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The prevalence of the 22° halo in cirrus clouds

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ABSTRACT

Halos at 22° from the sun attributed to randomly-orientated, pristine hexagonal crystals are frequently observed through ice clouds. These frequent sightings of halos formed by pristine crystals pose an apparent inconsistency with the dominance of distorted, non-pristine ice crystals indicated by in situ and remote sensing data. Furthermore, the 46° halo, which is associated with pristine hexagonal crystals as well, is observed far less frequently than the 22° halo. Considering that plausible mechanisms that could cause crystal distortion such as aggregation, sublimation, riming and collisions are stochastic processes that likely lead to distributions of crystals with varying distortion levels, here the presence of the 22° and 46° halo features in phase functions of mixtures of pristine and distorted hexagonal ice crystals is examined. We conclude that the 22° halo feature is generally present if the contribution by pristine crystals to the total scattering cross section is greater than only about 10% in the case of compact particles or columns, and greater than about 40% for plates. The 46° halo feature is present only if the mean distortion level is low and the contribution of pristine crystals to the total scattering cross section is above about 20%, 50% and 70%, in the case of compact crystals, plates and columns, respectively. These results indicate that frequent sightings of 22° halos are not inconsistent with the observed dominance of distorted, non-pristine ice crystals. Furthermore, the low mean distortion levels and large contributions by pristine crystals needed to produce the 46° halo features provide a potential explanation of the common sighting of the 22° halo without any detectable 46° halo.

1. Introduction

Halos at 22° from the sun are among the most frequently observed atmospheric optical phenomena [1–3]. For example, Sassen et al. [1] reported that 37.3% of the daytime sky observations in their ~10 years record over Salt Lake City, Utah, showed indications of the 22° halo, with bright and prolonged halos occurring in 6% of the record. Such halos are attributed to randomly-orientated hexagonal ice crystals with size parameters of the order of about 100 or greater in cirrus clouds [4,5]. Other less frequent optical phenomena, such as the 46° halo, are known to be caused by such hexagonal crystals as well. It is well understood from geometric optics how refraction of light rays through pristine hexagonal ice prisms with random orientation forms such halos [e.g., 6,2]. However, in situ observations in natural ice clouds indicate a general dominance of distorted, aggregated, non-pristine ice crystals [7–14]. Furthermore, satellite observations that sample the total and polarized light reflected towards backscattering angles also indicate non-pristine ice crystals, possibly with microscale surface roughness, to be predominant in tops of ice clouds [e.g., 15–18]. This distortion and roughening of ice crystals leads to a randomization of the refraction angles between crystal facets, which in turn

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generally yields featureless phase functions and therefore a lack of halos [6,19]. Thus, the frequent sightings of halos on the one hand and dominance of distorted, non-pristine ice crystals indicated by in situ and remote sensing data on the other hand pose an apparent inconsistency. Also the huge difference in frequency of sightings of the 22° and 46° halo [1,3], both formed by randomly oriented pristine hexagonal ice crystals, has been interest of past research. For instance, Shcherbakov [19] argued that the common situation of the sighting of the 22° halo without the presence of the 46° halo may be due to the anisotropic roughness of the prismatic facets of hexagonal ice crystals. The anisotropic roughness model may also be a plausible proxy for ensembles of pristine, hollow-ended columns and/or bullets [20].

Apart from diminishing the halos, distortion or roughening of hexagonal ice prisms also leads to a significant lowering of the asymmetry parameter of their scattering phase function [6,21–23]. Thus, the degree to which natural cirrus clouds contain pristine particles may have important implications for their influence on global climate [21,24–26].

Although the observability of halos in cirrus clouds may depend on cloud parameters such as optical thickness and extinction profile, the primary requirement for halos to be observable is that the halo features are present in the ice crystal scattering phase functions. Usually, studies on the presence of halo features in phase functions and how they relate to crystal distortion only consider collections of ice crystals with a single degree of distortion. However, in situ observations generally show a wide variety of crystal shapes in a single cloud volume [e.g., 12]. Furthermore, possible mechanisms that could cause crystal distortion and surface roughness such as aggregation, sublimation, riming and collisions are stochastic processes that likely lead to distributions of crystals with varying distortion levels [9,27]. In this paper, we explore the presence of the 22° and 46° halo features in phase functions of collections of ice crystals with varying distributions of distortion levels.

