Investigation of ice particle habits to be used for ice cloud remote sensing for the GCOM-C satellite mission

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1 Introduction

Ice clouds play an important role in the radiation balance of the Earth's atmospheric system, through interaction with solar radiation and infrared emissions (Liou, 1986). However, large uncertainties exist in quantifying the radiative impact of ice clouds. This is because they consist of ice particles with various microphysical characteristics, e.g., a wide range of habits and sizes (Labonnote et al., 2000; Forster et al., 2007; Baran et al., 2009; Cole et al., 2014; Yang et al., 2015). Different ice particle habits have varying single scattering characteristics, resulting in different radiative properties. Satellite observations are important as a means of inferring the ice clouds' optical properties and monitoring their radiative impact on a global climate system. However, retrieved ice cloud properties highly depend on the assumed ice particle model. In practice, one chooses an ice particle model, which may consist of a single habit or a mixture of habits, and look-up tables (LUTs) for ice cloud reflection and transmission characteristics are computed for a range of input optical properties such as optical thickness, cloud temperature, and effective particle size. The LUTs and a fast radiative transfer model are subsequently used for global operational retrievals. Thus, the choice of an ice particle model for a given satellite mission deserves rigorous investigation. The present study aims to better understand the performance of several ice cloud habit models, in conjunction with applications to the Global Change Observation Mission-Climate (GCOM-C) satellite mission.

Over the past two decades, aircraft and balloon in-situ observations have contributed greatly to understanding ice cloud microphysical characteristics and radiative properties (Baran et al., 1998; Baran et al., 1999; Baran et al., 2003; Heymsfield et al., 2002; Heymsfield, 2003; Zhang et al., 2009). A variety of ice particle models has been developed based on in-situ observations of ice particle habits and their single-scattering properties (e.g., Macke et al., 1996a, 1996b; McFarquhar and Heymsfield, 1996; Yang et al., 2000, 2005, 2013; Um and McFarquhar, 2007, 2009, 2011; Nousiainen et al., 2011; Baum et al., 2005, 2011; Baran and Labonnote, 2007; Ishimoto et al., 2012b; Liu et al., 2014 (a)). Numerous light-scattering computation methods have been employed to calculate the single-scattering properties of the various ice particles; including the finite-difference time-domain (FDTD) method (Yee, 1966; Yang and Liou, 1998a; Sun et al., 1999, Ishimoto et al., 2012a); the T-matrix (Havemann and Baran, 2001; Bi and Yang, 2014); the discrete dipole approximation method (Purcell and Pennypacker, 1973; Draine and Flatau, 1994; Yurkin et al., 2007); the boundary element method (Mano 2000; Groth et al., 2015); the pseudo-spectral time-domain method (Liu et al., 1997, 1998; Chen et al., 2008; Liu et al., 2012); the surface-integral equation method (Nakajima et al., 2009); the improved geometric optics method (IGOM) (Yang and Liou, 1996), geometric optics integral equation (GOIE) (Yang et al. 1996, Ishimoto et al., 2012a), and the ray-tracing geometric optics method (GOM) (Takano, 1989, 1993; Macke, 1993; Macke et al., 1996a; Yang and Liou, 1998b; Masuda et al., 2012).

Various ice particle models correspond to different radiative properties. Quantifying optical properties of these ice particle models is computationally expensive, and thus for application purposes, it is useful to establish a number of libraries that pre-calculate the single-scattering properties of various ice particle habits. Using hexagonal plates and columns with a random orientation, Hess et al. (1994) developed a single-scattering property database at wavelengths between 0.35 and 3.7 μm. Additionally, Yang et al. (2000) provided a database at wavelengths between 0.2 and 5 μm for six ice particle habits (plates, solid and hollow columns, planar bullet-rosettes, spatial bullet-rosettes, and aggregates); Yang et al. (2005) further included two more ice habits and extended the database to wavelengths between 3 and 100 μm. Recently, Yang et al. (2013) released a database of a full set of scattering, absorption, and polarization properties, assuming random orientation for a set of 11 habits at a number of wavelengths, ranging between 0.2 and 100 μm. This database involved the addition of roughness to the particle surfaces. This library is based on the Amsterdam discrete dipole approximation, T-matrix, and IGOM methods. Using this updated library, Baum et al. (2014) developed a new set of bulk scattering and absorption models, with habit mixtures for radiative transfer calculations and remote sensing retrievals of ice clouds.

There is increasing evidence that the ice particle model should contain some degree of surface roughness (Foot, 1998; Baran et al., 2001, 2003; Ottaviani et al., 2012a; van Diedenhoven et al., 2012, 2013, 12014; Cole et al., 2013, 2014, Holz et al., 2016). In particular, using an ensemble ice particle model, Baran and Labonnote (2007) and Baran et al. (2014) showed that featureless phase functions best fitted their multi-angle satellite measurements at solar wavelengths. Interestingly, using particle images of convective ice clouds from in situ measurements, Ishimoto et al. (2012b) developed a new habit of complex and highly irregular shapes, called the Voronoi aggregate. The phase function of the Voronoi habit varies smoothly with the scattering angle, which is similar to behaviour found from assuming severe surface roughness, including bubbles within the particle, or a combination of included bubbles and surface roughness. However, use of the Voronoi habit model for retrieval of the ice cloud's optical thickness has not yet been investigated.

Numerous articles have investigated the use of optimal ice particle habits derived from various ice habit models and remote sensing measurements from multiple angles, for use in cloud parameter retrievals (Baran et al., 1998; Chepfer, 1998; Baran et al., 1999; Labonnote et al., 2000; Chepfer et al., 2001; Masuda et al., 2002; Baran et al., 2003; Knap et al., 2005; Sun et al., 2006; Baran and Labonnote, 2006; Baran et al., 2007). Labonnote et al. (2000, 2001) and Doutriaux et al. (2000) developed models of randomly oriented hexagonal ice particles containing spherical air bubbles (the inhomogeneous hexagonal monocrystal (IHM) model) for use in the ice cloud retrievals of the POLarization and Directionality of the Earth's Reflectances (POLDER) measurements. Spherical albedo difference (SAD) analysis is employed to investigate the capability of the IHM model for retrieving the optical properties of ice clouds. It is illustrated that POLDER multi-angle measurements are sensitive to ice particle habits and roughness, at least for ice clouds having an optical thickness larger than 5. Chepfer et al. (2002) investigated effective ice particle habits using multi-angle and multi-satellite methods derived from visible reflectance satellite measurements.

