Ice Crystal Morphological Complexity and Asymmetry Parameter: Implications for Light Scattering Measurement

Guanglang Xu, Fritz Waitz, Shawn Wagner, Franziska Nehlert, Martin Schnaiter and Emma Järvinen

October 3, 2022

Ice crystal morphological complexity and asymmetry parameter: implications for light scattering measurements

Guanglang Xu,[a)] Fritz Waitz, Shawn Wagner, Franziska Nehlert, Martin Schnaiter, and Emma Järvinen

Karlsruhe Institute of Technology, Karlsruhe, Germany.

[a)] *Corresponding author: guanglang.xu@kit.edu*

Abstract. We developed a model-free algorithm for retrieving the asymmetry parameter of ice crystals from polar nephelometer measurements. In addition, we introduce the so-called C_p parameter for defining the degree of morphological complexity of ice crystals. The C_p is defined in such a way that it measures the decay rate of coefficients for Legendre expansion of the angular scattering function. It was found that the C_p parameter is strongly correlated with the distortion parameter of the ice crystal models. The effectiveness of C_p is validated using a case study on rimed particles.

INTRODUCTION

An accurate representation of cirrus cloud's radiative properties is important for climate study due to its large coverage over the Earth surface. It is recognized that cirrus cloud's interaction with solar and infrared radiation plays a significant role in the energy balance of the Earth-atmosphere system. In-situ measurements of the microphysical and light scattering properties of ice crystals are important for better constraining the ice clouds properties in climate models. The linkages between the microphysical and light scattering properties could also provide some valuable implications for remote sensing applications. With the advancement of measurement and instrumental techniques, increasing amount of valuable data from in-situ measurements are becoming available for the analysis of ice particle properties. To better utilize these data, we report results on 1) developing a model-free algorithm for retrieving the asymmetry parameter, an important optical scattering parameter of ice crystals, for the Particle Habit Imaging and Polar Scattering (PHIPS) probe, 2) the introduction of the so-called C_p parameter for measuring the complexity of ice crystals and 3) present a case study where we investigated the link between the asymmetry parameter and the C_p parameter on rimed particles. These results reveal some linkages between the microphysical and light scattering properties ice crystals, particularly the relation between the morphological complexity and asymmetry parameter.

A MODEL-FREE ALGORITHM FOR ASYMMETRY PARAMETER RETRIEVAL

Polar nephelometer measurements are restricted in their angular range due to inability to measure very close to ecaxt forward and backward scattering angles. Therefore, a retrieval algorithm is needed for inferring the asymmetry parameter from the measurements In geometrical optics range, we can use the following relation to derive asymmetry parameter,

$$g = \frac{1}{2\omega_0}[(2\omega_0 - 1)g_{GO} + g_D], \tag{1}$$

where $g_{GO} = \hat{c}_{GO,1}$ and $g_D = \hat{c}_{D,1}$ are the asymmetry parameter contributed by geometric-optics and diffraction, respectively. As the diffraction phase function is highly peaked, g_D is very close to unity. According to the analysis of scalar diffraction (SD) theory, most of the diffracted energy will be confined into the angular range of $\theta < 7/x$ (in radian). On a logarithmic scale, $g_D(d)$ can be approximated by a polynomial of degree 4, i.e,

$$\begin{aligned} g_D(d) = &-5.9270 \times 10^{-5} - 0.00130 \times ln(d) - 0.01087 \times (ln(d))^2 \\ &+ 0.04093 \times (ln(d))^3 + 0.94029 \times (ln(d))^4, \end{aligned} \tag{2}$$

where d is the particle diameter. The geometric-optics contribution g_{GO} can be obtained from polar nephelometer measurements by extrapolating the measurements by applying Gaussian quadrature. It should be noted that the retrieval is only valid for particle ensembles so in the case of the PHIPS single particle observations the measurements

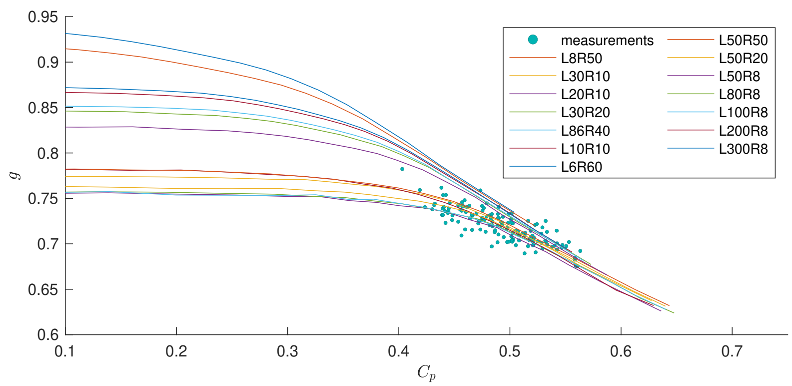

FIGURE 1. A case study on a cirrus cloud by applying the retrieval algorithm.

need to be averaged over a particle population. We can summarize our proposed method in the following. Step 1: Obtain averaged angular scattering data from measurement; Step 2: Find the Legendre coefficients $\hat{c}_{GO,l}$ that fit the data best; Step 3: Derive $g_D(d)$ based on particle size distribution; Step 4: Obtain the expansion coefficients $\hat{c}_l$ and hence the asymmetry parameter g. By applying this algorithm, we measure the asymmetry parameter of a cirrus cloud in the Arctic region, the results are compared to the model simulations, displayed in Fig. 1.

