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Atmospheric Measurement Techniques Discussions

Interactive comment on "Water droplet calibration of a cloud droplet probe and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC" *by* S. Lance et al.

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MAJOR COMMENTS

1) "The paper read more like a technical document than a journal article. A lot of details presented were not needed. I would encourage the authors to reorganize the paper leaving in only those details necessary to reach the conclusions of their study."

We take this comment into serious consideration and attempt to remove all unnecessary information from the introductory sections. However, two other reviewers requested additional introductory information (for instance, an optical schematic of the instrument and more basic description of the instrument operation). Since the paper is in review for a technical journal that deals specifically with measurement techniques, we believe that including this type of information is appropriate.

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2) “A main conclusion of the study is that an optical redesign of the CDP needs to be explored to reduce the coincidence bias (mentioned in both abstract and conclusions). The authors claim the CDP optics should be modified to limit the area viewable by the sizing detector. However, this may introduce another problem, namely an inability to obtain a statistically significant sample of cloud particles in multiple size bins needed to derive a drop-size distribution... What averaging times/distances would be required to get statistically significant samples of large particles and how does that impact the desired modifications to the CDP sample area?”

Reducing the extended sample area does not change the sampling rate of the instrument (or the statistics of sampling), because the qualified sample area remains unchanged (as long as the two masked regions overlap). We attempt to explain this more clearly in the revised paper.

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3) “The authors conclude that ice crystal shattering on the CDP cannot be significant because few particles are observed with the CDP in ice-phase conditions. However, I think more analysis is needed here (see also comment 5 on identification of phase). Several experiments are starting to show that at least some versions of the CDP do not seem to record any particles in ice clouds. Is this because no small ice crystals exist in ice-phase clouds, or is it because the CDP cannot detect these ice particles? Can the difference in the rectangular slit configuration of the CDP mask (instead of the circular masked central region of the FSSP) lead to the rejection of small ice crystals? This is especially concerning because some recent experiments presented at the Oregon cloud physics conference showed that the CDP does not detect ice particles even when

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an un-shrouded FSSP does detect ice particles. I think a more thorough investigation of the CDP's ability to measure ice crystals is needed before the statements about ice in this manuscript can be substantiated. In particular, can the calibration be repeated with non-spherical ice analogues?"

Since we are not fully aware of the results showing comparison between the CDP and FSSP, and because these results are not yet published, we believe that it is not appropriate to include discussion of our results in this context. It is not clear, for instance, if even an un-shrouded FSSP is free from ice shattering artifacts. The CDP and FSSP response in ice clouds can differ for several possible reasons, such as differences in: qualified sample areas, the distances between the instrument arms, the distances between the laser path and the arm tips, the instrument mounting angle relative to the aircraft attack angle, the shape of the arm tips, or the physical housing of the optical windows. If the geometry of the qualifier has an effect, it may also be possible that the FSSP with a circular mask records small particles in ice clouds when the CDP does not, because the velocity rejection criteria used in the FSSP does not adequately reject ice particles that transit across the edges of the laser beam and simultaneously classifies them (incorrectly) as small particles. However, discussion of this possibility is outside the scope of this paper. Since both instruments are designed to measure water droplets, not ice particles, our goal is simply to show that ice shattering on the CDP does not produce significant numbers of unexplained particles when comparing to independent LWC measurements. However, we do show in the paper that there are cases when we are unable to discern whether ice crystal shattering has significantly influenced the measured CDP size distributions (because the CDP-LWC in those cases is below the reliable detection limit of the hot-wire LWC measurements).

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4) "I am curious to what degree the conclusions presented in this paper refer to the NOAA CDP in particular, and to what degree the conclusions also pertain to other CDPs. In this regards, I have a couple of questions. During ARCPAC, there was

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one flight where the NOAA P-3 flew in coordination with the NRC Convair-580. It would seem that comparing the CDP data from the two aircraft would help answer this question, and also give more confidence on the data that were obtained by the NOAA CDP. I believe that the Convair CDP did not suffer the same systematic offset that is quoted in this paper. How did the size distributions between the probes in similar clouds compare? Also, to what degree did the calibration of the CDP drift during the field campaign (i.e., were the pulse heights as a function of diameter consistent with time)?"

Intercomparison between measurements from two CDPs during ARCPAC/ISDAC has been done. The droplet concentrations and sizes at a given altitude were comparable (Figure S1) although the two aircraft flew separately, with the Convair following about 5 minutes behind the WP-3D. The true test for coincidence errors is the CDP-LWC bias when evaluated as a function of droplet concentrations, which yielded a very similar trend for the ISDAC dataset as with the ARCPAC dataset (Figure S2). We also tested two CDPs in the laboratory, which exhibited very similar extended sample areas (Figure S3). The instrument manufacturer (DMT) asserts that the optical design of the CDP discussed in this paper is the standard.