The Second Generation Global Imager (SGLI) on board the GCOM-C satellite, scheduled for launch in 2017 by the Japan Aerospace Exploration Agency (JAXA), measures radiation at 19 visible and near-infrared wavelengths, in order to understand the global radiation budget, carbon cycle mechanism, and climate change (Imaoka et al., 2010). Since retrieving ice cloud properties on a global scale from satellite observations requires knowledge of ice microphysical models, it is crucial to identify an optimal choice of ice habits for SGLI. The objectives of this study are to better understand the performance of existing ice models used in other satellite missions, investigate the potential of the Voronoi model, and provide a recommendation for the GCOM-C.

The paper is organised as follows. In Section 2, in order to develop the ice cloud property products of the GCOM-C satellite, we describe the method for calculating single-scattering properties at the SGLI-operated wavelengths for the five ice particle habits, including the Voronoi model. In Section 3, we apply the newly calculated ice cloud properties to spherical albedo difference (SAD) analysis, using POLDER measurements as an example. In Section 4, we describe the results of the SAD analysis. Section 5 presents our conclusions.

2 Ice cloud models for the SGLI sensor

2.1 Single-scattering properties

Single-scattering properties for the five ice particle habits are calculated for the SGLI observation channels. The single-scattering properties are used to determine the optimal ice particle habits, using the SAD method. The SGLI is the successor sensor to the Global Imager (GLI) aboard ADEOS-II, which takes measurements at wavelengths ranging from the near-ultraviolet to the thermal infrared. The first satellite, GCOM-C1, is scheduled for launch in 2017 by the JAXA. The GCOM-C mission intends to establish a long-term satellite-observation system to measure essential geophysical parameters on the Earth’s surface and in the atmosphere on a global scale, to facilitate the understanding of the global radiation budget, carbon cycle mechanism, and climate change (Imaoka et al., 2010). As shown in Table 1, SGLI has 19 channels, including two polarisation channels at visible and near-infrared wavelengths. A detailed description of the SGLI is reported by Imaoka et al. (2010), Nakajima et al. (2011), and Letu et al. (2012).

Four of the ice particle habits (hexagonal columns, plates, bullet-rosettes, and droxtals) employed in this study were chosen by referring to the MODIS Collection 5 ice particle model (Baum et al., 2005) and ice cloud in-situ measurement data. The habits shown in Fig. 1 are defined with the same parameters (semi-width, length, aspect ratio and maximum dimension) as were employed in the scattering properties database by Yang et al. (2000, 2005). The Voronoi habit was numerically determined by extraction of Wigner–Seitz cells from a 3-D mosaic image of the ice cloud microphysical data (Ishimoto et al., 2012b). This habit is different from the aggregate model used in the scattering database reported by Yang et al. (1998b, 2013). Spatial Poisson–Voronoi tessellations were used to determine the complex structure of the ice particles for the 3-D mosaic image. The geometry of each cell in the Voronoi tessellation was defined and based on the method by Ohser and Mücklich

(2000).

A combination of the FDTD, GOIE and GOM methods was employed to calculate the single-scattering properties of Voronoi ice habits for a wide range of size parameters (SZP), and is given by

$$SZP = 2\pi \cdot re / \lambda \tag{1}$$

The refractive index of ice, published by Warren and Brandt (2008), is used in the computations. As shown in Table 2, the FDTD method is used to calculate the single-scattering properties of ice particles with small size parameters (SZP < 50). The GOIE and GOM methods are employed for calculating the scattering properties of ice particles with medium and large parameters, respectively. The wavelength selected for detailed calculations is determined by optimizing the results of the scattering database for the SGLI channels (Letu et al., 2010). Calculations are performed at 27 spectral wavelengths (λ) from the visible to the infrared spectral region in the SGLI channels shown in Table 2. The volume-equivalent radius (re) ranges from 0.7 to 533 μm, and is defined as a single particle radius of an equivalent volume sphere. The SZP ranges from 0.35 to 6,098.

Consideration of the edge effect (Bi et al., 2010; Bi and Yang, 2014) is important for calculating the extinction efficiency (Q_{ext}) and absorption efficiency (Q_{abs}) by the GOIE method when the size parameter is less than 1,000. The treatment of the edge effect is based on the method proposed by Bi et al. (2011) and Ishimoto et al. (2012a). Correction coefficients are calculated from comparison results of the FDTD and GOIE as

$$Q_{ext} = Q_{ext/GOIE} + K_1 \cdot SZP^{-2/3}, \ \ Q_{abs} = Q_{abs/GOIE} + K_2 \cdot SZP^{-2/3}, \tag{2}$$

where $Q_{ext/GOIE}$ and $Q_{abs/GOIE}$ are the extinction efficiencies calculated by the GOIE method. K_1 and K_2 are the coefficients of the edge-effect contribution. These coefficients are applied to correct the Q_{ext} and Q_{abs} of large particles calculated using GOIE; they are calculated by comparing Q_{ext} and Q_{abs} obtained from FDTD and GOIE for maximum extension from the centre of mass, ranging from 30 to 60 μm.

[Insert Fig. 1 about here]

[Insert Table 1 about here]

[Insert Table 2 about here]

2.2 Microphysical data and bulk scattering properties of the ice particle model

In this study, microphysical data obtained during 11 field campaigns were used to generate the particle size distributions (PSDs) of ice crystals using Eq. (3). To ensure the PSDs are unambiguously those of ice, microphysical data was filtered by limiting the cloud temperature to T ≤ -40°C. More than 14,000 individual

PSDs were selected to build bulk scattering properties of the ice particle models (Heymsfield et al., 2013). The microphysical data was obtained from the Space Science and Engineering Center, University of Wisconsin-Madison (http://www.ssec.wisc.edu/ice_models/microphysical_data.html), and the PSDs are described by the following equation:

$$n(D) = N_0 D^{\mu} e^{-\lambda D} \tag{3}$$

where D is the particle maximum dimension, $n(D)$ is the particle concentration per unit volume, N_0 is the intercept, λ is the slope, and μ is the dispersion.

