Reply

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1. Introduction

Gerber (2007, hereafter Ge07) and Garrett (2007, hereafter Ga07) have written comments in reference to Heymsfield et al. (2006, hereafter H06). Dr. Gerber is the developer of the cloud-integrating nelphelometer (CIN) probe that, with assumptions, directly measures the volume extinction coefficient in visible wavelengths and the asymmetry parameter (Gerber et al. 2000). Professor Garrett, using CIN data, wrote a seminal paper on the relationship of ice cloud effective radius to air temperature (Garrett et al. 2003). In their 2006 paper, H06 infer that the ice cloud volume extinction coefficient in visible wavelengths, σ, measured by the CIN probe may be overestimated by a factor of $\sim$2. The measurements supporting this were taken from CIN probes and particle probes on two aircraft in the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE, hereafter C-F) field campaign in Florida during the summer of 2002. Ge07 and Ga07 contend that the CIN measurements of σ are accurate using additional in situ measurements in liquid water regions and direct and remote sensing data from C-F and other field campaigns.

The aim of the research reported in H06 was to determine the relationship between σ and ice water content (IWC) in ice clouds. The authors would have liked nothing better than to have used CIN data in this endeavor. A necessary and time-consuming facet of cloud physics research using in situ measurements is the requirement to evaluate the probes providing the data. Such evaluations are necessary even if the instruments have been extensively calibrated in the laboratory. Airborne cloud physics measurements are prone to errors arising, directly or indirectly, in part from the 100–200 m s^{-1} speeds of research aircraft.

On numerous occasions during the course of preparing H06 the lead author discussed with Gerber and Garrett the evaluation of σ from the CIN and the forward scattering spectrometer probes (FSSPs). Four months before H06 was submitted, the lead author sent them draft copies of the article, inviting each to be a

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coauthor and asking whether they had scientific arguments disagreeing with the interpretations presented. Gerber's response was forwarded within days and is noted in H06's acknowledgments. Garrett also provided comments. The comments in Ge07 are addressed in section 2a and those of Ga07 in section 2b. Conclusions are summarized in section 3.

2. Responses to comments

a. *Gerber (2007)*

We initially address the first three conclusions reached by Ge07:

1) "A different opinion from that in H06 is reached here on the performance of the microphysics probes used on the Citation during the C-F study."
2) "The lack of agreement of LWC measured by the cloud probes in the C-F liquid water clouds, even though the droplet spectra fell within the range of these probes, raises doubt on the accuracy of the cloud-probe measurements described in H06 for C-F ice clouds."
3) "H06 argues that, since the FSSP LWC agrees with the LWC measured by the CVI [counterflow virtual impactor] and King probes on 9 July, the CIN must be the source of the factor of 2.5 difference they found between the extinction coefficients σ measured by the CIN and 2D-C+FSSP."

The primary means used to assess the calibration and performance of the FSSP on the Citation aircraft was from a brief penetration of liquid water regions near $-5°C$ during C-F. The quick-look products were produced using the Baumgardner correction for true airspeed [see Baumgardner and Spowart (1990) and articles referenced therein]. Later processing of a much larger dataset from liquid-only clouds, sampled in subsequent field campaigns, indicated that the FSSP and the King probe liquid water contents agreed well without it and the correction was removed (D. Delene 2006, personal communication). The University of North Dakota Citation group produced size distributions from 4.6 to 55 μm. In C-F on 9 July, data from the 2-DC and the cloud particle imaging probe (CPI) indicated clouds almost entirely composed of cloud droplets in the FSSP size range. The 5-s FSSP average liquid water content (LWC) derived from the FSSP size distributions is given in H06. The authors compared the FSSP-derived LWC with measurements of the total condensed water content (from a CVI) as well as with the LWC from a King hot-wire probe. To account for the offset in the baseline voltage, the King probe was adjusted to zero before and after the cloud penetrations.

