The shapes of very small cirrus particles derived from in situ measurements

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[1] The shapes of ice crystals have been derived from measurements in cirrus during the CRYSTAL/FACE experiment in July, 2002. The measurements were made in the size range from 5–45 μm with an optical particle spectrometer that measures forward (4–12°) and backscattered (168–176°) light from individual particles. The phase functions for ensembles of ideal crystal shapes were integrated over these collection angles to compare with the measured ratios of forward to backward scattered light from nine research flights. Approximately 90% of the crystals agreed with the theoretical model for a mixture of bullet rosettes, plates and hollow columns. Approximately 10% of the crystals were characterized as ice spheres. There was no significant dependency of shape on wind direction, temperature or relative humidity with respect to ice. **Citation:** Baumgardner, D., H. Chepfer, G. B. Raga, and G. L. Kok (2005), The shapes of very small cirrus particles derived from in situ measurements, *Geophys. Res. Lett.*, *32*, L01806, doi:10.1029/2004GL021300.

1. Background

[2] Surface and projected area are two important characteristics of an ice crystal and both are dependent on crystal shape. The albedo of cirrus clouds is sensitive to the projected area of crystals, particularly those whose sizes are smaller than 50 μm [*Arnott et al.*, 1994; *Jensen et al.*, 1994; *Heymsfield and McFarquhar*, 1996; *Yang et al.*, 2001] and that are frequently found in high concentrations [*Heymsfield and Platt*, 1984; *Knollenberg et al.*, 1993; *Heymsfield and McFarquhar*, 1996; *Boudala et al.*, 2002; *Gayet et al.*, 2002; *Garrett et al.*, 2003]. Very little shape analysis of sub-50 μm cirrus crystals has been done; however, since the majority of measurements are made with optical array probes, such as the PMS-2D spectrometer, that have a minimum resolution of 25 μm. Higher resolution instruments like formvar replicators, the Video Ice Particle Sampler [*Miloshevich and Heymsfield*, 1997] and the Cloud Particle Imager [*Lawson*, 2001] capture the crystal shape but analysis is labor intensive and only the projected area can be measured directly. An instrument capable of measuring the phase function directly of small, individual particles is the Polar Nephelometer [*Gayet et al.*, 1997]; however, there have been no publications that analyze crystal shapes in the sub-50 μm size range. The images from a CPI of sub-50 μm ice crystals in Arctic stratiform and cirrus clouds have been analyzed for their habits [*Korolev et al.*, 1999] and asphericity [*Korolev and Isaac*, 2003]. These investigators found that fewer than 50% of the ice crystals could be classified as spherical. These measurements were made in clouds warmer than 225 k, and tops lower than 10 Km.

[3] Here we present a new bi-directional light scattering technique for the shape analysis of individual crystals smaller than 50 μm measured in tropical and sub-tropical clouds during the 2002 CRYSTAL-FACE field campaign.

2. Measurement and Analysis Methodology

[4] The cloud and aerosol spectrometer (CAS) derives two intensity distributions from the light scattered by individual particles that pass through a focused beam from a diode laser [*Baumgardner et al.*, 2002]. Two cones of light, 4 to 12° and 168° to 176°, are measured by separate detectors and the peak amplitudes are classified into bins to create two frequency histograms, forward and backward, every second. The relationship between scattered light intensity and detector voltage output is established with monodispersed polystyrene latex and crown glass beads of known size and refractive index. The size range is limited by the diameter of the laser and the sensitivity and dynamic range of the detectors. For the CRYSTAL-FACE field campaign the size range was adjusted to 0.5 to 50 μm. The average forward to backscattering ratio (F2BR) is calculated from the sum of the forward scattering channels divided by the sum of the backward ones. The uncertainty in the derived ratio is approximately 20%, as a result of the accuracy of the calibration particles that have a standard deviation of ±10%, the variance in the laser intensity that is on the order of 15%, and electronic noise that contributes another 10%.

[5] The F2BR changes with refractive index; however, in clouds, the refractive index known, so that the F2BR only changes with shape and size.