Furthermore, spectral bulk scattering properties were calculated from SGLI single-scattering database, and the derived PSDs were based on the method described in Baum et al., (2011). The main steps for calculating the bulk scattering properties are as follows:

1) Extract the total projected area, total volume, maximum dimension, scattering cross-section and scattering phase function parameters at a specific wavelength for 5 ice particle models from the SGLI single-scattering property database.
2) Calculate the effective diameter (D_{eff}) for 5 ice particle models based on Eq. (4).
3) Calculate the bulk-averaged single-scattering albedo ($\overline{A_s}$), asymmetry factor ($\bar{g}$), extinction efficiency ($\bar{Q}_e$) and scattering phase function ($\bar{P}$) for 5 ice particle models based on Eqs. (5—8).
4) Select the single-scattering albedo, asymmetry factor, extinction efficiency and scattering phase function with small, medium and large D_{eff}s, and average the selected parameters over the PSDs to obtain the bulk scattering properties to be used in the SAD analysis.

$$D_{eff} = \frac{3}{2}\frac{\int_{D_{min}}^{D_{max}} V(D)n(D)dD}{\int_{D_{min}}^{D_{max}} A(D)n(D)dD} = \frac{3}{2}\frac{V_{Tot}}{A_{Tot}} \tag{4}$$

$$\overline{A_s} = \frac{\int_{D_{min}}^{D_{max}} A_s\, n(D)dD}{\int_{D_{min}}^{D_{max}} n(D)\, dD} \tag{5}$$

$$\bar{g} = \frac{\int_{D_{min}}^{D_{max}} g(D,\lambda)\sigma_{sca}(D,\lambda)n(D)dD}{\int_{D_{min}}^{D_{max}} \sigma_{sca}(D,\lambda)n(D)dD} \tag{6}$$

$$\bar{Q}_e = \frac{\int_{D_{min}}^{D_{max}} \sigma_{ext}(D)A(D)n(D)dD}{\int_{D_{min}}^{D_{max}} A(D)n(D)dD} \tag{7}$$

$$\bar{P}(\theta) = \frac{\int_{D_{min}}^{D_{max}} P(\theta,D,\lambda)\sigma_{sca}(D,\lambda)n(D)dD}{\int_{D_{min}}^{D_{max}} \sigma_{sca}(D,\lambda)n(D)dD} \tag{8}$$

where D_{min} and D_{max} are the minimum and the maximum sizes of the ice particles, and V_{Tot} and A_{Tot} are the total volumes and projected areas of the ice particles, respectively. The parameters A_s, g, σ_{sca}, σ_{ext} and

P are the single-scattering albedo, asymmetry factor, scattering cross-section, extinction cross-section, and phase function, respectively, for a single particle; and θ is the scattering angle.

3 Data and methods

Since 1996, three POLDER instruments have been flown to study clouds and aerosols using multiple angles and polarization capabilities. The POLDER-1 and POLDER-2 instruments aboard JAXA's ADEOS satellite were operated from November 1996 to June 1997 and December 2002 to October 2003, respectively. Both of the POLDER instruments observed intensity from 14 viewing directions, with scattering angles ranging from 60° to 180°. The spatial resolution of the product derived from POLDER-2 observation data is approximately 20 km, which is composed of 3 × 3 single pixels. POLDER-2 measured the upwelling total and polarized radiances from eight observing channels centred at wavelengths of 0.443, 0.490, 0.565, 0.670, 0.763, 0.765, 0.865, and 0.910 μm (Baran et al., 2006). POLDER-3 operates aboard the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar microsatellite (PARASOL), launched in 2004. POLDER-3 has nine observing channels, three of which had polarization capabilities. PARASOL/POLDER-3 views a given scene from up to 16 angles as the satellite passes overhead. However, the capabilities of the instrument, such as observing the radiances from multiple viewing angles in several visible channels, are important for investigating the representative ice particle models for retrieving ice cloud properties. In this study, 589 × 246 pixels of the POLDER-3 observation data with a global scale, obtained when flying over oceans on 20–22 of March, June, September and December 2008, were used to retrieve cloud optical thickness and spherical albedo in order to investigate the behaviour of the five ice particle habits.

Figure 2(a) shows the distribution of the number of directional samples used in the SAD analysis. The number of pixels is increased in the scattering angle range of 60° to 160° and is decreased in the scattering angle range from 160° to 180°. There is a peak value of the number of sample pixels in the scattering angle range of 140° to 160°. Figure 2(b) indicates the variation of the number of pixels by latitude; the number of pixels changes significantly as a function of latitude, and is lowest when the latitude is around 90°N and 90°S. There are three peaks of the number of pixels in the different latitudes, due to the location of more samples at mid-latitude, where storm tracks occur, as well as along the Intertropical Convergence Zone (ITCZ), where there are numerous deep convective clouds. Labonnote et al. (2000) and Baran et al. (2006) proposed the SAD method for testing the phase function of the various ice particle models, using POLDER observational data with multiple viewing angles. For investigating the phase functions (P_{11}) of the different ice crystal models for retrieving the cloud microphysical properties, the cloud spherical albedo as a function of scattering angle is required. For calculating the cloud spherical albedo, bi-directional reflection is first determined by

$$R_{cld}(\mu, \mu_0, \phi - \phi_0) = \pi L_{obs}(\mu, \mu_0, \phi - \phi_0)/\mu_0 F_0\,, \tag{9}$$

where u and u_0 are cosines of the satellite and solar zenith angles, $\phi - \phi_0$ is the relative azimuth angle between the satellite and the sun, L_{obs} is the reflected solar radiance observed by the satellite, and F_0 is the solar flux density. Cloud optical thickness is retrieved from the L_{obs} in each pixel of the POLDER measurements with various scattering angles (θ). The bi-directional reflection (R_{lcd}) for individual cloud effective radius in various zenith angles and relative azimuth angle can be calculated from retrieved optical thickness by using a radiative transfer model. Cloud-plane albedo (A_p) and spherical albedo (S) are calculated by integrating over all the zenith and azimuth angles as