THE C_p PARAMETER

In the development of an algorithm for retrieving the asymmetry parameter from the measurements of a polar nephelometer, we introduced a so-called C_p parameter that describes the smoothness and isotropic degree of the phase function. It is defined as:

$$C_p = (\sum_{l=0}^{\infty} |\hat{c}_{GO,l}|)^{-1}, \tag{3}$$

where $\hat{c}_{GO,l}$ is the expansion coefficients of phase function due to the $reflection - refraction$ of light ray by using a series of Legendre polynomials $P_l(cos(\Theta))$, i.e.,

$$P_{GO}(\Theta) = \sum_{l=0}^{\infty} (2l+1)\hat{c}_{GO,l} P_l(cos(\Theta)). \tag{4}$$

It was found that the C_p parameter is closely connected to the distortion parameter δ, designed for ray-tracing computation, as displayed in Fig. 2. C_p must fall in the range between 0 and 1, i.e.,

$$0 \leq C_p \leq 1, \tag{5}$$

where the case of 0 corresponds to a Dirac-delta function (i.e. no scattering) and 1 corresponds to isotropic scattering. Applying the definition of C_p to the Henyey-Greenstein (HG) phase function, we have a very simple relation between g and C_p by applying the geometric series , i.e.,

$$C_p + |g| = 1, \tag{6}$$

which indicates the strong correlation between the two. In addition, due to the properties of Gaussian quadrature, higher C_p value often gives higher accuracy in the asymmetry parameter retrieval.

A CASE STUDY ON RIMED PARTICLES

Here we report a case study on complex atmospheric particles with visible morphological complexity in the form of riming (i.e. the accretion of supercooled liquid droplets on the surface of ice crystals). The analysis on the

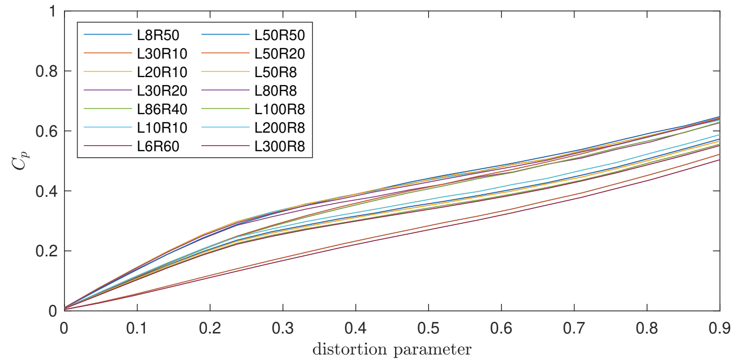

FIGURE 2. The correlation of C_p and distortion parameter applied in the ray-tracing code.

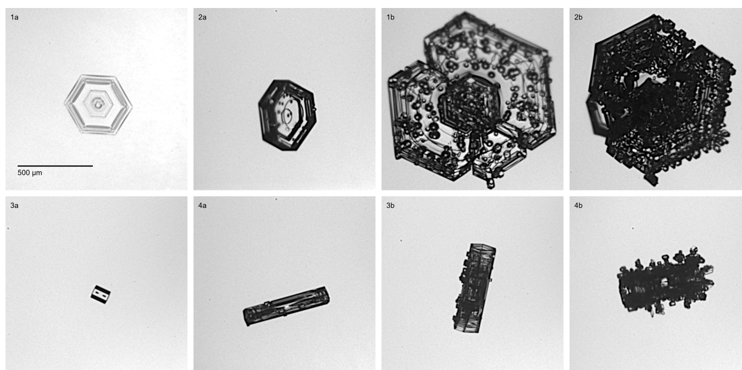

FIGURE 3. Examples of (1) columnar particles and (2) plates with different degrees of riming depending on the surface riming degree (SRD): unrimed (a, SRD = 0%), slightly rimed (b, $0\% < \text{SRD} \leq 25\%$), moderately rimed (c, $25 < \text{SRD} \leq 50\%$) and heavily rimed particles (d, $50\% < \text{SRD} \leq 100\%$).

category of rimed particles provides a convenient way to investigate the relation between particle complexity and their optical scattering properties, as the degree of riming is easy to differentiate visually using the corresponding stereo-microscopic images acquired by PHIPS. Data from two recent airborne campaigns were examined: (1) Arctic CLoud Observations Using airborne measurements during polar Day (ACLOUD) in May/June 2017 based in Svalbard (Spitsbergen, Norway), (2) Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES) in Jan/Feb 2018 based in Hobart (Tasmania, Australia). Exemplary ice crystals imaged by PHIPS are shown in Fig. 3. It can be seen that the differentiation between different Surface Riming Degree (SRD) is clear and reliable.

