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Assessment of the accuracy of the conventional ray-tracing technique: Implications in remote sensing and radiative transfer involving ice clouds

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ABSTRACT

A fundamental problem in remote sensing and radiative transfer simulations involving ice clouds is the ability to compute accurate optical properties for individual ice particles. While relatively simple and intuitively appealing, the conventional geometric-optics method (CGOM) is used frequently for the solution of light scattering by ice crystals. Due to the approximations in the ray-tracing technique, the CGOM accuracy is not well quantified. The result is that the uncertainties are introduced that can impact many applications. Improvements in the Invariant Imbedding T-matrix method (II-TM) and the Improved Geometric-Optics Method (IGOM) provide a mechanism to assess the aforementioned uncertainties. The results computed by the II-TM+IGOM are considered as a benchmark because the II-TM solves Maxwell's equations from first principles and is applicable to particle size parameters ranging into the domain at which the IGOM has reasonable accuracy. To assess the uncertainties with the CGOM in remote sensing and radiative transfer simulations, two independent optical property datasets of hexagonal columns are developed for sensitivity studies by using the CGOM and the II-TM+IGOM, respectively. Ice cloud bulk optical properties obtained from the two datasets are compared and subsequently applied to retrieve the optical thickness and effective diameter from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements. Additionally, the bulk optical properties are tested in broadband radiative transfer (RT) simulations using the general circulation model (GCM) version of the Rapid Radiative Transfer Model (RRTMG) that is adopted in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM, version 5.1). For MODIS retrievals, the mean bias of uncertainties of applying the CGOM in shortwave bands (0.86 and 2.13 μm) can be up to 5% in the optical thickness and as high as 20% in the effective diameter, depending on cloud optical thickness and effective diameter. In the MODIS infrared window bands centered at 8.5, 11, and 12 μm, biases in the optical thickness and effective diameter are up to 12% and 10%, respectively. The CGOM-based simulation errors in ice cloud radiative forcing calculations are on the order of 10 W m^{-2}.

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1. Introduction

Ice clouds are known to play an important role in regulating atmospheric radiation through interaction with both solar and infrared (IR) radiation fields [1,2]. Theoretical modeling of ice cloud radiative effects is indispensable in many atmospheric applications. The modeling approach typically begins with the single scattering of light by individual ice particles of different habits (shapes) and sizes contained in a scattering volume element, followed by the multiple-scattering calculations (i.e., the radiative transfer, or RT) involving ice clouds. For example, inferring the microphysical properties of ice clouds from observations by ground- and satellite-based instruments requires comparing the instrument observations to the model-simulated results obtained from the single-scattering properties and relevant multiple-scattering simulations [3–7]. To understand the ice cloud impact in the climate models, an accurate representation of ice cloud bulk-scattering properties is a critical component required by RT models to quantify the cloud radiative effect (CRE), such as radiative forcing of natural cirrus clouds [8,9] and anthropogenic contrails [10,11]. For this reason, much effort has been dedicated to developing physically representative ice cloud models (e.g., ice habits, particle size distributions, and mass-dimension relationships) and accurately computing the single-scattering properties of individual ice particles (i.e., the extinction efficiency, the single-scattering albedo, and the phase matrix).

However, solving Maxwell's equations for light scattering by ice particles from first principles is much more complex than light scattering by water droplets. Ice particles are nonspherical and morphologically complex, while having a broad range of particle sizes ranging from a few microns to centimeters. In a historical context, the majority of simulations [12–19] are based on geometric-optics principles that are asymptotically correct and approximately valid at large size parameters, i.e., when the particle size is sufficiently large relative to the wavelength. The ratio of the particle circumference to the wavelength is known as the size parameter. A number of physical-geometric optics methods have also been proposed to improve the accuracy in geometric-optics approximations [20–26].

Deschamps [27] addressed the importance of the “ray” concept of light in engineering, stating that “if the nature of light and Maxwell's equations had been known, earlier optical instruments would not have been invented so readily”! Similarly, the application of ray techniques in solving light scattering by individual ice particles in the atmospheric radiation discipline plays a critical role because it provides a first-order approximation for higher frequency scattering where rigorous solutions are unavailable. In other words, the knowledge of ice cloud radiation would have been severely limited in a modeling perspective without employing the geometric-optics method. A more specific example is that for an ice particle with a size parameter larger than 200, the ability to obtain a rigorous set of optical properties is almost beyond our current first-principle modeling capabilities. For this reason, the geometric-optics methods continue to be popular, but there is a growing awareness of the need to provide an accuracy assessment due to the inherent approximations [e.g.,28,29].

With the development of computational electrodynamics, numerical techniques to solve Maxwell's equations are now available to obtain numerically exact solutions. The power of these numerical techniques began to have an impact within the past two decades. A few frequently used computational techniques are the finite-difference time-domain (FDTD) [30–33], the pseudo-spectral time-domain (PSTD) [34–36], the discrete-dipole-approximation (DDA) [37–40], and the T-matrix method [41–45]. Based on the numerical techniques, a much better knowledge has been obtained of the optical properties of particles at small-to-moderate size parameters. The applicability of the geometric-optics in different size parameter domains is investigated whenever possible. For example, Mishchenko and Macke [46] investigated T-matrix computations of light scattering by circular cylinders and found that ice halos, an optical phenomenon predicted from geometric optics, would not be observed when the particle size parameter is less than approximately 100. Unlike the geometric-optics methods, the performance of numerical methods strongly depends on computational resources. As computer power increases, some new domains of rigorous solutions are being conquered. Meanwhile, because of its simplicity, the use of the geometric-optics method is preferred for a complete range of ice particle sizes in the wavelength spectrum from UV to the near-infrared.

To our knowledge, the induced uncertainties due to the nature of the approximations inherent in the ray-tracing technique have not yet been assessed in remote sensing and climate studies involving ice clouds, most likely because the rigorous solution domain is still extremely limited. The Invariant Imbedding T-matrix method (II-TM) [47–50] is applicable to a broad range of size parameters from the Rayleigh region up to the geometric optics domain where ice halos are observed. In this study, we use the II-TM to assess the accuracy of geometric-optics approximation and the resulting uncertainties in remote sensing and radiative transfer simulations.

The theoretical components of the employed geometric-optics method are delineated before the assessment because a number of modifications in geometric-optics methods exist in the literature. A brief review of available geometric-optics methods is provided in Bi and Yang [51]. The geometric optics methods most frequently used are the conventional geometric-optics method (CGOM) and the improved geometric-optics method (IGOM), although a few more rigorous, but relatively less computationally efficient, methods have also been developed [20–26]. One unique difference between the CGOM and the IGOM is that the latter considers the spreading of scattered beams (a physical-optics effect) when propagating from the near-field to the far-field region. As the particle size parameter increases, the IGOM simulated phase matrix transitions to that from the CGOM when the spreading effect is negligible. With the ray-spreading effect incorporated, the IGOM is applicable to relatively small size parameters (20–100) where the ice halos disappear, but the geometric-optics principles are still more