$$A_p(\mu_0) = \iint R_{cld}(\mu, \mu_0, \phi - \phi_0)\mu d\mu d\phi, \tag{10}$$

$$S = \int A_p(\mu_0)\mu_0 d\mu_0\,, \tag{11}$$

The total observation number (N) of L_{obs} with various θ values is up to 16, and is limited to the viewing geometries of the measurements. However, it is implied that cloud spherical albedo with multiple scattering angles ($S(\theta)$) can be calculated from the L_{obs} in each pixel of the POLDER measurements with various θ values by using Eqs. (9–11). Baran et al. (2006) assumed that if the scattering phase function of the ice particle model is correct, then calculated $S(\theta)$ in each direction should be the same, and the SAD, as shown in Eq. (13), should be 0. $\bar{S}$, SAD, and θ are given as

$$\bar{S} = (1/N)\sum S(\theta) \tag{12}$$

$$SAD = S(\theta) - \bar{S} \tag{13}$$

$$\cos\theta = \cos(\pi - u_0)\cos u + \sin u_0 \sin u \cos(\phi - \phi_0), \tag{14}$$

where u_0 and u are the solar and satellite zenith angles, respectively.

The steps for applying the SAD analysis to POLDER-3 measurements are as follows:

5) Calculate spherical albedo from the POLDER-3 measurements with 16 viewing geometries for each of the ice particle models.
6) Perform the SAD analysis by taking the difference between the directional and the direction-averaged cloud spherical albedo.
7) Assume that the phase function for each ice particle model adequately represents the phase function for all ice particles in each pixel of the satellite measurement, and that the retrievals of the optical thickness and spherical albedo from the POLDER measurements with different viewing geometries are the same.

When the SAD is 0, the mean spherical albedo and the spherical albedo from the specific angle of POLDER-3 measurements are the same. Therefore, the criteria for selecting the optimal particle habit of the ice cloud are defined as an SAD near 0 in the 16 viewing geometries of POLDER-3, and a small angular dependence.

[Insert Fig. 2 about here]

4 Results and discussion

4.1 Characteristics of the scattering properties

To confirm the accuracy of the calculated single-scattering properties, the phase functions computed in this study are compared with other results. Figure 3 shows comparisons of the phase function (P_{11}) of hexagonal and spheroid particles calculated from the FDTD method with those derived from the ADDA (Bi et al., 2011) and T-Matrix methods, respectively. Our FDTD results are the same as those calculated with the other methods. In addition, the results of Ishimoto et al. (2012b) and Masuda et al. (2012) verify that the phase functions of ice particles with medium and large size parameters are the same, through a comparison of the GOIE and GOM results, respectively.

The single-scattering albedo, asymmetry factor and extinction efficiency among the key parameters of the single-scattering properties of ice particles. Figure 4 shows the single-scattering properties of various ice particle habits at wavelengths of 1.05 and 2.2 μm for various size parameters. The value of the single-scattering albedo is close to 1.0 when size parameters are less than approximately 200 at wavelength 1.05 μm, and 50 at wavelength 2.2 μm; and the value decreases with increasing values of the size parameter. There is a smooth peak in the asymmetry factor for size parameters of 1 to 10, and the peak of the asymmetry factor at a wavelength of 2.1 μm is larger than that at 1.05 μm. The asymmetry factor does not increase monotonically because, due to the complex shapes of the Voronoi habit, the effect of side and back scattering is significant. This results in the asymmetry factor of the Voronoi model being smaller than that of the plate and solid column models. Furthermore, due to the absorption inside the particles, the side-back scattering and single-scattering albedo decreases with the increasing particle size. This results in the asymmetry factor increasing. Absorption of the ice particle in the wavelength of 1.05 μm is not so large, and as a result, the asymmetry factor of the Voronoi particle does not increase monotonically. The extinction efficiency increases with the size parameter for size parameters up to approximately 10, and converges gradually to 2 when the size parameter exceeds 100. The maximum values of extinction efficiency appear when the size parameter is around 10. However, the location of the maximum extinction efficiency varies with particle habit.

Bulk scattering phase functions of the column, droxtal, plate, bullet-rosette, and Voronoi habits, with various effective diameters at wavelengths of 1.05 μm, are given in Figure 5. The phase functions depend on the particle habit and effective diameters. There is a halo peak for the column, plate and bullet-rosette habits when effective diameters are 60 μm and 100 μm, as particle roughening is not applied in these calculations. For the droxtal, variation of the phase function is evident for different effective diameters. The POLDER-3 measures intensity from 16 viewing directions at scattering angles between 60° and 180°; for these scattering angles, the phase function curves of the various particles are different. The phase function of the Voronoi habit is very smooth, with features similar to those for severely roughened ice particle models and the IHM model, except for the halo peak region, as reported by Yang et al. (2013) and Doutriaux et al. (2000).

[Insert Fig. 3 about here]

[Insert Fig. 4 about here]

[Insert Fig. 5 about here]

4.2 SAD analysis

Figure 6 shows the SAD analysis as a function of the scattering angle, effective particle radius, and ice particle models. The SAD of the droxtal, column and plate show substantial variations in both the scattering angle and effective particle radius. The variation of SAD for the bullet-rosette model is more smoothly distributed close to 0 value of the SAD (hereafter, ‘zero line’) than with the droxtal, plate, and column models for small (D_{eff} = 10 μm), medium (D_{eff} = 60 μm), and large particles (D_{eff} = 100 μm). However, the SAD peak of the bullet-rosette model varies in the scattering angle range of 140° to 160° with medium and large particles. The SAD of the Voronoi model is closest to the zero line over the entire scattering angle range for small, medium and large particles. Both the Voronoi and bullet-rosette model with small particles are smoothly distributed along the zero line.

