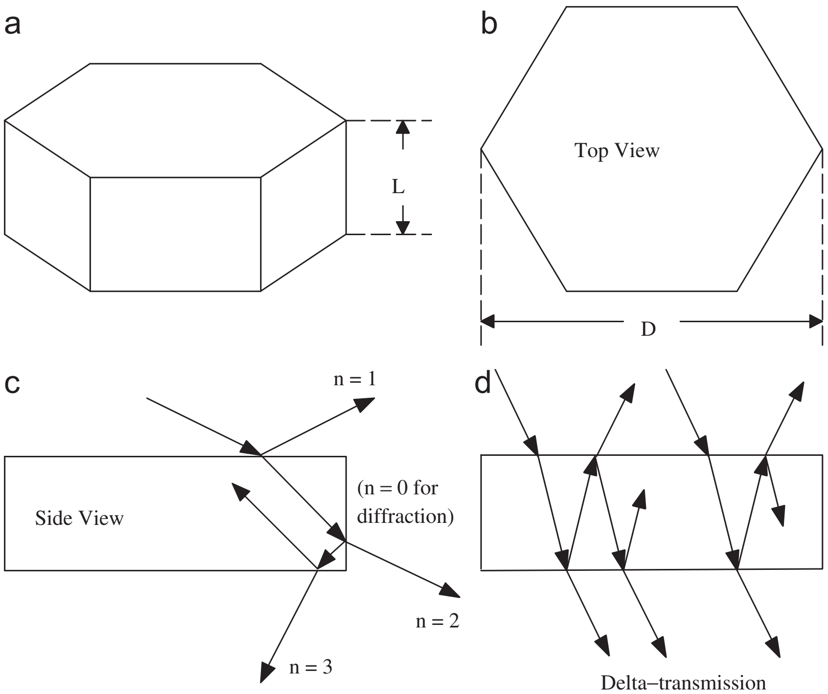

Fig. 1. (a) and (b) The geometry of a hexagonal ice plate. (c) Geometric optics rays of different orders. Note that $n = 0$ indicates the contribution from diffraction (not shown in the diagram). (d) Schematic illustration of the delta-transmission rays.