

IMPROVING ICE CLOUD BACKSCATTERING AND DETERMINING AN OPTIMAL ICE PARTICLE OPTICAL PROPERTY DATABASE FOR LIDAR-BASED APPLICATIONS

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Abstract

A new ice particle single-scattering database based on a Two Habit Model (THM) is developed to accurately retrieve ice cloud properties using lidar-based radiative transfer simulations. For moderate and large particle sizes, the approximate computational method known as the Improved Geometric Optics Method (IGOM) is used. A more accurate (particularly for backscattering computation) method known as the Physical Geometric Optics Method (PGOM) is used to calculate the phase matrix in backscattering directions. The backscattering properties of the single-scattering database are paramount for the accurate retrieval of ice cloud properties using lidar-based methods. Lidar ratio (LR) values are calculated using the bulk properties of the database. The integrated attenuated backscatter (IAB) values are calculated analytically from the LRs and various ice cloud optical thicknesses (ICOTs) that represent theoretical ice clouds. The calculated LRs and IABs of the new THM and a previous THM are compared to Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) LRs and IABs and CloudSat ice cloud optical depths (ICOTs). The results show that the LR and IAB values of the new THM database are significantly more consistent with observational data due to the PGOM-enhanced phase function backscattering which will lead to more accurate lidar-based retrievals if the new database is used. In addition, a smooth, hexagonal column is added to the new THM as a fraction of the “simple” habit to further improve consistency with the CALIOP data.

1 Introduction

Ice clouds cover about 20% of the Earth and thus influence both the climate system radiation budget and large-scale atmospheric circulations [1,2,3]. Ice clouds, however, are also the one of the least understood atmospheric parameters in remote sensing and radiative transfer calculations due to uncertainties in their microphysical and optical properties such as ice particle effective radius (R_{eff}) and ice cloud optical thickness (ICOT). Accurate estimation of R_{eff} and ICOT are important in understanding of the radiative effects that ice clouds have on the atmosphere [4,5] as they could even switch between having a net cooling or warming radiative effect on the atmosphere [2]. These properties can even be used to infer other microphysical and optical properties.

For example, the product of R_{eff} and ICOT is proportional to the ice water path (IWP).

Observations from remote sensing satellites are commonly used to infer ice cloud properties. Active-sensor, lidar observations provide ample information for retrieving ice cloud microphysical and optical properties [6,7]. Lidar signals for cloudy scenes are determined by the bulk backscattering properties of cloud particles. Commonly used lidar measurements are the lidar ratio (LR) and integrated attenuated backscatter (IAB). LR is physically defined as the ratio of the volume extinction coefficient to the volume backscatter coefficient, and is inversely proportional to the ice particle bulk phase function 180° backscattering direction. IAB is the integration of backscattered light after attenuation through a cloud layer, and is inversely proportional to LR. IAB is also closely related to ICOT which allows for the derivation of ICOT from IAB measurements [7,8] if the ice cloud is optically thin ($ICOT < 4$).

Since the LR is dependent on the 180° backscattering phase function of the ice particles comprising the ice clouds, developing an accurate ice particle optical property database is paramount in retrieving accurate ice cloud properties from lidar-based radiative transfer simulators. Ice particle optical property databases help to describe the microphysical and optical properties of ice clouds. Currently, most ice particle optical property databases are developed using the Invariant Imbedding T-Matrix Method (IITM) and/or IGOM [3,5,9]. The IITM is an exact method primarily used for small size parameters [10,11] and IGOM is an approximate method used for moderate and large size parameters [12,13]. Despite IGOM being a fairly accurate numerical method and computationally efficient, it has been shown to underestimate phase function backscattering [14] which is critical for accurate lidar-based retrievals of ice cloud properties. A more sophisticated geometric optics method known as the PGOM has been developed that provides accurate backscattering calculations [15]. Ice particle optical property databases comprised of backscattering calculations from PGOM can significantly improve active lidar-based retrievals.

