Light scattering by quasi-spherical ice crystals in tropical cirrus

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Shape statistics of small, quasi-spherical ice crystals are compiled through analysis of images collected by the Cloud Particle Imager (CPI) in tropical cirrus. Ray-optics simulations are conducted to obtain their single-scattering properties at 550 nm wavelength. Small tropical ice crystals are found to be more spherical than those in midlatitude cirrus and, correspondingly, their asymmetry parameters are higher. The difference is, however, not significantly larger than the variability within tropical cirrus. Sensitivity studies conducted imply that the asymmetry parameter is very sensitive to internal inhomogeneity about which no data currently exist.

INTRODUCTION

Tropospheric ice clouds are important parts of the Earth-atmosphere system. In particular, their scattering, absorption, and emission properties play a major role in distributing the solar and thermal radiative energy within the system. The radiative impact of ice clouds depends on the size-shape distribution of ice crystals, which varies considerably and is still poorly known. The impact of ice crystals smaller than 100 µm in maximum dimension (D) on ice-cloud radiative properties is especially uncertain.

To assess the radiative impact of ice clouds, it is of utmost importance to know the size-shape distributions of ice crystals in real clouds. Such information can be obtained, for example, by flying a Cloud Particle Imager (CPI) through clouds of interest. These measurements have revealed that small ($D < 100$ µm) ice crystals appear to be predominantly irregular and quasi-spherical in shape. However, there has yet to be a study to show whether the characteristics of these small ice crystals vary between different geographical locations. To this end, shapes and single-scattering properties of small ice crystals present in tropical cirrus are derived and compared against those found for midlatitude ice clouds by [1].

DATA

Ice crystal data were collected during the Tropical Warm Pool International Cloud Experiment (TWP-ICE) and during the Aerosol and Chemical Transport In Tropical Convection (ACTIVE) campaign over Darwin, Australia in early 2006. The data used here consist of CPI images of individual ice crystals obtained during three separate days, and cover different types of ice clouds from aged cirrus to freshly formed anvils [2].

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Based on Um's [3] analysis of the CPI data collected, it appears that quasi-spherical ice crystals with $D < 100$ µm contributed approximately 79% (26%), 51% (9%) and 57% (14%) to the total number (projected area) for the size distributions measured on 27 January, 29 January and 2 February, respectively. Example images of these ice crystals are shown in Fig. 1. The CPI instrument has a nominal resolution of 2.3 µm, but images of small particles tend to be blurred due to diffraction effects. Accordingly, ice crystals with $D < 20$ µm were excluded from the analysis.

MODELING APPROACH

The shapes of small, quasi-spherical ice crystals were modeled using the Gaussian random sphere geometry [4]. To this end, a statistical shape analysis was performed. About 1600 images were chosen for analysis and ice crystal silhouettes extracted from each image. The covariance function of radius was then computed for the silhouettes. The images used in the analysis were subject to objective and subjective quality criteria and were chosen in as unbiased a way as possible to ascertain representative shape statistics. The methodology was practically identical to that adapted by [1]. The shape statistics were computed separately for each of 17 flight legs that represented different meteorological conditions, temperatures, and varying temporal and spatial proximities to the convection that generated the cloud.

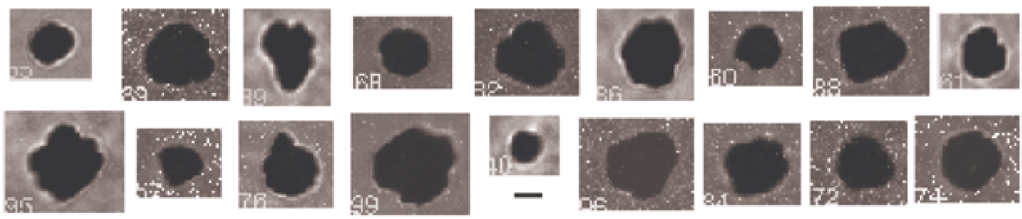

Figure 1. Example CPI images of small, quasi-spherical ice crystals observed in tropical cirrus. The scale bar shown is 11 pixels or about 25 µm long.

The single-scattering properties of the model ice crystals were computed using a modified ray-optics model RODS (Ray Optics with Diffuse and Specular interactions) introduced by [5]. The model consists of the geometric optics and diffraction parts, the latter of which is solved using the Fraunhofer approximation. The geometric optics part is augmented such that the target shape can be filled with internal scatterers, for example soot, sulphate, or air bubbles, with a given mean free-path length δ_0. The single-scattering properties of internal scatterers are given by specifying their scattering phase matrix and the single-scattering albedo. The approach is similar but more flexible than the use of internal Mie spheres adopted by [6].

To assess the impact of internal inhomogeneity on the single-scattering properties of small ice crystals, sensitivity studies with internal scatterers were conducted in addition to simulations of the homogeneous case. The phase matrix of internal scatterers was approximated by a parameterized Henyey-Greenstein phase matrix [5] with specific asymmetry parameter g_0. In the sensitivity study, g_0 and δ_0 were varied. No experimental data is available to constrain the values of these parameters.

