An Assessment of the Impact of Antishattering Tips and Artifact Removal Techniques on Cloud Ice Size Distributions Measured by the 2D Cloud Probe

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ABSTRACT

Prior estimates of ice crystal size distributions derived from 2D cloud probes (2DCs) have been artificially amplified by small ice crystals generated from the shattering of large ice crystals on the probe tips. Although antishatter tips and algorithms exist, there is considerable uncertainty in their effectiveness. This paper examines differences in ice crystal size distributions from adjacent 2DCs with standard and antishatter tips, and processed with and without antishattering algorithms. The measurements were obtained from the National Research Council of Canada Convair-580 during the 2008 Indirect and Semi-Direct Aerosol Campaign (ISDAC) and the National Center for Atmospheric Research C-130 during the 2011 Instrumentation Development and Education in Airborne Science (IDEAS-2011). The 2DC size distributions are compared with those from the Holographic Detector for Clouds (HOLODEC), which has antishatter tips and allows for identification of shattering through spatial statistics.

The ratio of the number concentration \(N\) of particles with maximum dimensions 125–500 \(\mu\m\) from the 2DC with standard tips to that from the 2DC with modified tips was correlated with median mass diameter and perimeter divided by area, but not with airspeed, attack, and attitude angles. Antishatter tips and algorithms reduced \(N\) by up to a factor of 10 for IDEAS-2011 and ISDAC, but neither alone removed all artifacts. For the period with coincident data, both \(N\) from the HOLODEC and 2DC with modified tips are around \(5 \times 10^3 \text{L}^{-1} \mu\m^{-2}\), suggesting that antishatter tips and algorithms combined remove artifacts from the 2DC for the conditions sampled during IDEAS-2011.

1. Introduction

Ice clouds cover around 30% of the planet (Wylie et al. 2005), contribute significantly to the diabatic heating of the upper troposphere (Ramaswamy and Ramanathan 1989), and may play a role in regulating sea surface temperatures in the tropics (Ramanathan and Collins 1991). They emit infrared radiation at lower temperatures than the surface, providing a longwave warming effect (Hartmann et al. 1992; Chen et al. 2000; Stephens 2005; Boudala et al. 2007) that competes with the shortwave cooling effect, the balance of which depends highly on ice particle properties such as size and shape (e.g., Heymsfield and Miloshevich 1991; Stephens et al. 1990; Stackhouse and Stephens 1991; Zender and Kiehl 1994; Zhang et al. 1999; McFarquhar et al. 2003; Boudala et al. 2007). The ice particle mass-weighted terminal velocity, which also depends on ice crystal properties, controls the gravitational settling and abundance of cirrus (Jakob and Klein 1999) and is an important control of cloud fraction and ice water path simulated by general circulation models (GCMs) (Mitchell et al. 2008; Sanderson et al. 2008).

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Mixed-phase clouds in all geographic regions also play important roles in global climate feedbacks and in shaping the earth’s radiative budget. Midlevel mixed-phase clouds cover around 22% of the planet (Warren et al. 1986) and occur at all latitudes (Yoshida et al. 2010). In the Arctic, mixed-phase clouds have a critical role in a complex feedback involving the sea ice, clouds, aerosols, and the atmosphere (Curry et al. 1993; Curry 1995), where rapid changes in temperature and sea ice coverage attributable to climate change are occurring (Edenhofer et al. 2014). The persistence of arctic mixed-phase clouds is driven by a balance between cloud-top radiative cooling, ice sedimentation rates, latent heat-phase clouds is driven by a balance between cloud-top radiative cooling, ice sedimentation rates, latent heat-and synoptic scale and surface forcing (Harrington et al. 2014). The persistence of arctic mixed-phase clouds is driven by a balance between cloud-top radiative cooling, ice sedimentation rates, latent heat-and synoptic scale and surface forcing (Harrington et al. 1999; Harrington and Olsson 2001; Avramov and Harrington 2010; Morrison et al. 2011, 2012; Solomon et al. 2011), the details of which depend on the ice particle properties. Therefore, accurate knowledge of ice and mixed-phase cloud properties is needed for process-oriented understanding as well as development of parameterization schemes for models.

The uncertainty in ice crystal concentrations translates into large uncertainties in sedimentation and single-scattering properties, which affects model evolution. For example, Mitchell et al. (2008) showed that increasing the fraction of ice crystals with $D < 150 \mu m$ compared to the total number concentration induced an upper-tropospheric warming of $3 K$ and a total cloud forcing of $-5 Wm^{-2}$ in the tropics through an increase of cirrus cloud coverage in a global model simulation relative to a control case. On the other hand, Boudala et al.’s (2007) simulation where contributions of crystals with $D < 150 \mu m$ were included had a net radiative forcing of $2.4 Wm^{-2}$ greater than that of a control case where such contributions were excluded. McFarquhar et al. (2003) showed that decreasing the ice crystal effective radius in a parameterization scheme affected the vertical profile of radiative forcing, which in turn impacted low cloud cover and hence longwave radiative forcing. Knowledge of ice crystal concentrations is not only needed for model parameterizations but also for evaluation of nucleation schemes for mixed-phase clouds (Fridlind et al. 2007; Yang et al. 2013a) and remote sensing retrievals (e.g., Yang et al. 2013b).

In situ observations of the number distribution function $N(D)$ are conventionally derived from two classes of cloud probes covering four orders of magnitude in particle size: forward scattering probes such as the Forward Scattering Spectrometer Probe (FSSP), the Cloud Droplet Probe (CDP), and the Cloud and Aerosol Spectrometer (CAS); and optical array probes, such as the two-dimensional cloud probe (2DC), cloud imaging probe (CIP), two-dimensional stereo probe (2DS), precipitation imaging probe (PIP), two-dimensional precipitation probe (2DP), and high-volume precipitation sampler (HVPS). Korolev et al. (2011) photographed ice crystals bouncing and shattering on the 2DC’s hemispheric tips and on a FSSP’s inlet, showing that shattered artifacts could be swept into the probe sample volume contributing to $N(D)$ for $D < 500 \mu m$. Several other studies hypothesized that the $N(D)$ measured by forward scattering and optical array probes is contaminated by the presence of such small crystals generated by the shattering of larger crystals (Cooper 1978; Gardiner and Hallett 1985; Gayet et al. 1996; Field et al. 2003, 2006; Korolev and Isaac 2005; Heymsfield 2007; McFarquhar et al. 2007a, 2011; Jensen et al. 2009; Zhao et al. 2011; Lawson 2011; Febvre et al. 2012; Korolev et al. 2013a,b).

The impact of ice crystal shattering on $N(D)$ from 2DCs is investigated in this paper. Following Korolev et al. (2011, 2013b), two strategies are used to reduce the contributions of shattered artifacts to calculated ice crystal concentrations:

1) Algorithms based on the time between which particles are detected in the sample volume (Field et al. 2003, 2006) and on the numbers, sizes, and gaps between fragments in a single image recorded by a probe (Korolev and Isaac 2005) are used to remove shattered artifacts;

2) 2DC tips modified to deflect most artifacts generated by the shattering of large ice crystals away from the sample volume (Korolev and Isaac 2005; Korolev et al. 2011; Lawson 2011; Korolev et al. 2013a,b) are used.