2 Methodology

2.1 The Lidar Two Habit Model

The newly-developed ice particle optical property database used for this study is known as a THM. It is

based on the concept that atmospheric ice particles can be separated into two categories in terms of geometrical complexity (i.e., simple and complex) that are dependent on particle size [16]. The simple particle geometry dominates small particle sizes and as the size increases, the complex geometry eventually becomes the dominate habit.

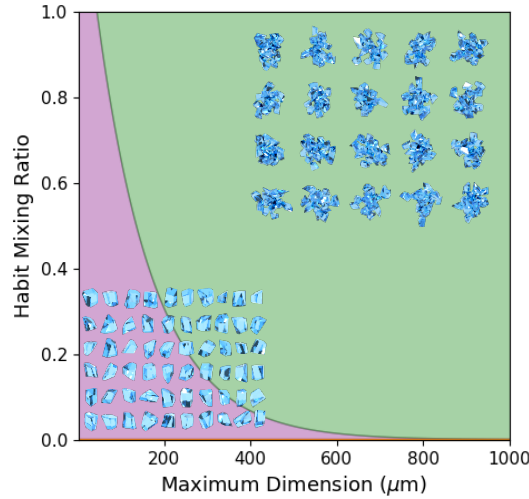


Figure 1 The THM-new habit fraction distribution diagram show two ensembles of different ice crystals and their mixing ratios. The 60-particle ensemble in the purple region irregularly-shaped single columns and the 20-particle ensemble in the green-shaded region are irregularly-shaped 20-column aggregates. The mixing ratios of the two habits add up to one.

$$f_{\text{single}} = \begin{cases} e^{-0.0076(D_{\text{max}} - 45)} & D_{\text{max}} \geq 45 \mu\text{m} \\ 1 & D_{\text{max}} < 45 \mu\text{m} \end{cases} \quad (1)$$

$$f_{\text{aggregate}} = 1 - f_{\text{single}} \quad (2)$$

The THM used for this study (THM-new) is shown in Fig. (1) and the equations describing the habit fractions are shown in Eqs. (1) and (2). THM-new contains the three lidar wavelengths of 355, 532, and 1064nm, and 189 maximum dimension (D_{max}) size bins ranging from 2.206 – 11031.337 μm . In addition to using IITM and IGOM calculations to develop the database, PGOM is used for moderate and large size parameters ($kD > 35$) to obtain more accurate backscattering. The PGOM scattering phase matrix calculations in the backscattering region are merged with IGOM's using a continuous weighting function that transitions the IGOM-based calculations to the PGOM calculations from 160° to 170° scattering angles. This THM is considered to be an update to the THM (THM-prev) that is composed of a roughened hexagonal column and 20-particle irregularly-shaped 20-column aggregates and only have IITM and IGOM calculations [5].

2.2 Lidar Ratio and Integrated Attenuated Backscatter

The LR is in unit of steradians (sr) and is defined as the ratio of the volume extinction coefficient to the volume backscatter coefficient. LR (S) can be given in terms of the backscatter phase function value defined as:

$$S = \frac{4\pi}{P_{11}(180^\circ) \bar{\omega}} \quad (3)$$

where $P_{11}(180^\circ)$ is the phase function in the 180° backscattering direction and $\bar{\omega}$ is the single-scattering albedo. Ice particles are non-absorbing at 355, 532, and 1064nm wavelengths and thus have $\bar{\omega}$ nearly equal to 1. Eq. (3) can be simplified to being inversely proportional to the normalized phase function in the 180° backscattering direction.

IAB is defined [6] as:

$$IAB = \frac{1 - e^{-2\eta\tau}}{2\eta S} \quad (4)$$

Where S is the LR, τ is the ICOT, and η is the multiple scattering coefficient. η is implicitly assumed to be independent of optical thickness for a uniform particle size distribution in ice clouds [6] and has a value of 0.7. Eq. (4) demonstrates that an IAB-ICOT relationship exists and that LR, Eq. (2), is inversely proportional to IAB. Based on Eq. (4), IAB becomes asymptotic and approaches a constant value of $1/2\eta S$ when optical thickness is large. This means that IABs derived from lidar observations are sensitive to optically thin clouds. For this study, ICOT values less than 4 are considered for the analytical calculations using THM-new and THM-prev as well as the observational data.