3. Theoretical Scattering Calculations

[6] Theoretical relationships between ice crystal shape and light scattering have been derived using geometric optics, T-matrix and finite differential time domain techniques [*Takano and Liou*, 1989; *Macke et al.*, 1996; *Noel et al.*, 2001; *Mishchenko et al.*, 2002]. These techniques were applied to compute the F2BR from theoretical scattering phase functions in the visible domain that are associated with different ice crystal shapes and sizes, as summarized in Table 1. The theoretical ratio, F2BT*, is computed by

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Table 1. Scattering Phase Functions[a]

Name	Crystal Shape	Crystal Size (μm)	Computation Method	Source	Ratio
Ice Spheres	Spherical	5 to 45	Mie	Mie	60 to 90
Columns MC	COL(Q=2.5)	50	GO	*Noel et al.* [2001]	4
Compacts MC	CP	50	GO	*Noel et al.* [2001]	2.5
Plates MC	PL	40	GO	*Noel et al.* [2001]	11
Ceres_contrail	CP+COL	18	GO	*Takano and Liou* [1989]	29
Droxtal	DRXT	1 to 6	FDTD	*Yang et al.* [2003], *Zhang et al.* [2004]	90 to 140
Droxtal	DRXT	7 to 20	FDTD	*Yang et al.* [2003], *Zhang et al.* [2004]	30 to 74
Dendrite	D		GO	*Takano and Liou* [1989]	32
MODIS1	BR+PL+HC	9	GO+FDTD	*Yang et al.* [2001]	39
MODIS-2	BR+PL+HC	33	GO+FDTD	*Yang et al.* [2001]	36
MODIS-rough	BR+PL+HC	30	GO+FDTD	*Yang et al.* [2001]	108
VIS 5-5	CP	5	GO+FDTD	*Takano and Liou* [1989]	84
VIS 10 - 5	COL(Q = 2)	7.5	GO+FDTD	*Takano and Liou* [1989]	117

[a]Particle shape: CP = hexagonal compacts (Q = 1), COL = hexagonal columns (Q > 1), BR = bullet-rosettes, PL = hexagonal plates (Q < 1), HC = hollow columns, D = dendrites. Computation theory: GO = Geometric Optic, GOM = Geometric Optic Modified, FDTD = Finite Differential Time Domain, MC = Mono-crystals.

integrating the phase function over the collection angles of the CAS. Some of the phase functions are associated with ensembles of mono-crystals (MC) with the same size and shape, but in random orientations, whereas others are associated with ensembles of crystals with differing diameters and shapes, where diameter is defined as that of a sphere with the same volume as the non-spherical crystal. Figure 1 illustrates the relationship between forward and backward scattered light and crystal shape for two common habits, hollow columns and thin plates. For diameters larger than 12.5 μm, the phase function is mainly prescribed by geometrical optics (size parameter = $2\pi r/\lambda > 60$), so that the value of F2BT* is a signature of a crystal shape that is nearly independent of the size. For smaller particles, variations of F2BT* are associated with changes in both size and shape. For diameters <9.5 μm, F2BT* tends to increase rapidly as diffraction significantly increases the energy scattered in the forward direction. Two exceptions, ISCCP and MODIS-rough, have higher values of F2BT* associated with large sizes. In these cases, the crystal surface is considered to be rough and leads computationally to a smoother behavior of the resulting phase function. The 13 phase functions considered in this study do not reproduce all possible sizes and shapes, but they cover a large range of the available state-of-the-art scattering phase functions in the visible domain, leading to values of F2BT* ranging between 5 and 183.

4. Results

[7] The CAS was flown during 12 research flights on the NASA WB-57F aircraft as part of the CRYSTAL/FACE project to study cirrus cloud properties [*Jensen et al.*, 2004] between July 3 and 29, 2002. Cirrus was generally observed between 9 and 15 km, at temperatures between 190° and 230°K and relative humidities with respect to ice (RHI) between 90 and 140%. The first three flights are not included in the current analysis because the CAS was operated at a different size range (0.3 to 20 μm) than in the remainder of the project (0.5 to 45 μm). In order to evaluate changes that are related only to shape, the F2BR is derived from the size distributions integrated from 5 μm to 45 μm.

[8] Figures 2a–2d show combined frequency distributions of the F2BRs from the nine flights. The F2BR is averaged in 10 second intervals during each cloud pass. Each panel in Figure 2 shows the F2BR distributions stratified according to different criterion. In addition, F2BR were computed from the size distributions assuming the particles were ice spheres (shown in blue). Deviation from this distribution implies asphericity. Figure 2a separates the distributions according the surface weighted diameter, D_{SFC}, of the size distributions. When D_{SFC} is smaller than 15 μm, the measured F2BRs are similar to those predicted for ice spheres, i.e., 60–90. When the crystal population has a larger D_{SFC} the average F2BR is larger than would be predicted for ice spheres from the same population and is similar to those predicted for ensembles of bullet rosettes, plates and hollow columns (BR+PL+HC) with rough surfaces, i.e., the MODIS-Rough model (Table 1). About 5% of these larger sizes had F2BR values similar to spherical ice. The F2BRs were further stratified by temperature (Figure 2b), RHI (Figure 2c) and wind direction (Figure 2d) to evaluate the influence of environ-