Figure 7 shows the slope of the regression function (SRF) and total relative albedo difference (TRAD) of the SAD for the same five ice particle models with small, medium and large particles, as shown in Fig. 6. Values of both the SRF and TRAD for small particles of the bullet-rosette, and for medium and large particles of the bullet-rosette and Voronoi, are the smallest of all the single-particle models considered. However, there is a peak value of the SAD in the scattering angle range of 140° to 160° for the bullet-rosette model with medium and large particles. The SRF and TRAD of the droxtal model for all sizes of particles are largest in all habit models. As we have described in Section 3, the optimal particle habit is defined as the smallest value of the SRF and TRAD. Thus, it was confirmed that the bullet-rosette model with small particles and Voronoi model with medium and large particles are sufficiently accurate for the retrieval of the ice cloud spherical albedo and optical thickness. Therefore, these models are sufficient to represent ice clouds in terms of optimal particle habits, for the purposes of the SGLI sensor.

Ice crystals in ice clouds are complex. To simulate this complexity, we assume different values of distortion (as defined by Macke et al., 1996) and apply these to the ensemble model. Numerous previous studies have shown that the degree of distortion is an important property to consider when retrieving ice cloud optical properties from multiple-view instruments. To investigate the influence of the distortion of the ice particle model on retrieval of the ice cloud properties, we performed the SAD analysis using the ensemble ice particle models with D_{eff} = 60 μm, assuming a number of distortion values (see Fig. 8). The variation of SAD for the no-distortion model in Fig. 8 (a) is largest, relative to the other distortion values. As a function of distortion value, there are significant variations in the SAD analysis in the scattering angle ranges of 60° to 80° and 140° to 160°. There is no obvious difference in the SAD between Fig. 8 (b), Fig. 8 (c) and Fig. 8 (d) for various degrees of the distortions. The SAD of the ice particle models with a distortion value of 0.4 with spherical air bubbles in Fig. 8 (e) is closest to the zero line. It is implied that the models with distortion or surface roughness are better for the retrieval of the ice cloud optical properties than if no distortion is applied to the model. The models that include spherical air bubbles and distortion have lower SAD values than models with distortion only.

Several conventional studies have demonstrated that ice particle models such as the ensemble ice particle model, IHM and GHM, and some aggregated complex models with rough surfaces, are useful for operational satellite data processing (Labonnote et al., 2000, 2001; Doutriaux et al., 2000; Baum et al., 2011, 2014; Baran and Labonnote, 2006, 2007; Cole et al., 2013). For evaluating the accuracy of the Voronoi model, the SAD of the Voronoi model is compared with that of the conventional IHM, GHM, 5-plate aggregate, and ensemble ice particle models with D_{eff} = 60 μm. As shown in Fig. 9, none of the selected models have strong angular dependencies. However, all the models in Fig. 9 have a rough surface, except for the IHM, which contains spherical air bubbles, and the Voronoi habit. This implies that the Voronoi habit model has a similar effect as some aggregated and mixed-habit ice particle models with roughened surfaces, and the IHM single-particle model contains air bubbles on retrieval of the ice cloud properties using remote sensing instruments. This conclusion is consistent with the conclusion of Liu et al. (2014b), which states that geometric irregularity and surface roughness are effectively equivalent.

Figure 10 shows the slope of the regression function (top panel) and total relative albedo difference (bottom panel) for the selected models in Fig. 9. The SRF for the GHM, Voronoi, and averaged-ensemble models is significantly smaller than for the other three models. The TRAD values for each habit model are not significantly different. However, the Voronoi model is slightly smaller than other models, except for the ensemble ice particle models. The Voronoi and ensemble-averaged models have small values of SRF and TRAD, indicating that the SAD of the Voronoi and averaged-ensemble models have a low angular dependence.

[Insert Fig. 6 about here]

[Insert Fig. 7 about here]

[Insert Fig. 8 about here]

[Insert Fig. 9 about here]

[Insert Fig. 10 about here]

5 Conclusions

Ice particle single-scattering properties were investigated for potential use in the GCOM-C satellite programme. The single-scattering properties of five different ice particle models (plates, columns, droxtals, bullet-rosettes, and Voronoi) were developed using the FDTD, GOIE and GOM methods. The accuracy of the single-scattering property was investigated by comparing the phase function from the FDTD method used in this study with conventional results from ADDA and T-Matrix methods. The FDTD phase functions were also compared with computational results from GOIE. Results indicate that the FDTD-based phase functions are consistent with results from the ADDA, T-Matrix and GOIE methods, which suggests that the single-scattering property database developed in this study is reliable for use in radiative transfer simulations and applications in the remote sensing of ice clouds.

The characteristics of the single-scattering property database for five different ice particle models were investigated by analysing the single-scattering albedo, asymmetry factor and the extinction efficiency. Bulk scattering phase functions for five different ice particle models at the wavelength of 1.05 μm were compared as a function of various effective diameters. It is concluded that phase functions depend on the particle habit and effective diameters. There is a halo peak for middle and large sizes of column, plate and bullet-rosette habits. For the droxtal particle, variation of the phase function is evident for different effective diameters. The phase function of the Voronoi habit is very smooth, with features similar to those of severely roughened ice particle models.

Furthermore, SAD analysis was performed to determine the optimal ice particle habit for retrieving the optical thickness and cloud spherical albedo using POLDER-3 multi-angle measurements. Retrievals were performed using 589 × 246 pixels of the POLDER-3 observation data on a global scale, recorded over oceans on 20–22 of March, June, September, and December 2003. The following conclusions are drawn from the results.

1) The SADs of the droxtal and column habits show significant variations in scattering angle and effective particle radius.
2) SAD variation for small particles with the bullet-rosette model is more smoothly distributed along the zero line than that with other habit models.
3) The Voronoi model SAD is closest to the zero line in scattering angle for all particle sizes.
4) The bullet-rosette habit for small particles and the Voronoi habit for all particle sizes are most suitable for retrieving the ice cloud spherical albedo and optical thickness.