The sizing performance of the CDP remained constant throughout the campaign, within uncertainties of the glass bead and PSL calibrations. Only after the field campaign had ended was the intensive calibration method using water droplets employed in the laboratory. Because the CDP-LWC bias as a function of droplet concentrations yielded a clear relationship, which was consistent from the beginning of the campaign to the end of the campaign, and a similar relationship was observed with the ISDAC dataset, we believe that the observed bias is truly a result of an instrument design flaw, and not the result of poor or drifting instrument performance.

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5) "What phase identification scheme has been applied to the collected data? Very

often phase varies with horizontal and vertical position, so phase identification typically needs to be determined at each point in cloud (where point is defined by the averaging interval). I'm not convinced this has been done here and it should be done. Then the analysis can be segregated according to those data points collected in liquid and those data points collected in ice. I think that the definition of ice-only for King hot-wire contents less than 0.1 g/mˆ3 will misidentify some liquid and ice-phase clouds. Was there a Rosemount probe for identifying supercooled water? Was the shape of the droplet size distribution used to help identify phase?"

This is a very good question, and we should be more explicit about this in the paper. Unfortunately, we did not have a Rosemount probe or any IWC measurement. We use only the cloud particle size distribution and LWC to identify the cloud phase.

Phase discrimination was performed for every 1 s sampling interval. The following criteria were used to identify mixed-phase clouds: > 10 cmˆ-3 particles with diameter smaller than 50 um > 0.01 Lˆ-1 particles with diameter larger than 400 um

The first criteria was used by Hobbs and Rangno [1998], whereas the second criteria is modified to reflect new information that has been discovered since 1998 about ice shattering artifacts (ice concentrations above ∼400 um are typically not significantly affected by these artifacts, but concentrations at 400 um are also typically ∼2 orders of magnitude lower than concentrations at 100 um) [Korolev et al, 2010].

As mentioned, an additional criteria (King-LWC > 0.1 g mˆ-3) was used in reporting the CDP-LWC bias, since the relative uncertainty at lower LWC values is quite high. There are times when we are unable to clearly discern whether the cloud sample is ice-only or mixed-phase, because the LWC is below this conservative threshold (which was chosen based on the fact that the presence of ice can apparently bias the LWC measurement by up to 0.08 g mˆ-3). In consideration of your comments, for these cases (when we cannot tell whether the cloud is ice-only or mixed-phase because LWC < 0.1 gmˆ-3), we will not by default consider these to be ice-only clouds, and will instead refer to them as ice- or mixed-phase clouds when CDP concentrations > 10 cm^-3 (since we are unable to say whether these small particles are ice or liquid).

Hobbs, P.V. and A.L. Rangno, Microstructures of Low and Middle-Level Clouds over the Beaufort Sea, Q. J. R. Meteorol. Soc., 2035-2071, 1998.

Korolev, A.V., E.F. Emery, J.W. Strapp, S.G. Cober, G.A. Isaac and M. Wasey, Small ice particle observations in tropospheric clouds: fact or artifact? Airborne Icing Instrumentation Evaluation Experiment, in review Bull. Am. Meteor. Soc., 2010.

DETAILED COMMENTS

"Page 3139, line 13: I do not understand why the baseline drift cannot be corrected for. Granted, one must take into account the uncertainty in correcting for the baseline drift in deriving the final LWC product, but to not do so would seem to produce a systematic error in the data (i.e., even LWC values greater than 0.1 g/m^3 would seem to be somewhat offset if the baseline is not removed)."

Since we often remained in-cloud for lengthy periods of time (e.g. up to 20 min ~ 150 km), it is unclear exactly how we should correct for baseline drift. It is not clear, for instance, if the drift occurs at a steady rate (for which a linear correction would be applied, using the starting and ending clear-air values for each cloud penetration to obtain the correction line) or whether the drift occurs suddenly at intervals when high ice mass is encountered. Hysteresis in the King-LWC measurements also occurs, which makes such correction even more difficult; the baseline can remain elevated for several minutes after exiting a cloud. We do not feel comfortable manually adjusting the data, under these conditions. It is also useful to realize that biases in the King-LWC measurement from impaction of ice is positive. Since coincidence errors are expected to increase the CDP-LWC bias (relative to the King-LWC), a positive bias in the King-LWC results in an underestimate of the coincidence error. Thus our estimate of the CDP coincidence error may be conservative, which we think is an appropriate approach. However, since the liquid-only and mixed-phase clouds exhibited similar trends, we do not believe that failing to remove baseline biases in the King-LWC measurements for mixed-phase clouds results in substantial underestimate of the CDP coincidence error (at least for LWC > 0.1 g mˆ-3).

“Page 3139, lines 16 to 18: How can the accuracy of the King LWC measurements be evaluated from the adiabatic profiles? The departure from adiabatic conditions could be much larger than the uncertainties of the measurements.”

It’s true that subadiabatic conditions were encountered. As mentioned in the paper, this was often the case, but superadiabatic values were not observed.

“Page 3139, lines 26 to 28: If the baseline offset is removed from the J-W LWC values, how do they compare against the King LWC values? This would seem to be a good test to perform before categorically rejecting all measurements from a particular probe!”