RESULTS

The shape analysis revealed that the derived covariance functions of radius closely resemble power-law covariance functions, that is, the weights of the Legendre expansion of the covariance function closely followed a power law. The standard deviation of radius, σ, varied in a range from 0.081 to 0.168, with a number-weighted mean $\langle\sigma\rangle = 0.117$. Likewise, the power law index ν varied from 2.32 to 3.29, with a mean of $\langle\nu\rangle = 2.9$. Incidentally, $\langle\nu\rangle$ is identical to that suggested for the small, quasi-spherical ice crystals in midlatitude cirrus. The mean $\langle\sigma\rangle$, however, is significantly smaller than the value of 0.15 obtained for midlatitudes by [1], and thus deviations from a spherical shape smaller.

To assess whether the power-law covariance function is a good model for the particles, model shapes were generated using both the actual retrieved covariance functions and their power-law fits. Light scattering simulations were then conducted for both sets of particles, while assuming the crystals to be homogeneous. As discussed in [1], the σ values retrieved from silhouettes were multiplied by 1.1 when generating model particles to account for the difference in radius statistics between three-dimensional bodies and their silhouettes; the actual difference depends on the shape, but the aforementioned modification is suitable for the shapes considered here.

Fig. 2 shows the asymmetry parameters obtained for each flight leg for both the original, retrieved covariance functions and their power-law fits. As can be seen, there is some, but not very substantial, variation between flight legs, signifying that the crystal shapes tend to be somewhat different in different conditions or locations. In general, the differences between flight legs are similar to the differences between original shapes and their power-law fits.

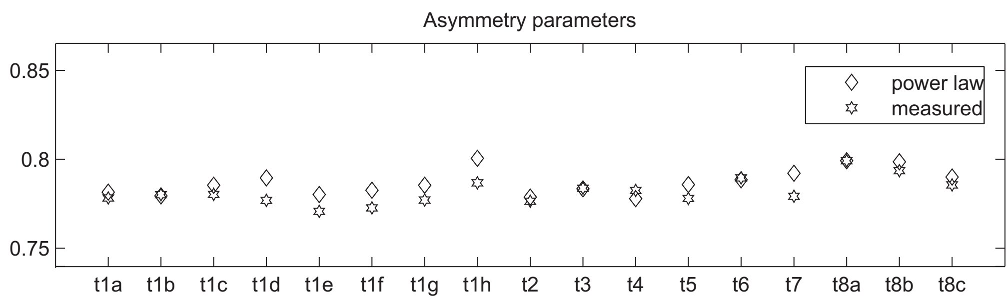

Figure 2. Mean asymmetry parameters obtained for small, quasi-spherical ice crystals observed during each flight leg. The stars depict values obtained for the original, retrieved shape statistics, and diamonds those based on their power-law parameterizations.

The mean shape statistics for the tropical cirrus yields $\langle g\rangle = 0.776$, slightly higher than the corresponding midlatitude value of 0.764 [1]. Thus, the difference between the midlatitude and tropical cases is similar to the internal variability within the tropical cirrus, and the differences are likely to be insignificant for climate.

The sensitivity studies with internal structure revealed that the presence of internal scatterers has a potentially huge impact on scattering. Not surprisingly, a decrease in g_0 or δ_0 decreased g. Internal scatterers cannot, however, increase g over the value obtained for homogeneous crystals, so their possible presence signifies a systematic impact on g. Even when δ_0 was as large as five times the mean crystal radius, g decreased by up to 4 %, depending on g_0. So, even relatively small amounts of internal scatterers caused substantial effects. It is noted, however, that a single micrometer-scale freezing nucleus inside a crystal is unlikely to impact scattering significantly (for a 100 µm crystal, δ_0 would be about 1000 times the crystal size).

Finally, there has been speculation that the CPI might cause the shattering of larger ice crystals so that a fraction of the observed small crystals are merely remnants of shattered particles. To investigate this, the dependence of shape statistics on the number concentration of large ice crystals was examined. Light scattering simulations based on the retrieved statistics showed that the asymmetry parameter varied by less than 0.01 for different large crystal concentrations. Since one of the classes had no large crystals present, it seems unlikely that the results reported here are biased by possible shattering effects. Further, of the 189,905 particles imaged by the CPI during these 3 flights, 98.45 % were the only particle recorded on a frame, suggesting shattering that would generate multiple particles per frame was not an important source of small crystal images.

CONCLUSIONS

A statistical shape analysis of CPI images of small, quasi-spherical ice crystals observed in tropical cirrus reveals that these crystals are closer to spherical than the corresponding crystals in midlatitude cirrus studied by [1]. Ray-optics simulations based on the derived model shapes reveal that their asymmetry parameters are larger than for the midlatitude counterparts. The difference of g between midlatitude and tropical cases is, however, similar to the variability within different types of tropical cirrus and unlikely to be significant for climate considerations.

Sensitivity tests conducted for the impact of internal structures on scattering imply that inhomogeneity of small ice crystals could potentially have a major impact on g and even on the radiative impact of the whole cloud. Unfortunately, no data are available on the inhomogeneity of small ice crystals. Considering the potential impacts, obtaining such data would be highly desirable.

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