In other words, results of the SAD analysis indicate that the Voronoi particle has the scattering characteristics that are useful for retrievals, e.g., agreement with POLDER/PARASOL polarized reflectances, a low asymmetry parameter, and a smooth phase function. Furthermore, the results of SAD analysis from the Voronoi model were compared with results from the conventional IHM, GHM, 5-plate aggregate, and ensemble ice particle models with moderate ice particle size, in order to evaluate the efficiency of the Voronoi model. It is concluded that the Voronoi habit model is similar to the conventional models for retrieval of ice cloud properties with thick optical thickness, using remote sensing instruments. The results of this study should be useful not only for developing the ice cloud products of the GCOM-C/SGLI satellite mission, but also for determining the optimal ice particle habit for ice cloud remote sensing. In future work, we will investigate how the Voroni particle behaves at low optical thickness values, in direct comparison with the retrievals from CALIPSO/CALIOP polarisation lidar data.

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References

Baran, A. J., Watts, P. D., and Foot, J. S.: Potential retrieval of dominating crystal habit and size using radiance data from a dual-view and multiwavelength instrument: A tropical cirrus anvil case. J. Geophys. Res., 103(D6), 6075–6082, 1998.

Baran, A. J., Watts, P. D., and Francis, P. N.: Testing the coherence of cirrus microphysical and bulk properties retrieved from dual-viewing multispectral satellite radiance measurements. J. Geophys. Res., 104(D24), 31673–31683, 1999.

Baran A. J., Francis, P. N., Labonnote, L. C., Doutriaux-Boucher, M.: A scattering phase function for ice cloud: Tests of applicability using aircraft and satellite multi-angle multiwavelength radiance measurements of cirrus.Q. J. R. Meteorol. Soc. 127: 2395 – 2416, 2001.

Baran, A. J, Havemann, S, Francis, P. N, Watts, P. D.: A consistent set of single-scattering properties for cirrus cloud: tests using radiance measurements from a dual-viewing multi-wavelength satellite-based instrument. JQSRT, 79–80:549–67, 2003.

Baran, A. J. and C.-Labonnote, L.: On the reflection and polarization properties of ice cloud, J. Quant. Spectrosc. Ra., 100, 41–54, 2006.

Baran, A. J. and C.-Labonnote, L.: A ensemble ice particle scattering model for cirrus, I: The solar region, Q. J. Roy. Meteor. Soc., 133, 1899–1912, 2007.

Baran, A. J., Hill, P., Furtado, K., Field, P., and Manners, J.: A Coupled Cloud Physics–Radiation Parameterization of the Bulk Optical Properties of Cirrus and Its Impact on the Met Office Unified Model Global Atmosphere 5.0 Configuration, J. Climate, 27, 7725-7752, 2014.

Baum, B. A., Yang, P., Heymsfield, A. J., Platnick, S., King, M. D., and Bedka, S. T.: Bulk scattering models for the remote sensing of ice clouds. Part 2: Narrowband models, J. Appl. Meteorol., 44, 1896–1911, 2005.

Baum, B. A., Yang, P., Heymsfield, A. J., Schmitt, C., Xie, Y., Bansemer, A., Hu, Y.-X., and Zhang, Z.: Improvements to shortwave bulk scattering and absorption models for the remote sensing of ice clouds, J. Appl. Meteorol. Clim., 50, 1037–1056, 2011.

Baum, B. A., P. Yang, A. J. Heymsfield, A. Bansemer, B. H. Cole, A. Merrelli, C. Schmitt, and C. Wang.: Ice cloud single-scattering property models with the full phase matrix at wavelengths from 0.2 to 100 μm, J. Quant. Spectrosc. Radiat. Transfer, 146, 123-139, 2014.

Bi, L., P. Yang, G. W. Kattawar.: Edge-effect contribution to the extinction of light by dielectric disk and cylindrical particles, Appl, Opt, 49, 4641-4646, 2010.

Bi, L., Yang, P., Kattawar, G. W., Hu, Y., and Baum, B. A.: Scattering and absorption of light by ice particles: solution by a new physical-geometric optics hybrid method, J. Quant. Spectrosc. Radiat. Transfer., 112(9), 1492-1508, 2011.

Bi, L., and P. Yang.: High-frequency extinction efficiencies of spheroids: rigorous T-matrix solutions and semi-empirical approximations, Optics Express, 22, 10270-10293, 2014.

Bi, L., and P. Yang.: Accurate simulation of the optical properties of atmospheric ice crystals with invariant imbedding T-matrix method. J. Quant. Spectrosc. Radiat. Transfer, 138,17-35, 2014.

Chen G, Yang P, Kattawar GW.: Application of the pseudospectral time-domain method to the scattering of light by nonspherical particles, J Opt Soc Am A, 25, 785–90, 2008.

Chepfer, H., Brogniez, G., and Fouquart, Y.: Cirrus clouds' mi- crophysical properties deduced from POLDER observations, J. Quant. Spectrosc. Radiat. Transfer, 60, 375–390, 1998.

Chepfer, H., Goloub, P., Riedi, J., de Haan, J. F., and Hove- nier, J. W.: Ice crystal shapes in cirrus clouds derived from POLDER-1/ADEOS-1, J. Geophys. Res., 106, 7955–7966, doi:10.1029/2000JD900285, 2001.

Chepfer, H., P. Minnis, D. Young, L. Nguyen, and R. F. Arduini, Estimation of cirrus cloud effective ice crystal shapes using visible reflectances from dual-satellite measurements, J. Geophys. Res., 107(D23), 4730, doi:10.1029/2000JD000240, 2002.

Cole, B., P. Yang, B. A.Baum, J. Riedi, L. C.-Labonnote, F. Thieuleux, and S. Platnick.: Comparison of PARASOL observations with polarized reflectances simulated using different ice habit mixtures, J. Appl. Meteor. Clim. 52, 186-196, 2013.

Cole, B. H., P. Yang, B. A. Baum, J. Riedi, and L. C.-Labonnote.: Ice particle habit and surface roughness derived from PARASOL polarization measurements, Atmos. Chem. Phys., 14, 3739-3750, doi:10.5194/acp-14-3739-2014, 2014.

Doutriaux-Boucher, M., Buriez, J. C., Brogniez, G., Labonnote, L. C., and Baran, A. J.: Sensitivity of retrieved POLDER directional cloud optical thickness to various ice particle models. Geophys. Res. Lett., 27, 109–112, 2000.

Draine, B. T., and Flatau, P. J.: Discrete-dipole approximation for scattering calculations. JOSA A, 11(4), 1491-1499, 1994.