As mentioned in the paper, we do not trust the JW-LWC measurements during ARC-PAC, because the values often drifted apparently randomly, even in clear-air. Sometimes the JW-LWC values were negative (as low as -0.5 g mˆ-3) in ice precipitation, which does not make sense, and sometimes the values were as high as 0.2 g mˆ-3 in ice precipitation. Since the King-LWC appeared to be much more reliable, and since we do not know how we would reconcile two measurements of the same parameter that do not agree, we simply use the King-LWC measurements (which are corrected using a standard procedure).

“Page 3140, line 4 to 5: There are many algorithms readily available for removing shattered particles from CIP/PIP probes, for correcting the sizing of particles due to out-offocus images, and for identifying other artifacts in the data. I understand not wanting to discuss all the uncertainties in these data, but I think these corrections should be applied so that the corrected data are used."

The PIP data from ARCPAC very seldom contained hollow, out-of-focus images, as can be seen in Figure S4 for both ice and liquid precipitation. Fewer than 7% of images of liquid precipitation show a Poisson spot, which could be used to correct the size of these out-of-focus images, as described by Korolev [2007]. However, for ice crystals and ice aggregates, this size correction technique does not apply. Since, as far as we know, there is no standard correction algorithm for nonspherical images, we believe that this issue remains outside the scope of the paper. Furthermore, we believe that the sizing error introduced by not correcting for out-of-focus images in the PIP dataset is negligible (using the raindrop images in Figure S4 as an example), especially given other sources of uncertainty for the sizing of nonspherical particles from 2-dimensional images, and these errors do not detract from the conclusions of this paper.

As identified by Korolev and Isaac [2005], there are really two separate issues for ice shattering artifacts: (1) the shattering of particles upon impaction with the instrument arms upstream of the probe sample area, resulting in erroneous measurement of many small ice particles, and (2) the relatively gentle breakup of large ice aggregates as a consequence of shear-induced stresses. Ignoring images that correspond to the first process makes sense, because particles that impact on the instrument arms should not be counted, as their trajectory should have remained outside of the instrument sample volume. However, ignoring images corresponding to the second process results in undercounting of large ice particles, and underestimate of ice mass. Particle interarrival time corrections do not distinguish between these two different processes, as can be seen in Figure S5, where the gentle breakup of ice aggregates (resulting in two large ice crystal aggregates in close proximity, instead of just one) is classified as ice shattering, in the same way that production of many small ice particles from direct impaction of ice crystals is classified as shattering. These images have been classified using Alexei Korolev's image analysis software (for which a license was obtained through DMT with purchase of the imaging instruments).

Korolev et al [2010] show that ice shattering artifacts typically result in a positive bias in small particle concentrations, while the measured concentrations of large precipitation particles (with cutoff diameter somewhere between 100-400 um) remains relatively unaffected. Figure S6 shows a comparison for the ARCPAC dataset between: (1) ice crystal concentrations obtained using the uncorrected PIP observations with different criteria for the lower size cut, and (2) ice crystal concentrations obtained using Alexei Korolev's image analysis software, where shattered particles are identified from particle interarrival time criteria. Since the results agree to within 20% (with Pearson's correlation coefficient, Rˆ2 = 0.86) when particle diameter is > 400 um, we are confident in the values reported in this paper (using the uncorrected PIP observations).

The CIP data are not used for quantification of ice crystal concentrations, but only to bridge the gap between CDP and PIP measurements in the range 50-200 um (in Figure 6 of the paper, only).

Korolev, A., G.A. Isaac, Shattering during Sampling by OAPs and HVPS. Part I: Snow Particles, J. Atmos. Oceanic Technol., 22, 528-542, 2005.

Korolev, A., Reconstruction of the Sizes of Spherical Particles from Their Shadow Images. Part I: Theoretical Considerations, J. Atmos. Oceanic Technol., 24, 376-389, 2007.

Korolev, A.V., E.F. Emery, J.W. Strapp, S.G. Cober, G.A. Isaac and M. Wasey, Small ice particle observations in tropospheric clouds: fact or artifact? Airborne Icing Instrumentation Evaluation Experiment, in review Bull. Am. Meteor. Soc., 2010.

"Page 3143, lines 24 to 27: Can you be more specific in how the probability of less than 5% is calculated from the quoted concentrations, sample volumes, and sampling frequencies (i.e., give equation or other source)?"

The probability of two droplets transiting through SAQ at the same time is P = 1-exp(-

lambda * tau), where lambda = N * SAQ * TAS, and where N is the droplet concentration, SAQ is the qualified sample area, TAS is the aircraft True Air Speed and tau is the average transit time of droplets across the CDP laser beam. In the absence of coincidence errors, lambda is the droplet counting rate (drops/second). A form of this equation was used by Baumgardner et al [1985] and Brenguier and Amodei [1989].