Previous studies differ on whether the use of algorithms or modified tips is more effective at removing shattered artifacts. Korolev et al. (2011) concluded that the modified tips removed more shattered artifacts than algorithms for the 2DC and CIP, but Lawson (2011) concluded that algorithms were more effective for the 2DS. Typically, a combination of the two approaches removes the most shattered artifacts (McFarquhar et al. 2011). The number of shattered fragments have been hypothesized to depend on a variety of factors, such as particle size, shape, concentration, degree of riming, temperature $T$, true airspeed TAS, aircraft attitude angle, and angle of attack (Vidtaurre and Hallett 2009; Korolev et al. 2011, 2013a,b). The dependence of the shattering on concentration and size were characterized in Korolev et al. (2013b). In this study, data from the Indirect and Semi-Direct Aerosol Campaign (ISDAC) and the 2011 Instrumentation Development and Education in Airborne Science (IDEAS-2011) project in
which 2DCs with both standard and modified tips were installed on the same aircraft are used to answer the following questions:

1) How does the ratio of particle concentrations between standard and modified 2DCs in different size ranges vary as a function of particle size, shape, concentration, temperature, true airspeed, aircraft attitude angles, and angle of attack?

2) How does the ratio of particle concentrations in different size ranges from a 2DC using artifact removal algorithms and not using artifact removal algorithms vary as a function of particle size, shape, concentration, habit, temperature, true airspeed, aircraft attitude angles, and angle of attack?

This extends previous studies in that data from two additional projects using particle probes with different size resolutions and time responses are used to determine the degree to which conventional probes are contaminated by particle shattering and hence assess the degree to which prior data may be correctable. Further, a simplified model is developed to explain how the number of shattered artifacts depends on cloud and environmental parameters.

During ISDAC, the National Research Council (NRC) of Canada Convair-580 flew in the vicinity of Barrow and Fairbanks, Alaska, in April 2008. The NRC Convair-580 flight on 30 April 2008 had two 2DCs installed, one with standard tips and one with modified tips. During IDEAS-2011, the National Science Foundation (NSF)/National Center for Atmospheric Research (NCAR) C-130 flew over Colorado and Wyoming during October and November 2011. Two flights, 25 October and 1 November 2011, in deep precipitating systems generating snowfall over southeastern Wyoming were used because they provided the most data (~5 h) from a standard 2DC and a 2DC with modified tips. Both datasets contain data in ice and mixed-phase clouds, with sampling of a wide range of particle sizes and habits, for a variety of true airspeed from 80 to 150 m s\(^{-1}\), angles of attack from 0° to 7°, roll angles of ~0°, and pitch angles from 0° to 8°.

The remainder of the paper is organized as follows. Section 2 highlights the instrumentation used, sampling strategies, and data collection and processing methods. Section 3 describes the algorithm used to identify shattered artifacts. The effects of the modified tips and shattering removal algorithms on the measurements in different size ranges are discussed in section 4. The principal findings of the study are summarized in section 5.

2. Methodology

a. Instrumentation

Table 1 lists the instruments installed on the two aircraft from which data were used in this study. On each aircraft, the 2DC probes with standard and modified tips were mounted adjacent to each other, as shown in Fig. 1, to minimize the impact of cloud inhomogeneities over larger spatial scales on probe intercomparisons. On the C-130, the 2DC with modified tips was mounted at a 45° angle relative to the 2DC with standard tips. This difference should not have a big impact on the measurement of \(N(D)\) because only particles with large aspect ratios, like columns, should fall with preferential orientation (McFarquhar et al. 1999). The 2DCs on the C-130 were mounted at different locations on a pod, whereas the 2DCs on the NRC Convair-580 were installed on pylons under a wing. Because the different locations of the 2DCs on a pod during IDEAS-2011 could have affected the nature of the shattering, it is important that data from both projects be used to look at common trends. The 2DC data were processed using the algorithms described in section 2b that were originally developed at NCAR and subsequently modified at the University of Illinois at Urbana–Champaign. Because of the poorly defined depth of field and errors related to digitizing of binary images of 2DCs for small ice crystals (Korolev et al. 1998; Baumgardner and Korolev 1997), particles with \(D < 125 \mu m\) are not considered in this study.

### Table 1. List of instrumentation from IDEAS-2011 and ISDAC.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Quantity</th>
<th>Use during ISDAC?</th>
<th>Use during IDEAS-2011?</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DC with standard tips</td>
<td>(N(25 &lt; D &lt; 1600 \mu m)) (IDEAS-2011), (N(25 &lt; D &lt; 800 \mu m)) (ISDAC)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2DC with modified tips</td>
<td>(N(25 &lt; D &lt; 1600 \mu m)) (IDEAS-2011), (N(25 &lt; D &lt; 800 \mu m)) (ISDAC)</td>
<td>Yes, Korolev et al. (2011) design</td>
<td>Yes, 45° angle</td>
</tr>
<tr>
<td>CPI</td>
<td>High-resolution images</td>
<td>Yes</td>
<td>Yes, 1 Nov 2011 only</td>
</tr>
<tr>
<td>RICE</td>
<td>Presence of supercooled water</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>CDP</td>
<td>(N(2 &lt; D &lt; 50 \mu m))</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>FSSP</td>
<td>(N(2 &lt; D &lt; 50 \mu m))</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Pitot-static system</td>
<td>Airspeed, pitch, roll angle, angle of attack</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Rosemount sensor</td>
<td>Ambient air temperature</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
A unique comparison of 2DC size distributions against those measured by the Holographic Detector for Clouds (HOLODEC) instrument is conducted here. The HOLODEC captures a 3D snapshot of up to 20 cm$^3$ volumes of cloud air at a rate of 3.3 Hz. Recorded holograms are numerically reconstructed, yielding the size, shape, and 3D location of cloud particles with $6 \mu m < D < 1$ mm in the sample volume. More details on the holographic technique and HOLODEC are available elsewhere (Fugal et al. 2004; Fugal and Shaw 2009; Fugal et al. 2009; Spuler and Fugal 2011). The 3D nature of the HOLODEC data allows for identification of shattering by analyzing spatial statistics of particle sizes and locations. Particles generated by the shattering
of large crystals on probe tips appear in holograms as clusters of particles with smaller variability in interparticle separation distances than expected from Poisson statistics and are located primarily within the first few centimeters from the edges of the sample volume. This method can be considered a spatial analog of antishattering algorithms that remove ice contamination through interarrival time statistics, such as that employed for the 2DC data described in section 3 of this paper. By analyzing the 3D particle positions in each hologram, individual holograms that contain shattering events can be identified and excluded from the analysis.

Other state and aircraft parameters placed the 2DC in the appropriate context. A pitot-static sensor measured angle of attack. The true airspeed and angle of attack at the 2DCs on the C-130 could be altered by the nearby wings and pod. However, since the 2DC images were not elongated in the time direction, the probe was likely recording the images at the correct clock speed. Therefore, it can be assumed that particles arrive at the probe at approximately the true airspeed.

b. 2DC data processing technique

The software used to process the 2DC data includes corrections to the sample volume for the size dependence of the depth of field (Baumgardner and Korolev 1997). The interarrival time \( \Delta t \) for each particle was the time between the arrival of the current and previously detected particle. The maximum dimension of a particle \( D \) was defined by the maximum length in any direction, not just parallel or perpendicular to the diode array. If a particle was touching the edge of the photodiode array, then it was not detected. The true interarrival time \( \Delta t \) was computed using the image reconstruction technique of Heymsfield and Parrish (1978). SA varies from 102 mm\(^2\) to 234 mm\(^2\) for \( D = 3.2 \) mm for the 64-photodiode 2DC.

The University of Illinois software sorts each particle into nine habit categories following Holroyd (1987). To correct for the overshizing of hollow spherical particles due to diffraction, the correction algorithm of Korolev (2007) adjusts \( D \) for particles classified as spheres. Diffraction effects are also possible for nonspherical particles, but there are no existing algorithms to correct for such effects.