2.3 Satellite Data

For this study, the CALIOP Level-2 5km Cloud Layer Product [17] and the CloudSat 1 km ancillary Collection 6 Moderate Resolution Imaging Spectroradiometer (MODIS) cloud property product (MOD06-AUX) [18] from the year 2009 are collocated to compare observed IAB and ICOT with the analytical results. The CALIOP product is also used to compare observed LR with those inferred from the bulk scattering properties of the new lidar database.

The associated parameters used to find collocated thin ice clouds include time, latitude and longitude from both products, number of cloud layers and feature classification flags from the CALIOP lidar product. During 2009, both the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) carrying the CALIOP sensor, and CloudSat satellites orbit the same orbital plane along with 3 other satellites known as the A-train. CloudSat leads CALIPSO by about 15 seconds and thus feasible to collocate the data of both products. As the products are in different resolutions, the nearest-neighbour estimation method is used to collocate ice cloud cases of CALIOP 5km pixels with those of CloudSat 1km pixels.

The CALIOP Cloud Layer product provides cloud mid-layer temperature as well as LR and IAB at 532 nm. MOD06-AUX provides ICOT from a MODIS two-channel retrieval method using band 7 (2.1 μm) and either band 1 (0.65 μm), 2 (0.86 μm), or 5 (1.2 μm). To ensure that the highest quality of the collocated data is obtained, CALIOP pixels that have a single layer, transparent ice cloud classification with a mid-layer temperature of -40°C are considered for this study. From the MOD06-AUX product, MODIS-retrieved ICOTs are limited to be less than 4 since IAB is expected to reach an asymptotic, maximum value beyond this value.

3 Preliminary Results

3.1 Phase Function Backscattering and Lidar Ratio

Incorporating PGOM backscattering calculations to existing IGOM calculations of the scattering phase matrix of THM-new is shown to have significant differences from THM-prev. Fig. (2) shows that the THM-new 532nm phase function (P11) in the backscattering region now has a pronounced peak at 180° scattering angle for both small and moderate particle sizes.

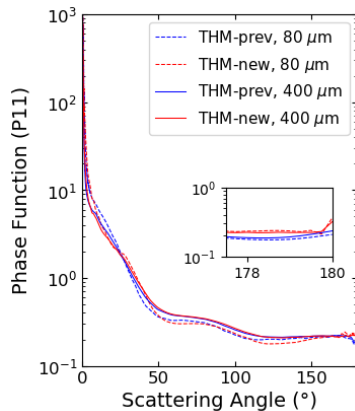


Figure 2 532nm wavelength P11 of the THM-prev (blue) and THM-new (red) databases at D_{max} of 80 (dashed) and 400 μm (solid). The backscattering region ($177.5^\circ - 180^\circ$) is enhanced to show differences between the databases and particle sizes.

The LR values calculated using the bulk P11 values at the 180° scattering angle for THM-prev and THM-new are shown in Fig. (3). At wavelengths 355 and 532 nm, the LRs for THM-new are significantly less than those of THM-prev throughout the effective radii range. Since Eq. (3) shows the P11 value at 180° scattering angle being inversely proportional to LR, the higher P11 backscattering values of THM-new due to the PGOM calculations correspond to lower LRs. For 1064nm, the LRs of THM-new are only slightly less than the LRs of THM-prev. This is due to 1064nm belonging to the near-infrared regime where backscattering is dampened.

