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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Remote sensing of ice crystal asymmetry parameter using multi-directional polarization measurements – Part 2: Application to the Research Scanning Polarimeter" *by* B. van Diedenhoven et al.

B. van Diedenhoven et al.

bastiaan.vandiedenhoven@nasa.gov

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We thank the reviewer for the kind words and very helpful suggestions. Below are repeat the reviewer's comments followed by our replies.

COMMENT 1) As in several other papers on this topic the term roughness and "microscale distortion" is wrongly used. The "distortion" is realized by random tilts of the (physically infinitely extended) plane crystal facets. That corresponds to an ensemble of columns or plates, which deviate from a perfect macroscopic hexagonal crystal structure. This is not a microscale property.

REPLY: In the revised paper we elaborate further on the interpretation of the distortion parameter in the Macke et al. (1996) model. The following was added to section 2.1:

“The ice crystal optical properties are calculated using the standard geometric optics code developed by Macke et al. (1996). This ray tracing code takes distortion of ice crystals into account in a statistical manner by perturbing, for each interaction with a ray, the normal of the crystal surface from its nominal orientation by an angle varied randomly with uniform distribution between 0 degree and delta X 90 degree, where delta is referred to as the distortion parameter. Thus, this approach represents the stochastic large-scale distortion of a collection of ice crystals. However, Yang et al. (2008) found that this approach is also an efficient, yet accurate treatment of microscale surface roughness. For a large collection of ice crystals, microscale surface roughness and large-scale particle distortion both lead to a similar randomization of the angles between crystal facets, which in turn leads to the diminishing of features in the scattering phase matrix. Increasing the number of impurities within ice crystals also has a similar effect (Hess et al., 1998). Thus, we consider the distortion used here a proxy of randomization of the angles between crystal facets possibly caused by any of these effects.”

Consistent with this discussion we state that the retrievals indicate “roughened or distorted ice crystals” in the conclusions and abstract. Furthermore, we refer to delta as “distortion” rather than “microscale distortion” throughout the paper.

COMMENT 2) It might be worth to briefly note where the polarization information is used in the retrieval to distinguish between particle shapes? Plates and columns have rather different polarizations in the range of scattering angles, I assume.

REPLY: To discuss the variation in polarization with aspect ratio and distortion some more we have added the following to section 2.1: "As shown in Part 1, smooth undistorted hexagonal columns produce strong features in the degree of polarization func-

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tions at the scattering angles usually observed by multi-directional polarimeters (> 100 degree). Similar, but sharper features are generally obtained for plates (e.g., Takano and Liou, 1989). Such features are systematically diminished with increasing distortion or microscale surface roughness (Part 1; Macke et al., 1996; Yang et al., 2008). Furthermore, as shown in Part 1, the polarization from hexagonal ice crystals generally increases when their aspect ratio increasingly deviates from unity, especially at scattering angles smaller than about 140 degree."

COMMENT 3) The main concept of the RSP retrieval is the use of aspect ratio and "distortion" of hexagonal columns or plates as free parameters. That might be OK if the crystals mostly consist of this general hexagonal geometry. However, Fig. 4 for example shows that the majority of the ice particles are irregular. I assume one could to the same exercise with spheroids (to vary aspect ratio) and air bubble inclusions (to vary inhomogeneneity), for example. So, some words to justify the approach might be in order.

REPLY: The following clarification was added to section 2.1: "Furthermore, our approach is based on the common assumption that ice crystals consist of fundamental hexagonal structures that can be either smooth or distorted. Some evidence exists that, under some conditions, small ice crystals can form or evolve into other shapes, such as spheroids (e.g., Mishchenko and Sassen, 1998; Nelson, 1998; Lawson et al., 2010; Gayet et al., 2012). In future work, application of our approach to clouds consisting of particles fundamentally different from hexagonal prisms should be evaluated."

Also, as explained better in the revised version of the paper, the distortion parameter used in the geometric optics code can be considered as a proxy of randomization of the angles between ice crystal facets possibly caused by either large-scale particle distortion, microscale roughness or impurities (e.g., bubble inclusions). (See our reply to comment 1.)

COMMENT 4) 71, 20-25: Please provide some arguments why the (existing) correction

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of cloud top heights due to transmissivity and multiple scattering is not applied. Cirrus clouds are optically thin and the assumption of opaque clouds may not be approriate. And for optically thicker clouds, multiple scattering gets more important, of course. So, it seems that there is always a strong need for that correction.

REPLY: First, we meant to say that the correction for multiple Rayleigh scattering is not applied. The cloud itself is assumed opaque and to have the same contribution to the polarized reflection in the blue and red wavelength bands used. We have added the word "Rayleigh" in the references to multiple scattering in section 2.2. Secondly, such look-up-tables are instrument-specific and not yet available for RSP. Furthermore, such a correction is not as straightforward as we might have seemed to suggest. Development and testing of a more versatile cloud top height retrieval algorithm for RSP would be the subject of a separate paper. It should also be noted that the contribution of multiple scattering of clouds to the polarized reflectance that is used in the cloud top height estimates does not increase dramatically for optically thicker clouds, but rather is saturated at an optical depth of $\sim$5 (see Fig. 1). It is actually thinner clouds that are more of a problem. Since we are mainly focusing here on relatively optically thick clouds for which the corrections are assumed to be minimal, such potential corrections are not applied here. We have added clarifying statements to the revised paper in section 2.2.

COMMENT 5) Figs. 3b and 3c: Is the RSP retrieved extinction the mean value for the cloud column? If so, comparison with in-situ extinction at the flight lag is problematic. Same for RSP retrieved g near cloud top and in-situ g at a certain flight altitude. Both g do not seem to show any correlation. So, extensive discussion of the differences may not be required.

REPLY: The panels labeled (b) of Figs 3 and 8 give the RSP cloud optical thickness in black as well a the CIN extinction in orange, as already labeled in the figures and in the caption. RSP cannot be used to measure extinction. CIN extinction is given as a reference for the location of the Citation aircraft within the cloud and as an indication of

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the relative differences of the cloud parts sampled by the CIN. For the case in which the Citation flew straight legs through the cloud, we do not discuss any quantitative comparison between extinction measured by the CIN and cloud optical thickness by RSP. In the case of Citation spirals through the cloud, we estimate the optical thickness from the CIN extinction measurements, which are compared to the RSP cloud optical thickness. As discussed in the paper, these spirals also suggest that there is vertical variation of the asymmetry parameter, although relatively weak. With these considerations taken into account, we feel that an extensive discussion about the comparison of the asymmetry parameter retrieved by RSP and the CIN is justified and needed.

COMMENT 6) General: Given the small radiometer field of view and the strong cloud inhomogeneity I assume that 3d-effects may play a role. I understand that this is beyond the scope of the present study, but could get mentioned in the conclusions.

REPLY: 3D effects may be expected to cause variability in the retrievals over an inhomogeneous cloud deck. However, for most of the case studies presented, the variability of the retrievals is rather small. A more detailed study using simulated measurements calculated with a 3D vector radiative transfer code is planned for the future. We now list possible 3D effects as one of the remaining issues to be studied in future work in the conclusions, as suggested.

COMMENT 7) Conclusion: First three paragraphs are merely summary. Please remove or move to previous section.

REPLY: It is customary for a final section titled "conclusions" to include a summary. Owing to the complicated nature of comparing remote sensing and in situ results, the individual subsections of section 3 contain many details. Therefore we feel that a summary of the results is useful and warranted. The subsection 3.5 is more a discussion than a summary and we have relabeled that section ‘Discussion’.

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