Each particle is accepted or rejected based on a series of criteria designed to remove spurious stuck bits, splash artifacts, blank records, and streaker particles. With \( A_p \) representing the projected area of the particle, \( L \) representing the length of the particle in the direction perpendicular to the diode array, and \( W \) representing the length of the particle in the direction parallel to the diode array, a particle is rejected if (i) \( L/W > 5 \) (6 if a particle touches the edge) to remove streakers and stuck bits with large aspect ratios, and (ii) if \( A_p/[(\pi/4)D^2] < 0.2 \) to remove particles such as stuck bits and streakers with a low number of shaded photodiodes relative to a shaded circle with diameter \( D \).

Korolev and Isaac (2005) concluded that the presence of three or more isolated images in an identified particle were likely shattering events because the 2DC only detects multiple particles as a single particle when there are at least two slices between particles. This corresponds to a \( \Delta t \) of at most 6.2 \( \times 10^{-7} \) s at an airspeed of 100 m s\(^{-1}\). Single particles with three or more fragments typically have a low percentage of shaded area \( A/LW \). Images with \( A/LW < 0.25 \) were thus classified as shattering particles following Lawson (2011). This criterion classified 3.7% of all particles imaged by the 2DC with standard tips and 2.1% of the particles from the 2DC with modified tips as shattering artifacts during ISDAC and IDEAS-2011.

c. Derivation of median mass diameter

To estimate the mass distribution function \( M(D) \), information about the relationship between crystal mass \( m \) and \( D \), which depends on ice crystal habit, is required. Following Jackson et al. (2012), two different techniques were used for estimating \( M(D) \). The mass distribution function \( M(D) \) was derived as

\[
M(D) = \sum_j \sum_h f_h(D_j) \alpha_h D_j^{\beta_h} N(D_j) \Delta D_j,
\]

where \( f_h(D_j) \) is the fraction of crystals in the bin centered at \( D_j \) having crystal habit \( h \), \( \alpha_h \) and \( \beta_h \) are habit-dependent coefficients listed in Table 2 that define the mass of an individual crystal \( m = \alpha_h D_j^{\beta_h} \), and \( N(D_j) \) is the number distribution function for bin \( j \) with midpoint \( D_j \) and width \( \Delta D_j \). For 30 April 2008 and 1 November 2011, the 2.3-\( \mu \)m resolution cloud particle imager (CPI) images were used to determine \( f_h(D_j) \) using the habit classification scheme of Um and McFarquhar (2009). Because the CPI has a smaller sample volume than the 2DC, the averaging period required to obtain a statistically significant sample (Hallett 2003) is larger, and hence the habit distributions were applied to each of the 2DC size distributions occurring within the CPI averaging period. The three-view CPI (3V-CPI) was not installed on the NSF/NCAR C-130 on 25 October 2011, so \( f_h(D_j) \) were derived from the 2DC data using the Holroyd (1987) technique for that day. The \( M(D) \) was then used to derive the median mass diameter \( D_{\text{mm}} \).
d. Overview of flights

Data from three flights were used in this study. On 25 October 2011, a 1000-hPa low pressure system moved southward through southern Wyoming into Colorado and produced a deep precipitating stratocumulus that persisted over Cheyenne, Wyoming, for ~12 h. On 1 November 2011, a 1012-hPa low pressure system moved southward through southern Wyoming into Colorado and produced another deep precipitating system that persisted over Cheyenne for ~12 h. On both sorties the NSF/NCAR C-130 penetrated the deformation zone of the system over Cheyenne in an ascending spiral pattern from a height of 2 km to a height of 7 km for 1 h followed by a descending spiral pattern for 30 min from a height of 7 km to a height of 2 km at airspeeds from 90 to 150 m s\(^{-1}\) and sampling temperatures from 0° to 30°C.

On 30 April 2008, cold (<0°C) air from a 1036-hPa high pressure system over the North Pole encountered a warm (>0°C) air mass from a 1006-hPa low pressure center located about 500 km east of Fairbanks, Alaska. This produced a cold front that provided forcing for a precipitating multilayer mixed-phase stratocumulus cloud system over Nenana and Fairbanks. The NRC Convair-580 ascended from the ground at Fairbanks to 7 km above Nenana for 20 min, and then it performed a descending spiral from a height of 7 km to a height of 1.5 km for 15 min followed by a 15-min ascending spiral from a height of 1.5 km to a height of 7 km through the cloud system before returning to Fairbanks. The NRC Convair-580 sampled from 0.5 km (~−5°C) to 7 km (~−40°C) at airspeeds from 50 to 120 m s\(^{-1}\).

No data on these three flights were collected in exclusively liquid-phase conditions. A phase identification scheme (McFarquhar et al. 2007b; Jackson et al. 2012) using information from a Rosemount icing detector (RICE), the shape of forward scattering spectrometer probe size distributions, and manual inspection of 2DC/CPI imagery divided all 1-s averaged measurements in clouds into mixed- and ice-phase conditions.

3. Interarrival time analysis

This section provides the basis for defining the threshold particle \(\Delta t\) below which all particles are identified as shattered artifacts. The dependencies on the frequency distribution of \(\Delta t\) are also explored using a Monte Carlo simulation.

To remove the greatest number of particles from the shattered particle mode while removing the fewest from the natural particle mode at larger \(\Delta t\), Field et al. (2006) calculated the best fit of a normalized frequency distribution \(dP(\Delta t)/d\ln\Delta t\) to a bimodal Poisson probability density function given by

\[
\frac{dP(\Delta t)}{d\ln\Delta t} = (1 - A) \frac{\Delta t}{\tau_1} \exp\left( - \frac{\Delta t}{\tau_1} \right) + (A) \frac{\Delta t}{\tau_2} \exp\left( - \frac{\Delta t}{\tau_2} \right),
\]

(2)

where \(\tau_1, \tau_2\) represent the \(\Delta t\) for the natural and shattered particle modes, respectively; and \(A\) represents the relative contribution of the shattered particle mode to \(dP(\Delta t)/d\ln\Delta t\). Field et al. (2006) classified particles with \(\Delta t_s < 2\tau_2\) as shattered artifacts in order to remove 90% of the particles from the second mode. The initial particle arriving before this identified artifact, which frequently had \(\Delta t_s > 2\tau_2\), was also classified as a shattered artifact.

Normalized frequency distributions of \(\Delta t\) from the standard and modified 2DCs for all three flights are shown in Figs. 2 and 3 for ice-phase and mixed-phase conditions, respectively. All frequency distributions exhibit two modes: the first mode at larger \(\Delta t\) represents natural particles and the second mode at smaller \(\Delta t\) represents shattered artifacts (Field et al. 2003, 2006). To account for natural particles that may be removed by