In his Figs. 1 and 2 and Table 2, Ge07 presents preliminary CVI data that were submitted by C. Twohy, the principal investigator (PI) and a coauthor on the H06 paper, to the CRYSTAL-FACE archive one or two days after the flight. Preliminary data are submitted as a courtesy to experimenters to provide a quick look at the flight conditions. They are produced rapidly and are understood to not necessarily represent the final calibrated and quality-controlled values. In CRYSTAL-FACE, the preliminary CVI data suffered from a calibration error that was discovered after the experiment and was subsequently corrected in the final dataset. The use of these data in a journal publication sets a disturbing precedent. The publication not only allows erroneous data to be perpetuated, but also puts at risk the whole structure of the field environment, where preliminary data are freely shared with the explicit understanding that they are, in fact, only preliminary. These CVI data were clearly labeled "Quick Look, Preliminary Data" in the header. Anyone who has participated in multiple field experiments knows that the final data often change, sometimes significantly, from those produced in quick-look form in the field. The discrepancies pointed out by Ge07 only highlight the dangers of using preliminary data for substantive quantitative conclusions. Preliminary data should never be used in lieu of the final data, which undergo lengthy quality checks by the principal investigators who are most familiar with the instrument. The preliminary FSSP data for C-F also did not incorporate the final corrections, and so were altered somewhat for the final dataset. Since Ge07's Figs. 1 and 2 and Table 2 utilize preliminary data, they have no real validity for probe intercomparison purposes.

In Fig. 1a, for the case on 9 July, we compare final corrected LWC derived from the FSSP, CVI, and King probes at a frequency of 1 Hz. Because of drift of the baseline voltage, the King probe is less accurate at low LWCs, as was the case here. Nonetheless, there is excellent agreement between the probes. Heymsfield et al. (2007) also discuss this case and the accuracy of the CVI in an appendix. Ge07 reported two additional brief encounters: 40 s in a warm cloud composed almost entirely of cloud droplets that fell in the FSSP size range. Figures 1b,c compare LWC for the three probes on the two additional days. Here again the agreement is good, excepting the CVI on 11 July where the cloud was penetrated after only 4 min of flight when the CVI system was just beginning to stabilize and collect useful data. The King probe measurements for the two latter pen-

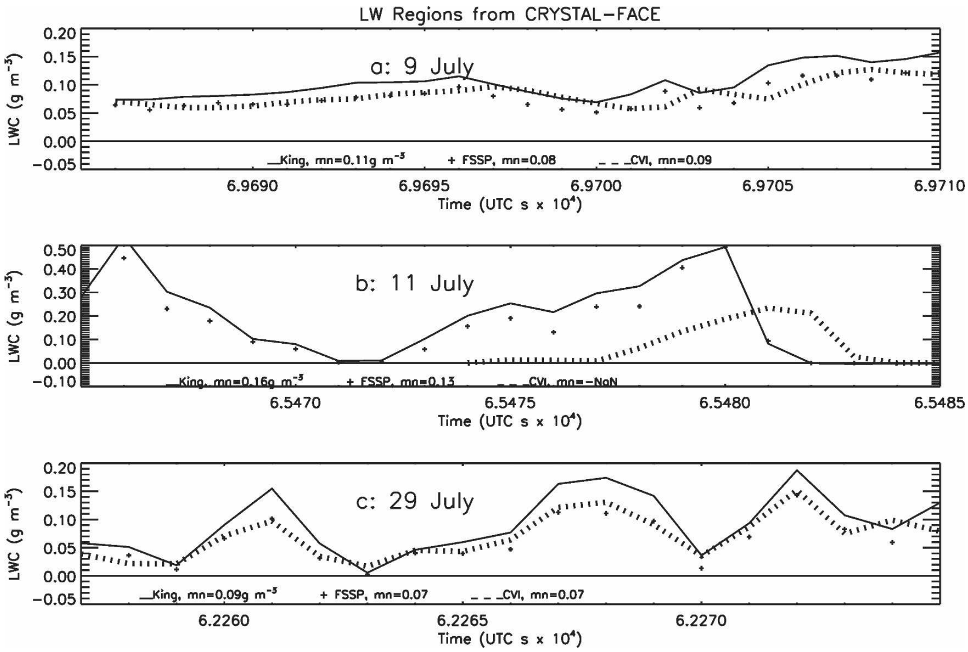

FIG. 1. Comparison of liquid water contents from FSSP, CVI, and King probes on three days during C-F, for the times identified in Ge07. Mean values are shown.

