

Review1:

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

This is a review for the revised manuscript “Investigation of ice particle habits to be used for ice cloud remote sensing for the GCOM-C satellite mission” submitted to ACP by Letu et al.

Based on reviews of myself and the other reviewer, several changes to the manuscript are made. I thank the authors for the changes made to the manuscript so far and for clarifying some issues. I will accept the authors’ choice to include pristine ice crystals in their study. Unfortunately, for some reason the authors missed all of my minor comments, which are repeated below. Also, the revised version that I received did not contain an abstract so I cannot judge that. The revised abstract should reflect the use of size – integrated properties now.

Answer: According to the suggestions, we have revised the abstract as shown bellow:

Abstract: “...The characteristics of calculated extinction efficiency, single-scattering albedo, and asymmetry factor of the five ice particle habits are compared. Furthermore, size-integrated bulk scattering properties for the five ice particle habit models are calculated from the single-scattering database and microphysical data. Using the five ice particle habit models, the optical thickness and spherical albedo of ice clouds are retrieved from the Polarization and Directionality of the Earth’s Reflectances-3 (POLDER-3) measurements, recorded on board the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) satellite.”

In addition, I think the SAD method should be explained better, as explained below. After these minor corrections, I would recommend publication of the paper. The description of the SAD method was altered. However, it is still unclear how the POLDER measurements are used in the method. The authors state that “the spherical albedo can be calculated from the Lobs in each pixel ... to investigate the P11 element of ice particle models.” It is not that trivial and it is not explained how this is done. If I understand correctly, optical thickness is retrieved from the measurements at each angle and in some way the spherical albedo is derived. Please work with the experienced co-authors to describe this method more clearly.

Answer: According to the suggestions, we have revised the manuscript as shown bellow:

In line 6-18, page 8: “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

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

$$S = \int A_p(\mu_0) \mu_0 d\mu_0, \quad (11)$$

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).”

One minor error in the revised version is in equation 6, where the area in the numerator does not seem to belong there.

Answer: According to the suggestion, we have checked the equation 6.

Minor comments repeated from first review (page and line numbers refer to original submission):

P31669, L1: Perhaps the most important update in the 2013 version of the Yang et al. database was the addition of roughness to the particle surfaces. That should be mentioned here.

Answer: According to the suggestions, we have added the description about the Yang et al. database. In page 3, line 6-8: “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.”

P316670, L6: The van Diedenhoven et al. (2012) paper is cited here, but this paper only describes a method to retrieve crystal roughness. Other papers by this group show the method applied to data, such as van Diedenhoven et al. (2014; already cited) and van Diedenhoven et al. (2013; ACP, vol 13, 3185-3203, doi:10.5194/acp-13-3185-2013.). These would be better references here.

Answer: According to the suggestions, we have added the references in the manuscript.

P316671-72: Are the Voronoi model optical properties based on a single realization of the Voronoi habit or are several averaged?

Answer: Optical properties of the Voronoi model are based on a single realization of the Voronoi habit as shown in the following Figure (Ishimoto et al., 2012).

Does the geometry of this model depend on size or not?

Answer: Yes, the geometry of this model depends on the size.

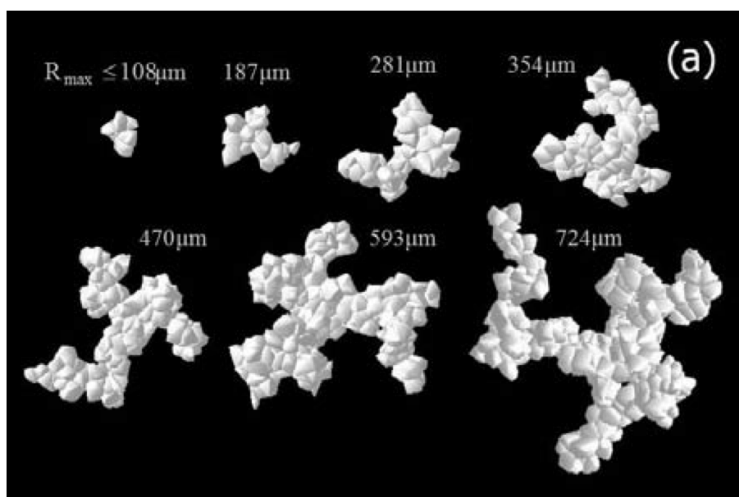


FIGURE 1. A set of seven Voronoi aggregates arranged to be consistent with the shape properties of measured ice particles in convectively generated cirrus. (Ishimoto et al., 2012)

P316673, L27: Please point out that the scattering angle ranges observed depend on latitude, possibly adding lines to the figure to show the different sampling in various latitude bands.

