Comments on "Effective Radius of Ice Cloud Particle Populations Derived from Aircraft Probes"

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1. Introduction

The recent paper by Heymsfield et al. (2006, hereafter H06) comments on the accuracy of various in situ measurements of the extinction coefficient σ by in situ cloud probes. The measurements have particular relevance for their contribution to understanding cloud-radiative properties. Climate models are largely concerned with predicting fields of electromagnetic radiation. However, they instead track constituent phase and mass. To relate phase and mass to the shortwave and longwave radiative flux divergences, values of σ are obtained using the parameterized radiative length scale known as the effective radius r_e. From the cloud condensed-phase mass density, or water content (WC),

$$\sigma = \frac{3\mathrm{WC}}{2\rho r_e}, \tag{1}$$

where ρ is the bulk density of the condensed phase (Foot 1988).

H06 described how, historically, the integral properties WC and σ have been inferred from in situ measurements of the integrand, that is, the component concentration size distributions $n(r)$ of the cloud particulate population, where r is some representative spherical particle radius. In principle, calculating r_e for water clouds is straightforward. This is because cloud droplets are spheres, in which case

$$r_e = \frac{\int_0^\infty n(r)r^3\,dr}{\int_0^\infty n(r)r^2\,dr}.$$

For ice clouds, the varied morphology of ice crystals considerably complicates the problem. The relation of crystal geometry to ice water content (IWC), σ, and r_e means employing considerable assumptions, especially when in situ aircraft data have traditionally deployed particle probes that measure only crystal dimension or cross-sectional area. Accordingly, determination of r_e from these data has been called the "indirect approach."

More recently, a new suite of aircraft probes has enabled more direct measurements of integral WC and σ (Garrett et al. 2003, hereafter G03). This "direct approach" shows values of IWC/σ (and hence r_e) in low-latitude cirrus that tend to be significantly lower than those obtained previously with the "indirect approach." The significance of this finding is that these lower values for r_e point to considerably greater radiative cross sections per unit mass in cirrus than are currently being considered in GCMs (cf. McFarquhar et al. 2003). The modeled sign of the cirrus cloud–climate feedback might switch if these newer values are considered more accurate (Stephens et al. 1990).

H06 compared the in situ direct and indirect measures of σ, as well as remotely sensed values from lidar. They argued that there is a factor-of-2 to -2.5 overestimate of σ from the direct-extinction measurement probe used in G03: the cloud integrating nephelometer (CIN; Gerber et al. 2000). The source of the error was not identified, but it was speculated that large ice crystals shatter on the housing of the instrument aperture, subsequently intersecting the CIN sample volume.

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Shattering does not affect mass density because it merely divides mass rather than changes it. However, it does increase total surface area, and hence, plausibly, measured values of σ. H06 concluded that indirect measurements of r_e remain most suitable for employment in GCMs.

In this comment, we reassess the H06's analysis and conclusions and provide an alternate perspective on discrepancies observed between measurements of IWC and σ derived from aircraft probes.

2. Measurements in water cloud

a. Citation observations during CRYSTAL-FACE

First, we reanalyze the discussion of H06 in their examination of supercooled water clouds was observed within a broad time range between 64 820 and 69 350 s UTC on 9 July from aboard the University of North Dakota (UND) Citation during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE). Cloud droplet size distribution measurements were obtained with a forward scattering spectrometer probe (FSSP)-100 (3–57-μm diameter) and precipitation drops with an optical array probe (OAP)-2D-C and high-volume precipitation spectrometer (HVPS) probe (0.06–25 mm). Direct measurements of LWC were obtained with a cloud virtual impactor (CVI) and a King hot-wire probe. The CVI had a small time offset, and the King probe had a floating baseline offset and periodic voltage spikes, both of which are removed from the analysis described here. Measurements of σ were obtained with a CIN.

Here, and in G03, we use data from the CRYSTAL-FACE archive for all instruments but the CIN. The principal investigator (PI) for the CIN on the Citation (H. Gerber) provided to this author raw instrument voltages and calibration coefficients, from which values of σ and the asymmetry parameter g were independently calculated. These values of σ and g were essentially the same as those archived by H. Gerber, except for some minor differences associated with the treatment of instrument drift and noise. In approximate agreement with the analysis described by Gerber (2007), we find that icing was limited to the later parts of the flight, after 69 400 s UTC based on the physically implausible values of g and the ratio of forward to back-scattering that were measured. To be conservative, however, no Citation data from 9 July were included in the analysis described in G03.

