

Effects of ice particles shattering on optical cloud particle probes

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Recently, considerable attention has been focused on the issue of large ice particles shattering on the inlets and tips of cloud particle probes, which produces copious ice particles that can be mistakenly measured as real ice particles. Currently two approaches are being used to mitigate the problem: (1) Based on recent high-speed video in icing tunnels, probe tips have been designed that reduce the number of shattered particles that reach the probe sample volume, and (2) Post processing techniques such as image processing and using the arrival time of each individual particle. This paper focuses on exposing suspected errors in measurements of ice particle size distributions due to shattering, and evaluation of the two techniques used to reduce the errors. Data from 2D-S probes constitute the primary source of our investigation, however, comparisons with 2D-C and CIP measurements are also included. Analysis of 2D-S data shows that a particle arrival time algorithm is more effective than probe tips designed to reduce shattering, although application of both techniques ought to be complementary. This finding contrasts results from a recent investigation that found that modified probe tips were more effective than an arrival time algorithm when applied to 2D-C and CIP measurements. The reason for these differing results may be linked to the improved ability of the 2D-S to image small ice particles. The analysis techniques in this paper can be used to estimate the effects of shattering. For example, the additional spurious concentration of (small) shattered ice particles can be measured as a function of the mass concentration of (large) ice particles. The analysis provides estimates of upper bounds on the concentration of natural ice, and on the remaining concentration of shattered ice particles after application of the post-processing techniques. However, a comprehensive investigation of shattering is required to quantify effects that arise from the multiple degrees of freedom associated with this process, including different cloud environments, probe geometries, airspeed, angle of attack, particle size and type.

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1 Introduction

Ice particles shattering on the inlets and tips of cloud particle probes produce small ice artifacts that can be erroneously included in measurements of ice particle size distributions. Artifacts produced from shattering of ice particles on optical cloud particle probes were reported in the literature over three decades ago (e.g., Cooper, 1978; Gardiner and Hallett, 1985). Cooper (1978) recognized the problem and introduced a method for removing shattered ice in post processing. Based on examination of two-dimensional images from the Particle Measuring Systems (PMS) model 2D-C probe (Knollenberg, 1970), he suggested that a burst of closely spaced particles, which is the typical pattern resulting from shattering, could be removed by comparison of individual particle arrival times. In simplistic terms, if ice particles are assumed to be randomly distributed in a cloud with concentration $< \sim 1 \text{ cm}^{-3}$, than particles with arrival times equivalent to a spacing that is less than about 2 cm are considered artifacts, and are removed. Cooper (1978) introduced the arrival time approach, which was later refined by Field et al. (2003, 2006), Korolev and Isaac (2005) and Baker et al. (2009). The work presented by Baker et al. (2009) considers removal of splashing raindrops, which closely resembles shattered ice particles.

While the issue surrounding ice particles shattering on the inlets and tips of optical particle probes (hereafter referred to simply as “shattering”) has been known since the 1970’s, it has only been recently that the magnitude of the effect has been brought to the attention of the cloud physics community. Advances in high-speed digital videography and cloud particle probes have provided new insights into the shattering process. High-speed videography of ice particles shattering on probe tips in the icing research tunnel (IRT) at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) showed some remarkable results. Alexei Korolev of Environment Canada (EC) has shown digital videography of millimeter-size ice particles shattering on probe tips, with small ice particles bouncing several mm upstream into the 100 m s^{-1}

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airflow, and then traversing up to 3 cm across the airflow into the probe sample volume (Korolev et al., 2010).

Advances in the electro-optics of linear-array cloud particle probes have provided new insights into measurements of cloud particle size distributions. The 2D-S probe incorporates advanced electro-optical technology, including a 128-photodiode linear array and a high-speed front-end amplifier. The photodiode array is strobed at 20 MHz and has been demonstrated to have 10- μm pixel resolution at airspeeds exceeding 200 m s^{-1} (Lawson et al., 2006a). In comparison, the 2D-C probe (Knollenberg, 1970) has μm pixels with 32 photodiodes that are strobed at 5 MHz. An improved version of the 2D-C probe, the cloud imaging probe (CIP) was designed and built by Droplet Measuring Technology (DMT) in the late 1990's (Baumgardner et al., 2001). The CIP has 64 photodiodes, 25 μm pixels and is strobed at 8 MHz. However, due to limitation of the time response of the photodiode array and front-end amplifier, the actual particle resolution of CIP and 2D-C may exceed 25 μm . Lawson et al. (2006a) showed measurements that suggest the 2D-C does not image particles $< \sim 125 \mu\text{m}$ at an airspeed of 103 m s^{-1} . Recent measurements show that a newer version of the CIP is capable of imaging 50- μm drops at 150 m s^{-1} , but that performance degrades at higher airspeeds (Lawson et al., 2010). The time response and effective particle-size resolution of optical array probes is germane to this discussion of shattering, because reliable sizing of ice particles $< \sim 100 \mu\text{m}$ is critical to the ability to remove the effects of shattering in post processing.

This paper is focused on exposing suspected errors in measurements of ice particle size distributions due to shattering, and evaluation of techniques used to reduce the errors. It is not intended to be a comparison of the relative performance of various imaging probes. However, Korolev et al. (2010) recently evaluated shattering effects on 2D-C and CIP probes and suggested that specially modified tips were more effective than an arrival time algorithm in reducing the effects of shattering. In this paper it is seen that, when considering the newer technology 2D-S probe, we find the opposite; i.e., an arrival time algorithm is more effective in reducing the apparent effects of

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shattering than modified tips. We focus our attention on 2D-S measurements, which themselves also contain uncertainties, some known and others that will likely be exposed over time. Given this caveat, we assume that 2D-S data are sufficiently reliable to be capable of revealing significant uncertainties in other cloud particle probe data. A comparison of 2D-S and historical measurements also leads to implications regarding how uncertainties may impact cloud particle data in archives.