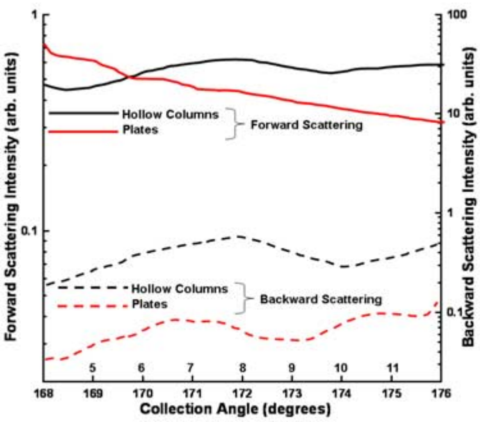

Figure 1. The relative intensities of light scattered in the forward (solid lines) and backward (dashed) directions are compared for two crystal shapes, hollow columns (black) and thin plates with a thickness to diameter ratio of 0.05 (red).

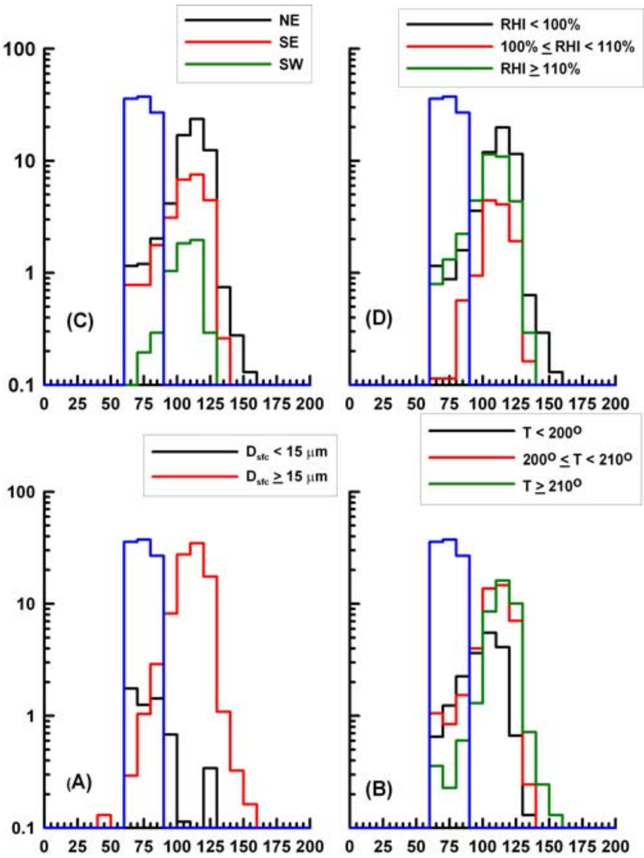

Figure 2. The frequency of finding a particular forward to back ratio was computed from measurements made during nine research flights and is shown in these histograms (a) by average surface diameter, (b) by temperature range, (c) by RHI, and (d) by wind direction. The distribution shown in blue is derived from the size distributions, assuming spherical ice particles.

mental factors. There was no significant differences observed in the F2BR frequency distributions that could be related to changes in any of these three variables.

5. Discussion

[9] Approximately 90% of the observed F2BRs are in agreement with the rough surface model (BR+PL+HC–MODIS-rough) that assumes an average crystal dimension of 30 μm and the remaining 10% are explained by ice spheres. In a previous study of crystal shapes in stratiform clouds [*Korolev and Isaac*, 2003], spherical crystals between 20 and 30 μm were found on average less than 50% of the time. In our current study only 10% of particles less than 45 μm can be considered spherical. The lack of spherical shapes suggests that the majority of ice crystals were either formed by heterogeneous nucleation or, if formed by the freezing of water droplets, they no longer maintained their original shape. This result is reasonable given that laboratory studies [*Gonda and Takahashi*, 1984] have shown that water droplets will change to capped columns or other aspherical crystal habits within 10 to 20 minutes after freezing. The cirrus clouds in the current studies were sampled during different stages of their lifetime but very few were younger than an hour old. The lack of correlations between the crystal shapes and other environmental parameters also suggests that the clouds were sufficiently aged so that little evidence remained of the processes that originally formed the ice crystals.

[10] We emphasize that the agreement between a measured and modeled F2BR does not prove that the cirrus crystals were actually the specific habit matched in the comparison, but only that the scattering patterns matched those particular crystal types. Even so, the results from this study can be used for parameterizations in radiative transfer and climate models, as well as in the testing and development of cloud microphysical retrieval algorithms for remote sensors.

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