To demonstrate the statistical correlation between rimming degree and C_p parameter, we compute the $C_p - SRD$ distribution together with the $g - C_p$, displayed in Fig. 4. In doing so, we assume that the *SRD* degree is randomly and evenly distributed within each category. Each data point represents an average of 25 particles. It can be seen that the C_p parameter is very well correlated with the *SRD* in a linear fashion. As the complexity metric, *SRD*, is derived independently from image analysis, such correlation can be seen as experimental evidence for the effectiveness of using the C_p parameter in measuring the morphological complexity of ice crystal.

CONCLUSIONS

In summary, we have developed an algorithm to retrieve the asymmetry parameter and a complexity (C_p) parameter from polar nephelometer measurements. Based on both numerical simulations and a case study on rimed particles, we have shown that the C_p parameter is able to quantify the degree of morphological complexity ice crystals. In future work, the measured relation between C_p and the asymmetry parameter will be applied to improve the accuracy of the parameterization of the optical properties of ice clouds.

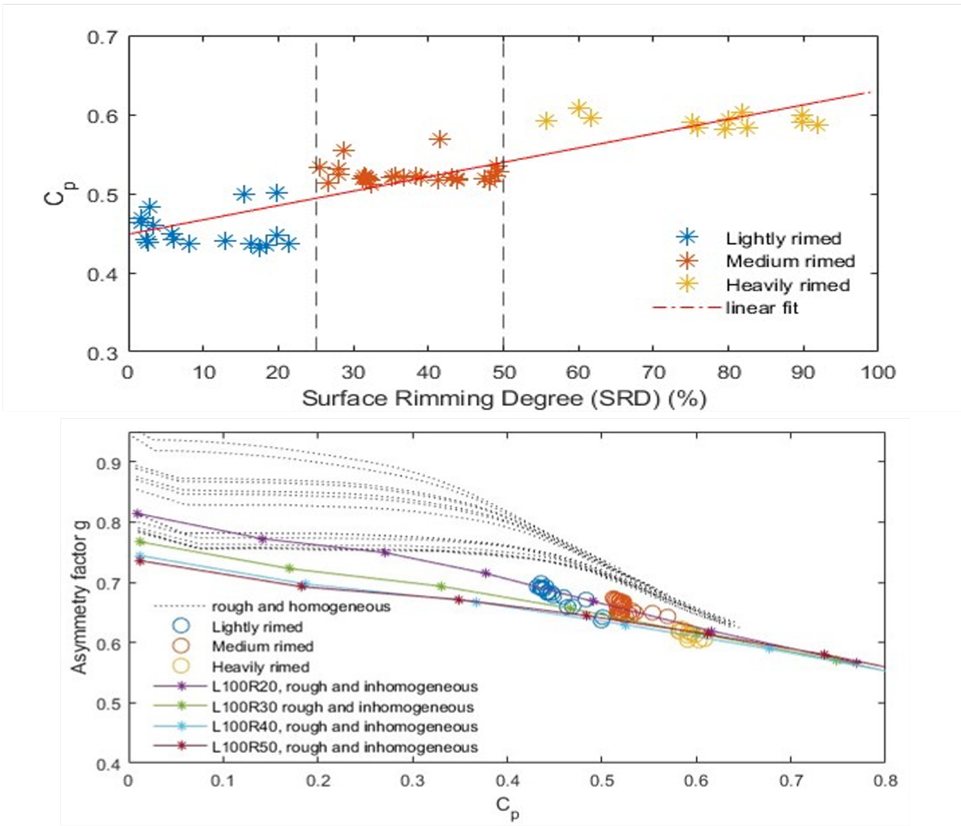

FIGURE 4. The correlation between C_p and Surface Rimming Degree (*SRD*) and the relation between C_p and asymmetry parameter.

ACKNOWLEDGMENTS

This work was funded by the Helmholtz Association's Initiative and Networking Fund (grant agreement no. VH-NG-1531).

REFERENCES

1. K.-N. Liou, "Influence of cirrus clouds on weather and climate processes: A global perspective," Monthly Weather Review **114**, 1167–1199 (1986).
2. G. Xu, M. Schnaiter, and E. Järvinen, "Accurate retrieval of asymmetry parameter for large and complex ice crystals from in-situ polar nephelometer measurements," Journal of Geophysical Research: Atmospheres **n/a**, e2021JD036071 (2022).
3. G. Xu, F. Waitz, S. Wagner, F. Nehlert, M. Schnaiter, and E. Järvinen, "Towards better constrained optical scattering models for natural ice crystals," (under review) Journal of Geophysical Research: Atmospheres **n/a** (2022).
4. M. Schnaiter, E. Järvinen, A. Abdelmonem, and T. Leisner, "Phips-halo: the airborne particle habit imaging and polar scattering probe – part 2: Characterization and first results," Atmospheric Measurement Techniques **11**, 341–357 (2018).