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MICROPHYSICAL OBSERVATIONS OF CIRRUS AND WAVE CLOUDS

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1. INTRODUCTION

Previous aircraft investigations of the microphysical properties of cirrus and wave clouds have reported measurements from PMS 2D imaging probes (e.g., Heymsfield and Platt 1984; Dowling and Radke 1990; Gayet et al. 1996a). The (pixel) size resolution of the PMS 2D-C probe is generally 25 to 33 µm. However, recent laboratory investigations reported by Strapp et al. (2001) show that the PMS 2D-C probe actually has a size detection limit of about 75 µm at the speed of jet aircraft, which is typically in excess of 150 m s^{-1} at the altitude of cirrus and the colder regions of wave clouds. Thus, particles smaller than this size may have been missed in previous aircraft investigations and the shapes of larger particles were likely to be distorted.

The research reported here utilizes two relatively new instruments that provide new insights into the microphysical properties of cirrus and wave clouds. The cloud particle imager (CPI) produces high-definition (2.3 µm pixel size) images of cloud particles. The CPI reveals the shapes of smaller ice particles that were previously indistinguishable from 2D-C images. **Figure 1** shows a comparison of CPI and 2D-C images taken from the data set collected for this study. The CPI images show that the ice particles, collected at –46 ° C in a wave generated cirrus cloud, are mostly small, 50 to 100 µm budding bullet rosettes. The 2D-C probe, on the other hand, recorded mostly blank frames with only a few one-pixel (33 µm) particles. We show later in this paper that a large fraction of the particles observed at temperatures between about –28 and –60 ° C in non-convective clouds (i.e., cirrus and orographic clouds) are bullet rosettes. Bullet rosettes have been shown (e.g., Lawson et al. 1998) to have scattering phase functions that are distinctly different from ray-tracing models of columns and plates, which are the phase functions often assumed in models of radiative transfer. Thus, this information could have significant impact on models that describe the earth's radiative energy budget.

In this paper, we show vertical profiles from –26 to –60 ° C of ice particle size distributions, shape and ice water content based on measurements collected by a Learjet research aircraft in an orographically generated cirrus (i.e., wave) cloud. This example is fairly typical of microphysical characteristics of ice particles in a data set consisting of over twenty flights in cirrus and wave clouds.

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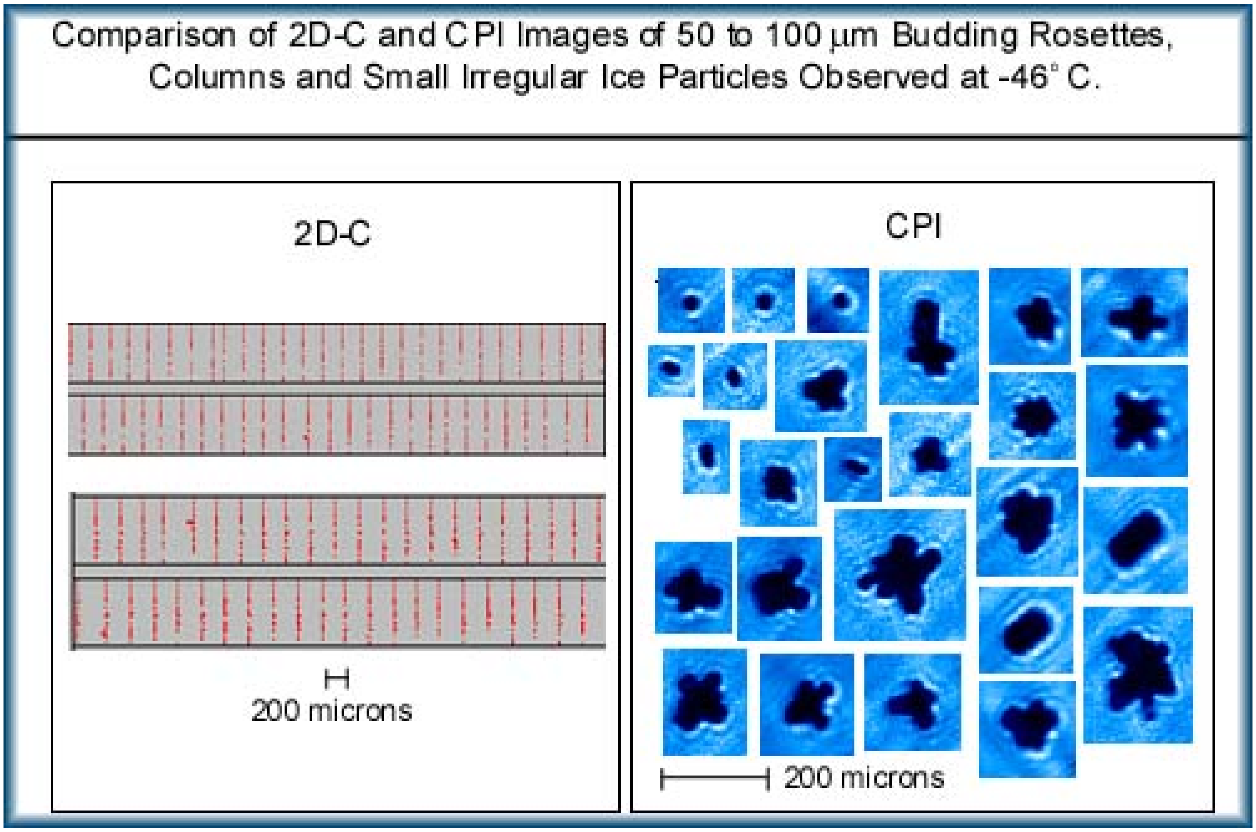