### Table 2. List of \(m-D\) relationships used in Eq. (1).

<table>
<thead>
<tr>
<th>Habit</th>
<th>(m-D) relationships</th>
<th>(a) (g cm(^{-3}))</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiny</td>
<td>Brown and Francis (1995)</td>
<td>0.002 94</td>
<td>1.9</td>
</tr>
<tr>
<td>Oriented</td>
<td>Brown and Francis (1995)</td>
<td>0.002 94</td>
<td>1.9</td>
</tr>
<tr>
<td>Linear</td>
<td>Mitchell (1996), “hexagonal columns”</td>
<td>0.001 66 (125 &lt; (D) &lt; 300 (\mu)m)</td>
<td>1.91 (125 &lt; (D) &lt; 300 (\mu)m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.000 907 ((D) &gt; 300 (\mu)m)</td>
<td>1.74 ((D) &gt; 300 (\mu)m)</td>
</tr>
<tr>
<td>Aggregate</td>
<td>Brown and Francis (1995)</td>
<td>0.002 94</td>
<td>1.9</td>
</tr>
<tr>
<td>Irregular</td>
<td>Brown and Francis (1995)</td>
<td>0.002 94</td>
<td>1.9</td>
</tr>
<tr>
<td>Graupel</td>
<td>Mitchell (1996), “lump graupel”</td>
<td>0.049</td>
<td>2.8</td>
</tr>
<tr>
<td>Dendrite</td>
<td>Mitchell (1996), “broad-branched crystal”</td>
<td>0.000 516</td>
<td>1.80</td>
</tr>
<tr>
<td>Plate</td>
<td>Mitchell (1996), “hexagonal plate”</td>
<td>0.007 39</td>
<td>2.45</td>
</tr>
</tbody>
</table>
excluding particles with $\Delta t_0 < 2\tau_2$, the number concentrations are multiplied by $1/(2e^{-\tau_2/\tau_1} - 1)$ (Field et al. 2006). Fits to the normalized frequency distributions for ice- and mixed-phase conditions sampled during each flight were performed using Eq. (2) with the results depicted in Figs. 2 and 3. For the mixed-phase conditions encountered on all three sorties, $dP(\Delta t)/d\ln\Delta t$ is still bimodal. The $A$ for the 2DC with standard tips varies from 0.20 to 0.29, while $A$ from the 2DC with modified tips varies from 0.00 to 0.17 in mixed-phase conditions. Meanwhile, $A$ from the 2DC with standard tips varies from 0.20 and 0.29 and $A$ from the 2DC with modified tips varies from 0.06 to 0.17 in ice-phase conditions. This suggests shattered artifacts are likely still present in the mixed-phase conditions because of the presence of ice.

The $\tau_1$ and $\tau_2$ were, in general, larger for ISDAC than for IDEAS-2011. To assess the differences in $\tau_1$, $\tau_2$, $A$, and $dP(\Delta t)/d\ln\Delta t$ between projects, Monte Carlo simulations of particle shattering events were performed. For these simulations, particles with the median maximum dimension of 650 $\mu$m recorded by the 2DC with modified tips with concentration $N_{\text{natural}}$ were assumed...
to arrive at an SA of 125 mm$^2$ for the 64-diode 2DC and an SA of 74.6 mm$^2$ for the 32-diode 2DC. The particles were traveling at a TAS and were randomly distributed according to Poisson statistics. Particles also arrived according to Poisson statistics at the location of the probe tips, which had a cross-sectional area TA of 92 mm$^2$. Upon contact, the particles were assumed to shatter into a train of $n$ fragments that were distributed according to Poisson statistics across some length $l$ in the direction of the flight as demonstrated in Fig. 4. The probability of a single fragment entering the sample volume is given by $K$ and was assumed to be independent of the probability of any other fragment entering the volume. Thirty-second simulations with varying $N_{natural}$, TAS, $l$, and $n$ were run 100 different times to create 100 different versions of $dP(\Delta t)/d\ln \Delta t$. The $\tau_1$, $\tau_2$, and $A$ were then determined from the best fit of Eq. (2) to the average of the 100 versions of $dP(\Delta t)/d\ln \Delta t$.

The sensitivity of $\tau_1$, $\tau_2$, and $A$ to $N_{natural}$, $l$, $n$, and TAS were explored in these idealized simulations and provide guidance on what factors determine the locations and relative importance of modes corresponding to natural and shattered particles. The results are shown in Fig. 5, with the coefficients of the linear best-fit lines, Pearson correlation coefficient $R$, and the significance

Fig. 3. As in Fig. 2, but for all mixed-phase time periods.
level of the correlation coefficient $p$, according to an $F$ test listed in Table 3. For each panel in Fig. 5, one variable was allowed to vary while the other variables were kept constant at the control values listed in the caption of Fig. 5. The $\tau_1$, $\tau_2$, and $A$ are assumed to be correlated in a statistically significant sense and dependent on $N_{\text{natural}}$, $l$, $n$, or TAS when $p_r < 0.05$ and when $\tau_1$, $\tau_2$, and $A$ vary by more than the width of the 95% confidence interval. The range of $N_{\text{natural}}$ and TAS used in the simulations was selected from the ranges observed during ISDAC and IDEAS-2011. The $l$ varies from 0 to 10 cm, as Korolev et al. (2011) stated that $l$ does not typically exceed 10 cm. The formvar replicator data of Vidaurre and Hallett (2009) was used to define the range of $n$ values from 0 to 200. From Table 3 and Figs. 5a, 5d, and 5g, it is seen that $\tau_1$ is inversely correlated with and dependent on $N_{\text{natural}}$ and TAS, but not on $l$ or $n$. In addition, $\tau_1$ does not change when $K$ decreases from 5% to 0.5%. The decrease of $\tau_1$ with $N_{\text{natural}}$ is consistent with ISDAC and IDEAS-2011 observations because...
FIG. 5. (a)–(l) Best-fit parameters $\tau_1$, $\tau_2$, and $A$ to Eq. (2) of the mean $P(\Delta t)$ of all ensemble simulations described in section 3. The 95% confidence intervals of $\tau_1$, $\tau_2$, and $A$ are shown as error bars as a function of $N_{\text{natural}}$, TAS, $l$, and $n$. The control values of all parameters in each panel are $l = 1$ cm, $N_n = 1$ L$^{-1}$, $\text{TAS} = 100$ m s$^{-1}$, $k = 5\%$, and $n = 10$. 
particles arrived in the sample volume more frequently when there were more of them; similarly, increases in TAS lead to a more frequent arrival of particles. On the other hand, \( \tau_1 \) is independent of the number or spacing between shattered particles or how many shattered particles enter the sample volume because it is describing only the mode of naturally occurring particles.

In Table 3, \( \tau_2 \) is significantly correlated with and dependent on \( N_{\text{natural}} \) and \( l \), and inversely correlated with and dependent on TAS and \( n \). Artifacts arrive in the sample volume more frequently if either the number of artifacts or airspeed increases, or if the same number of artifacts is spread over a smaller distance. The \( \tau_2 \) is also smaller when \( K \) is larger because a larger fraction of particles enters the sample volume. Although \( A \) is sometimes correlated with \( N_{\text{natural}} \), \( l \), and TAS with \( p_2 < 0.05 \), \( A \) does not depend on these variables because it is approximately constant. Term \( A \) is correlated with \( n \) because when more fragments are generated by a collision, there are more particles to contribute to the mode of \( dP(\Delta t)/d\ln\Delta t \) corresponding to shattered artifacts. The lack of dependence of \( A \) on TAS is probably not realistic because the number of fragments generated by a collision may increase with increasing TAS; however, there were no data to determine a relationship between \( n \) and TAS and hence no such dependence was assumed.

These simulations show that \( \tau_1 \) is correlated with \( N_{\text{natural}} \) and TAS, while \( \tau_2 \) also depends on \( l \) and \( n \) as well as \( N_{\text{natural}} \) and TAS. However, the \( n \), \( k \), and \( l \) could not be identified from the 2DC observations. Therefore, to place the idealized simulations in context of the ISDAC and IDEAS-2011 observations, simulations where performed where parameters related to particle shattering, (i.e., \( n \), \( k \), and \( l \)) were kept constant, while parameters related to how natural particles arrive in the sample volume were varied corresponding to each 1-s averaged TAS and \( N_{\text{natural}} \) measured by the 2DCs with modified tips processed using the shattered artifact removal algorithms. Figure 6 shows \( dP(\Delta t)/d\ln\Delta t \) generated from all the simulations for ISDAC and IDEAS-2011 separately. As in the observations shown in Fig. 2, the \( \tau_1 \) of 0.015 s for ISDAC is greater than the \( \tau_1 \) of 0.0053 s for IDEAS-2011. Further, Fig. 6 shows that there is reasonable similarity in the \( dP(\Delta t)/d\ln\Delta t \) obtained from the simulations and those obtained from Poisson statistics using the given \( \tau_1, \tau_2, \) and \( A \) in Eq. (2) from the simulations. But, the simulated \( dP(\Delta t)/d\ln\Delta t \) is wider than that generated by Eq. (2) for the mode at \( \tau_1 \). Since \( \tau_1 \) is related to TAS and \( N_{\text{natural}} \), this is likely caused by the superposition of many different natural particle modes of \( dP(\Delta t)/d\ln\Delta t \) from periods with different TAS and \( N_{\text{natural}} \) periods during ISDAC and IDEAS-2011. This and the correlation between \( \tau_1 \) and \( N_{\text{natural}} \), and \( \tau_1 \) and TAS, show that differences in \( \tau_1 \) between ISDAC and IDEAS-2011 can be explained by differences in how often natural particles are arriving at the probe sample volume.