2 Comparison of measurements from a 2D-S and historical measurements

Historical aircraft measurements of ice particle size distributions using optical probes in deep stratus cloud systems, such as thick cirrus, have generally revealed a vertical profile where small ice particles exist and typically dominate the size distribution throughout the depth of cloud (e.g., Lawson et al. 2006b). This is contrary to conventional thinking, which suggests that smaller particles will nucleate in higher concentrations at cold temperatures near cloud top and subsequently sublimate and disappear, grow via vapor diffusion, or aggregate into larger ice particles as they fall toward cloud base.

To help visualize the effects of shattering on archival data, we show two examples of vertical profiles of ice particle size distributions collected in relatively deep cirrus clouds. The first example shows average ice particle size distributions using older cloud particle probes that are believed to be subject to errors from shattering. The second example shows data from the 2D-S probe, which used modified probe tips based on the Korolev design technique and particle arrival times (Baker et al., 2009) to remove shattered ice in post processing. Figure 1 shows an example from Lawson et al. (2006b) of particle size distributions and number concentrations based on multiple penetrations of cirrus clouds. Composite size distributions were put together using measurements from a forward scattering spectrometer probe (FSSP), a cloud particle imager (CPI) and a 2D-C probe. The FSSP was used to establish the small particle end of the size distribution (generally less than about 30 μm) and the 2D-C established

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the large end. CPI data were scaled to merge with the FSSP and 2D-C measurements (see Lawson et al., 2006b for details).

A combination of gravity waves and homogenous nucleation at these cold temperatures is a possible theoretical explanation for the relatively high (846 L^{-1}) average ice concentration near cloud top in Fig. 1 (Kärcher and Ström, 2003; Jensen et al., 2009). Some investigators have reported even higher ($>1 \text{ cm}^{-3}$) ice concentrations in regions where the maximum particle size is about $100 \mu\text{m}$ (Gayet et al., 2002; Kärcher and Ström, 2003; Lawson et al., 2006b). Shattering is not thought to be a major contributor to ice concentration in this situation. However, the high (2.17 cm^{-3}) average ice concentration near cloud base in Fig. 1 cannot be explained theoretically.

Using particle arrival times from a fast FSSP, Field et al. (2003) shed light on this issue when they showed that the FSSP was very sensitive to shattering, and that the shattered artifacts could significantly increase the small particle concentration. Most of the measurements that suggest high concentrations of small ice in regions with large ice (i.e., $>$ a few hundreds of microns) have been reported using (or in the case of the CPI scaled by) a scattering probe such as the FSSP (e.g., Fig. 1).

In contrast to the vertical distribution of small ice particles seen in Fig. 1, the measurements in Fig. 2 were collected using a 2D-S probe in a deep cirrus cloud investigated from 19:36:30–19:59:00 UTC on 10 February 2010 during the Small PARTICles in Cirrus (SPARTICUS) project. This example was chosen from the SPARTICUS dataset because it shows high (2.7 cm^{-3}) concentrations of small ice near cloud top (and the CPI images reveal nearly all small ice), but only 44 L^{-1} near cloud base, including bullet rosettes with sizes of hundreds of microns. A comparison of the size distributions in Figs. 1 and 2 show that both the concentration and mass distributions have similar shapes near cloud top where there were few large ice particles. However, lower in the cloud where there are higher concentrations of large ice particles, the mode of the mass distribution in Fig. 1 peaks between 10 and $100 \mu\text{m}$, whereas the mass mode peaks between 100 and $500 \mu\text{m}$ in Fig. 2. The much smaller mass mode in Fig. 1 is most likely due to particle shattering on the inlet of the FSSP used in these studies. Jensen

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size distribution with the unmodified probe tips and without application of the arrival time removal algorithm (green trace) contains the most particles with sizes $< 200 \mu\text{m}$. The size distribution with modified probe tips and without application of the arrival time removal algorithm (red trace) contains the second most particles with sizes $< 200 \mu\text{m}$, which suggests that the probe modified probe tips are somewhat effective in reducing shattering. However, the two size distributions that have been processed using the arrival time algorithm to remove shattered particles contain far fewer particles $< 200 \mu\text{m}$ than either of the other size distributions, regardless whether the probe has modified tips, or not. Thus, in this case, the arrival time algorithm is more effective than the modified probe tips in reducing the effects of shattering on these 2D-S probes.

The average bulk parameters, total number concentration (N), extinction coefficient (β_{ext}) and ice water content (IWC) are also shown in Fig. 5. In this example, without application of the arrival time algorithm the modified tips make a significant difference in N (707 L^{-1} vs 214 L^{-1}). Application of the arrival time algorithm reduces N from 707 L^{-1} to 37 L^{-1} with the standard tips and from 214 L^{-1} to 50 L^{-1} with the modified tips. Thus, the modified tips reduce N by 493 L^{-1} and application of the arrival time algorithm reduces N by only an additional 177 L^{-1} . On the other hand, without application of the arrival time algorithm the modified tips make no difference in β_{ext} and only 3 mg difference in IWC. When the arrival algorithm is used in the computation of β_{ext} and IWC, the differences are much larger. Application of the arrival time algorithm reduces β_{ext} from 2.5 km^{-1} to 2.0 km^{-1} with the standard tips, and from 2.5 km^{-1} to 2.2 km^{-1} with the modified tips. The arrival time algorithm reduces IWC from 100 mg m^{-3} to 84 mg m^{-3} with the standard tips, and from 103 mg m^{-3} to 90 mg m^{-3} with the modified tips. Thus, in this example application of the arrival time algorithm makes a much more significant impact on the second and third moments of the size distribution than does the modified tips.