Thank you for pointing out that this statement is confusing, as written. The 1Hz sampling rate is not used in the calculation, because what matters is how many droplets cross the sample area at the same time (i.e. within the transit time of the droplets, tau ∼2 us). Thus the "sample volume" of 0.06 mmˆ3 is also incorrectly labeled; rather, it is actually the sensitive volume of the CDP laser beam (equivalent to SAQ * TAS * tau).

We now include this in the paper.

Baumgardner, D., Strapp, W., and Dye, J. E.: Evaluation of the forward scattering spectrometer probe. Part II: Corrections for coincidence and dead-time losses, J. Atmos. Oceanic Technol., 2, 626–632, 1985.

Brenguier, J.L. and L. Amodei, Coincidence and Dead-Time Corrections for Particle Counters. Part I. A General Mathematical Formalism, J. Atmos. Oceanic Technol., 6, 575-584, 1989.

"Page 3147, line 30: Is this 10% ratio measured here or from the Wendisch study? If from the Wendisch study, how can you know that the ratio is the same?"

The ∼10% ratio is derived from the geometry of the system. Since we use the same viewing angle relative to the incident light (130 degrees) as used in the Wendisch study, the same ratio is obtained. Figure 1a in the paper gives physical evidence that this calculation is correct. At a viewing angle of 130 degrees, a change of 10 degrees results in a change of < 1.6% for Dglares/Dtrue. The uncertainty in viewing angle for our calibrations is actually much less than 10 degrees. We now add this to the paper.

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Interactive Comment

“Page 3149, lines 29-30: This seems surprising. Given the importance of this calibration can you find or speculate on some reason to explain this monotonic response?”

This is indeed surprising. We have spent a good deal of time attempting to address this question. Knollenberg [1976] suspected that Mie resonance structure could be dampened with the use of a multi-mode laser, and Korolev [1985] used this idea to explain the lack of observed resonance for their FSSP when calibrated with water droplets. However, Pinnick et al [1982] stated that “…the theoretical response calculations adequately predict the FSSP response for spheres, regardless of effects that may be caused by multimode operation of the instrument laser source that might render the plane wave assumption in Mie theory invalid”. Also, simulations by Hovenac and Lock [1993] did not show significant suppression of Mie resonances for a multimodal FSSP laser beam. The CDP does not use a multimodal laser, however, other non-idealities in the instrument performance could potentially result in a response that differs from the Mie calculations.

We speculate that the optical model is insufficient for this particular instrument due to optical misalignment (beyond the symmetrical $\pm$0.5 degree shift modeled). If the qualified sample area is out of alignment with the center of the laser beam, this would result in a different range of collection angles for qualified droplets than the 4-12 degree specification. Incomplete blocking of the primary forward scattering lobe can result in a dampening of the Mie resonance structure (if the misalignment is nonsymmetrical) and also an increase in scattered intensity (Figure S7). The result of this type of misalignment was determined by integrating the Mie solution over different collection geometries. A lateral displacement of $\sim$1 mm for the qualified sample area relative to the center of the laser beam, results in a change in collection geometry for qualified droplets as depicted in Figure S8. We now add a paragraph in the paper describing the simulated effect of this type of nonsymmetrical optical misalignment and also an appendix describing the technical details of these simulations.

Figure S7 Caption: The calibrated response of the CDP to PSL and glass beads, and the calculated response for PSL, glass beads and water droplets assuming that all forward scattered light 4-12 degrees is collected by the sizing detector. The light blue dots show the modeled CDP response for water droplets given a 1 mm misalignment in the y-dimension (laterally across the laser, and perpendicular to the droplet trajectories). The dark blue dots similarly show the modeled CDP response for water droplets given a slightly greater misalignment. The fit to the water droplet calibrations is shown for comparison. The CDP response to PSL and glass beads, given these misalignments, are also shown, and often agree well with the PSL and glass bead calibrations.

Figure S8 Caption: Scattering functions for 10 um (left) and 40 um (right) droplets, respectively, as projected on a flat plane at 4 cm distance from the droplet (approx. the location of the dump spot, which nominally collects light 0-4 degrees off-axis). Image intensity represents the logarithm of scattered irradiance normalized by the incident laser intensity (for an unpolarized light source with lambda = 658 nm). The solid white circles represent 4-12 degrees symmetric collection angles. The dotted white circles represent collection geometry accounting for a lateral displacement of 1 mm in y (top) and 1mm in both x and y (bottom) for qualified droplets relative to the intended optical alignment.

Hovenac E.A. and J.A. Lock, Calibration of the Forward-scattering Spectrometer Probe: Modeling Scattering from a Multimode Laser Beam, J. Atmos. Oceanic Technol., 10, 518-525, 1993.

Knollenberg, R. G. The use of low power lasers in particle size spectrometry, Practical applications of low power lasers, Soc. Photo-opt. Instru., 92, 137–152, 1976.

Korolev, A. V., Makarov, Yu. E., and Novikov, V. S.: On the calibration of photoelectric cloud droplet spectrometer FSSP-100, TCAO, 158, 43–49, (in Russian), 1985.