On the request of H06, this author provided a list of time intervals when it seemed that the CIN was in a water cloud but probably not affected by icing

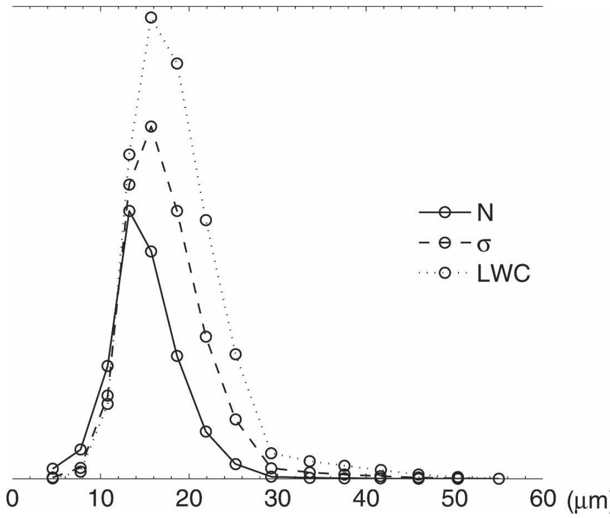

FIG. 1. Concentration distributions of droplet number N, extinction σ, and liquid water mass LWC as a function of droplet diameter, based on measurements in liquid water cloud obtained on 9 Jul.

[(67 170–67 210), (68 060–68 300), (69 290–69 350)]s UTC. A smaller subset of data was obtained by restricting measurements to time periods when the King LWC was >0.05 g m^{-3}, temperatures about $-6°$C, and precipitation water content was negligible ($<2 \times 10^{-4}$ g m^{-3} in the reanalysis here).

The number, extinction, and mass size distributions for this cloudy subset chosen by H06 are shown in Fig. 1. The data show a narrow monomodal size distribution. Provided there was no icing, this would appear to be a good case for intercomparison of cloud probes. Although numbers were not provided, H06 argued that the FSSP-100 measured almost the same LWCs as the CVI. H06 further implied that in nondrizzling regions the same was true for FSSP-100 comparisons with the King probe. H06 noted that CIN measurements of σ were 2.5 times higher than values of σ derived from the FSSP-100. H06 argued that this discrepancy indicated overestimation by the CIN because the FSSP-100 LWCs agreed with the CVI and King LWC data, and were therefore "correct."

In our reanalysis of the case, we include estimates of instrumental error based on the relevant literature for the FSSP-100 (Baumgardner et al. 1990, 1992), the CVI and King probe (Twohy et al. 1997; C. H. Twohy 2005, personal communication), and the CIN (Gerber et al. 2000; Garrett et al. 2003). The uncertainties are reflected in Table 1, which shows that, as described by H06, there is indeed a factor-of-2.5 difference in estimates of extinction from the CIN and the FSSP-100, and that the CVI and FSSP-100 give similar values of

TABLE 1. Mean values for supercooled liquid cloud sampled on 9 Jul 2002. Values of r_e from the CVI and King probes are calculated with reference to the CIN [Eq. (1)]. Estimated uncertainty in the measurements is given in parentheses.

	FSSP-100	CVI	King	CIN
LWC (g m^{-3})	0.043 (0.024)	0.053 (0.007)	0.071 (0.01)	
σ (m^{-1})	7.4 (3.7)			19 (3)
r_e (μm)	8.4 (1.3)	4.1 (1.2)	5.7 (1.7)	

LWC, to within 25%. However, we find in opposition to H06 that the King LWC is substantially higher than the FSSP-100 LWC, by a factor of 1.6.