Another method for examining the effects of shattering is to generate a scatter plot of the concentration of small (shattered) particles versus the mass of large (shattering) particles (Jensen et al., 2009). In this way, it is possible to see if the concentration

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provide an estimate of the remaining spurious effects of shattering, i.e. in this case $\sim 350 \text{ L}^{-1}$ of small ice particles per g m^{-3} of large ice are produced from shattering. Since it is not possible to know the actual concentration of small ice particles, in this case: (1) 350 L^{-1} per g m^{-3} is an estimate of the upper bound of the possible remaining effects of shattering, or (2) an upper bound of the natural ice concentration in the cloud.

The measurements shown in Figs. 5 and 6 suggest that the modified tips reduce the number of small (shattered) particles, but not as effectively as the arrival time algorithm. Also, there is still a trend for increasing small particles with increasing ice water content, even with modified tips and application of the arrival time algorithm. This can be explained either by a process that is actually generating small particles when there are more large ice particles (e.g., particle-particle collisions), or that not all of the shattered particles are being removed by the modified tips and arrival time algorithm. We would like to point out a scenario where a shattered particle can be counted as a natural ice particle. If only one shattered small particle passes through the sample volume (i.e., the remainder of the shattered small particles are out of the depth of field), the one small particle in the depth of field will be not be rejected by the arrival time algorithm and will be counted as a natural ice particle. Since the depth of field of imaging probes is very small for small particles, the effective particle concentration is increased dramatically. The probability of this occurring is unknown at this time and would require a dedicated investigation, perhaps requiring high-speed video of shattered particles in various airborne flight and cloud conditions. However, the methodology presented here (i.e., Fig. 6 and associated discussion) is a method for estimating the maximum contribution from shattering.

After examining the data in Fig. 6, it is tempting here to state that shattering may have artificially increased the concentration of small particles by an order of magnitude. However, it is important to keep in mind that the contribution from shattering is relative to the natural concentration of small particles. If the contribution from shattering of very large particles in the example in Fig. 6 was hypothetically added to the concentration of natural small particles at the top of the cirrus cloud example in Fig. 2, then the

contribution from shattering would add <10% to the total particle concentration. For this reason, we recommend reporting quantified *additive* effects and to avoid reporting *multiplicative* values (i.e., Field et al., 2003; McFarquhar et al., 2007; Jensen et al., 2009; Korolev et al., 2010).

3.2 Airborne Icing Instrumentation Evaluation (AIIE) field project

The AIIE was conducted near Ottawa in March–April 2009 (Korolev et al., 2010). Data were collected with the National Research Council (NRC) of Canada Convair 580 research aircraft in deep precipitating glaciated cloud systems associated with frontal clouds. There was only one 2D-S probe available, so the probe was flown on one research flight without the modified tips, and then on another flight with the modified tips. Figure 7 is reproduced from Fig. 5 in Korolev et al. (2010), with the addition of 2D-S measurements from the same time period. The data in Fig. 7a show that, contrary to 2D-S data shown in Fig. 6, modified 2D-C tips are more effective in removing small (shattered) particles than is the arrival time algorithm (indicated by “corr.” in the figure)¹. The CIP data in Fig. 7b shows the same trend as the 2D-C in Fig. 7a. In both Fig. 7a and b, 2D-S data without (“no corr.”) and with (“corr.”) arrival time corrections are shown with modified probe tips. A comparison of all data in Fig. 7 suggest that the 2D-S probe with application of arrival time correction removes the most small (shattered) particles. The 2D-C probe with arrival time correction is closest to the 2D-S PSD, with the CIP probe showing the most deviation from the 2D-S results.

Figure 8 shows 2D-S measurements from data collected during the AIIE field program on two different flights in similar cloud conditions; one flight when the probe was flown without modified probe tips, and the second flight with modified tips. The data in Fig. 8 are shown in the same format as the SPARTICUS data in Fig. 6, except in this case the data extend over a larger ice water content range, are shown on log scales, and the concentration of small particles is shown for particles < 50 μm. Data from the

¹The particle arrival time algorithm applied to the AIIE data was developed and applied by Alexei Korolev.

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flights with and without the modified tips were processed with and without application of the arrival time algorithm, producing the four scatter plots seen in Fig. 8. The data in Fig. 8 show that without applying the arrival time algorithm, the concentration of small ice particles is about $6000 \text{ L}^{-1} \text{ per g m}^{-3}$ with the unmodified tips, compared with about $1000 \text{ L}^{-1} \text{ per g m}^{-3}$ with the modified tips. However, there is still a strong correlation between increasing concentration of small and ice water content, until the application of the arrival time algorithm. Once the arrival time algorithm is applied the average concentration of small ice particles is about $20 \text{ L}^{-1} \text{ per g m}^{-3}$ with both the unmodified and modified tips, and there is no correlation between increasing small ice particles and ice water content.

The data in Fig. 8 suggest that, for the 2D-S probe in these cloud conditions, the modified tips reduce, but do not eliminate the trend of increasing small particles with increasing ice water content. On the other hand, the data in Fig. 8 do show that, in this case, the arrival time algorithm eliminates the correlation between large and small (shattered) particles. It should be pointed out, however, that because there is no way of knowing the actual concentration of small particles (i.e., there could be none), this does not imply that the arrival time algorithm eliminates all of the shattered particles. As in Fig. 6, though, an estimate of the upper bound on the amount of shattered ice particles and natural ice particles can be derived from these scatter plots. The results shown in Figs. 6 and 8 are only two examples, and shattering is likely to depend on many factors, including ice crystal size, type, airspeed, angle of attack and temperature, to mention some of the more important factors. For example, the data in Fig. 6 still show a (weak) correlation between large and small particles in the large particle region of an anvil cloud, even with modified tips and application of the arrival time algorithm.