In Fig. 6, \( \tau_2 \) for ISDAC is \( 1.1 \times 10^{-4} \) s, higher than \( \tau_2 \) of \( 9.1 \times 10^{-5} \) s for IDEAS-2011. The \( A \) from the 2DC with modified tips is 0.20 for ISDAC and 0.14 for IDEAS-2011, whereas the \( A \) from the 2DC with standard tips is 0.20 and 0.28 for ISDAC and IDEAS-2011, respectively. Therefore, the changes in simulated \( \tau_2 \) and \( A \) between ISDAC and IDEAS-2011 are smaller than, but consistent with, changes in the observed \( \tau_2 \) and \( A \). Therefore, even though \( \tau_2 \) is related to TAS and \( N_{\text{natural}} \), the fact that simulated changes are smaller than observed changes in \( \tau_2 \) and \( A \) show that the variability in \( n \), \( k \), and \( l \) from changes in ice crystal habit, size, density, impact velocity, angle of impact, temperature, and angle of attack (Korolev et al. 2011, 2013b) are likely greater factors in determining \( \tau_2 \) and \( A \) than changes in TAS and \( N_{\text{natural}} \). In addition, the different mounting locations of the 2DCs during ISDAC and IDEAS-2011 during

<table>
<thead>
<tr>
<th>Fit displayed</th>
<th>( K = 5% )</th>
<th>( R, p_1 ) (( K = 5% ))</th>
<th>( k = 0.5% )</th>
<th>( R, p_1 ) (( k = 0.5% ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best fit of ( \tau_1 ) vs ( n )</td>
<td>( \tau_1 = -1.2 \times 10^{-9}n + 0.076 )</td>
<td>(-0.26, 0.43)</td>
<td>( \tau_1 = 4.1 \times 10^{-9}n + 0.076 )</td>
<td>( 0.61, 0.05)</td>
</tr>
<tr>
<td>Best fit of ( \tau_1 ) vs TAS</td>
<td>( \tau_1 = 0.00091 \text{TAS} + 0.17 )</td>
<td>(-0.95, 0.00)</td>
<td>( \tau_1 = -0.0095 \text{TAS} + 0.18 )</td>
<td>(-0.96, 0.00)</td>
</tr>
<tr>
<td>Best fit of ( \tau_1 ) vs ( l )</td>
<td>( \tau_1 = -0.0002l + 0.0735 )</td>
<td>(-0.51, 0.02)</td>
<td>( \tau_1 = -0.0002l + 0.0735 )</td>
<td>(-0.47, 0.04)</td>
</tr>
<tr>
<td>Best fit of ( \tau_1 ) vs ( N_n )</td>
<td>( \tau_1 = 0.026 \exp(-0.07N_n) )</td>
<td>(-0.90, 0.00)</td>
<td>( \tau_1 = 0.027 \exp(-0.07N_n) )</td>
<td>(-0.90, 0.00)</td>
</tr>
<tr>
<td>Best fit of ( \tau_2 ) vs ( n )</td>
<td>( \tau_2 = -4.4 \times 10^{-7}n + 6.7 \times 10^{-5} )</td>
<td>(-0.97, 0.00)</td>
<td>( \tau_2 = -4.4 \times 10^{-7}n + 1.2 \times 10^{-4} )</td>
<td>(-0.74, 0.01)</td>
</tr>
<tr>
<td>Best fit of ( \tau_2 ) vs TAS</td>
<td>( \tau_2 = -9.4 \times 10^{-4} \text{TAS} + 1.8 )</td>
<td>(-0.95, 0.00)</td>
<td>( \tau_2 = 1.5 \times 10^{-5} \text{TAS} + 2.9 \times 10^{-4} )</td>
<td>(-0.96, 0.00)</td>
</tr>
<tr>
<td>Best fit of ( \tau_2 ) vs ( l )</td>
<td>( \tau_2 = 7.51 \times 10^{-4}l + 0.0735 )</td>
<td>(-0.87, 0.00)</td>
<td>( \tau_2 = 7.55 \times 10^{-4}l + 0.027 )</td>
<td>(-0.86, 0.00)</td>
</tr>
<tr>
<td>Best fit of ( \tau_2 ) vs ( N_n )</td>
<td>( \tau_2 = -3.9 \times 10^{-7}N_n + 6.5 \times 10^{-5} )</td>
<td>(-0.73, 0.01)</td>
<td>( \tau_2 = -2 \times 10^{-8}N_n + 1.3 \times 10^{-4} )</td>
<td>(-0.80, 0.01)</td>
</tr>
<tr>
<td>Best fit of ( A ) vs ( n )</td>
<td>( A = 0.0023n + 0.62 )</td>
<td>(0.64, 0.04)</td>
<td>( A = 0.0033n + 0.26 )</td>
<td>(0.88, 0.00)</td>
</tr>
<tr>
<td>Best fit of ( A ) vs TAS</td>
<td>( A = 4.1 \times 10^{-5} \text{TAS} + 0.68 )</td>
<td>(-0.32, 0.34)</td>
<td>( A = 8.7 \times 10^{-5} \text{TAS} + 0.19 )</td>
<td>(0.09, 0.80)</td>
</tr>
<tr>
<td>Best fit of ( A ) vs ( l )</td>
<td>( A = -0.0008l + 0.689 )</td>
<td>(-0.87, 0.00)</td>
<td>( A = -0.0034l + 0.201 )</td>
<td>(-0.49, 0.03)</td>
</tr>
<tr>
<td>Best fit of ( \tau_1 ) vs ( N_n )</td>
<td>( A = -0.006N_n + 0.68 )</td>
<td>(-0.99, 0.00)</td>
<td>( A = -0.0012N_n + 0.16 )</td>
<td>(-0.97, 0.00)</td>
</tr>
</tbody>
</table>
ISDAC and IDEAS-2011 could have affected the shattered artifacts and contributed to the variations in magnitude and location of the shattered particle mode for ISDAC and IDEAS-2011. The fact that the simulations cannot reproduce the differences in $t^2$ and $A$ during ISDAC and IDEAS-2011 shows that further understanding on how particle size, habit, airspeed, angle of attack, and probe configuration affect $n$, $k$, and $l$ is required.

The observation of bimodal interarrival time distributions also could occur if there was a plausible natural mechanism through which ice crystals could form such clusters. One potential explanation for such particle clustering would be the inertial response of particles within a turbulent flow, sometimes referred to as preferential concentration (Siebert et al. 2010). Careful laboratory measurements of the inertial clustering of water droplets in homogeneous isotropic turbulence (Saw et al. 2012) showed that the correlation function increases smoothly and monotonically with decreasing length scale. Figure 4 from Saw et al. (2012) shows that the correlations at $r/r_K > 30$ (where $r$ is the droplet separation distance and $r_K$ is the Kolmogorov microscale, approximately 1 mm for typical cloud turbulence) are due to turbulent mixing and the correlations at scales less than $r/r_K \approx 30$ are due to inertial clustering. These measurements were for weakly inertial particles with relatively minimal gravitational settling, so ice crystals would be expected to behave somewhat differently. In particular, ice particles are typically more sparse in tropospheric clouds than are water drops, so it may take long times for them to come together because of turbulence. Further, larger differences in terminal fall speeds of ice crystals may prohibit the maintenance of such crystals even if they form. Thus, the explanation of natural clustering seems unlikely for the quick interarrival times of ice crystals.