Pinnick, R.G., D.M. Garvey and L.D. Duncan, Calibration of Knollenberg FSSP Light-Scattering Counters for Measurement of Cloud Droplets, J. Appl. Meteor., 20, 1049-

1057, 1981.

“Page 3151, line 20: Why not show data from all flights together to show that the behavior is consistent between all flights?”

Good idea. We updated Figure 5 in the paper by including CDP data from all flights (Figure S10), but we still highlight the trend from the liquid-only flight on 29 March. Since you are specifically interested in the other flights, we also provide Figure S9 here, in case you’d like to see how individual flights differed.

“Page 3152, line 5: What is the fractional contribution to the mass of the liquid in the mixed-phase clouds? Korolev and others have shown that mixed-phase clouds are typically dominated by either liquid or ice. If you estimate the ice content from the size distributions (e.g., through application of some m=a*Dˆb relationship, where a and b chosen dependent on the habit types that are dominant), you should be able to estimate this. If the clouds are liquid dominated, the King probe probably will work to give a reasonable estimate of liquid water content.”

Ice water content (IWC) is estimated using the parameterization by Mitchell et al [1990],

m = 0.022 * Dˆ2.0,

where m is the mass (mg) of a single particle with maximum linear dimension D, in mm. Lawson and Baker [2006] show that this parameterization may underestimate IWC by more than a factor of two for the Arctic stratus that they analyzed. However, given the possibility of even such a large underestimate of IWC, it is clear that the mixed-phase clouds sampled during ARCPAC were dominated by liquid water. IWC estimated using the Mitchell et al [1990] parameterization was almost always < 0.01 g mˆ-3. Greater values (but almost never > 0.1 g mˆ-3) were found only below cloud (when droplet concentrations were < 10 cmˆ-3).

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Lawson, R.P. and B.A. Baker, Improvement in Determination of Ice Water Content from Two-Dimensional Particle Imagery. Part II: Applications to Collected Data, J. Appl. Meteor. Climat., 45, 1291-1303, 2006.

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

“Page 3153, lines 13-15: Can you state what the sample areas Q and E are?”

SAQ = 0.3 mmˆ2 and SAE = 20.5 mmˆ2. We now add this to the paper here – thank you.

“Figure 2: how did pulse amplitude with droplet diameter vary over the course of ARC-PAC?”

The sizing performance of the CDP remained constant throughout the campaign, within uncertainties of the glass bead and PSL calibrations. The detailed analysis of pulse amplitudes, and calibration with water droplets, was performed only after the campaign had finished.

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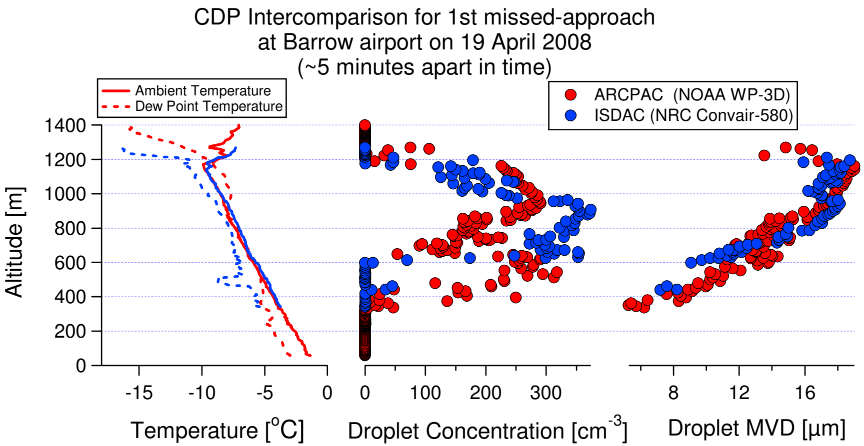

Fig. 1. (S1) Intercomparison between CDP observations on board the NOAA WP-3D and the NRC Convair-580

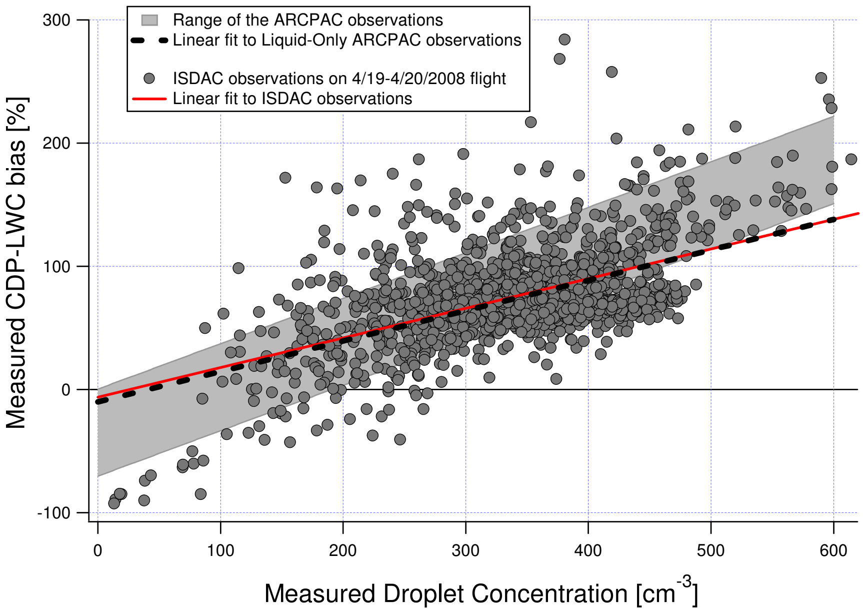

Fig. 2. (S2) CDP-LWC bias as a function of measured droplet concentration for the ISDAC dataset. The range and best fit to the ARCPAC observations are also shown.

