Journal of Quantitative Spectroscopy & Radiative Transfer 178 (2016) 134–141

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

The effect of roughness model on scattering properties of ice crystals

Igor Geogdzhayev*, Bastiaan van Diedenhoven

Columbia University, 2880 Broadway, New York, NY 10025, USA

ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form
1 March 2016
Accepted 1 March 2016
Available online 7 March 2016

ABSTRACT

We compare stochastic models of microscale surface roughness assuming uniform and Weibull distributions of crystal facet tilt angles to calculate scattering by roughened hexagonal ice crystals using the geometric optics (GO) approximation. Both distributions are determined by similar roughness parameters, while the Weibull model depends on the additional shape parameter. Calculations were performed for two visible wavelengths (864 nm and 410 nm) for roughness values between 0.2 and 0.7 and Weibull shape parameters between 0 and 1.0 for crystals with aspect ratios of 0.21, 1 and 4.8. For this range of parameters we find that, for a given roughness level, varying the Weibull shape parameter can change the asymmetry parameter by up to about 0.05. The largest effect of the shape parameter variation on the phase function is found in the backscattering region, while the degree of linear polarization is most affected at the side-scattering angles. For high roughness, scattering properties calculated using the uniform and Weibull models are in relatively close agreement for a given roughness parameter, especially when a Weibull shape parameter of 0.75 is used. For smaller roughness values, a shape parameter close to unity provides a better agreement. Notable differences are observed in the phase function over the scattering angle range from 5° to 20°, where the uniform roughness model produces a plateau while the Weibull model does not.

1. Introduction

Ice cloud feedbacks play an important role in global climate and are among the more important sources of uncertainty for modeling climate change [1–5]. Improving our understanding of the optical properties of ice clouds is thus an important component in the efforts to reduce this uncertainty through both climate modeling and remote sensing of clouds. Studies indicate that microscale surface roughness significantly affects the optical properties of ice crystals, smoothing out the scattering features, suppressing the formation of halos, and reducing the asymmetry parameters [6–10]. Remote sensing results indicate that the degree of surface roughness is generally high in tops of natural ice clouds, but depends on location, temperature and atmospheric state [11,12]. Furthermore, laboratory studies [13–15] demonstrate that the microscopic structure of ice crystals is complex and highly dependent on the environmental conditions.

To calculate optical properties of crystals with arbitrary surfaces, numerically exact methods are available such as the discrete dipole approximation [16,18], the pseudo-spectral time domain method [17] and the invariant imbedding *T*-matrix method [19], but their application to particles with larger size parameters (defined as $\pi D/\lambda$, where D is a characteristic length of the particle and λ is the wavelength of light) is presently limited because of their computational burden. Approximate methods based on geometric optics (GO) [20,21] are often used for larger particles. To account for crystal surface roughness, stochastic approaches are implemented in such GO

* Corresponding author.

http://dx.doi.org/10.1016/j.jqsrt.2016.03.001
0022-4073/

applications. Liu et al. [22] demonstrated that such stochastic models are an efficient and relatively accurate means for simulating scattering properties of crystals with roughened surfaces. However, while such stochastic approaches have been implemented in available GO codes in significantly different ways [20,21,23], a thorough investigation of the impact of the choice of roughness model on the scattering properties of ice crystals is not available to date. The goal of this study is to investigate how the choice of microscale roughness model affects calculated scattering properties of ice crystals.

In Section 2, we will first summarize different roughness models and discuss their interpretation before showing results in Section 3. We conclude the paper in Section 4.

2. Approach

To calculate scattering properties of hexagonal ice crystals we use the Monte Carlo ray-tracing code developed by Macke et al. [20,24]. In this study we used two models of surface roughness that are both based on randomly tilting the normal to the crystal surface by a certain angle at each ray reflection or refraction event. The two models differ in the assumed distribution of the random tilt angles. The model originally used in [20] assumes that the zenith tilt angle is distributed uniformly between 0° and some maximum angle smaller than 90° (i.e. $\sigma_{uni} \times 90°$), where the parameter σ_{uni} is commonly referred to as the roughness parameter. Shcherbakov et al. [23] performed calculations and an analysis of the scattering properties of ice crystals using the ray-tracing code from [20,24] with a model of surface roughness implemented that is based on the two-parameter Weibull statistics [25]. In this model the cosine of the zenith tilt angle μ is generated using the following expression:

$$\mu = 1/\left[1+\sigma^2(-\ln t)^{1/\eta}\right)\Big]^{1/2},$$

where t is a random number uniformly distributed on the interval [0, 1] and σ and η are two parameters determining the height and shape of the distribution, respectively.