Figure 1. Comparison of PMS 2D-C and CPI particle images Data were collected in the top of a wave-generated cirrus cloud.

2. DATA COLLECTION AND INSTRUMENTATION

Data were collected using the SPEC Learjet research aircraft (**Figure 2**), equipped with microphysical sensors shown in **Table 1**. The CPI and methods for combining particle size distributions from the FSSP, CPI and 2D-C particle probes are described in Lawson et al. (2001). This is the first time an extensive data set of measurements have been collected in cirrus and wave clouds using the Nevzorov liquid and total (condensed) water content device, described by Korolev et al. (1998). The Nevzorov TWC portion of the probe measures ice water content (IWC) in all-ice clouds, and is a more direct estimate of ice mass than obtained by estimating mass from CPI and 2D-C images. Previous measurements in cirrus clouds using the FSSP (Knollenberg 1981) have often been ignored due to suspected errors due to the irregular shape of ice and possible errors attributed to large particles (Gardner and Hallett 1985; McFarquhar and Heymsfield 1996). However, McFarquhar and Heymsfield (1996) note that very high concentrations of small ice particles were observed by an FSSP in tropical cirrus. More recently, investigators (e.g., Poellot et al. 1999; Lawson et al. 2001; Gayet et al. 1996b, 2002) show evidence strongly suggesting that the FSSP reliably counts small ice particles, although there may be errors in sizing. Another sensor that is critical for this study is the Rosemount icing probe (Baumgarder and Rodi 1989; Mazin et al. 2001; Cober et al. 2001), which is a reliable indicator of the presence of supercooled liquid water in excess of about 0.005 g m^{-3}. The measurements presented here were all collected in regions where the Rosemount icing detector suggested that there was no supercooled liquid water, so the FSSP is assumed to be responding only to ice particles.

Figure 2. Photograph of the SPEC Learjet research aircraft used in this cirrus and wave cloud study, shown here exciting a cumulus cloud.

Equipment List	***Sensor Manufacturer & Model***	***Range***	***Accuracy***
Temperature	**Rosemount Model 102 & 510BH Amp**	**-50 to +50 °C**	**0.5 °C**
Supercooled Icing Detector	**Rosemount 851**	**0.005 g m^{-3} (det. lim)**	**N/A**
Cloud Total Water	**Sky Tech Nevzorov TWC Probe**	**0 to 10 g m^{-3}**	**N/A**
Aircraft Position	**Garmen model GPS-92**	**N/A**	**50 m**
Aircraft Heading	**Learjet Sperry Directional Gyro**	**0 to 360°**	**1°**
Horizontal Wind	**GPS plus Heading Information**	**0 to 360° 5 – 100 m s^{-1}**	**5° 5 m s^{-1}**
2-D Optical Array Spectrometer	**PMS Model OAP-2D-C**	**33 to 1056 μm**	**N/A**
Forward Scattering Spectrometer	**PMS Model FSSP-100**	**3 to 45 μm**	**N/A**
Cloud Particle Imager	**SPEC model 230-X**	**10 to 2000 μm**	**N/A**

Table 1. List of Learjet sensors pertinent to this study.