We describe the simulations in Section 2, show results in Section 3 and conclude in Section 4.

2. Simulations

Ice crystal phase functions are calculated using the standard geometric optics code developed by Macke et al. [6]. This ray tracing code takes distortion of ice crystals into account in a statistical manner by perturbing, for each interaction with a ray, the normal of the crystal surface from its nominal orientation by an angle varied randomly with uniform distribution between 0° and $\delta \times 90°$, where δ is referred to as the distortion parameter. Thus, this approach represents the stochastic large-scale distortion of a collection of ice crystals. Liu et al. [23] found that such an approach is also an efficient, yet relatively accurate treatment of low to moderate microscale surface roughness, although for more severe roughness some significant differences with exact calculations were found. For a large collection of ice crystals, microscale surface roughness and large-scale particle distortion both lead to a similar randomization of the angles between crystal facets, which in turn leads to the diminishing of features in the scattering phase matrix. Increasing the number of impurities within ice crystals also has a similar effect [28]. Thus, we consider the distortion used here as a proxy of randomization of the angles between crystal facets possibly caused by any of these effects [cf. 27]. Although several arguably more realistic, alternatives to the uniform distribution of crystal facet tilt angles have been proposed [29,30,19,27], the general conclusions of this work are considered to be independent of the distortion distribution shape, as further argued below.

Calculations are performed at a wavelength of 555 nm with a refractive index of $1.3108 + i2.564 \times 10^{-9}$ [31]. The distortion parameter is varied between 0 and 0.8 in steps of 0.05 and results are linearly interpolated in between. The aspect ratio of columns is varied between 1 and 50 with 26 geometrically increasing steps. The aspect ratios of plates are the inverse of those for columns, for a total of 51 aspect ratios. Similarly as described by van Diedenhoven et al. [22], sizes are varied so that the projected areas of the particles, assuming random orientation, correspond to the projected areas of spheres with radii of 40, 56, 80, 113, 160, 226 and 320 μm. This leads to maximum and effective crystal dimensions that vary with aspect ratio, but since these calculations are performed at a wavelength where ice absorption is very weak, the geometric optics calculations are size invariant. The phase function calculations are performed on a 1-degree resolution and interpolated in between.

As criteria for the presence of the halo features, we use halo ratios as defined by Gayet et al. [32] and Shcherbakov [19], i.e.,

$$h = \frac{P(\theta_1)}{P(\theta_2)}, \quad (1)$$

where $P(\theta_1)$ and $P(\theta_1)$ are values of the scattering phase function evaluated at scattering angles θ_1 and θ_2, respectively. Following Shcherbakov [19], for the 22° halo ratio (h_{22}) we use $\theta_1 = 22°$ and $\theta_2 = 18.5°$ and for the 46° halo ratio (h_{46}) we use $\theta_1 = 46.5°$ and $\theta_2 = 43°$. We consider the halo features to be present in the phase functions if h_{22} and h_{46} are larger than unity and to increase in strength with increasing halo ratio.

3. Results

Fig. 1 shows the h_{22} and h_{46} halo ratios as a function of crystal aspect ratio and distortion parameter. As expected, h_{22} and h_{46} decrease with increasing distortion, and for distortion parameter values greater than about 0.15–0.2, halo ratios are below unity and thus both halo features are not present anymore. Plates show a stronger decrease of the h_{22} ratio with distortion than columns. The h_{46} ratio is greatest for compact particles and decreases with aspect ratio increasingly deviating from unity. Only for crystals within a narrow range of distortion parameters between about 0.1 and 0.15, the situation occurs that the 22° halo feature is present while the 46° halo is generally not, which is consistent with previous conclusions by Shcherbakov [19].