etrations on 29 July may also have been affected to some extent by the Citation's steeper angle of attack. The penetrations on 11 and 29 July had angles of attack of 9° and 10°, while the angle of attack on 9 July was 2.5°.

These results suggest that the CIN and not the CVI is the reason for the poor agreement between the two methods of calculating effective radius shown in Ge07's Fig. 3.

Figures 2a–c are for the same periods as in Fig. 1. They compare the extinction coefficient in visible wavelengths, σ, given by twice the cross-sectional area, derived from the FSSP's size distributions. They assume spherical particles (here, droplets) with those measured by the CIN. For these periods the CIN σ were 2 or more times larger than those from the FSSP for the same periods. These higher-frequency data and additional cases allow us to reject the first three conclusions in Ge07 and related ones in Ga07. For the reasons given earlier, we also reject the idea that quick-look CVI and FSSP data are more accurate than later products.

Conclusion 4 of Ge07 states that

- The CIN used on the Citation was also used previously during other aircraft cloud studies and gave results in agreement with other estimates of σ.

As stated in the beginning of this article, our goal has been to examine the relationship of σ to IWC in ice clouds, primarily from Citation data during C-F and, to a lesser extent, from the WB57 in the same program. We do not comment on the CIN's performance in other field campaigns nor on retrievals of effective radii from cloud optical thicknesses from the Moderate Resolution Imaging Spectroradiometer (MODIS) airborne simulator instrument on the National Aeronautics and Space Administration (NASA) ER-2 during the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment-Arctic Cloud Experiment (FIRE-ACE).

b. *Garrett (2007)*

The responses to Ga07 are in the order given in his conclusions.

- The CIN is appropriately calibrated.

The Ga07 conclusion that the CIN is appropriately calibrated rests upon comparing extinction from a laser transmissometer and the CIN. The comparison is from instruments on the Meteorological Service of Canada (MSC) Convair during 540 s of level transects through warm (above freezing) cumulus clouds on 9 days of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) experiment. It is further stated that the aircraft had a full complement of microphysical probes, including two FSSPs, although their output was not used in the evalu-