3. DISCUSSION OF THE DATA

The data presented here were collected by the SPEC Learjet on 20 October 2001 in glaciated regions of a wave cloud located over the Front Range of the Rocky Mountains near Boulder, Colorado. The Learjet made horizontal transects of the wave cloud at seven altitudes from cloud base at FL250 (-26 ° C) to cloud top at FL390 (-60 ° C) and a spiral from cloud top down to cloud base. Two of the seven altitudes were repeated. Based on comparable microphysical data when the aircraft sampled the same region of cloud on repeated occasions, it appeared that the cloud was generally in a steady-state condition during the course of the mission.

Figures 3 and **4** show data averaged over glaciated regions of the cloud at seven different levels. The duration of the data collection period ranged from five to fifteen minutes (50 to 150 km). There are several key points that are elucidated by **Figures 3** and **4** that are not found in the published literature.

3.1 *High Concentration of Small Ice Particles*

The particle size distributions (PSDs) and total particle concentration measurements in **Figures 3** and **4** show that there are relatively high (1 to 4 cm^{-3}) average concentrations of small ice particles distributed throughout the cloud. Peak concentration values are even higher and exceed 10 cm^{-3}. These values are comparable to those observed by the Learjet in several other wave and cirrus clouds. Similar concentrations of small particles have been observed in midlatitude cirrus in both the northern and southern hemispheres (Gayet et al. 2002) and in an Arctic cirrus cloud (Lawson et al. 2001). One possible explanation for the existence of the small particles is that they are produced by large ice particles shattering on the inlets of the probes. However, as seen in **Figures 3** and **4**, average concentrations of small particles on the order of 1 to 2 cm^{-3} are observed at cloud top where there are no large particles. However, higher concentrations of small particles are observed lower in the cloud at relatively warmer temperatures where there are large particles present. Since nucleation theory suggests that the particle concentration will increase with decreasing temperature, it is worthwhile investigating the relationship between the relative concentrations of large and small particles.

Figure 5 shows scatterplots of the concentration from the FSSP (i.e., small particles) versus the concentration of 2D-C particles larger than 200 μm (i.e., large particles). These data show that in the region with a moderate concentration of large particles, there is a relatively poor correlation between increasing numbers of small particles and large particles. However, in the region with a high concentration of large particles, there is a good correlation in increasing numbers of small particles with large particles. This suggests that in the region with a high concentration of large particles, there may be a (slight) enhancement in the concentration of small particles. However, there is no evidence to prove that this is due to shattering of crystals on the inlet of the FSSP; it may be due to crystal-crystal shattering. The CPI also observes high concentration of small particles, and these particles do not look like they are shattered pieces of larger particles, but instead, they are almost always small spheroids (but not perfectly spherical). Also, regions with relatively high concentrations of large particles (i.e., > 1 m^{-3} of 1 mm particles) are comparatively rare in cirrus and wave clouds. In wave clouds, these are glaciated regions that are generally observed at temperatures from –25 to –35 ° C and immediately downwind of the leading cloud edge where supercooled liquid water is found.