Foot, J. S.: Some observations of the optical properties of clouds. II: Cirrus. Q. J. R. Meteorol. Soc., 114, 145–164, 1988.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R.: Changes in Atmospheric Constituents and in Radiative Forcing, in: IPCC Fourth Assessment Report WG 1, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (Eds.), Cambridge University Press, Cambridge, UK, 129–234, 2007.

Hess, M., and M. Wiegner.: COP: A data library of optical properties of hexagonal ice crystals. Appl. Opt., 33, 7740–7746, 1994.

Heymsfield, A. J., Bansemer, A., Field, P. R., Durden, S. L., Stith, J. L., Dye, J. E., Hall, W., and Grainger, C. A.: Observations and Parameterizations of Particle Size Distributions in Deep Tropical Cirrus and Stratiform Precipitating Clouds: Results from In Situ Observations in TRMM Field Campaigns, J. Atmos. Sci., 59, 3457–3491, 2002.

Heymsfield, A. J.: Properties of Tropical and Midlatitude Ice cloud Particle Ensembles. Part I: Median Mass Diameters and Terminal Velocities, J. Atmos. Sci., 60, 2573–2591, 2003.

Heymsfield, A. J., C. Schmitt, and A. Bansemer.: Ice cloud particle size distributions and pressure dependent terminal velocities from in situ observations at temperatures from 0° to -86°C, J. Atmos. Sci., 70, 4123-4154, 2013.

Imaoka, K., Kachi, M., Fujii, H., Murakami, H., Hori, M., Ono, A., and Shimoda, H.: Global Change Observation Mission (GCOM) for monitoring carbon, water cycles, and climate change. Proceedings of the IEEE, 98(5), 717-734, 2010.

Ishimoto, H., Masuda, K., Mano, Y., Orikasa, N., and Uchiyama, A.: Optical modeling of irregularly shaped ice particles in convective cirrus. In radiation processed in the atmosphere and ocean (IRS2012): Proceedings of the International Radiation Symposium (IRC/IAMAS) 1531, 184-187, 2012a.

Ishimoto, H., Masuda, K., Mano, Y., Orikasa, N., and Uchiyama, A.: Irregularly shaped ice aggregates in optical modeling of convectively generated ice clouds, J. Quant. Spectrosc. Radiat. Transfer, 113, 632–643, 2012b.

Knap, W. H., L. C.-Labonnote, G. Brogniez, and P. Stammes.: Modeling total and polarized reflectances of ice clouds: Evaluation by means of POLDER and ATSR-2 measure- ments. Appl. Opt., 44, 4060–4073, 2005.

C.-Labonnote, L., Brogniez, G., Doutriaux-Boucher, M., Buriez, J. C., Gayet, J. F., and Chepfer, H.: Modeling of light scattering in cirrus clouds with inhomogeneous hexagonal monocrystals. Comparison with in-situ and ADEOS-POLDER measurements, Geophys. Res. Lett., 27, 113–116, 2000.

C.-Labonnote, L., Brogniez, G., Buriez, J. C., and Doutriaux- Boucher, M.: Polarized light scattering by inhomogeneous hexagonal monocrystals: validation with ADEOS-POLDER measurements, J. Geophys. Res. 106, 12139–12153, 2001.

Holz, R. E., Platnick, S., Meyer, K., Vaughan, M., Heidinger, A., Yang, P., ... & Nagle, F.: Resolving ice cloud optical thickness biases between CALIOP and MODIS using infrared retrievals. Atmos. Chem. Phys. 16(8), 5075-5090, 2016.

Letu, H., Nakajima, T. Y., and Matsui, T. N.: Development of an ice crystal scattering database for the global change observation mission/second generation global imager satellite mission: Investigating the refractive index grid system and potential retrieval error. Appl. Opt., 51, 6172-6178, 2012.

Liou, K. N.: Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective, Mon. Weather Rev., 114, 1167–1199, 1986.

Liu, Q. H.: The PSTD algorithm: a time-domain method requiring only two cells per wavelength, Microwave Opt. Technol. Lett., 15, 158–165, 1997.

Liu, Q. H.: The pseudospectral time-domain (PSTD) algorithm for acoustic waves in absorptive media, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 45, 1044–1055, 1998.

Liu, C., Panetta, R. L., Yang, P.: Application of the pseudo-spectral time domain method to compute particle single-scattering properties for size parameters up to 200, J. Quant. Spectrosc. Radiat. Transfer., 113, 1728-1740, 2012.

Liu, C., Yang, P., Minnis, P., Loeb, N., Kato, S., Heymsfield, A., and Schmitt, C.: A two-habit model for the microphysical and optical properties of ice clouds, Atmos. Chem. Phys., 14, 13719-13737, 2014 (a).

Liu, C., R. L. Panetta, and P. Yang.: The effective equivalence of geometric irregularity and surface roughness in determining particle single-scattering properties, Opt. Express, 22, 23 620–23 627, doi:10.1364/OE.22.023620, 2014 (b).

Macke, A.: Scattering of light by polyhedral ice crystals. Applied Optics., 32, 2780-2788, 1993.

Macke, A., Mishchenko, M. I., and Cairns, B.: The influence of inclusions on light scattering by large ice particles, J. Geophys. Res., 101, 23311–23316, 1996a.

Macke, A., Mueller, J., and Raschke, E.: Single Scattering Properties of Atmospheric Ice Crystals, J. Atmos. Sci., 53, 2813–2825, 1996b.

Masuda, K., Ishimoto, H., and Takashima, T.: Retrieval of cirrus optical thickness and ice-shape information using total and polarized reflectance from satellite measurements. J. Quant. Spectrosc. Radiat. Transfer, 75, 39-51, 2002.

Masuda, K., Ishimoto, H., and Mano, Y.: Efficient method of computing a geometric optics integral for light scattering, Meteorology and Geophysics ., 63, 15–19, 2012.

McFarquhar, G. M., and Heymsfield, A. J.: Microphysical characteristics of three anvils sampled during the Central Equatorial Pacific Experiment. J. Atmos. Sci., 53, 2401-2423, 1996.