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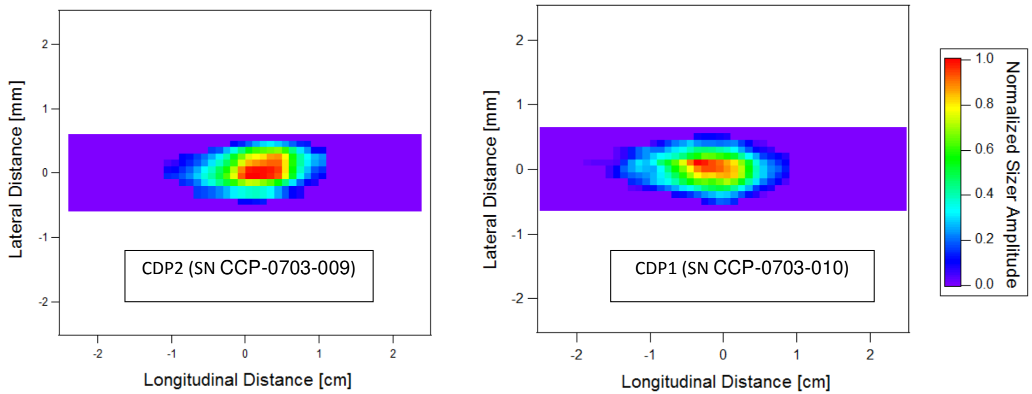

Fig. 3. (S3) Extended Sample Area for two CDPs, calibrated in the laboratory with water droplets

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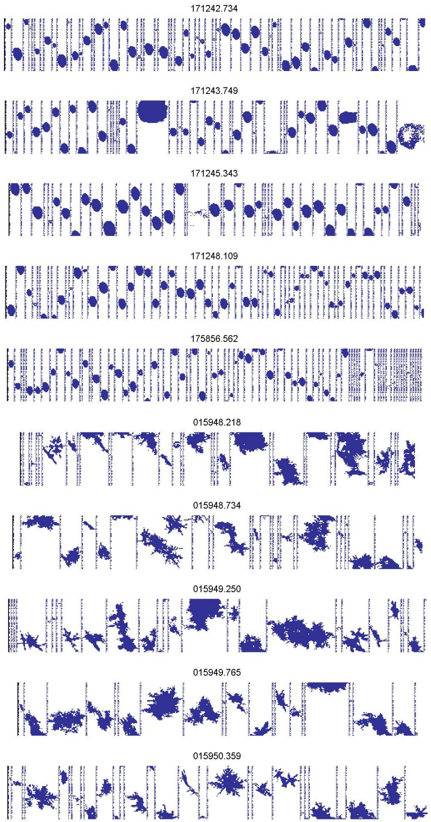

Fig. 4. (S4) Images in liquid and ice clouds obtained from the PIP

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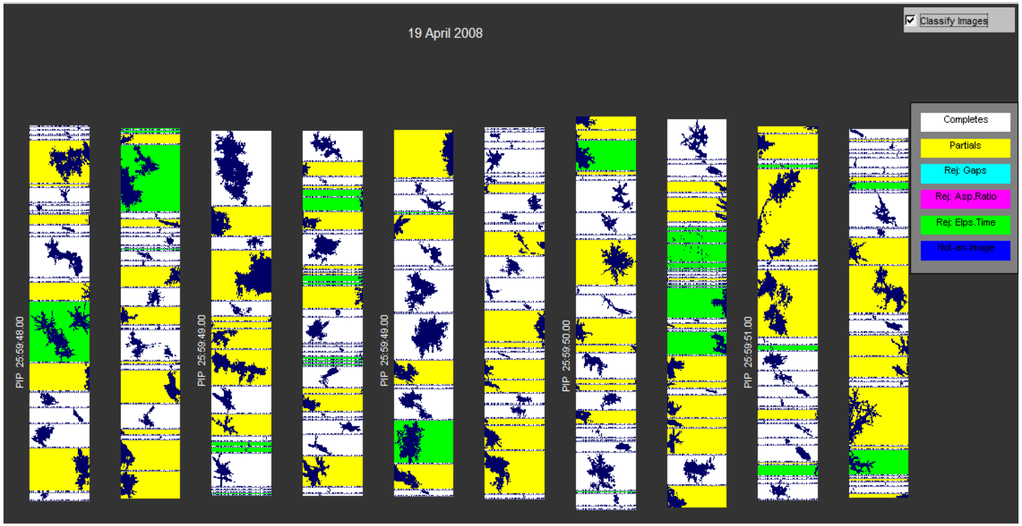

Fig. 5. (S5) Image Analysis of PIP observations using Alexei Korolev's software. Images rejected due to interarrival time criteria are highlighted in green.