Even with predicted measurement uncertainties accounted for, there is an absence of overlap in the King and FSSP-100 estimates of LWC. Therefore, it is unreasonable for H06 to argue that instrument errors were peculiar to CIN measurements of σ alone. Moreover, because the measured clouds lacked precipitation, it is inconsistent for H06 to argue that hydrometeor shattering on instrument inlets could account for the higher values of σ seen by the CIN.

b. WB-57F observations during CRYSTAL-FACE

A similar instrument package as that flown on the Citation was flown aboard the WB-57F, which focused on higher, colder clouds. The FSSP-type probes used here were a regular FSSP-100 updated with the Droplet Measurement Technologies Signal Processing Package (SPP-100), which has faster electronics that eliminate dead-time errors, and a cloud and aerosol spectrometer (CAS), which also has faster electronics than the FSSP-100, but is modified to measure backscattering as well. The CAS was part of a larger probe system—the cloud, aerosol, precipitation spectrometer (CAPS)—which included a cloud imaging probe (CIP) for the measurement of large ice crystals (>50-μm diameter).

H06 argued that in ice clouds, CIN measurements of σ were typically a factor of 2 higher than CAPS measurements of σ. This is not disputed here. What is disputed is that this implies the CIN was in error.

A useful analysis is intercomparison of FSSP-type probes and the CIN in water clouds from CRYSTAL-FACE. The WB-57F aircraft flew through nonprecipitating trade wind cumulus sampled on 28 July at 1-km altitude near Key West, Florida (Fig. 2). As was the case in ice clouds (H06), the results in liquid cloud also show a factor of at least 2 discrepancy between CIN and CAS measurements of σ. It is also important to note that there were also similar degrees of discrepancy between the two FSSP-type probes. The CAS and SPP-100 σ were 1.9 and 5 times lower than the CIN σ, respectively. In this regard, the differences in the FSSP measurements were primarily due to differences in droplet number concentration, which were, on average, 115 ± 50 cm^{-3} for the CAS, and 30 ± 17 cm^{-3} for the SPP-100; both probes indicated a value for r_e of about 8.5 μm. It is unclear why measured values of σ were so different between probes, especially when the FSSP-type probes operate on essentially the same principles.

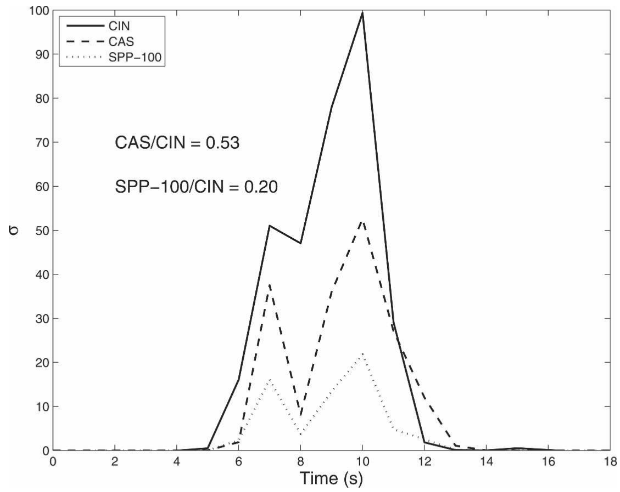

FIG. 2. Measured values of the extinction coefficient σ taken with CAS, SPP-100, and CIN probes flown by the WB-57F aircraft in trade wind cumulus near Key West between 85 581 and 85 524 s UTC on 28 Jul.

Unfortunately, there were no direct measurements of LWC available at the time of the cumulus transect. However, maximum values of CAS and SPP-100 LWC measured in the middle of the cumulus cloud were 0.28 and 0.13 g m^{-3}, respectively. These values seem unusually low for nonprecipitating trade wind cumuli. Regardless, it is interesting that the relationship between CIN and FSSP-type probes is similar within both nonprecipitating liquid cloud and ice cloud.

3. Measurement in ice cloud

a. Theoretical considerations

In ice, comparing direct and indirect measures of σ is more complicated than in water clouds. The CIN does not strictly measure σ directly. Rather, it measures only 635-nm light scattered between 10° and 175°, and calculates extinction assuming some value for the fraction of scattering it misses (absorption of visible light by ice and water is negligible). This measurement principle works well because the fraction of light f scattered in the forward 10° missed by the CIN is narrowly constrained: Babinet's principle requires that diffraction is