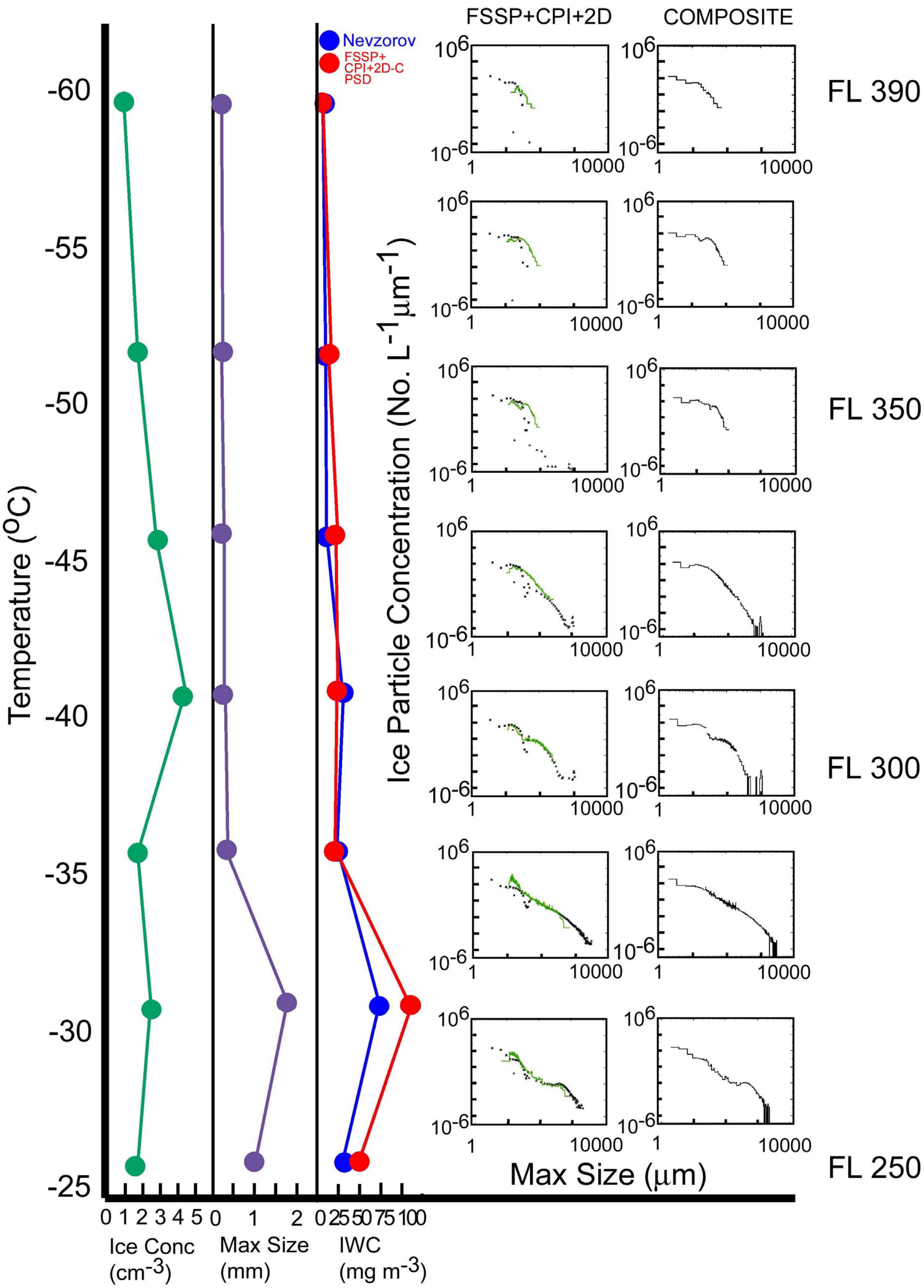

Figure 3. Plots of pass-average values from 20 October 2001 wave-generated cirrus cloud showing ice particle concentration, particle size and IWC with corresponding PSDs from FSSP (∗), CPI (green line) 2D-C (Δ) and composite PSD determined by combining appropriate portions of individual PSDs.