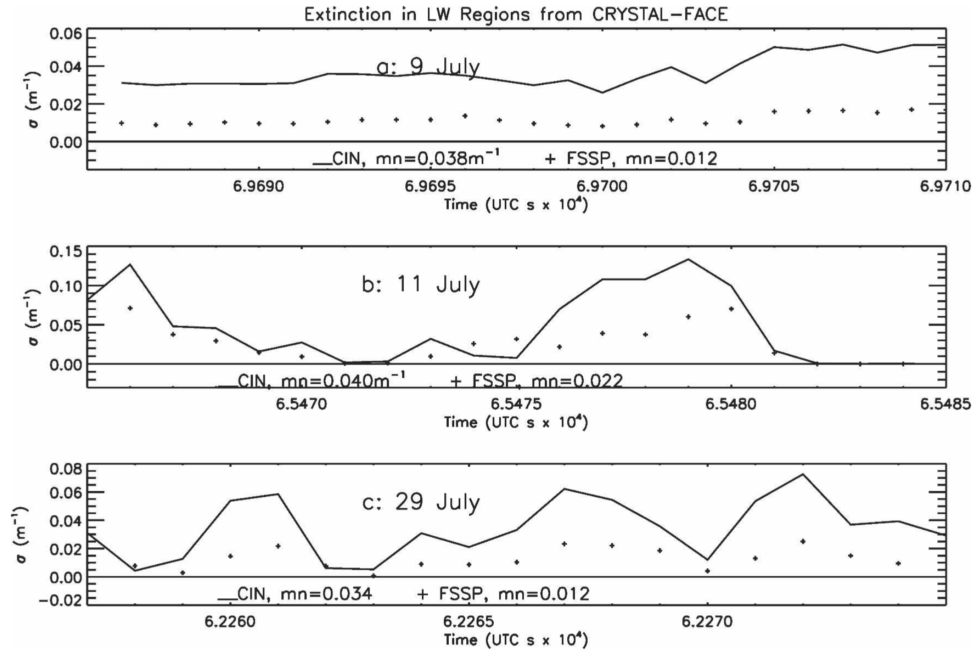

FIG. 2. For the same times as in Fig. 1, extinction coefficients estimates from the FSSP data and measured by the CIN.

ation. In the Surface Ocean–Lower Atmosphere Study (SOLAS) project, also involving the Canadian Convair, there was reasonable agreement between the CIN and the FSSPs in flights through (liquid) maritime stratus (W. Strapp 2006, personal communication).

Ga07 also reports that the level of agreement between the transmissometer and the CIN in the ICARTT project showed no sensitivity to possible precipitation-sized particles breaking up on the CIN inlet, concluding, "it implies that to the extent that particles did shatter on the CIN, they contributed only a negligible amount to the CIN measurements. Thus, it appears that the CIN is appropriately calibrated for in-cloud measurements of σ, and is insensitive to shattering of precipitation-sized particles on its aperture." Whether this conclusion actually applies to ice crystals is unclear. Many studies have shown that liquid water sheds from imaging probes, producing "streakers" (e.g., Cober et al. 2001), which are long, thin images caused by splash or shatter products traveling slower than the true airspeed through the sample volume. The same process could occur for the CIN but be stripped away from the probe housing, out of the depth of field. This deformation process is not feasible for ice.

- Similarly, the discrepancy between CIN and particle-probe measurements of σ seen during CRYSTAL-FACE was independent of whether measurements were in ice or nonprecipitating water clouds, which also suggests that shattering could not have been a component of the observed discrepancy.

Because it is unlikely that the FSSP produces shattered droplets in nonprecipitating water clouds but does shatter particles in ice clouds (i.e., Field et al. 2003), we suggest that the same may be true of the CIN. These findings support our view that measurements from both instruments may be similarly contaminated by ice particle shattering.

- Measurements of cirrus r_e and σ derived using a CIN probe are in agreement with those derived from a variety of passive remote sensors employing different retrieval algorithms. The comparison with lidar data in H06 was not appropriate.

Ga07 reports a comparison of cloud optical depth, τ, retrieved from *Geostationary Operational Environmental Sounder-8* (*GOES-8*) imagery, derived during a spiral climb by the Citation on 21 July during C-F. The conclusion drawn by Ga07 from this comparison is suspect because

1) The Minnis et al. (1998) retrieval method is based on randomly oriented hexagonal ice crystals and particle size distributions derived from midlatitude, synoptically generated ice clouds reported on by Heymsfield (1975) and Heymsfield and Platt (1984).

However, in the C-F case, the particle habits derived from the CPI imagery were complex, partially rimed aggregates and the size distributions broad, because of particle origin in deep convection. This could account for the uncertainty of about ±25% in the estimate of τ from the GOES retrieval (P. Minnis 2006, personal communication).

2) The Citation spiral ascent required 18 min. The loops of the spirals were 10–16 km in diameter. During the ascent, the standard deviation of the CIN (and particle probe) extinction varied by ±50% about the mean. The variation of σ during each loop of the spiral varied by about the same amount. We conclude that, because of the mismatches in spatial extent and variability, and the mismatch in time between the spiral and an instantaneous GOES image, differences in τ could amount to ±50% added to the uncertainty in the microphysical retrieval. It is therefore inconclusive whether the CIN or the particle-probe extinctions are correct.