4. Uncertainty in $N(D)$ due to the presence of shattered artifacts

a. Assessment of algorithms and modified tips

In the remainder of this paper, subscripts $s$ ($m$) are used to denote standard (modified) tips and superscripts $a$ (na) denote that algorithms were (were not) used to derive number concentration $N$ from the 2DC probes. For example, $N_{na}$ is the number concentration of particles from the 2DC with standard tips without the use of algorithms. The mean and range of the ratio of the
number concentration from the 2DC using standard tips $N_s$ to that from the 2DC using modified tips $N_m$ in differing size ranges is plotted as a function of median mass diameter $D_{mm}$ derived from the 2DC with modified tips for ice-phase conditions during IDEAS-2011 in Fig. 7 and during ISDAC in Fig. 8. The mean and ranges were determined from all 10-s averaged size distributions (SDs) within the 0.15-mm $D_{mm}$ bin on the horizontal axis. The ISDAC data are cutoff at a smaller $D_{mm}$ because of the use of a 32-photodiode 2DC instead of the 64-photodiode 2DC used during IDEAS-2011. Even with application of reconstruction techniques, only particles with $D_{mm} > 1.6$ mm could be detected with any statistical significance during ISDAC. Hence, $D_{mm}$ may have been underestimated for the ISDAC data.

Figures 7a, 7b, 8a, and 8b show that $N_s^a/N_m^a > 2$ for $125 < D < 300 \mu m$ and $300 < D < 500 \mu m$ for $D_{mm} > 1.6$ mm, meaning that algorithms do not remove all shattered particles. This is consistent with Korolev et al.’s (2011, 2013b) findings from the Airborne Icing Instrumentation Evaluation Experiment.

During IDEAS-2011, the $R$ between $N_s^a/N_m^a$ of $125 < D < 300 \mu m$ with $D_{mm}$ was 0.47, and between $N_s^a/N_m^a$ at $300 < D < 500 \mu m$ and $D_{mm}$ was 0.42. For ISDAC, these correlation coefficients were 0.39 and 0.30, respectively. The increase of $N_s^a/N_m^a$ with $D_{mm}$ is consistent with previous studies that showed the likelihood of a particle shattering on the 2DC hemispheric tips is related to particle size (Korolev and Isaac 2005), particle mass, and impact velocity (Vidaurre and Hallett 2009). Another significant finding is that $N_s^a/N_m^a < 2$ for $D > 500 \mu m$, indicating that the shattered artifacts are smaller than $500 \mu m$ for the two diverse datasets examined. However, since there were no environments with little to no shattering potential sampled, nor were there any flights where two 2DCs with identical tips flown on the same aircraft, a comparison to determine the possible effects of the differences in 2DC electronics and mounting position on $N_s/N_m$ was not performed, yet these factors can potentially have an effect on $N_s/N_m$. Despite these differences, a similar threshold for shattered artifacts as in other projects using probes with different response times and resolutions (Korolev et al. 2011, 2013a) were found. Therefore, this 500-μm threshold seems to apply to most 2DC probes and over the types of ice crystals observed in field projects thus far.

Figure 9 examines the effect of the artifact removal algorithms on concentrations in different size ranges by plotting the ratio of concentrations determined using algorithms $N^a$ to those calculated without the use of algorithms $N^{ma}$ as a function of $D_{mm}$ for probes with both standard and modified tips. During IDEAS-2011 $N_s^a/N_s^{ma}$ for $125 < D < 300 \mu m$ and $300 < D < 500 \mu m$ increases from 1 to 10 as $D_{mm}$ increases. Increases with $D_{mm}$ were also noted for ISDAC, with, for example, $N_s^a/N_s^{ma}$ consistently greater than 2 for $125 < D < 300 \mu m$. This
shows that the use of algorithms alone did not remove all shattered artifacts for particles $125 < D < 500 \mu m$, consistent with Korolev et al.’s (2011) findings. This indicates that the use of both shattered artifact removal algorithms and modified tips is important for removing shattered artifacts in 2DC data.

The relative importance of the probe tips and shatter removal algorithms can be compared by examining Figs. 7 and 9. For IDEAS-2011, the impact of the shatter removal algorithms with standard probe tips is seen in Fig. 9 as $N_m^{na}/N_m^{a}$ at $125 < D < 300 \mu m$ and $300 < D < 500 \mu m$ vary from 1 to 10 and from 1 to 5, respectively. In Fig. 7 the modified tips remove a similar fraction of particles when algorithms are not applied first with $N_m^{na}/N_m^{a}$ at $125 < D < 300 \mu m$ and at $300 < D < 500 \mu m$ varying from 1 to 10 and from 1 to 5, respectively. Further, the differences between concentrations determined by applying and not applying algorithms to data collected by probes with modified tips, and determined from the standard and modified probes after algorithms are first applied are similar. Thus, for the IDEAS-2011 data, the modified tips removed a similar number of artifacts as the shatter removal algorithms.

However, a different finding is obtained when inspecting the ISDAC data. In Figs. 9c and 9d, $N_m^{na}/N_m^{a}$ at $125 < D < 300 \mu m$ and $300 < D < 500 \mu m$ vary from 1 to 3, while $N_m^{na}/N_m^{a}$ at $125 < D < 300 \mu m$ and $300 < D < 500 \mu m$ vary from 1 to 7 in Fig. 8, indicating that the tips removed more particles than did the algorithms. The reason for the difference in findings between IDEAS-2011 and ISDAC is not known, but may be due to the different response times of probes affecting how well the 2DCs detect small particles or may be due to different distributions of particles or mounting locations of the probes in the two projects. Given the differences between IDEAS-2011 and ISDAC, and given that probes with different response times, designs, configurations, and resolutions are still in use, the important conclusion is that both techniques must be applied to remove the majority of shattered artifacts for IDEAS-2011 and ISDAC.

Figures 10a and 10b show the mean $N_m^{na}(D)$, $N_m^{a}(D)$, $N_m^{na}(D)$, and $N_m^{a}(D)$ for all ice-phase conditions during IDEAS-2011 and ISDAC, respectively. The bootstrap technique (Efron and Tibshirani 1993; McFarquhar and Heymsfield 1997) generates alternate versions of the average SDs by randomly drawing, with replacement, from the population of SDs. The standard deviations in $N(D)$ from the alternate average SDs from the bootstrap technique were then displayed as error bars. These error bars show that $N_m^{na}(D)$ is greater than $N_m^{a}(D)$, $N_m^{na}(D)$, and $N_m^{a}(D)$ in a statistically significant
manner for $D < 400\,\mu m$. This indicates that the shattered artifacts most likely have $D < 400\,\mu m$ for IDEAS-2011 and ISDAC.

**b. Comparison with $N(D)$ measured by HOLODEC**

The analysis in section 4a showed that the use of modified tips and algorithms combined removed more shattered artifacts than the use of either technique alone. However, it is not known whether the two methods combined remove all artifacts. As shown in Korolev et al. (2013b), they may also remove naturally occurring crystals. To further investigate the fidelity of the size distributions derived from the 2DC, the 2DC SDs were compared against those measured by the HOLODEC because its unique 3D nature gives an alternate viewpoint for detecting and eliminating shattered artifacts, and hence offers an independent confirmation on the extent to which the modified tips and algorithms remove shattered particles.

