

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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"This paper presents strong evidence indicating that an attempt by Droplet Measurement Technologies, Inc. to solve the problem of shattering, common to other forward scatter probes, with its new Cloud Droplet Probe (CDP) has led to a serious exaggeration of the co-incidence problem, which is present in all these probes. This conclusion is postulated on basis of a comparison of integrated particle volume measured by the CDP to a King probe measurement, and confirmed by computer simulations. The sim-

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ulation results are convincing. They show how the superposition of scattered light from particles in the laser outside the sizing volume at same time particles are going through the sampling volume can result in both undercounting and over sizing. The results of the measurement comparison (Fig. 5) are closely matched by the simulations (Fig. 9a). What needs to be explained though in words is why the coincidence error in LWC is linear and zero crossing such that at very low concentrations where no coincidence is to be expected the CDP integral is 30-40% low (Fig. 5). One would expect the curve to level off at some concentration if coincidence were the cause of this error."

We suspect that the negative CDP-LWC bias observed at low droplet concentrations results from a positive bias (on the order of 36%) in the King-LWC measurements due to the presence of ice. We did not correct for the ice bias on the King-LWC measurements, because we do not know of a correction procedure during sustained sampling in mixed-phase conditions that does not require a good deal of manual manipulation, which we felt was subjective, especially given the possibility of measurement hysteresis. However, we estimate that the presence of ice can shift the King-LWC baseline by as much as 0.08 g m^{-3} , since LWC can remain elevated at this level for several minutes after exiting a liquid-containing cloud (Figure S1). When the King-LWC is in the range of $0.1\text{--}0.2 \text{ g m}^{-3}$, which is common for the mixed-phase clouds sampled, this results in as much as 40-80% error. Also, a linear fit to the liquid-only observations (Figure 5 of the paper) has an intercept much closer to zero, providing further evidence for a bias in the King-LWC measurements in mixed-phase clouds.

Ice water content (IWC) presented in Figure S1 is estimated using the PIP data and the parameterization by Mitchell et al [1990],

$$m = 0.022 * D^{2.0},$$

where m is the mass (mg) of a single particle with maximum linear dimension D , in mm.

The linear trend of the CDP-LWC-bias versus droplet concentration is due to the separate trends for sizing and concentration errors resulting from coincidence. At low

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droplet concentrations, the concentration error due to coincidence is small, but the sizing error has a significant effect (since CDP-LWC error is proportional to sizing error to the 3rd power). When the concentration increases, the sizing error is counteracted somewhat by undercounting errors. The undercounting errors grow exponentially with droplet concentration, while the sizing error begins to level out. This is because the sizing error has an upper limit, since the qualifier signal must be greater than the sizing signal in order for a droplet to be counted at all. The sizing error also levels out because the relative increase in size with a given percentage increase in voltage is nonlinear. In other words, the first coincident droplet typically has a larger effect on the measured drop size than a second coincident droplet. At some point, when the majority of droplets suffer from coincidence to the point that the average sizing signal is more than twice the signal for each qualified droplet, the undercounting error begins to dominate, and the CDP-LWC bias will begin to decrease. At sufficiently high droplet concentrations, the CDP will fail to count any droplets at all.

Also, don't forget that the x-axis for Figure 5 (and Figure 11) of the paper is the measured (or simulated) droplet concentration, not the actual (or prescribed) concentration of droplets that transit through the qualified sample area. When the CDP-LWC bias is plotted as a function of the prescribed droplet concentration, the trend is sublinear (Figure S2).

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.

"In this context one wonders also what weight to place on the mixed cloud results. The instrument is calibrated using liquid water drops, and this calibration is presumably used to size the ice crystals as well as the drops. The integral thus includes potential ice volume, while the King probe does not."

Actually, it appears that the reverse is true for our dataset: the King-LWC measure-

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ments are biased by the ice in mixed-phase clouds, while the CDP measurements are not. Or rather, we do not believe there actually are a significant number of small ice particles in the clouds that we sampled (and therefore the CDP measurements are unaffected by the presence of ice). We make this latter assertion because the CDP-LWC and King-LWC measurements track each other very well over time (Figure S1) independently of the ice phase (as observed by the imaging probes). Also, if the CDP were biased by the presence of a significant number of small ice particles, the CDP-LWC bias would be positive at low droplet concentrations, not negative (unless the King-LWC bias due to ice were even greater).

"Another important question addressed in the paper is how valid is the traditional method of calibrating forward scatter probes by use of glass spheres of known size and extrapolate to water drops on basis of modeled (Mie code) instrument's response. It is good to see that overall the old method seems to hold, because it is so much easier to perform, which is important on a field deployment. However, the water drop calibration does suggest some discrepancy with calculated response for particles in the Mie-resonance region (1-10 micron diameter) which, although of little importance except in the rapid growth region near cloud base, shows the importance of using calibrations rather than calculated response curves to determine channel boundaries and pulse height/drop size correspondence.