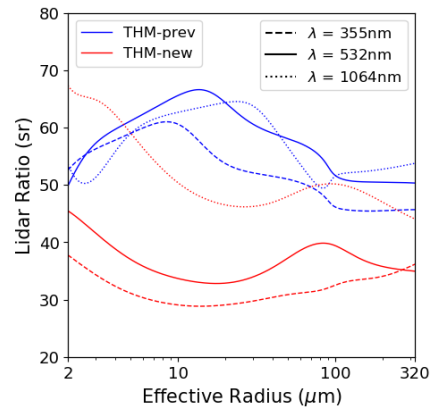


Figure 3 LR values of THM-prev (blue) and THM-new (red) with respect to effective radii from 2 to 320 μm for 355 (dashed), 532 (solid), and 1064 nm (dotted) wavelengths.

3.2 Integrated Attenuated Backscatter and Ice Cloud Optical Thickness Relationship

The calculated 532nm LRs at specified R_{eff} s of the THM-new and THM-prev databases are used to calculate their corresponding IABs over a range of ICOTs. The analytical IAB-ICOT relationship is plotted over a 2-dimensional frequency distribution of collocated CALIOP IAB/CloudSat ICOT data shown in Fig. (4). The THM-new IAB-ICOT relationship for all chosen R_{eff} s are significantly more consistent to the collocated observational data than THM-prev, especially for ICOTs from 0.25 to 1. Unfortunately, THM-new appears to still slightly underestimate IAB for optically thicker ice clouds (ICOT > 1). This improvement in IAB-ICOT relationship consistency between the analytical and observational data will likely lead to improved lidar-based retrievals when using the THM-new database.

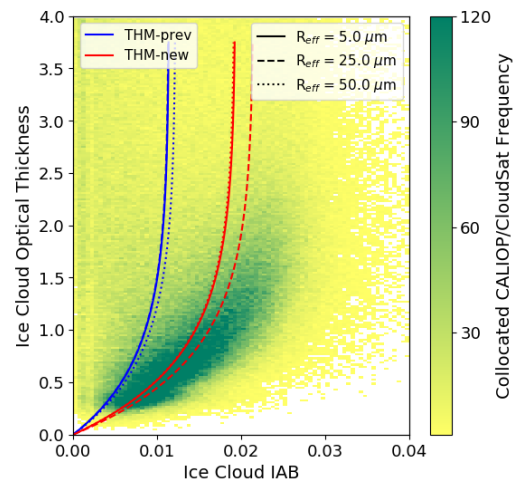


Figure 4 Comparison of ice cloud IAB-ICOT relationship of analytical calculations using THM-prev (blue) and THM-new (red) and collocated CALIOP/CloudSat 2009 data frequency. The analytical IAB-ICOT relationships have effective radii of 5 (solid), 25 (dashed), and 50 μm (dotted).

3.3 Adding Smooth Hexagonal Column to the New Database

As a preliminary test, another version of the new THM is developed with the inclusion of 8% smooth hexagonal column single-scattering properties in the “simple” particle habit (THM-hex). Fig. (5) shows that the inclusion of a smooth hexagonal column, even a small habit fraction, noticeably further decreases the LR of the THM for all three wavelengths. The decrease in LR is concentrated between the R_{eff} range of 10 to 200 μm . Since IAB is inversely proportional to LR, THM-hex is expected to have higher IABs than THM-new and will likely lead to further improved consistency with the collocated observational data. Further analyses will be done to determine the optimal smooth hexagonal column habit fraction to be included in the new THM.

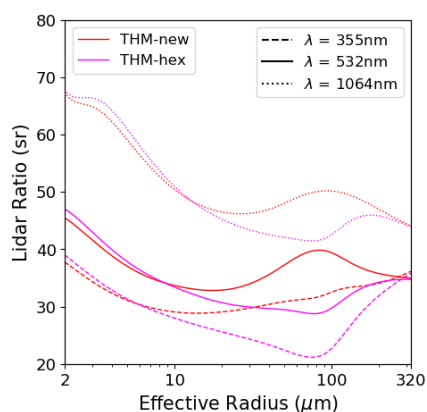


Figure 5 LR values of THM-new (red) and THM-hex (purple) with respect to effective radii from 2 to 320 μm for 355 (dashed), 532 (solid), and 1064 nm (dotted) wavelengths.

4 References

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