On 26 July in C-F, the WB57 made a 200-s descent through a cold cloud layer as the ER-2 passed overhead (Roskovensky et al. 2004). Ga07 has suggested a consistency between τ as derived from the ER-2 MODIS airborne simulator products on this occasion. Although unmentioned in Ga07, for almost half of the descent through cloud the CIN extinction was below the stated detection threshold of 0.0004 m^{-1}. Not only was it below its detection level for some time, but, from the particle probe and the National Center for Atmospheric Research (NCAR) video ice particle sampler (VIPS) measurements from the WB57, it fell below the detection threshold as soon as the cloud was optically thick. Interestingly, at the bottom of the descent, the extinction as determined independently by the VIPS, and cloud, aerosol, precipitation spectrometer (CAPS) probes shows a significant increase that coincided with a marked decrease in the CIN extinction. Furthermore, during its descent the WB57 covered 0.3° of latitude, or about 30 km. Cloud radar from the ER-2 showed an inhomogeneous cloud layer. The bottom of the layer sampled from the WB57 would have differed from the top layer of the penetration. We therefore conclude that there is no way to reliably confirm a consistency between ER-2 and CIN optical depth estimates.

- The comparison with lidar data in H06 was not appropriate.

For the sake of brevity, not all the details of the lidar–CIN–particle probe intercomparisons were given in H06. For 23 July H06 did not use CIN in 219 lidar–particle probe intercomparisons because the data were bad. Based upon discussions with the author of Ga07, H06 reports using a lower detection threshold of 0.0004 m^{-1} in the CINs on the WB57 and the Citation. This is clearly illustrated by Fig. 5 in H06, in which all of the open circles representing CIN are above that threshold. The use of a threshold of 0.001 m^{-1}, suggested by Ga07 for the Citation, would have had almost no effect (see H06, their Fig. 3).

The conclusion reached by Ga07 that the extinction estimates from the cloud physics lidar (CPL) on the ER-2 aircraft used in the H06 evaluation were inappropriate is incorrect and invalid. Most of the periods used in the lidar–particle probe–CIN extinction were for transmissive cirrus, especially for the WB57. For example, for the 26 July WB57F case, only 3.5% of the lidar images were fully attenuated (McGill et al. 2004, their Table 2). This is why σ values for the intercomparison, especially for the WB57, fell on the lower end of the range of σ (see H06, their Fig. 3a). The readers are referred to the article by Chepfer et al. (2005) for lidar imagery from the WB57 cases. For the Citation, approximately 1/2 of the points were from transmissive cirrus. For transmissive cirrus, there is no assumption involved in the lidar extinction-to-backscatter estimate. As noted in McGill et al. (2003), for transmissive cloud the CPL is able to provide a definitive estimate of the extinction-to-backscatter (S ratios) (and, hence, extinction) by examining the Rayleigh signal above and below the cloud. Our accuracy of such a derivation is limited only by the ability to calibrate the lidar, which is done using Rayleigh signal and not by any a priori assumption about the S ratio. This is an accepted method for backscatter lidar and has been verified many times over. Moreover, it is repeatedly found from the observations with the CPL that cirrus have S ratios of 21 ± 2 sr, and this value agrees well with measurements from other researchers.

- Measurements from different FSSP-type probes, even though they operate on the same basic principle, can differ greatly in their estimation of WC and σ. This is true both between and within aircraft. This absence of consistency in particle probe measurements implies that our understanding of their measurements is incomplete. For example, it is shown here that employing the common assumption that particles in ice clouds are spheres can lead to an underestimate of σ by as much as a factor of 6.