The 2D-S, 2D-C and CIP probes were also flown together in April 2008 on the NRC Convair 580 research aircraft during the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Indirect and Semi-Direct Aerosol Campaign (ISDAC). Figure 9 shows typical particle images and size distributions from several particle probes that were flown together below the base of a precipitating Arctic stratus



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cloud investigated from 01:20:00 to 01:26:40 UTC on 26 April 2008. The instrument acronyms shown on the figures and their affiliations are listed in the figure caption. Figure 10 shows typical particle images and size distributions from the same instruments flown in the mixed-phase region 300 m above the base of the same Arctic stratus cloud from 02:48:40 to 02:48:53 UTC. None of these probes had inlets removed or probe tips with aggressive designs to reduce shattering. However, the 2D-S probe did have tips that were designed to reduce shattering, based on understanding of ice particle shattering at that time.

The lower left sides of Figs. 9 and 10 show size distributions without removing shattered particles, while the right sides show the same time periods using an arrival time algorithm to remove shattered (i.e., closely spaced) particles on the SPEC 2D-S and fast FSSP, the EC 2D-C and the DMT CIP.² The size distributions without application of the arrival time algorithm are all in reasonably good agreement, both below cloud base in precipitating dendrites (where small particles are not thought to be abundant), and in the mixed-phase region where the CDP and FSSP probes show about 80 cm^{-3} . In the precipitating dendrite size distributions (Fig. 9), the SPEC fast FSSP and 2D-S probes show a significant reduction in the concentration of small particles with the arrival time algorithm applied. The particle concentration in the size range from 5 to $300 \mu\text{m}$ is reduced from about 20 to 2 L^{-1} . The 2D-C, which has a $25\text{-}\mu\text{m}$ pixel size, also shows a reduction in particle concentration of about 1 to 0.1 L^{-1} in the 25 to $300 \mu\text{m}$ size range. On the other hand, there is very little change in the CIP size distribution and the small particle concentration actually increases in the smallest bins (due to re-sizing of some of the larger donut-shaped particles). In this case the application of an arrival time algorithm has a result similar to the AIEE results shown in Fig. 7, where both the 2D-S and 2D-C size distributions show significant reductions in small particles, whereas the CIP shows much less of an effect.

²2D-C and CIP arrival time algorithm developed and applied by Greg McFarquhar's group at the University of Illinois.

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In the mixed-phase region of the same cloud (Fig. 10), the natural small particle (i.e., cloud drop) concentration is about 80 cm^{-3} , which is much higher than below cloud base. Even though the concentration of large particles in the mixed-phase is about the same as in the precipitation below cloud base, the total particle concentration is not significantly affected when the arrival time algorithm is applied. The most significant difference when the arrival time algorithm is applied is seen in the region from about 50 to $150\text{ }\mu\text{m}$, but the percentage change is still quite small. When shattered particles are removed particle concentration changes from 1.4 to 0.4 L^{-1} , extinction coefficient goes from 0.08 to 0.05 km^{-1} and ice water content changes from 7 to 5 mg m^{-3} . The percentage change in small (cloud drop) particles when shattered particles are removed is negligible. Particle concentration changes from $66\,304$ to $66\,295\text{ L}^{-1}$, extinction coefficient goes from 10.78 to 10.76 km^{-1} and liquid water content changes from 40.3 to 40.0 mg m^{-3} . A comparison of Figs. 9 and 10 emphasizes the reason why shattering should be reported as an additive effect and not a multiplicative effect. Jensen et al. (2009) show a result similar to Figs. 9 and 10 for low and high concentrations of natural small ice at the top of an aged tropical anvil cloud; i.e., shattering with low natural ice makes a significant contribution to total particle concentration, whereas this is not the case when the natural ice concentration is high.

4 Summary and discussion

We investigate the effects of ice particles shattering on the inlets and tips of optical particle probes, which we refer to in this paper as “shattering”. While shattering has been known for over 35 years, under certain cloud conditions the magnitude of the contribution of shattered particles can be significant. The 2D-S probe has been shown to have the capability to significantly reduce the amount of shattered particles. Two methods contribute to the ability of the 2D-S to reduce the effects of shattering: (1) Probe tips designed with the assistance of Alexei Korolev and based on

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tests in the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) Icing Research Tunnel (IRT), and (2) a more effective method that uses individual particle arrival times. The recorded data are post processed using an algorithm to remove closely-spaced particles that IRT high-speed video showed are the result of shattering. The software algorithm is an outgrowth of work originally reported by Cooper (1978) and refined by Field et al. (2003, 2006), Korolev and Isaac (2005) and Baker et al. (2009). Data from the 2D-S probe is used as a basis for comparison of shattering results from the PMS 2D-C and DMT CIP probes.

High-speed video photography from the NASA GRC IRT shows that large ice particles shatter into hundreds and perhaps thousands of small ice crystals with sizes that range from about 10 to 100 μm . As suggested from the comparison of 2D-S particle images in Fig. 4 and size distributions in Fig. 5, the large majority of these particles are in the size range from 10 to 50 μm (or perhaps even smaller). In order to effectively reject these shattered images, a two-dimensional probe has to have the capability to image particles in approximately the 10 to 100 μm size range.

The 2D-S has demonstrated the ability to image particles that are 10 μm and larger (Lawson et al., 2006a; Baker et al., 2009). However, when the 2D-S has been flown together with a PMS 2D-C probe and/or a DMT CIP probe, the data suggest that the 2D-C and CIP are not capable of imaging particles smaller than 50 μm at the speed of jet aircraft (Lawson et al., 2010), and in some cases the minimum particle imaged was about 100 μm (Lawson et al., 2006a). The apparent reason for this is that the front-end electro-optics of the 2D-C and CIP probes are not fast enough to record images of these small particles, even though the optical pixel resolution is 25 μm . Thus, when a blast of shattered ice particles goes through the sample volume of the 2D-C and CIP probes, several of the smallest particles may be missed all together.