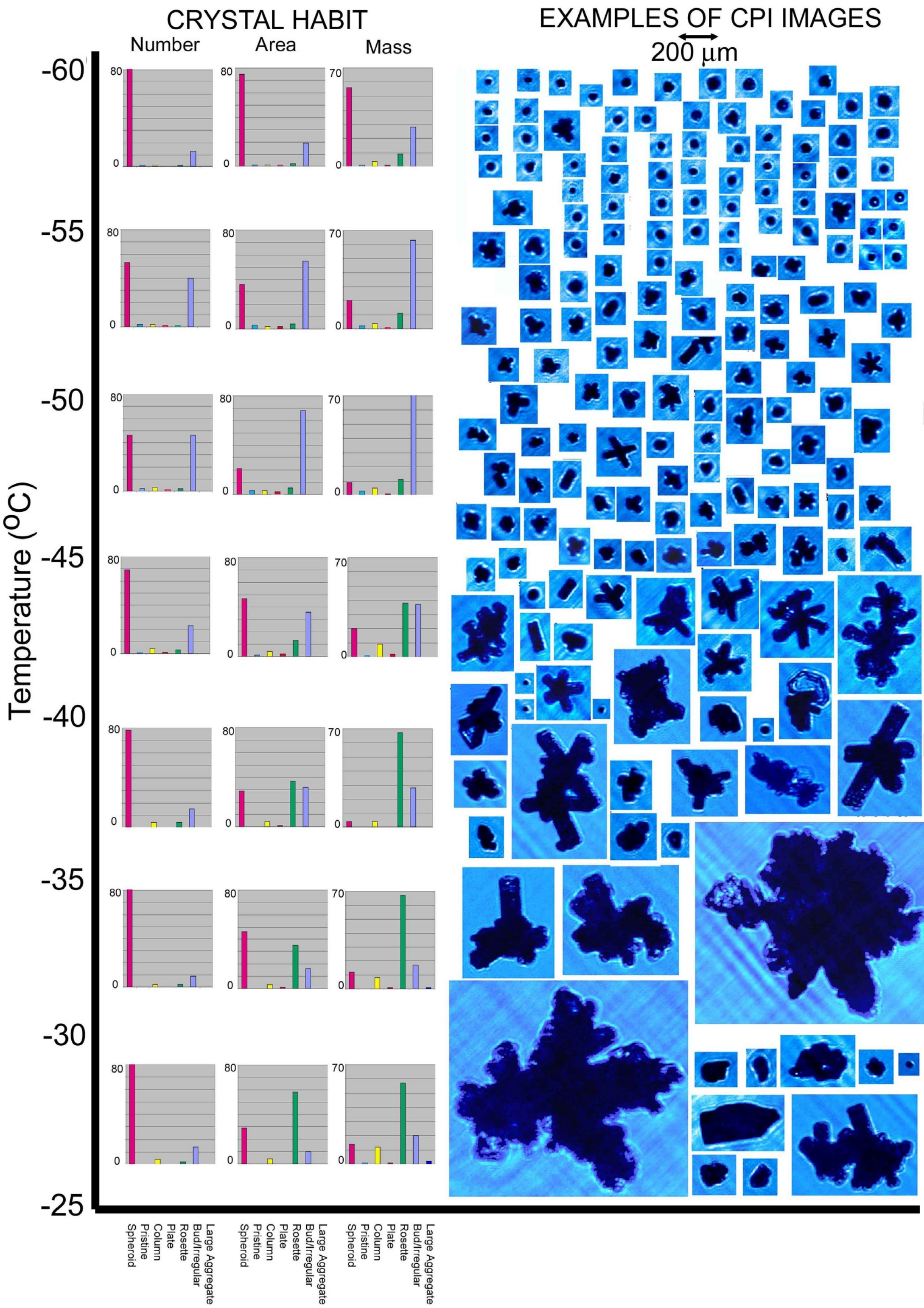

Figure 4. Histograms showing percentage distribution of particles by crystal habit and examples of CPI images collected at the seven different levels by SPEC Learjet in wave-generated cirrus cloud on 20 October 2001.