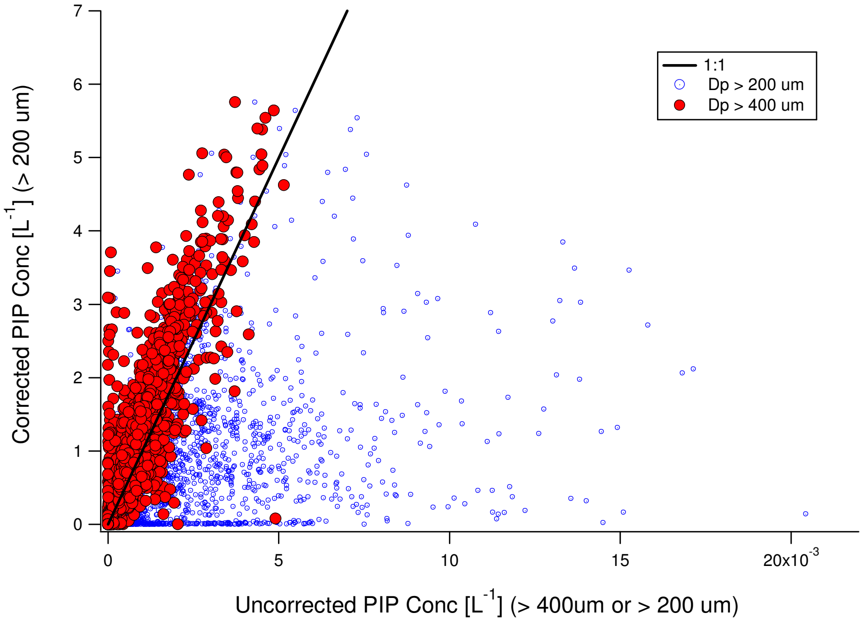

Fig. 6. (S6) Corrected versus uncorrected ice particle concentrations.

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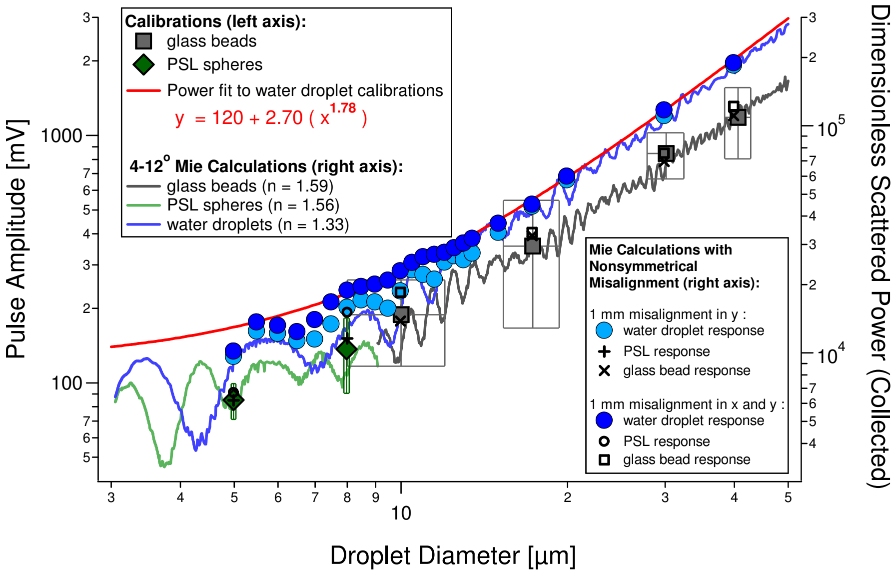

Fig. 7. (S7) Simulated CDP response curves assuming varying degrees of misalignment