Figure 10c shows $N(D)$ measured by the 2DCs with and without modified tips and by the HOLODEC. The HOLODEC has Korolev-style antishattering tips installed, which may account for the minor difference between the calculated $N(D)$ for $D > 125\,\mu m$ when shatter detection algorithms are and are not applied to $N(D)$ from the HOLODEC. Both $N(125 < D < 300\,\mu m)$ from the HOLODEC and the 2DC modified tips have values around $5 \times 10^{-3} \, L^{-1} \, \mu m^{-2}$ in Fig. 10c. It is emphasized that the 2DC and HOLODEC instruments are fundamentally different measurement methods (focused imaging vs digital reconstruction of an interference pattern, respectively), with distinct spatial
sampling methodology (continuous sampling of single particles versus instantaneous sampling of volumes containing multiple particles, respectively) and distinct identification of shattering events (temporal statistics vs spatial statistics, respectively). Expression \( N(125 < D < 300 \mu m) \) from the 2DC with standard tips is around \( 3 \times 10^{-2} \text{L}^{-1} \mu m^{-3} \), or about 6 times higher than \( N(D) \) from both the HOLODEC and 2DC with modified tips. Thus, this further demonstrates that the modified tips should be used in combination with shattered artifact removal algorithms for the cloud conditions sampled on 25 October 2011. Only particles with \( D > 125 \mu m \) from the HOLODEC probe are included in Fig. 10c. Because there are few, if any, probes that provide accurate measurements of the numbers of particles with \( D < 125 \mu m \), such particles may also make large and unknown impacts on quantifying the effects of shattering on \( N(D) \). Further, because of the limited amount of HOLODEC data available for this study, more data collected in projects with a 2DC with standard tips, a 2DC with modified tips, and a HOLODEC should be collected for a wide range of aircraft, probe configurations, and cloud conditions to test the generality of the conclusion presented here.

c. Dependence of shattering on other parameters

Although section 4a showed that \( N_{na}^{ns}/N_{m}^{na} > 1 \) for \( D < 500 \mu m \) with \( N_{na}^{ns}/N_{m}^{na} \) increasing with \( D_{mm} \), there was still substantial spread in \( N_{na}^{ns}/N_{m}^{na} \) for the same \( D_{mm} \), showing other factors influence the amount of shattering. To identify the cause of this spread, the correlation between \( N_{na}^{ns}/N_{m}^{na} \) for \( 125 < D < 300 \mu m \) and \( 300 < D < 500 \mu m \) with true airspeed, angle of attack, pitch angle, roll angle, airspeed, and \( T \) was examined. Algorithms to remove shattered artifacts were not used in this analysis to more easily identify the presence of shattered artifacts.

Table 4 shows that \( N_{na}^{ns}/N_{m}^{ns} \) for both \( 125 < D < 300 \mu m \) and \( 300 < D < 500 \mu m \) had a correlation coefficient of \( R \approx 0.5 \) with \( T \). The correlation coefficients of \( N_{na}^{ns}/N_{m}^{ns} \) for \( 125 < D < 300 \mu m \) and \( 300 < D < 500 \mu m \) with airspeed \( (R \approx -0.3) \), roll angle \( (R \approx -0.2) \), and angle of attack \( (R \approx -0.1) \) were weaker. No angle-of-attack data were available on 30 April 2008 during ISDAC. The likelihood of shattering is expected to be proportional to the particle’s impact velocity (Vidaurre and Hallett 2009), and the likelihood of shattered particles entering the sample volume is expected to increase when the drag force (pressure) is lower (Korolev et al. 2013a). Therefore, the correlation coefficients of \( \sim 0.6 \)
between \(N_s^{na}/N_m^{na}\) and pressure, and the weak correlation coefficient of \(R \approx -0.3\) between \(N_s^{na}/N_m^{na}\) at 125 < \(D < 300\) \(\mu\text{m}\) and 300 < \(D < 500\) \(\mu\text{m}\) with airspeed at first seem inconsistent with expectations. However, the correlation coefficient between airspeed and \(T\) was –0.51 and, between airspeed and pressure was 0.97 as the aircraft flew faster at higher altitudes and lower pressures. Further, \(D_{mm}\) were smaller at lower temperatures and pressures, hence explaining the weaker correlations. The counterintuitive lack of correlations with airspeed, angle of attack, and pitch attitude show that particle type is perhaps the dominant factor in influencing the amount of shattering rather than aircraft parameters. Therefore, a larger dataset stratified by particle type is needed to further address the causes of the scatter illustrated in section 4a.

Table 5 shows the correlations calculated over time periods when \(D_{mm} < 1.6\) mm and \(D_{mm} > 1.6\) mm separately in order to account for the dependence of \(N_s^{na}/N_m^{na}\) at 125 < \(D < 300\) \(\mu\text{m}\) and 300 < \(D < 500\) \(\mu\text{m}\) on \(D_{mm}\). The correlation coefficient between \(N_s^{na}/N_m^{na}\) at 125 < \(D < 300\) \(\mu\text{m}\) and 300 < \(D < 500\) \(\mu\text{m}\), and between \(T\) and pressure are still around –0.5 for both \(D_{mm} < 1.6\) mm and \(D_{mm} > 1.6\) mm in Table 5.

The \(N_s^{na}/N_m^{na}\) in two different size ranges as a function of \(D_{mm}\) for \(T > -8^\circ\text{C}\) and \(< -8^\circ\text{C}\) for data collected during IDEAS-2011 and ISDAC is shown in Fig. 11. The \(N_s^{na}/N_m^{na}\) at 125 < \(D < 300\) \(\mu\text{m}\) and 300 < \(D < 500\) \(\mu\text{m}\) is greater when \(T > -8^\circ\text{C}\) (the median \(T\) observed), according to a Mann–Whitney \(U\) test at a 99% significance level for \(D_{mm} > 1600\) \(\mu\text{m}\) for IDEAS-2011. However, they were similar for \(T > -8^\circ\text{C}\) and \(T < -8^\circ\text{C}\) during ISDAC. It is hard to interpret shattering solely in terms of \(T\), as particle growth habits are determined by a multitude of factors and because crystals are typically not observed at the \(T\) where they grow. Figures 11e and 11f show representative images of ice particles obtained by the CPI with \(D > 1\) mm from the 1 November 2011 flight for \(T > -8^\circ\text{C}\) and \(T < -8^\circ\text{C}\), respectively. At \(T < -8^\circ\text{C}\), rimed particles were observed 11% of the time in ice-phase conditions, while they were observed 62% of the time in ice-phase conditions at \(T > -8^\circ\text{C}\). This suggests the dependence on \(T\) for the IDEAS-2011 data might actually originate from a dependence on riming. The lack of dependence on \(T\) for ISDAC is consistent with this result because rimed particles were observed only 0.03% of the time for all temperatures sampled during that project.

To quantitatively determine the dependence of \(N_s^{na}/N_m^{na}\) on the degree of riming. Fig. 12 shows \(N_s^{na}/N_m^{na}\) in two different size ranges as a function of \(D_{mm}\) and separated according to whether particles were identified as graupel or dendrites following Holroyd (1987), namely, whether the perimeter divided by the area of particles with \(D > 0.5\) mm \(S < 0.013\) \(\mu\text{m}^{-1}\) versus when \(S > 0.013\) \(\mu\text{m}^{-1}\). Particles with \(D < 500\) \(\mu\text{m}\) were not used in the calculation to avoid contamination from shattered artifacts. The medians of \(N_s^{na}/N_m^{na}\) for 125 < \(D < 300\) \(\mu\text{m}\) and 300 < \(D < 500\) \(\mu\text{m}\) are higher in graupel at a 99% significance level according to a Mann–Whitney \(U\) test for 1.6 mm < \(D_{mm}\) < 2.2 mm during IDEAS-2011, and were the same for \(D_{mm} < 1.6\) mm during IDEAS-2011 and during ISDAC. To confirm the increased shattering when particles were identified as graupel, Fig. 13 shows greater contributions of the shattered particle mode to \(dP/d\Delta t\) for these time periods. In fact the difference between \(A\) from the 2DC with standard and modified tips when particles were identified as graupel is 0.46 compared to 0.20 when particles were identified as dendrites. Thus, it is hypothesized that graupel particles shatter into a greater number of fragments because of either their increased mass or more fragile structure. The lack of a relationship between \(N_s^{na}/N_m^{na}\) and \(T\) or between \(N_s^{na}/N_m^{na}\) and \(S\) on 30 April 2008 is consistent with the lack of riming observed on this sortie.