Nakajima, T. Y., Nakajima, T., Yoshimori, K., Mishra, S. K., and Tripathi, S. N.: Development of a light scattering solver applicable to particles of arbitrary shape on the basis of the surface integral equations method of Muller-type (SIEM/M): Part I. Methodology, accuracy of calculation, and electromagnetic current on the particle surface, Appl. Opt., 48, 3526–3536, 2009.

Nakajima, T. Y., Tsuchiya, T., Ishida, H., Matsui, T. N., and Shimoda, H.; Cloud detection performance of spaceborne visible-to-infrared multispectral imagers. Applied optics, 50(17), 2601-2616, 2011.

Nousiainen, T., Lindqvist, H., McFarquhar, G. M., and Um, J.: Small irregular ice crystals in tropical cirrus, J. Atmos. Sci., 68, 2614–2627, doi:10.1175/2011JAS3733.1, 2011.

Ohser, J., Mücklich F.: Statistical analysis of microstructures in materials science, Chichester: Wiley; 2000.

Purcell, E. M., and Pennypacker, C. R.: Scattering and absorption of light by nonspherical dielectric grains. The Astrophysical Journal, 186, 705-714, 1973.

Sun, W., Q. Fu, and Z. Chen.: Finite-difference time-domain solution of light scattering by dielectric particles with perfectly matched layer absorbing boundary conditions. Appl. Opt., 38, 3141–3151, 1999.

Sun, W., Loeb, N., and Yang, P.: On the retrieval of ice cloud particle shapes from POLDER measurements, J. Quant. Spectrosc. Radiat. Transfer., 2006.

Takano, Y. and Liou, K. N.: Solar radiative transfer in cirrus clouds. Part I. Single-scattering and optical properties of hexagonal ice crystals, J. Atmos. Sci., 46, 3–19, 1989.

Takano, Y., and Liou, K. N.: Transfer of polarized infrared radiation in optically anisotropic media: application to horizontally oriented ice crystals., JOSA A, 10, 1243-1256, 1993.

Um, J. and McFarquhar, G. M.: Single-scattering properties of aggregates of bullet rosettes in cirrus, J. Appl. Meteorol. Clim., 46, 757–775, doi:10.1175/JAM2501.1, 2007.

Um, J. and McFarquhar, G. M.: Single-scattering properties of aggregates of plates, Q. J. Roy. Meteorol. Soc, 135, 291–304, doi:10.1002/qj.378, 2009.

Um, J. and McFarquhar, G. M.: Dependence of the single-scattering properties of small ice crystals on idealized shape models, Atmos. Chem. Phys., 11, 3159–3171, doi:10.5194/acp-11-31592011, 2011.

Van Diedenhoven, B., Cairns, B., Geogdzhayev, I. V., Fridlind, A. M., Ackerman, A. S., Yang, P., and Baum, B. A.: Remote sensing of ice crystal asymmetry parameter using multi- directional polarization measurements – Part 1: Methodology and evaluation with simulated measurements, Atmos. Meas. Tech., 5, 2361–2374, doi:10.5194/amt-5-2361-2012, 2012.

Van Diedenhoven, B., Cairns, B., Fridlind, A. M., Ackerman, A. S., & Garrett, T. J.: Remote sensing of ice crystal asymmetry parameter using multi-directional polarization measurements–Part 2: Application to the Research Scanning Polarimeter, Atmos. Chem. Phys., 13, 3185-3203, 2013.

Van Diedenhoven, B., A.M. Fridlind, B. Cairns, and A.S. Ackerman.: Variation of ice crystal size, shape and asymmetry parameter in tops of tropical deep convective clouds. J. Geophys. Res. Atmos., 119, no. 20, 11809-11825, 2014.

Warren, S. G., and Brandt, R. E.: Optical constants of ice from the ultraviolet to the microwave: A revised compilation. J. Geophys. Res, (1984–2012), 113(D14), 2008.

Yang, P., and Liou, K. N.: Geometric-optics-integral-equation method for light scattering by nonspherical ice crystals. Appl. Optics, 35, 6568-6584, 1996.

Yang, P., and K. N. Liou.: An efficient algorithm for truncating spatial domain in modeling light scattering by finite-difference technique, J. Comput. Phys., 140, 346-369, 1998a.

Yang, P. and Liou, K. N.: Single-scattering properties of complex ice crystals in terrestrial atmosphere, Contrib. Atmos. Phys., 71, 223–248, 1998b.

Yang, P., K. N. Liou, K. Wyser, and D. Mitchell.: Parameterization of the scattering and absorption properties of individual ice crystals., J. Geophys. Res., 105, 4699-4718, 2000.

Yang, P., H. Wei, H.-L. Huang, B. A. Baum, Y. X. Hu, G. W. Kattawar, M. I. Mishchenko, and Q. Fu.: Scattering and absorption property database for nonspherical ice particles in the near- through far-infrared spectral region., Appl. Opt. 44, 5512-5523, 2005.

Yang, P., L. Bi, B. A. Baum, K. N. Liou, G. W. Kattawar, M.I. Mishchenko, and B. Cole.: Spectrally consistent scattering, absorption, and polarization properties of atmospheric ice crystals at wavelengths from 02 to 100 μm. J. Atmos. Sci., 70, 330-347, 2013.

Yang, P., K. N. Liou, L. Bi, C. Liu, B. Q. Yi, and B. A. Baum.: On the radiative properties of ice clouds: Light scattering, remote sensing, and radiation parameterization. Adv. Atmos. Sci., 32(1), 32–63, 2015.

Yee, S. K.: Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media, IEEE Trans. Antennas Propag., 14, 302–307, 1966.

Yurkin, M. A., Maltsev, V. P., and Hoekstra, A. G.: The discrete dipole approximation for simulation of light scattering by particles much larger than the wavelength. J. Quant. Spectrosc. Radiat. Transfer., 106(1), 546-557, 2007.

Zhang, Z., Yang, P., Kattawar, G., Riedi, J., Labonnote, L. C., Baum, B. A., ... and Huang, H. L.: Influence of ice particle model on satellite ice cloud retrieval: lessons learned from MODIS and POLDER cloud product comparison, Atmos. Chem. Phys., 9, 7115–7129, 2009.