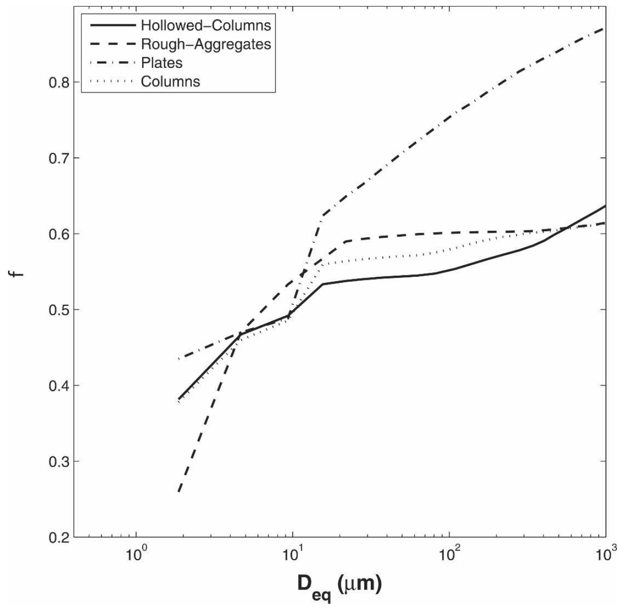

FIG. 3. Theoretical calculations of the fraction of scattering f not detected by the CIN, for various ice crystal shapes, as a function of area-equivalent spherical diameter. Here f is the integrated forward 10° of scattering by randomly oriented particles, according to phase-function data described by Yang and Liou (1998).

one-half of scattered energy in the geometric optics limit. In other words, f must be at least 0.5. Of course, a small fraction of energy is also refracted into the forward 10°, but this added energy is a second-order correction that can be estimated theoretically based on assumptions of particle shape (Gerber et al. 2000).

In cirrus, CIN calculations of σ are made assuming that ice crystal shapes are nonspherical. For a typical range of particle shapes and sizes, Fig. 3 shows that the value of f is about 0.57 (0.5 from diffraction plus 0.07 from refraction). The approximate uncertainty is ± 0.02, which translates to an uncertainty in calculation of σ of $\pm 5\%$. This was the value for f that was used in G03. We note that much larger values of f are seen associated with idealized plates. However, we suspect that this is because direct transmission through the basal surfaces of plates is associated with relatively high probabilities of forward scattering (P. Yang 2006, personal communication). In nature, it is probably unlikely that crystal facets are perfectly parallel. This is because ice crystals grow preferentially along their edges, where surface area density is highest, leading to hollowing of crystal facets (Pruppacher and Klett 1997). Even if plates with parallel facets did indeed predominate in CRYSTAL-FACE cirrus, the hypothetically erroneous assumption of $f = 0.57 \pm 0.02$ would correspond to an *underestimate* of σ by the CIN, not the overestimate described by H06 (Gerber et al. 2000).

For extinction calculations from the FSSP-type probes, H06 assumed that small ice crystals were spheres. It is important to note here that FSSP-type probes do not measure size explicitly, but rather they infer it from the amount of 635-nm laser light scattered between 4° and 12° away from the direct beam, based on an *assumption* that particles are spheres. H06's justification for this assumption is that ice crystals, particularly small ones, may be quasi-spherical or at least isometric (i.e., the basal and prism face of a hexagonal prism have equivalent dimensions).

However, the assumption of crystal shape made by H06 may be a poor one. While it may be almost reasonable to approximate the *geometric* properties of the crystal as spherical, the same does not hold for their *electromagnetic* properties. For example, G03 showed that the asymmetry parameter g, which is a measure of the degree a particle scatters light in the forward direction, was about 0.75 in CRYSTAL-FACE cirrus anvils. Similar values of g have been observed in cirrus elsewhere (Gerber et al. 2000; Garrett et al. 2001) using independent instrumentation (Auriol et al. 2001). These values are considerably different than characteristic values for g of 0.86 that are expected theoretically for spheres, and are observed by the CIN in water clouds. Such low values of g are more typical of aspherical shapes with either roughened surfaces (Yang and Liou 1998) or internal bubbles (Mischchenko and Macke 1997).