Because of the uncertainty in the concentrations of particles with \(D > 1.6\) mm during ISDAC from the use of the 32-photodiode 2DC, particles with 1.6 mm < \(D < 3.2\) mm were not considered in the calculation of \(D_{mm}\) for ISDAC. Since particle mass scales approximately with the square of \(D\) (e.g., Brown and Francis 1995),
FIG. 11. Expression $N_{m}^{na}/N_{m}^{na}$ for (a) 125 $\mu$m < $D$ < 300 $\mu$m and (b) 300 $\mu$m < $D$ < 500 $\mu$m as a function of $D_{mm}$ for both sorties during IDEAS-2011. Solid lines denote means; widths of shading denote 10th and 90th percentiles. (c) As in (a), but for ISDAC. (d) As (b), but for ISDAC. No artifact removal algorithms applied. Red shading and lines calculated using time periods when $T > -8^\circ$C, and red lines calculated using time periods when $T < -8^\circ$C. (e) Representative CPI images of particles of $D > 1$ mm on 1 Nov 2011 when $T > -8^\circ$C. (f) As (e), but for $T < -8^\circ$C.
$D_{mm}$ is affected by the absence of large particles in the ISDAC calculations. To test the sensitivity of excluding particles with $D > 1.6$ mm, Fig. 16 shows $N_s^{na}/N_m^{na}$ in two different size ranges as a function of $D_{mm}$ for IDEAS-2011 divided according to whether particles were identified as graupel or dendrites, with only particles with 0.125 < $D$ < 1.6 mm considered in the calculation of $D_{mm}$. Figure 14 shows that the medians of $N_s^{na}/N_m^{na}$ for 125 < $D$ < 300 μm and for 300 < $D$ < 500 μm are still higher for 1225 < $D_{mm}$ < 1500 μm compared to when particles were identified as graupel at a 99% significance level. This shows that the dependence of $N_s^{na}/N_m^{na}$ on particle habit is not sensitive to the exclusion of particles with $D > 1.6$ mm.

5. Conclusions

In situ aircraft measurements of ice crystal number distribution function $N(D)$ were acquired by a 2DC probe with standard tips, mounted immediately adjacent to a 2DC probe with tips modified to reduce the number of shattered fragments entering the sample volume on the NRC Convair-580 during ISDAC and on the NSF/NCAR C-130 during IDEAS-2011. The impact of the tips and...
the artifact removal algorithms (Korolev and Isaac 2005; Field et al. 2006) on the derivation of ice crystal concentrations \( N \) in different size ranges was assessed as a function of cloud sampling conditions and aircraft parameters in this study. A collocated HOLODEC probe used during IDEAS-2011 also identifies and eliminates shattered particles because the artifacts appear as clusters in the holograms; insight into the 2DC shattering problem is obtained through comparison against the HOLODEC’s size distributions. A series of Monte Carlo simulations with varying ice crystal concentrations, numbers of shattered particles, length of train of shattered fragments, and probabilities of shattered particles entering the sample volume was also conducted and used to interpret the measured distribution of particle interarrival times by the 2DCs. The principal conclusions of this study are as follows:

1) The differences in the interarrival time modes corresponding to natural particles from the 2DCs were likely due to the different number concentrations of natural particles observed, different 2DC sample volumes, and different airspeeds flown between ISDAC and IDEAS-2011. But, the differences between projects in the interarrival time modes corresponding to shattered particles were likely due to the different ways the particles shattered on the 2DC probe tips. In addition, differences in the number of artifacts the 2DCs could have observed due to observed differences in natural number concentration, 2DC sample volumes, and airspeed could have contributed to the variations in the modes.

2) The ranges of ratios between the number concentration from the 2DC with standard tips to the number concentration from the 2DC with modified tips without the use of algorithms \( N_{s}\)/\( N_{m}\) at \( 125 < D < 300 \mu m \) and \( 300 < D < 500 \mu m \) were from 1 to 10 and from 1 to 5, respectively, equal to the \( N_{s}/N_{m} \) of 1 to 10 and 1 to 5 in these same size ranges. This indicates that the modified tips removed as many shattered artifacts as the use of antishattering algorithm. For ISDAC, \( N_{s}/N_{m} \) at \( 125 < D < 300 \mu m \) and \( 300 < D < 500 \mu m \) varied from 1 to 7, while \( N_{s}/N_{m} \)
at \(125 < D < 300 \mu\text{m}\) and \(300 < D < 500 \mu\text{m}\) varied from 1 to 3, indicating that algorithms removed fewer shattered artifacts than modified tips.

4) The \(N(125 < D < 300 \mu\text{m})\) for the HOLODEC and for the 2DC with modified tips had values of around \(5 \times 10^{-3} \text{L}^{-1} \mu\text{m}^{-1}\). Further, there was a factor of 6 difference in \(N(D)\) between the HOLODEC and from the 2DC with standard tips. This demonstrates that the modified tips used in combination with shattered artifact removal algorithms are removing artifacts with \(125 < D < 300 \mu\text{m}\) during IDEAS-2011. Therefore, both modified tips and antishattering algorithms should be applied to correct 2DC particle size distributions.

5) The \(N_{s}^{m}/N_{m}^{m}\) is larger and a greater number of particles classified as shattered artifacts when particles of \(D > 500 \mu\text{m}\) were identified as graupel and with \(D_{\text{mm}} > 1.6 \text{mm}\) during IDEAS-2011. This suggests graupel particles shatter into a greater number of fragments than dendrites of equivalent maximum dimension because of either their increased mass or their shape.

The comparisons made in this paper estimate the uncertainty due to shattered artifacts on \(N(D)\) from 2DCs in the cloud conditions sampled in three sorties during ISDAC and IDEAS-2011 and for the specific probes used. The response time of the 2DC used during IDEAS-2011 was lower than that from the 2DC used during ISDAC because of the upgraded electronics of the 64-diode 2DC, increasing the probability of detection of particles \(D < 500 \mu\text{m}\). However, because of the limited subset of conditions encountered in this study, it is important to note that the results of this paper cannot necessarily be generalized to any other 2DC probe, cloud, probe installation, aircraft, or project. Despite these differences and limitations, some very common trends in the data that have been also observed in previous studies have been noted in this paper. Therefore, the differences between quantities calculated between probes with standard and modified tips, and processed with and without artifact removal algorithms provide guidance on the uncertainties that shattering induces on \(N(D)\) for cloud conditions commonly encountered in field projects using commonly used instrumentation.

It is important that these investigations be conducted for a variety of probes with different response times to understand the impact of shattering in a wider variety of conditions. Future studies should concentrate on acquiring data in ice clouds at colder temperatures (e.g., \(-24 \text{ to } -40 ^\circ\text{C}\)), in a wider range of aircraft operating parameters (e.g., higher true airspeeds), in a wider range of crystal habits (e.g., more rimed particles and graupel), using different probe installations (e.g., pairs of standard 2DCs with different configurations), and with a wider variety of probes (e.g., two-dimensional stereo probe, cloud imaging probe) with different designs of probe tips for deflecting shattered particles from the probe sample volume (e.g., Korolev et al. 2013a).

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