2D-S data collected during SPARTICUS in 2010 were compared with cirrus data collected using an FSSP and 2D-C from 1998 through 2004. The comparison suggests that under some cloud conditions shattering on the inlet and tips of the older probes added significantly to small particle concentration. 2D-S probe data from two recent

particles are missed, producing large gaps that defeat the arrival time algorithm, and/or groups of small particles are blurred together and appear as one larger particle.

Analysis of ISDAC data collected by a 2D-S probe in precipitating dendrites below cloud base shows that the arrival time algorithm substantially reduced the concentration of small particles, making a significant effect on total particle concentration. However, analysis in the mixed-phase region just above cloud base that contained about the same concentration of dendrites showed a minimal impact on total particle concentration. Thus, when the natural concentration of small particles (cloud drops in this example) is high, the contribution from shattering can be insignificant. Due to this result, it is important that investigators refrain from reporting the multiplicative factor due to shattering (e.g., “shattering increases the small particle concentration by an order of magnitude”), but instead, the additive effect of shattering (e.g., “shattering is estimated to add 1000 L^{-1} per g m^{-3} to the small particle concentration). That is, the effects of shattering can dominate the small particle concentration in precipitating ice where there are few natural small particles, but may be insignificant when the concentration of natural small (water or ice) particles is high (say, $>\sim 1 \text{ cm}^{-3}$) and the concentration of large particles is low. In the first case with precipitating ice the multiplicative factor may be orders of magnitude, and in the second case it may be $<10\%$. However, in both cases if the mass of large ice is the same, the additive factor (i.e., the actual number of small particles added) is actually the same.

Scatter plots of the concentration of small ice particles versus the mass of large ice particles shows the trend of increasing concentration of suspected shattered particles with increasing ice water content. This type of plot can provide estimates of the upper bound of small ice particles due to shattering, or the number of natural small ice particles. Since the result can be a combination of both shattered and natural small ice, the most useful application of this form of plot is regions where the concentration of small ice particles is thought to be very low, or nonexistent, such as precipitating ice below cloud base.

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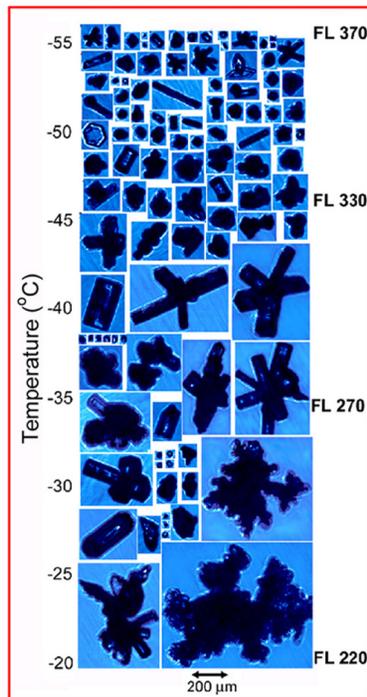
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Cirrus Images

16 November 1998



Cirrus Cloud PSDs

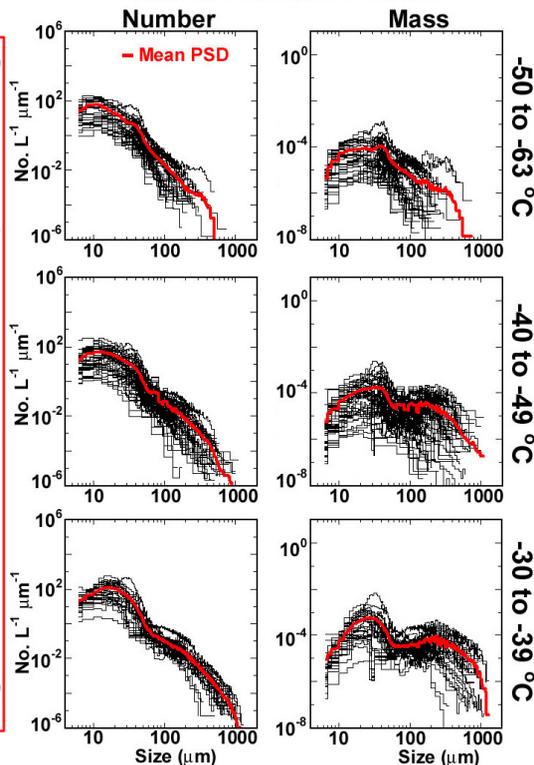


Fig. 1. Example of (left) vertical profile of CPI images in a deep orographically generated cirrus, and (middle and right panels) number and mass particle size distributions for three temperature ranges generated from 102 horizontal legs in cirrus, where average size distribution distributions are shown in red. Small end of the size distributions are based on measurements from FSSP and large end from 2D-C probe, with CPI data scaled to fit in between. Adapted from Lawson et al. (2006b).