The difference in shape model is important for FSSP-100-type probe measurements of particle size, as these have substantial sensitivity to assumed shape. Figure 4 shows the relationship between integrated intensity in the 4° and 12° as a function of size. We note that we have used an area-equivalent effective diameter as the most appropriate measure of the equivalent size seen by the instrument (D. Baumgardner 2006, personal communication). If, as in H06, particles are assumed to be spheres in cirrus, particle size is underestimated by as much as a factor of 2.5. Such mis-sizing would plausibly translate to underestimates of σ by FSSP-type probes by as much as a factor of 6. Therefore, using an incorrect shape assumption could easily account for the observed discrepancy between CAPS and CIN measurements of σ in cirrus.

While shape considerations are obviously an important factor not included in the extinction calculations described by H06, the omission might not be quite as grave as it initially appears. Fortuitously, a "rough aggregates" ice crystal shape model in Fig. 4 has a similar scattering profile to a spherical model. Also, a rough-aggregates model may be most suitable. CIN measurements of g during CRYSTAL-FACE (G03) and for-

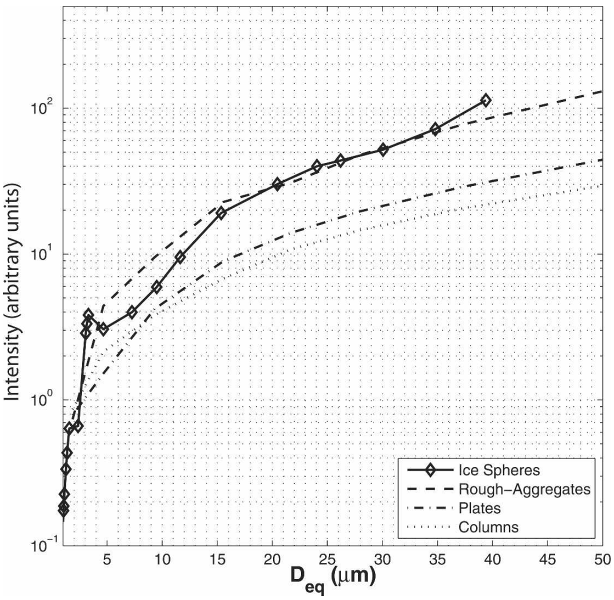

FIG. 4. Relationship between scattered intensity and area-equivalent spherical diameter in an FSSP-type probe for different idealized ice crystal particle shapes.

ward to backscattering ratios obtained with the CAS probe (Baumgardner et al. 2005) are most consistent with a phase function represented by a rough-aggregates model.

The implication is that a spherical shape assumption may in some circumstances work well for FSSP-type probes. This might explain why the factor of ~2 difference between the CIN and CAPS probe measures of σ was consistent for warm cumulus and cold cirrus. H06 argued that ice crystals selectively shatter on the CIN aperture, artificially enhancing σ. Because the water clouds that exhibited the factor of ~2 difference contained no large precipitation-sized particles, shattering does not seem a plausible explanation for the discrepancy. Shattering could not have occurred only in ice clouds, affected only the CIN, yet still produced the same disagreement between probes as was seen in non-precipitating water clouds.

b. *WB-57F observations during MidCiX*

A similar suite of instruments, with similar configurations to those used aboard the WB-57F during CRYSTAL-FACE, was employed again during the Middle Latitude Cirrus Experiment (MidCiX) during April and May 2004. The study focused on subtropical cirrus blowoff near Texas, but also included a study of lenticular orographic wave clouds that formed downwind of the Colorado Rocky Mountains on 5 May. H06 showed partial microphysical results from a transect through one wave cloud, and compared these to results from a homogeneous nucleation model designed to simulate wave-cloud formation.

H06 did not provide details of how the model was initialized, nor how exactly it was decided what model values of IWC to compare to what measured values: the model showed substantial IWC well before any was observed by the cloud probes, but good agreement was seen for other times; it was only for these times of good agreement that H06 focused the analysis.

The figures in H06 showed good agreement between model, SPP-100, and CVI measurements of IWC while CAS measurements of IWC were 30%–50% lower. However, H06 claimed instead that the figures showed that particle-probe measurements of IWC were actually in general agreement with both model and CVI IWC.

The figure showed that CIN measurements of σ agreed closely with the model, and that CAS and SPP-100 measurements were a factor of 2.5 lower. In H06, the factor-of-2.5 difference was emphasized, and the agreement between model and CIN measurements of σ was argued to be fortuitous. It was stated that the model assumed particles to be spheres, and therefore model σ should be scaled downward by 10%–20% to account for more realistic crystal shapes.