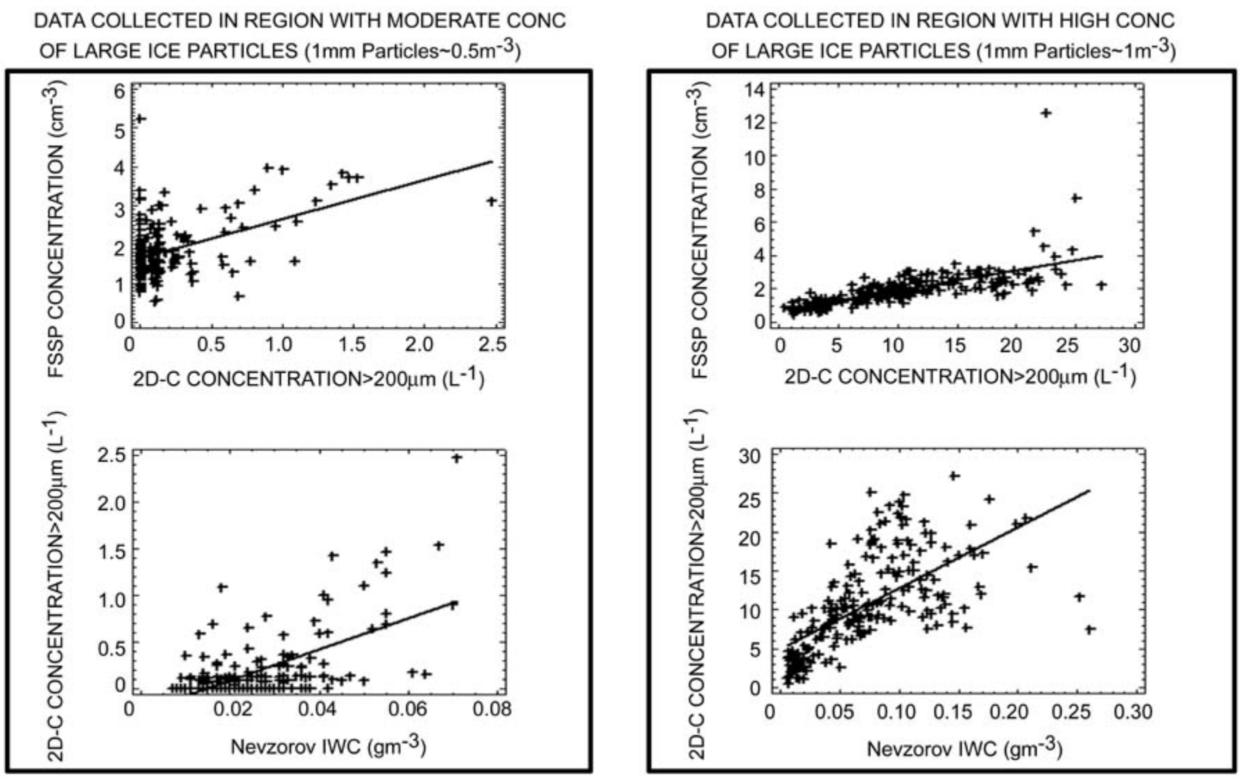

Figure 5. Comparison of data collected in region with moderate and high concentrations of large ice particles used to assess possibility of crystal shattering. See text for explanation.

3.2 *Crystal Habits*

As shown in **Figure 1**, CPI images provide the ability to distinguish the shapes of particles that are larger than about 50 μm, whereas the PMS 2D-C will not even detect a 50 μm particle at the speed of a jet aircraft. This new information (**Figure 4**) shows that, as a function of particle area and particle mass, budding bullet rosettes (and small irregulars), bullet rosettes and aggregates of bullet rosettes are the dominant crystal types between about –30 and –55 ° C. However, as a function of particle number, small (< 50 μm) spheroidal particles are the dominant crystal type throughout the entire depth of cloud. The fact that bullet-like particles dominate the crystal habit regime from about –30 to –55 ° C is new information and has strong implications for models of radiative transfer that assume a particle shape. For example, measurements from Lawson et al. (1998) show that the average scattering phase function of a bullet rosette is much flatter and more featureless than a hexagonal crystal as predicted by ray tracing.

The CPI images in **Figure 4** also show that side plane growth is only evident on particles larger than about 200 μm that are observed at temperatures warmer then –36 ° C. Since 200 μm is the size threshold for riming, and riming is only observed at temperatures warmer than –36 ° C, this is suggestive that side planes may grow from a drop that has frozen to the surface of a crystal. Below –36 ° C, the highest level where supercooled liquid water is observed, the particles are seen to be heavily rimed, aggregated and contain side planes. Although the original habits of these particles are disguised, their shapes are very suggestive of bullet rosettes.

3.3 *Ice Water Content*

Ice water content (IWC) was measured by the Nevzorov probe and computed from the composite PSD using the relationship of length to mass determined from Mitchell et al. (1990). The agreement in trend between the two IWC measurements seen in **Figure 3** is quite good. The agreement in absolute value is fair; except for the very lowest value observed at cloud top (where the instruments are near the noise level and differ by a factor of three) the average agreement between the two measurements is about 25%. Since the two measurement techniques are drastically different, the (limited) data suggest that the IWC measurements are fairly reliable. The data in **Figure 3** shows that IWC remained fairly constant at < 25 mg m^{-3} from cloud top (-60 ° C) down to –36 ° C. However, IWC increased sharpely at and below the level of riming, with pass-average values at –31 and –26 ° C ranging from 35 to 110 mg m^{-3}. Peak values of IWC were on the order of 300 mg m^{-3} in this region.