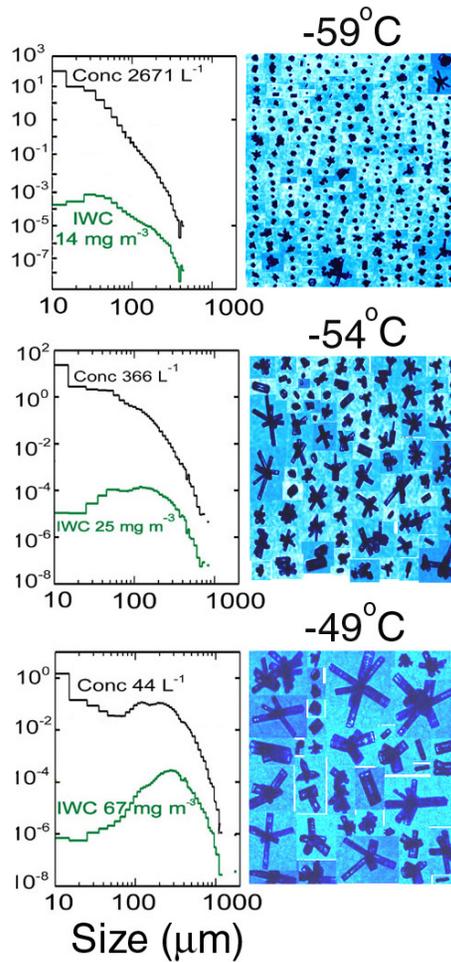


Fig. 2. Example from the SPARTICUS project showing (left) concentration and mass particle size distributions derived from the 2D-S and (right) images from the CPI.

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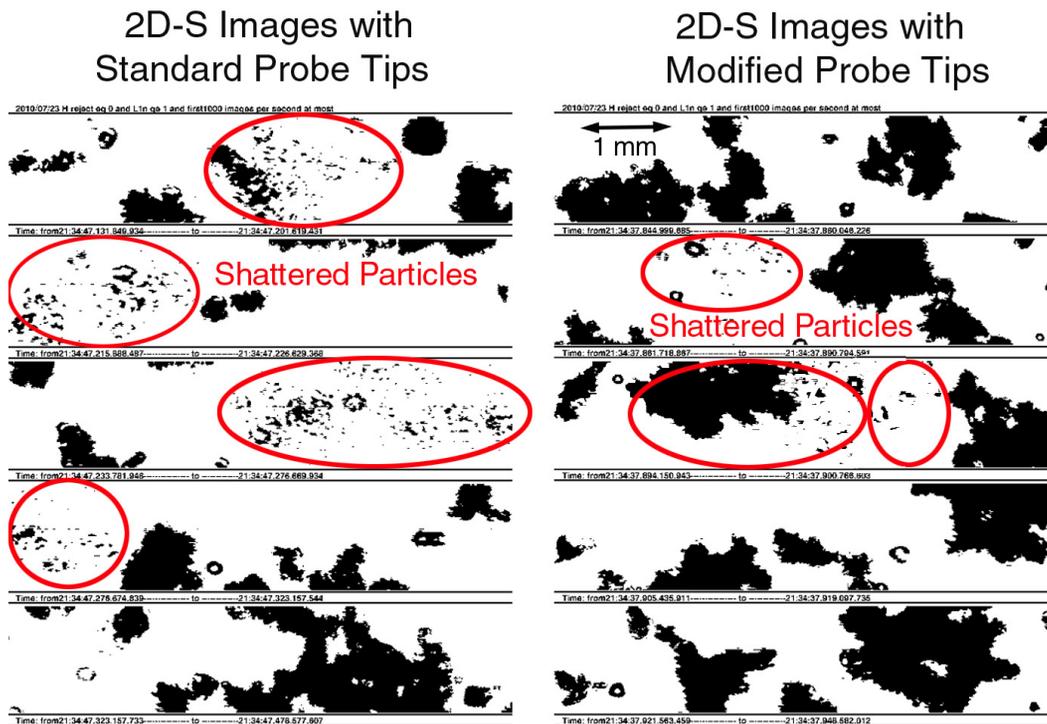


Fig. 4. Examples of 2D-S images from two 2D-S probes flown side-by-side on the SPEC Learjet (Fig. 3) during the SPARTICUS project, one probe had standard 2D-S probe tips (left) and (right) the other with tips modified to reduce the effects of shattering.

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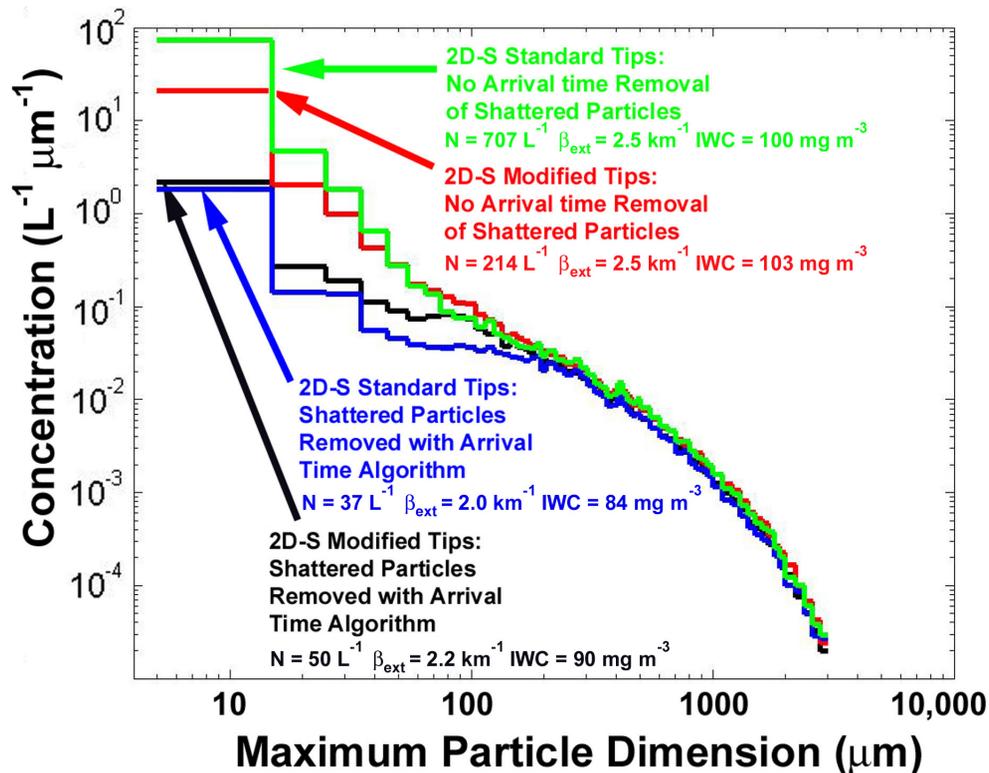


Fig. 5. Average particle size distributions derived from 2D-S measurements collected in large ice aggregates from 21:34:18–21:37:16 UTC on 23 July 2010. Data are from two 2D-S probes installed side-by-side on the SPEC Learjet (Figs. 3–5). One probe had standard probe tips and the other probe was equipped with probe tips modified to reduce shattering. Size distributions are shown with and without the effects of an arrival time algorithm to remove shattering. Total particle concentration (N), extinction coefficient (β_{ext}) and ice water content (IWC) were derived from each average size distribution.