Even in liquid water regions there is a history of inconsistency in particle probe measurements from the same aircraft (Gayet et al. 1996). Recently, however, more standard methods of calibrating 2D and FSSP

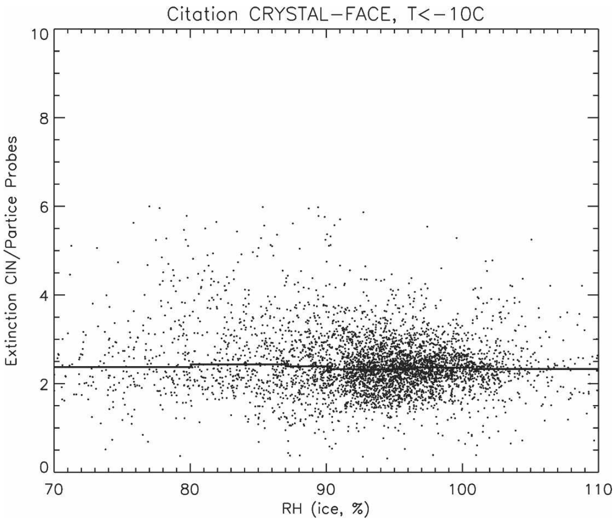

FIG. 3. Ratio of CIN to particle-probe extinction as a function of relative humidity with respect to ice as derived from a tunable diode laser hygrometer on the Citation aircraft during C-F. The nearly horizontal line shows the median values of the ratio in intervals of equal numbers of particles.

probes have been developed by Droplet Measurement Technologies and others.

In Ga07 the point is made that the assumption of particle sphericity in ice regions can lead to serious underestimation of their size. During the analysis of the results reported in H06, the lead author suggested to Gerber and Garrett that it might be possible to test whether assumed particle sphericity for the ice sampled by the FSSP could lead to the factor-of-2 difference noted between σ from the CIN and the particle probes using the following argument: Images from the cloud particle imager and the NCAR balloonborne ice crystal replicator indicate that crystals lose their faceted structure and become rounded in conditions of subsaturation with respect to ice. With this observation as a guide, more than five thousand 5-s data points from the Citation for C-F were plotted as a function of the relative humidity as measured by a tunable, diode laser hygrometer. This figure was presented to them (Fig. 3). Mean values for the ratio of CIN to particle-probe extinction, as derived in RH increments of about 5 s, show no dependence of this ratio on RH, suggesting that it is unlikely that asphericity could explain the difference.

As reported in H06, the wave cloud transects by the WB57 during the Middle Latitude Cirrus Experiment (MiDCiX) provide additional insight into the CIN/FSSP because they were designed to provide information in situations where large ice particles and their shattering would be virtually nonexistent. A numerical model was used that considers the growth of cloud condensation nuclei from initialization at a relative humidity of 60% with respect to water to the formation of haze particles and activation of cloud droplets, followed by homogeneous nucleation and subsequent growth with vertical velocities comparable to those measured by the WB57. The model input parameters were selected to yield ice concentrations and temperatures about the same as those measured by the FSSP-type probes and our VIPS probe. As reported in H06 and elsewhere, the model has been evaluated in wave cloud flights from earlier studies. The model IWC is not sensitive to the number of particles nucleated but given by the thermodynamics of vapor-to-ice condensation at the temperatures involved. To some extent, errors in measured ice concentrations would affect extinction. Within the cloud there is excellent agreement between the CVI, FSSP, and the model IWC although data from the cloud and aerosol spectrometer probe (CAS, an FSSP-like device) are below the measured values.

In Ga07 it is suggested that the nonsphericity of the ice particles may result in underestimates of their measured sizes and of σ, of up to a factor of 6. Most likely owing to their origin as frozen droplets, small ice particle shapes are typically imaged as quasi-spherical or droxtal. The particles in the MidCiX wave clouds almost certainly originated as frozen droplets, as suggested by our VIPS imagery. Figure 4 shows images of 20–30-μm ice particles sampled in a wave cloud by our balloonborne replicator (see also Zhang et al. 2004), indicating the quasi-spherical or droxtal shapes of wave-cloud particles. Because of the air temperature, we also infer their origin to be via homogeneous ice nucleation. Had there been significant sizing errors in the FSSP in this situation, we would not have had the near agreement between the measured, modeled, and FSSP-derived and, more than likely, not in most ice cloud particle situations. Because the IWC is a higher moment than σ (third versus second), we reject the suggestion by Ga07 that significant FSSP sizing errors could lead to the mismatch between FSSP- and CIN-derived σ.