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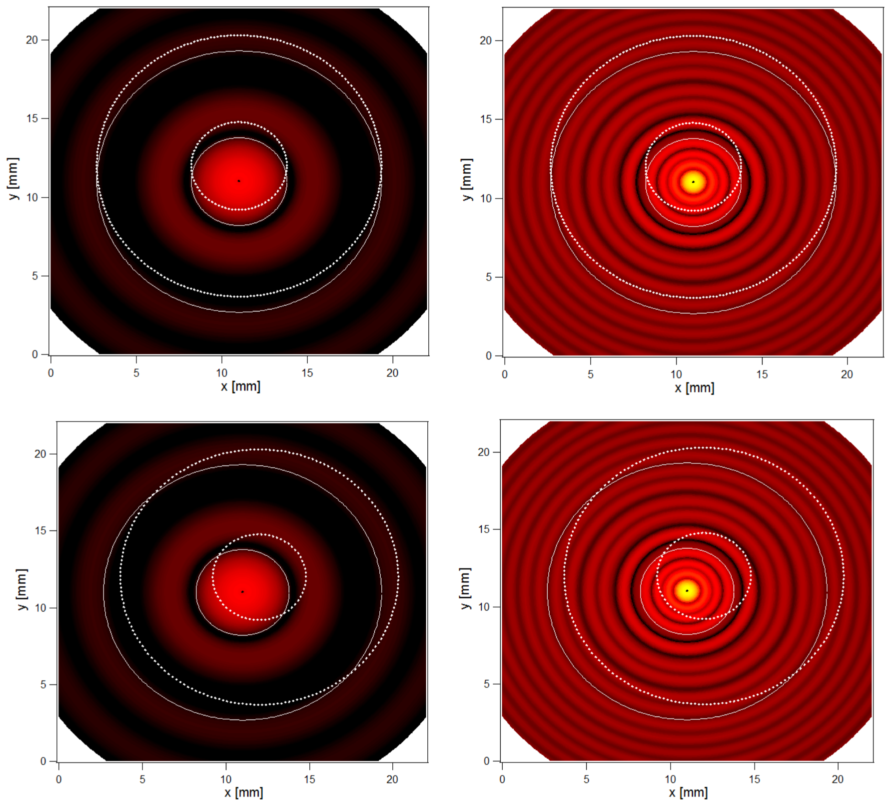

Fig. 8. (S8) Scattering Functions for 10 and 40 um droplets.

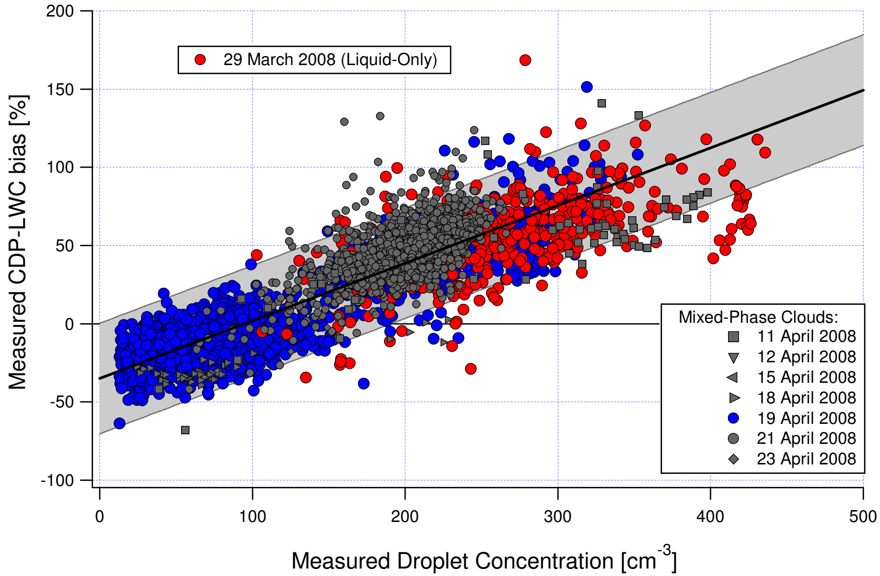

Fig. 9. (S9) CDP-LWC bias for all flights during ARCPAC, with each flight indicated

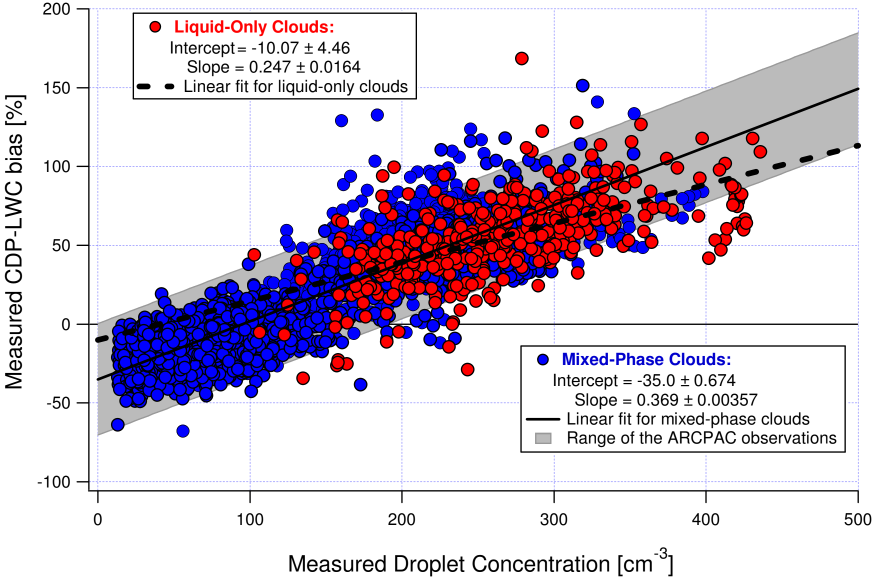

Fig. 10. (S10) CDP-LWC bias for all flights during ARCPAC, colored by cloud type