There are several problems here. First, as was the case during CRYSTAL-FACE, indirect CAS and SPP-100 measurements of IWC differed by a factor of 2. H06 provided no explanation for this discrepancy. Second, H06 selectively applied the shape adjustment considerations to the model results but not to the particle-probe data, even though these also assumed particle sphericity in calculation of IWC and σ.

Finally, the CVI data in wave clouds are misrepresentative of the observations found during MidCiX as a whole. By selectively choosing wave-cloud cirrus, H06 exaggerated differences in probe intercomparison. If the MidCiX project as a whole is considered, excellent agreement is found between the CAPS and direct probes when flying in cirrus (Fig. 5). (Here calculations of σ and IWC from the CAPS were made by assuming particles smaller than 50-μm diameter were spheres and by reducing measurements of larger-particle projected area to an equivalent projected area sphere.) Of course this may be partly fortuitous given the aforementioned uncertainties in instrument measurements. However, it is significant that both bulk and particle probes gave very similar values for IWC and σ across two orders of magnitude in cloud density.

In wave clouds, however, values of IWC from the CVI were lower than those from either the Harvard probe or CAPS probe, by about 30% and 50%, respectively. We are unsure of the explanation for this differ-

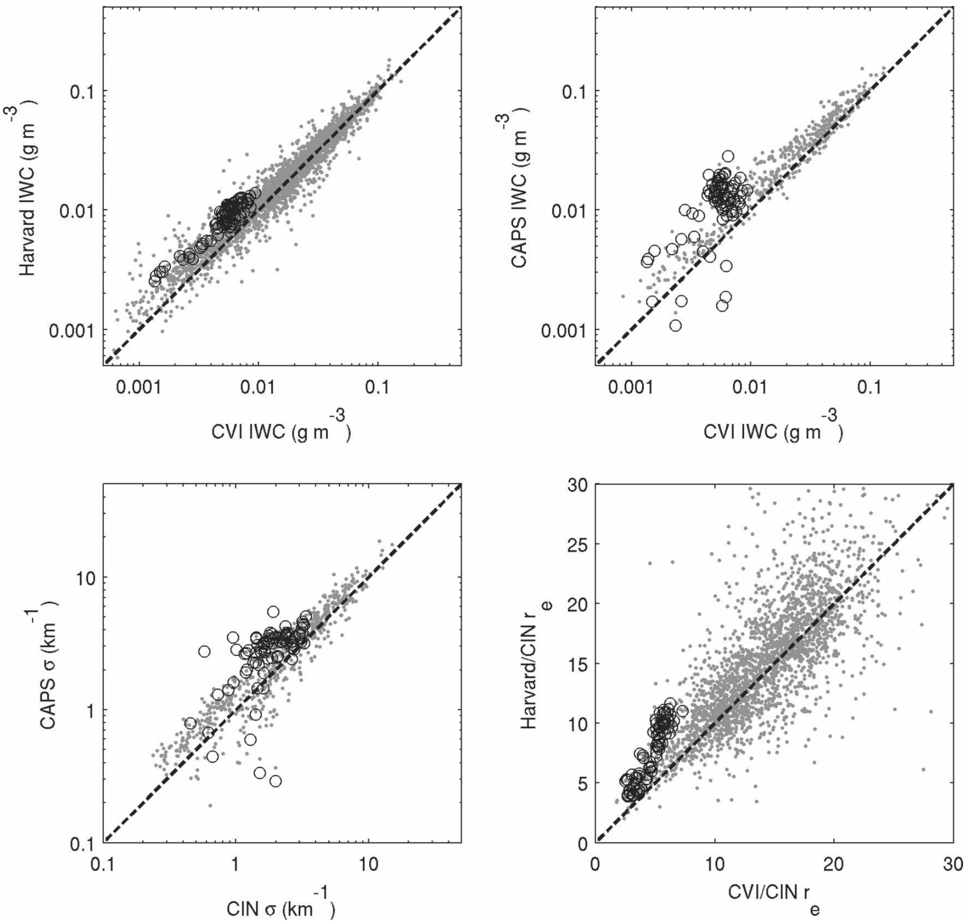

FIG. 5. Comparisons between instrument measurements of σ_{ext}, IWC, and r_e during MidCiX. The CAPS data represent a combination of the CAS and CIP instruments for particles between 2 and 1500 μm. The Harvard water, CVI, and CIN probes are bulk instruments. Points in gray are from cirrus, and black circles are from wave clouds.