Answer: We have newly added the descriptions in the manuscript as shown bellow: In page 7, Line 26-28: “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.”.

P316674, L2: What is meant with a “changing peak”. Please explain in the paper or rephrase. Also on page 31678.

Answer: As you pointed out, the expression of the “changing peak” in the manuscript is not suitable. We have changed the “changing peak” to “peak value” in the manuscript.

P31677, Figure 5: The y-axis in figure 5 is such that the relevant differences between the models are not apparent. The asymmetry parameters appear to range from 0.5 to 0.9, which is a huge range in terms of radiative effects. Please change the y-axis range to at least 0.5-1 to make the differences between the models apparent.

Answer: According to the suggestions, we have modified Figure 5 in the manuscript.

Page 31679, L8, Fig. 9: Please explain what is meant with “averaged over all distortion values”. Which distortion values are that? 0, 0.15 and 0.25?

Answer: The averaged ensemble phase function is simply the phase function averaged over all four distortions.

Page 31679, L16: Please replace “most efficient” with something like “more consistent with measurements”.

Answer: According to the suggestions, we have replaced “most efficient” with “more consistent” in the manuscript.

Page 31680, L2: This conclusion is consistent with the conclusion of Liu et al. (2014) that of geometric irregularity and surface roughness are effectively equivalent. Please include this citation.

(Liu, C., R. L. Panetta, and P. Yang, 2014: 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.)

Answer: According to the suggestions, we have added the citation of Liu et al., 2014 in the conclusion.

Figure 8 and 11: These figures show similar information but for different particle types. I suggest to make the style the same so it is obvious that these are similar figures. In figure 8, the word “different” in the y-axis title (That’s corrected, but still wrong in the caption) should be “difference”.

Answer: According to the suggestions, we have modified Figure 8 and 11 in the improved manuscript.

Review2:

Major comment:

As noted in the author responses, the choice of hexagonal columns, plates, bullet rosettes, and droxtals was simply to provide a sense of different optical properties to compare with their new particle, the Voronoi ice habit. The ice habit comparison is featured in Figures 4, 5, and 6. I think this paper would make a much larger scientific contribution if the droxtal was replaced with an aggregate of solid columns, as is used later in the manuscript. Here's my argument for doing so.

First, the droxtal was promoted initially as an idealized small circular particle to represent the smallest (<10-20 micron) particles at the top of the coldest ice clouds. It was never meant to be used for larger particles as in this paper and is an unrealistic choice for comparisons.

Second, the CERES team uses a roughened solid hexagonal particle for their ice cloud retrievals and flux calculations, while the MODIS team now uses an aggregate of solid columns for the Collection 6 cloud products (reference: Holz et al., Resolving ice cloud optical thickness biases between CALIOP and MODIS using infrared retrievals, *Atmos. Chem. Phys.*, 16, 5075-5090, 2016, doi:10.5194/acp-16-5075-2016). If the goal of this paper is to decide upon a model to use with the GCOM-C SGLI satellite sensor, then a proper comparison (and an important one) would be to compare the suggested model (e.g., Voronoi) with the roughened column used by CERES and the roughened aggregate used by MODIS. Basically, my suggestion is to replace the droxtal with the aggregate of solid columns.

Answer: Thank you for your constructive suggestions. As the reviewer pointed out, only small droxtal particles exist in the nature ice cloud. However, the reason for adopting the droxtal habits with large sizes in the SAD analysis is not only for investigating the shape of the droxtal, but also for investigating whether the optical property of the droxtal habits with various size can satisfy the SAD measurements as an optimal ice particle model.