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REFERENCES

Baumgardner, D., and A. Rodi, 1989: Laboratory and wind tunnel evaluation of the Rosemount Icing Detector. *J. Atmos. Oceanic Technol.,* **6,** 971-979.

Cober, Stewart G., George A. Isaac and Alexei V. Korolev, 2001: Assessing the Rosemount Icing Detector with In Situ Measurements. *J. Atmos. and Oceanic Technol.*, **18**, 515-528.

Dowling, D. R., and Radke, L. F., 1990. A summary of the physical properties of Cirrus clouds. *J. Appl. Meteor.,* **29,** 970-978.

Gardiner, B. A. and J. Hallett, 1985: Degradation of in-cloud forward scattering spectrometer probe measurements in the presence of ice crystals. *J. Atmos. Ocean. Tech.*, 171-180.

Gayet, J-F., G. Febrvre, G. Brogniez, H. Chepfer, W. Renger and P. Wendling, 1996a: Microphysical and Optical Properties of Cirrus and Contrails: Cloud Field Study on 13 October 1989. *J. of Atmos. Sci.* **53**, 126-138.

Gayet, J., G. Febvre and H. Larsen, 1996b: The reliability of the PMS FSSP in the presence of small ice crystals. *J. Atmos. Oceanic Technol.*, **13**, 1300-1310.

Gayet, J.F., F. Auriol, A. Minikin, J. Ström, M. Seifert, R. Krejci, A. Petzold, G. Febvre, and U. Schumann, 2002: Quantitative measurement of the microphysical and optical properties of cirrus clouds with four different in situ probes: Evidence of small ice crystals., Accepted for publication in *Geophys. Res. Lettrs.*

Heymsfield, A. J., and C. M. R. Platt, 1984: A parameterization of the particle size spectrum of ice clouds in terms of the ambient temperature and the ice water content. *J. Atmos. Sci.,* **32,** 799-808.

Knollenberg, R.G., 1981: Techniques for probing cloud microstructure. *Clouds Their Formation, Optical Properties, and Effects,* P.V. Hobbs and A. Deepak, Eds., Academic Press, New York, NY. 15-91.

Korolev, A.V., J.W. Strapp, G.A. Isaac and A.N. Nevzorov, 1998: The Nevzorov Airborne Hot-wire LWC-TWC Probe: Principle of operation and performance characteristics. *J. Atmos. Oceanic Technol.*, **15**, 6,1495-1510.

Lawson, R. P., A.J. Heymsfield, S.M. Aulenbach and T.L. Jensen, 1998: Shapes, sizes and light scattering properties of ice crystals in cirrus and a persistent contrail during SUCCESS. *Geo. Res. Let.*, **25**(9), 1331-1334.

Lawson, R.P., B.A. Baker, C.G. Schmitt and T. L. Jensen, 2001: An overview of microphysical properties of Arctic clouds observed in May and July during FIRE.ACE. *J. Geophys. Res.*, **106,** 14,989-15,014.

Mazin, I. P, A. V. Korolev, A. Heymsfield, G. A. Isaac, and S. G. Cober, 2001: Thermodynamics of icing cylinder for measurements of liquid water content in supercooled clouds. *J. Atmos. Oceanic. Technol*., **18**, 529-542.

McFarquhar, G.M. and A.J. Heymsfield, 1996: Microphysical characteristics of three cirrus anvils sampled during the Central Equatorial Pacific Experiment (CEPEX). *J. Atmos. Sci.*, **53**, 2401-2423.

Mitchell, D.L., R. Zhang and R.L. Pitter, 1990: Mass-Dimensional Relationships for Ice Particles and the Influence of Riming on Snowfall Rates. *J. Applied Meteor.*, **29**, 153-163.

Poellot, M.R., W.P. Arnott and J. Hallett, 1999: In Situ Observations of Contrail Microphysics and Implications for Their Radiative Impact. *J. Geophys. Res.*, **104** (D10), 12,077-12,084.

Strapp, J. Walter, Frank Albers, Andreas Reuter, A. V. Korolev, Uwe Maixner, E. Rashke and Z. Vukovic, 2001: Laboratory Measurements of the Response of a PMS OAP-2DC. *J. Atmos. and Oceanic Technol.*, **18**, 7, 1150-1170.