ence. One possible consideration is that the CVI had a nominal 50% cutoff for the instrument counterflow (designed to filter interstitial aerosol) at 5-μm particle diameter. The wave-cloud particles had particularly low values of r_e. Conceivably, if some portion of the ice crystal size distribution fell below the cutoff threshold, some portion of the IWC present would be missed by the CVI. Thus, discrepancies between instrument and model data in H06 were likely because the CVI underestimated IWC in wave clouds, not because the CIN overestimated σ.

4. Comparisons with remote sensors during CRYSTAL-FACE and MidCiX

H06 compared lidar retrievals of σ from the ER-2 (McGill et al. 2004) with coincident measurements from the CIN and particle probes aboard the WB-57F and Citation. H06 state they used Citation data from 19 and 23 July, and WB-57F data from 23, 26, and 29 July. Good agreement was found between lidar retrievals and particle-probe values of extinction, but a factor-of-2 discrepancy was observed between lidar and CIN measures of σ.

There are several problems with H06's analysis. First, because of instrument failure, there were in fact no measurements of σ from the CIN aboard the WB-57F on 23 July, so H06 could not have analyzed this case. Second, data used in the comparisons came primarily from time periods when σ was below the CIN's lower sensitivity threshold ($\lesssim$0.001 m^{-1} aboard the Citation and $\lesssim$0.0004 m^{-1} aboard the WB-57F); H06 was comparing lidar returns with shot noise in the CIN photomultiplier tubes. Finally, lidar retrievals of σ were based on an assumed relationship between lidar backscatter and extinction. Without justification, H06 stated

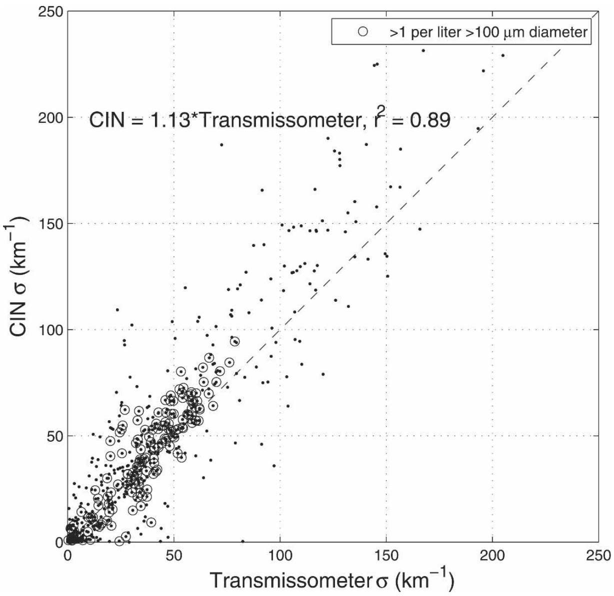

FIG. 6. Comparison of the CIN extinction coefficient σ with the Nevzorov transmissometer σ in warm cumulus during ICARTT. Circles indicate time periods when the concentration of particles >100 μm diameter was greater than 1 L^{-1} (maximum measured was 26 L^{-1}).

that the assumptions made were unlikely to account for a factor-of-2 error. This is incorrect. The lidar backscatter-to-extinction ratio in cirrus can be highly variable, typically by a factor of 3, but by as much as a factor of 10 within a single cloud (Ansmann et al. 1992). Without providing more detailed analysis, no evaluation of CIN measurement of σ can be made from coincident lidar measurements.

There are several other comparisons from CRYSTAL-FACE that can be considered instead. During CRYSTAL-FACE, *Geostationary Operational Environmental Satellite* (*GOES*)-*8* Visible Infrared Solar-Infrared Split Window Technique (VISST)-derived cloud products (Minnis et al. 1998) were matched to a spiral flight by the UND Citation through a cirrus anvil sampled on 21 July (Garrett et al. 2005). The cumulative optical depth τ for the layer derived from CIN in situ measurements of σ was 21.7. By comparison, τ retrieved from *GOES-8* imagery was 15.1 $\pm$ 4. Both in situ and *GOES-8* retrieved values of r_e were approximately 20 μm at the upwind edge of the anvil where it was thickest. Accounting for uncertainties in associating in situ and satellite cloud imagery in a dynamic cloud field, there is no indication of a factor-of-2 to -2.5 underestimate by the CIN.