The importance for determining the optimal ice particle model in ice cloud remote sensing is considered as follows: the range of the minimum observation scale (1×1 pixel) varies in different satellite sensors and is determined by the spatial resolution of the sensor. For example, the scale of the 1×1 pixel in the MODIS satellite sensor for visible channels is 500 m. For the ice clouds observed in the MODIS instrument, the radiance from various ice particle sizes and habits on the $500 \text{ m} \times 500 \text{ m}$ spatial scale with horizontal and vertical directions is recorded as a single pixel value. Thus, to retrieve the cloud parameter exactly from satellite observation data, it is necessary to select the effective ice particle habit, the phase function of which represents the total phase function from all ice particles included in the 1×1 pixel. Thus, even only small droxtal particles exist in the nature ice cloud, optical property of the droxtal habits was selected to investigate the optimal ice particle models in the 1×1 pixel scale of the satellite measurements.

In this study, we did not calculate the single scattering properties of the aggregate of solid habit. We are going to compare the optical property of the Voronoi model with the aggregate of solid columns with rough surface used in the Collection 6 product as a future work.

Minor comments:

page 2, line 11: there's a "pi" symbol after the word "subsequently" for whatever reason.

page 4, line 3: ...using the same micro-physically consistent habit mixture model throughout the spectrum—> ...using a habit mixture model based on comparisons with microphysical measurements throughout the spectrum...

page 4, line 6: the relation between —> the relationship between

page 5, line 10: size parameter is first mentioned here, but the definition is provided on line 20. Suggest moving Equation 1 to where size parameter is first mentioned.

page 6, line 5: change "is used" to "are used" because datum is singular; data are plural.

page 6, line 7: a proper reference for the thousands of size distributions is this reference:

Heymsfield, A. J., C. Schmitt, and A. Bansemmer, 2013: 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.

Answer: According to the suggestions above, we have modified the manuscript.

page 7, lines 27-28 and Figure 2: do the authors have any insight as to why there are 3 large peaks in Figure 2b?

Answer: I think the peaks are due to the fact that we are sampling ice clouds so we have more samples at mid latitude where storm tracks occur as well as along the ITCZ where there are lots of deep convective clouds. So the fig2b looks very much like the latitudinal distribution of ice clouds.

page 9, lines 2-3: Is the criterium for selecting the optimal habit a value of the SAD near zero or simply a minimum value of the SAD? How much of the time is the minimum value near zero?

Answer: The criteria for selecting the optimal habit model is that slope of the regression function (SRF) and total relative albedo difference (TRAD) of the SAD values indicate the minimum value in the various ice particle models.

page 9, line 15, discussion of Figure 4: I am puzzled by the results for the asymmetry factor - my experience is that the asymmetry factor increases monotonically with size parameter (but since these results are for a fixed wavelength, the results are really increasing with particle size). Do you have any insight as to why the asymmetry factor does not increase monotonically with particle size?

Answer: 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 $1.05 \mu\text{m}$ is not so large ($n = 1.3007 + 0.216e-5i$), and as a result, the asymmetry factor of the Voronoi particle does not increase monotonically.

page 9, line 18: suggest rewording: “the value decreases when size parameter is increasing” to “the value decreases with increasing values of the size parameter”

page 9 line 24: Voronoi habit —> Voronoi habits

page 10, line 21: I’ve read this sentence many times and cannot make sense of it - please reword: “The SRF and TRAD for all size of particles with droxtal model are largest in the all ice particle models

page 11, one 6: air bubbles and distortion is most efficient —> air bubbles and distortion have lower SAD values than models with distortion only. (Do I have the sense of this right? If not, please reword this sentence to make it more understandable)

page 11, line 20: This sentence is awkward - please reword as it could be interpreted more than one way: “However, that for the Voronoi model is slight smaller than for the other models...”

page 11, lines 21-22: But it seems to me that the Voronoi particle seems to have a larger TRAD than the ensemble model.

page 12, line 26-28: This sentence is long and awkwardly worded. Basically it appears to me that the 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. This helps to justify use of this particle for the GCOM-C mission.

About the figures, a general comment: please increase the font size for labels on the figure axes - the

labels use small letters that will only decrease further in the publication. Also, it helps to use a font like Arial, Palatino, or Helvetica rather than a font like Times Roman. Second, help the reader out by increasing the amount of information in the captions. For example, in Figure 4, there is little information in the caption. What is A_s , for example (I think it's single scattering albedo) - why not use SSA rather than A_s ? Define what "g" and Q_{ext} represent in the caption.

[Answer: According to the suggestions above, we have modified the manuscript.](#)