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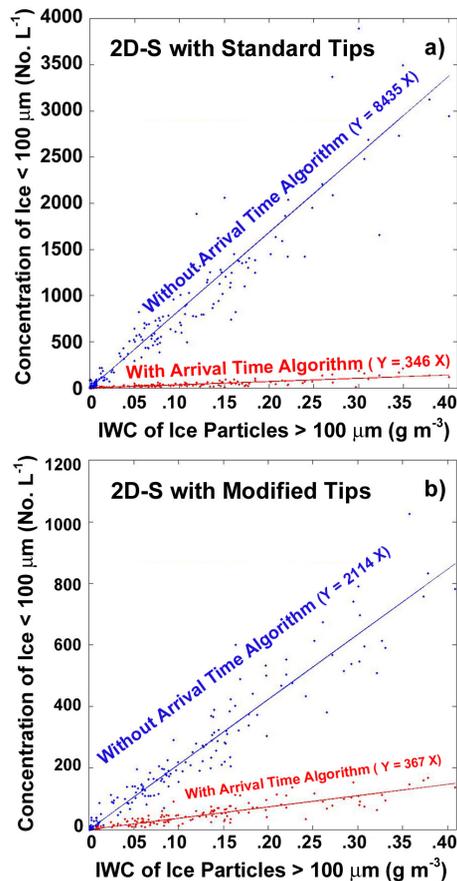


Fig. 6. Scatter plots of the concentration of ice particles <math>< 100 \mu\text{m}</math> versus ice water content. Data collected in large ice aggregates with two 2D-S probes installed side-by-side on the SPEC Learjet (Figs. 3–5). One probe **(a)** had standard probe tips and the other probe **(b)** was equipped with probe tips modified to reduce shattering. Effect of the arrival time algorithm to remove shattering is shown on each plot.

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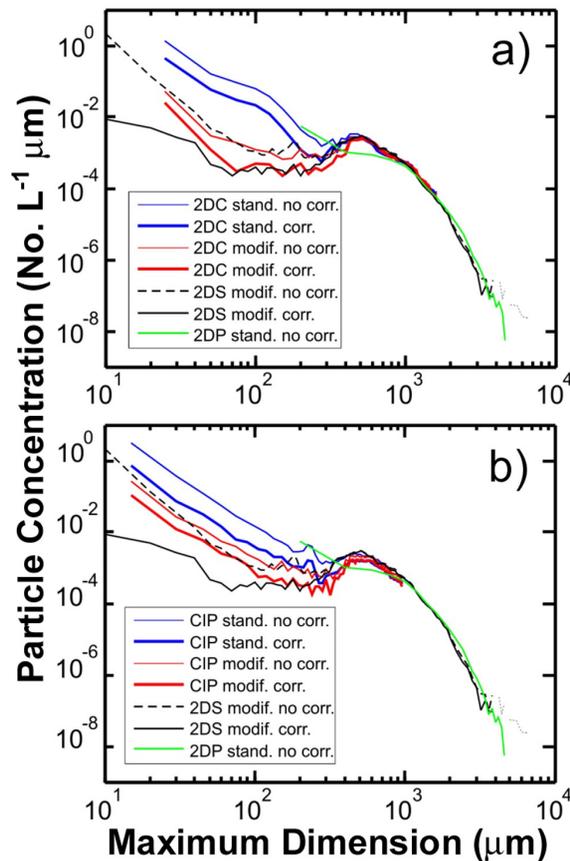


Fig. 7. Particle size distributions from the AIIIE field project. Data are reproduced from Korolev et al. (2010) with the addition of 2D-S data for the same time period. “stand.” means standard probe tips; “modif.” means modified probe tips, “corr.” means data have been adjusted using an arrival time algorithm and “no corr.” means that no arrival time algorithm has been applied.

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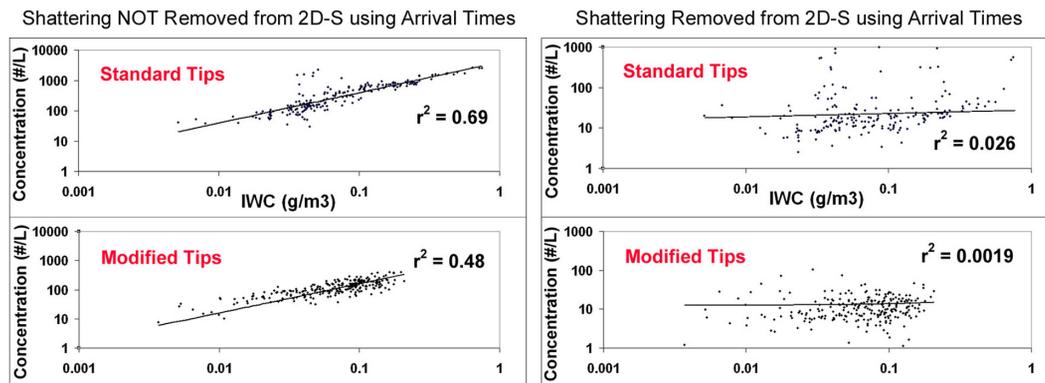


Fig. 8. Scatter plots of the concentration of ice particles ($<50\ \mu\text{m}$) versus ice water content. Data collected during the AIIE field project with a 2D-S probe installed on the NRC Convair 580. The 2D-S probe was flown with standard tips on one flight (top two panels), then with modified tips in similar conditions on a second flight (bottom two panels). Effect of the arrival time algorithm to remove shattering is shown on plots on the right side.