Similarly, Roskovensky et al. (2004) compared ER-2 Moderate Resolution Imaging Spectroradiometer (MODIS) airborne simulator (MAS) optical depth and effective diameter (twice effective radius) products (King et al. 2003; Platnick et al. 2003) on 26 July to coincident WB-57F in situ values derived from the CIN (for σ), Harvard water probe (for IWC), and ER-2 lidar (for cloud depth). Both techniques indicated cloud optical depths of about unity and values of effective diameter of about 20 μm.

5. Comparison with an in situ transmissometer during ICARTT

In August 2004, four months after the MidCiX experiment, the CIN flew on the Canadian CV-580 aircraft for the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) project. The CV-580 also had on board a full suite of microphysical probes, including a version of the Nevzorov transmissometer. The Nevzorov instrument is distinguished by its truly first-principles measurement of extinction. A near-infrared light source is reflected to a small sensor by a mirror 2.33 m distant. In the single-scattering regime, the loss of light intensity at the sensor is directly proportional to the extinction coefficient. Because the laser is in the free airstream and there is no inlet, the instrument has no possible sensitivity to hydrometeor shattering. Because the CIN and Nevzorov flew together, there was opportunity for independent airborne assessment of the CIN accuracy in flight.

However, while it may be first principles, the Nevzorov is a less robust probe than the CIN, and is sensitive to errors from aircraft vibration, temperature fluctuations, incorrect zeroing in flight, and fogging of the optics. The estimated magnitude of uncertainty in measured σ was 25% (A. Korolev 2006, personal communication). To limit these uncertainties, this analysis focuses only on level transects through warm (above freezing) cumulus clouds, where the zero offset upon cloud entrance and exit was similar. In total, 540 s of cloud data were analyzed from nine flights.

On average, the observed discrepancy between the Nevzorov and CIN measurements of σ was very small—about 13%—and well within the range of uncertainty in both instruments (Fig. 6). Also, the level of agreement showed no sensitivity to the presence of precipitation-sized particles that might have broken up on the CIN inlet. This is important because 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 the CIN is appropriately calibrated for in-cloud measurements of σ, and is insensitive to shattering of precipitation-sized particles on its aperture.

Similar conclusions were reached by Gerber (2007), who compared the CIN to a ground-based transmissometer, and found differences in measurements of σ that were within 5% on average.

6. Conclusions

H06 pointed out cases during CRYSTAL-FACE and MidCiX when CIN measurements of σ were a factor of 2 to 2.5 higher than coincident measurements derived from other techniques. H06 claimed that the differences were due to systematic overestimates by the CIN. Accordingly, H06 recommended that for implementation of r_e parameterizations in climate models it is more appropriate to use results derived solely from "indirect" particle-probe measurements of σ, rather than those suggested by G03.

We have reexamined H06's study, and with some contributing work from elsewhere, we paint a different picture. The primary conclusions are as follows.

- The CIN is appropriately calibrated. On aircraft, it agrees with first-principles transmissometer measurement to within known measurement uncertainties ($\sim$15%). The level of agreement is independent of whether precipitation is present, which suggests an absence of sensitivity to shattering of particles on the CIN aperture.
- 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.
- Measurements of cirrus r_e and τ 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.
- 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. Particle probes do provide important detail about size distributions, but their indirect estimates of integral properties (e.g., WC and σ) are most useful when they are constrained with independently calibrated direct probes. If agreement between direct and indirect probes is consistent across more than one mode (as it was during MidCiX), then we can have considerable confidence that the particle probes provide useful size-resolved information. Otherwise, particle size distribution probe measurements of bulk quantities should not be considered to be more "reliable" than direct measurements, as was argued by H06.
- Based on current understanding of airborne bulk probe measurements of σ and WC, the G03 effective radius parameterization is a defensible representation of the clouds that were measured.

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