In both the uniform and Weibull models the azimuth tilt angles are distributed uniformly between $[0,2\pi]$. Parameter σ_{uni} of the uniform distribution and parameter σ of the Weibull distribution play similar roles and are referred to as the "roughness parameter" below. Parameter η of the Weibull model modifies the shape of the distribution. In particular, setting $\eta=1$ results in a Gaussian distribution as used by, e.g. [21]. Neshyba et al. [13] demonstrated how the above parameters relate to a general mean surface normal roughness metric. The code does not handle the shadowing and ray re-entry effects associated with highly tilted facets that occur more frequently for high roughness parameters. For this reason we limit our calculations to roughness parameters smaller or equal than 0.7.

Fig. 1 compares the relative frequency of occurrence of tilt angles as a function of the tilt angle in degrees for the two models with the roughness parameter of 0.2 (upper panel) and 0.7 (lower panel) and Weibull shape parameter η between 0.5 and 1. One can see that the uniform model is characterized by a sharp drop-off at the maximum tilt angle $\sigma_{uni} \times 90°$ (18° and 63° , respectively) while the Weibull models result in a smooth distribution that covers all of the theoretically possible tilt angles. Furthermore, Weibull distributions with all but the smallest shape parameters result in a maximum in the tilt angles that is sharper than the uniform distribution with the same roughness. For the smaller roughness parameter, Weibull distributions show a significant proportion of tilts higher than the uniform threshold, while for the large roughness this is only true for η smaller than approximately 0.75.

It is of interest how the model roughness parameter relates to physical microscopically rough structures on the ice crystals. Within the framework of the GO approximation, the problem of determining such structures is reduced to constructing a physical crystal surface that, when illuminated by light rays, will result in a distribution of tilts equivalent to the one represented by the roughness model. The exact solution to this problem may be complex or may not exist because the shape of such a surface may potentially depend on the direction of incident and refracted rays.

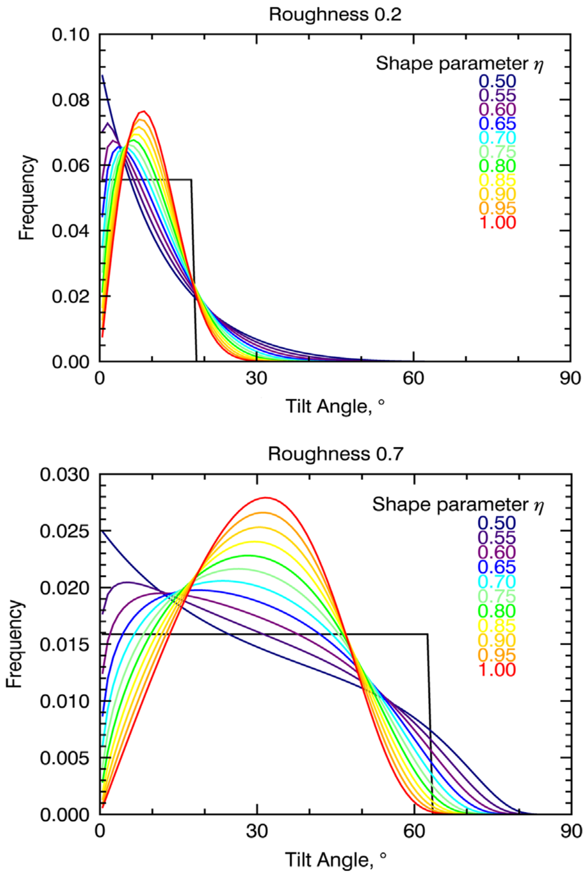

Fig. 1. Relative frequency of occurrence of tilts for the uniform (black line) and Weibull (colored lines) models of surface roughness for roughness parameter 0.2 (upper panel) and 0.7 (lower panel) and shape parameter η varying between 0.5 and 1. Note the difference in vertical scales. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)