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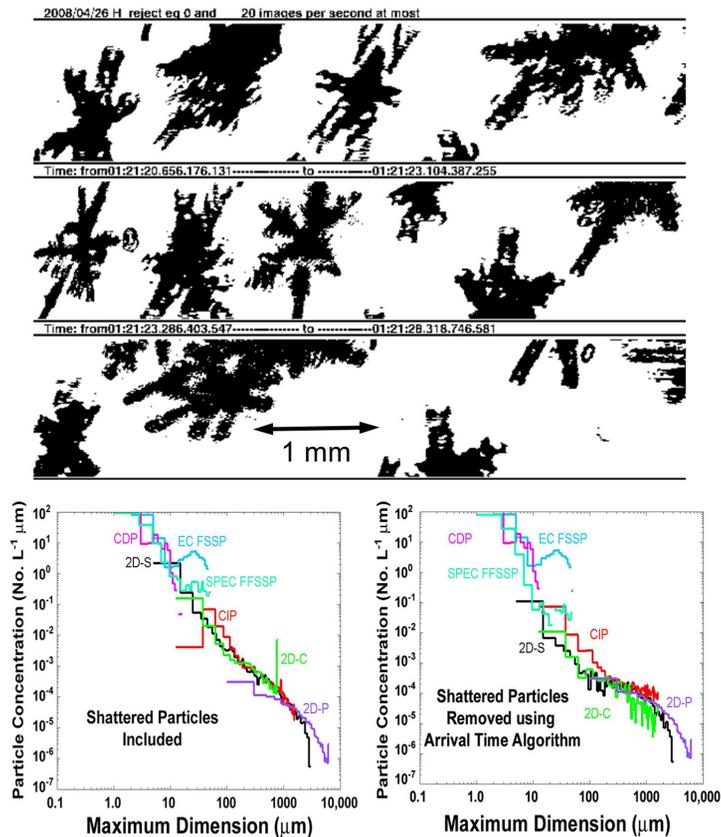


Fig. 9. 2D-S Images and (bottom) particle size distributions from several cloud particle probes flown on the Canadian Convair 580 in precipitating dendrites below cloud base during ISDAC. Left panel shows measurements with shattered particles included and right panel with shattered particles removed using arrival time algorithm. EC FSSP = Environment Canada FSSP. CDP = DMT CDP. SPEC FSSP = SPEC Fast FSSP. CIP = DMT CIP. 2DC = EC 2DC. 2DP = EC.

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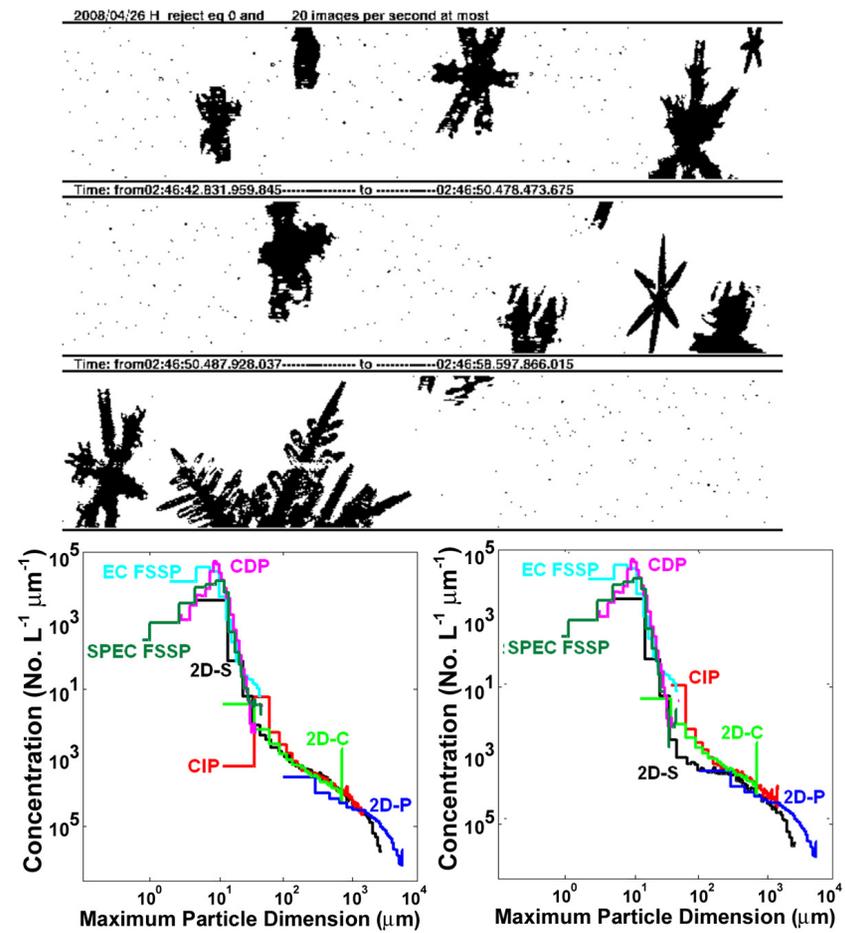


Fig. 10. As in Fig. 9, except data were collected in the mixed-phase region of the same Arctic cloud.

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