Lastly, the paper provides a good summary of the fundamental problems that are known to affect measurements by forward scatter probes in general. It might be pointed out however, that there are other important problems which, although not fundamental to the technique, often cause as large or larger errors in size distribution measurements. Misalignment or mis-assembly of optical elements and attenuation of laser intensity on dirty lenses commonly shift the instruments' calibration and alter the pulse-height/drop-size correspondence."

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This is an excellent point. We now add these to our list of sources of uncertainty for the CDP. Electronic noise and/or drifting electronic baselines can also have a significant effect.

"A big question is also how to convert a pulse height due to an ice crystal to 'size'. Is there really any justification for presenting a diameter, or volume, for a pulse generated by a particle of unknown phase and shape (such as is measured in mixed phase clouds)?"

We understand this concern, and agree that the CDP (Cloud Droplet Probe) was designed to measure only liquid water droplets, not ice crystals or frozen drops. A hidden assumption in this paper is that the CDP measured only liquid droplets during ambient sampling (even in mixed-phase clouds). We make this assumption because the King-LWC and CDP-LWC measurements track each other in ways that we can understand. We also believe that the conditions encountered allow for this assumption, since there is a natural size separation between liquid droplets and ice crystals due to the rapid growth of ice crystals at near saturated conditions (allowing liquid water droplets to co-exist). We assume that the spurious ice crystal that transits the CDP laser beam does not have a significant effect on the reported droplet concentrations or the CDP-LWC (even if the forward scatter signal is within the range of the CDP detectors) simply due to the much lower number concentration of ice crystals than cloud droplets. Shattering of large ice crystals is a much greater concern, since the concentration of small artificially produced ice crystals can be comparable or greater than natural concentrations of cloud droplets. However, this concern is nullified by the fact that the King-LWC and CDP-LWC measurements track each other well (whether or not large ice crystals are present), and because we can almost always explain biases arising between these two measurements without resorting to shattering artifacts.

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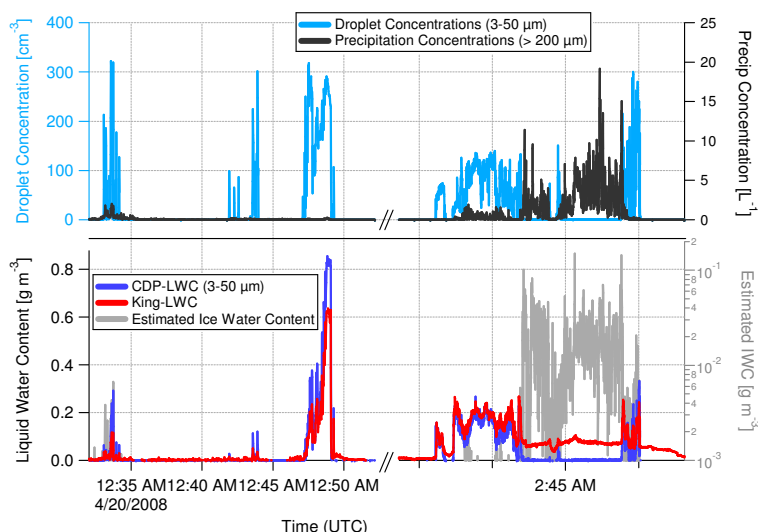


Fig. 1. (S1) Cloud microphysical observations on the 4/19-2/40/2008 flight during ARCPAC

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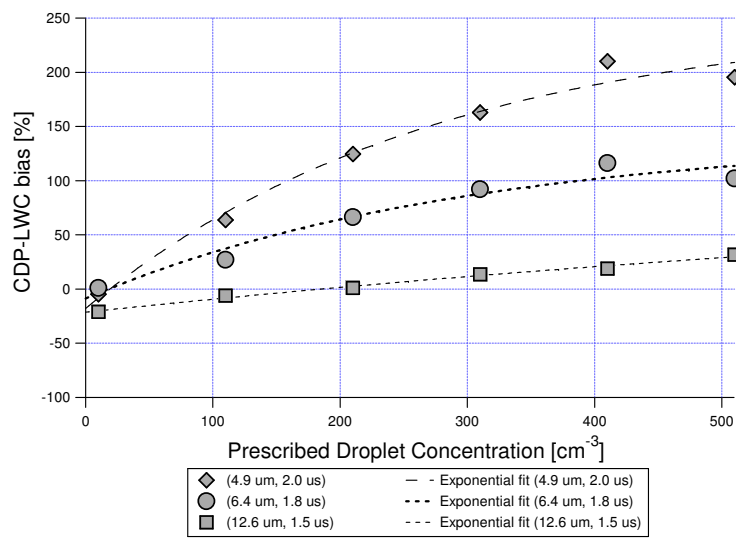


Fig. 2. (S2) Simulated CDP-LWC bias for a given prescribed droplet concentration