3. Conclusions

Ge07 and Ga07 offer no compelling reasons to contradict the following two conclusions of Heymsfield et al. (2006):

1) "Because of the discrepancy in σ estimates between the direct (CIN) and indirect (from particle probe) approaches, there is a factor of 2 to 3 difference in [IWC/σ] between them."
2) "Although there are significant uncertainties in-

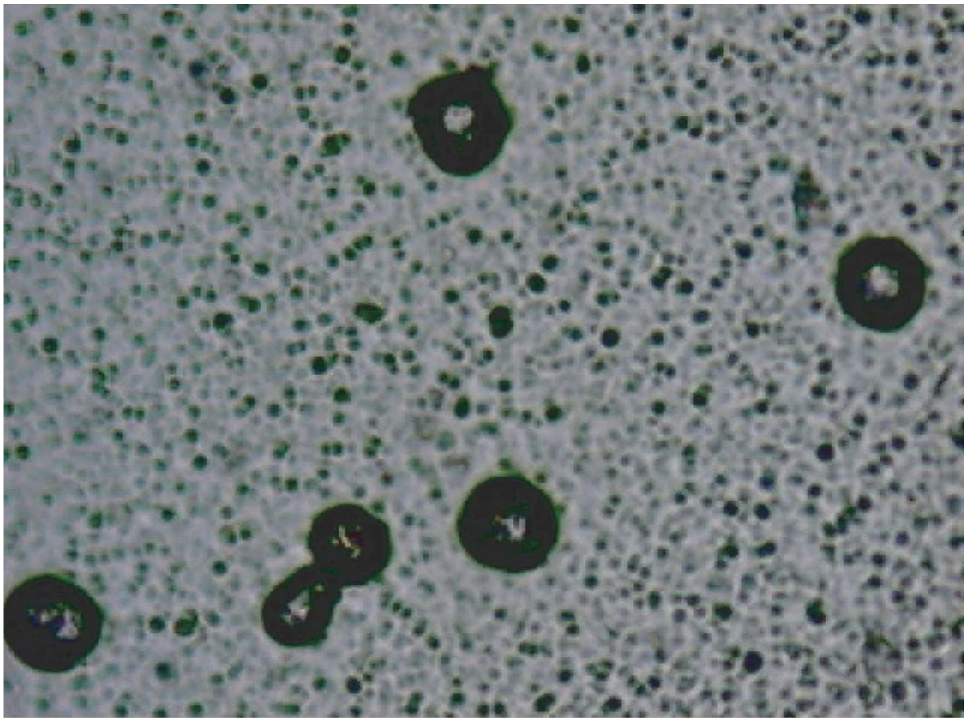

FIG. 4. Examples of balloonborne ice crystal replicator data collected in an orographic wave cloud on 13 Nov 1996 over Boulder, CO. Particle sizes are 20–30 μm in diameter; temperature is about $-40°$C.

volved in its use, comparisons with several independent data sources suggest that the indirect method is the more accurate of the two approaches."

In addition, Ge07 and Ga07 minimize the possible reason for much of the discrepancy—the shattering of ice particles on the inlets or leading edges of microphysical probes and possibly the CIN. A recent study by Field et al. (2006) highlights this point for the 2D imaging probes. Ice particles can shatter on the probe tips, producing small ice particles that can transit through the 2D probe sampling volume. They can be removed through statistical analysis, as outlined in Field et al. (2006). Using this approach, we assessed how much our 2D probe extinction results from the C-F dataset may have been overestimated because of breakup. The ratio of 2-DC σ with shattering removed to the original values was 0.95 ± 0.05, further increasing the discrepancy between CIN and particle probe σ by about 2.5%.

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