We thank the Reviewer #2 for evaluating our paper.   The reviewer's comments, and our replies/revisions, are in red and black, respectively.

The paper combines parcel modelling of streamlines through wave clouds with observations from aircraft to test the DeMott et al. 2010 ice nucleation parameterization. The authors also attempt to investigate the importance of time dependent freezing.

The paper is well written and concise and potentially a good test of a commonly used ice nuclei representation. However, the determination of ice concentration from 50 micron size particles, that is used to directly compare to the DeMott et al. formula is my biggest concern. Measurements of these particle sizes is highly uncertain and this problem needs to be addressed more thoroughly before this paper can be published.

Major points:

26597:13-26598:20

The determination of ice concentration from 50 micron size particles is my biggest concern. This needs to be addressed before this paper can be published.

Shattering has been discounted, but it would be easy to quickly assess the fraction of particles with unusually short interarrival times to support the authors assumption.

Author's Response: We provide an analysis of interarrival time in Appendix A (attached).

That analysis backs up what we say in the paper on P26597L20. Also, after L24, we added text telling the reader that further analysis of the 2DC measurements is provided in Appendix A.

Author's Addition to Manuscript: Crystal concentration and crystal interarrival time measurements, derived using the 2DC, are analyzed in greater detail in Appendix A.

The authors quote a comparison made between oil coated slides and the 2DC as proof of the reliability of using that measurement. At best that comparison is only valid for the 2dc probe with the configuration of electronics, optics and processing used at the time. I think that the later paper by Strapp et al. (2001, J. Atmos. Ocean. Technol.,18, 1150–1170) is more general and supersedes those previous findings.

Author’s Response:

We talked with Perry Wechsler, our engineer. His technical records indicate that with the exception of the addition of RAM, to replace shift registers and routine maintenance including laser replacement, the probe's optical and mechanical characteristics are the same as in Cooper and Saunders (1980). However, data recording and processing of the raw data has changed and neither was implemented, in our work, as in Cooper and Saunders (1980).

An analysis of measurements, made in 2011, with the Wyoming 2DC and our CIP probe, purchased in 2009, is described in Appendix A (attached). That result is consistent with the findings of Cooper and Saunders (1980).

Strapp et al. 2001 note that variation in time response and thresholds for the 2DC probes mean that sizing for particles smaller than 125 micrometers is highly uncertain. That uncertainty in sizing affects the assumed depth of field and translates into large uncertainties and biases in the concentration. Corrections have been proposed (references in Strapp et al.), but knowledge of the response characteristics, depth of field and detection threshold is required.

Author's Response:

A comparison of 2DC- and CIP-derived concentrations is provided in Appendix A (attached). We demonstrate reasonable agreement among 2DC-derived and CIP-derived concentrations for crystals greater than 50 um. Our finding (Appendix A) runs contrary to the expectation that the faster responding CIP should report concentrations larger than the slower responding 2DC (Baumgardner et al., 2001). We conclude that the 2DC concentrations (D>50um) are not as strongly biased as suspected by the reviewer.

Baumgardner, D., H.Jonsson, W.Dawson, D.O'Connor and R.Newton, The cloud, aerosol and precipitation spectrometer: a new instrument for cloud investigations, Atmos. Res., 59-60, 251-264, 2001

Possible solutions are to use a larger ice size threshold for which the concentrations are more reliable combined with an estimate of the number concentration of ice crystals larger than that threshold.

Author's Response: We don't agree with the approach suggested by the reviewer. The CIP/2DC comparison (Appendix A) supports our contention that the 2DC-derived concentrations (D>50um) are sufficient for comparing ice in clouds to the prediction of the D10 parameterization. Also, indirect support can be found in Heymsfield et al. (2013; their Appendix A), who compared CIP-derived and 2DS-derived concentrations (D>50um) and report good agreement.

Heymsfield, A.J., C.Schmitt, and A.Bansemer, Ice cloud particle size distributions and pressure-dependent terminal velocities from in situ observations at temperatures from 0° to −86°C, J. Atmos. Sci., 70, 4123–4154, 2013

26605:10 Mixedphase time. I like what the authors have attempted to do, but the 5K temperature ranges are large. From DeMott et al 2010, the change in ice concentration would need to be greater than a factor of 2 in order to be observed for a 5K temperature window. I think that the authors need to add this to their discussion about what they are able to say about the importance of time dependent ice nucleation.

Author's Response: We missed this point and have modified the text accordingly:

Author's Change to Manuscript: As was discussed in the introduction, there is an outstanding question in atmospheric science community regarding the time-dependent nature of ice nucleation. Of relevance for our data set, with its average t_{MP} =221 s (Sect. 3.2), is the possibility that the characteristic time for a subcritical ice embryo to transition to a detectable ice particle is comparable to t_{MP}. If that were the case, we would expect that streamlines associated with larger mixed-phase times, all other things equal, would have larger IC concentrations. The work of Vali and Snider (2014) provides an estimate the effect. They show that time dependency can alter crystal concentrations by up to a factor of three depending on whether stochastic or singular theory is used to describe nucleation.

Author's Change to Manuscript (start of paragraph): We investigated time dependency by stratifying our 80 determinations of $\{N_{IC}, n_{0.5}, T_{low}, t_{MP}\}$ into four T_{low} subsets.

Added Reference: Vali, G. and Snider, J. R., Time-dependent freezing rate parcel model, Atmos. Chem. Phys. Discuss., 14, 29305-29329, doi:10.5194/acpd-14-29305-2014, 2014

Author's Response: Related to this, we changed the following paragraph:

Author's Change to Manuscript: In spite of these suggestions of a connection between crystal concentration and mixed-phase time we cannot argue convincingly that time-dependent effects were significant for crystals within the clouds we studied. Our ability to argue for, or against a dependence on t_{MP}, was limited by the strong temperature-dependence of ice nucleation. This is evident from Fig. 3a where the value $k_2 = 0.22\ ^{o}C^{-1}$ can be used to demonstrate that a 5 ^{o}C decrease corresponds to a factor of three increase in nucleated concentration. Also limiting is the relatively few data values within our 5 ^{o}C subsets. Thus, in future wave cloud studies, attention should be paid to strategies which generate an adequate number of points within specified temperature and aerosol ranges.

Minor points:

26593:5. By 'latter' do you mean heterogeneous freezing?

Author’s Response: We removed the sentence.

26601:10. At this point in the text I don’t understand why the relative value was computed.

Author’s Response: The relative value is used later in the paper (P26605L23) to discard points associated large mixed-phase time uncertainty.

26602:24. Condition 1) indicates that N(D>25micrometers) has to be greater than 2xN(D<50micrometers) for inclusion.

Author’s Response: We strived to make this statement consistent with what we said in Section 2.2. We revised this to improve clarity:

Author’s Change to Manuscript: (1) $N_{IC}(D<50\mu m)$ must be smaller than $0.5 \cdot N_{IC}(D>25\mu m)$ (Sect. 2.2),

Appendix A

In this appendix we examine the reliability of ice crystal concentrations derived using the University of Wyoming 2DC. We derive concentrations using the Wyoming 2DC, with its slower-responding photodiode array (Gayet et al., 1993; Baumgardner and Korolev, 1997; Strapp et al., 2001), and compare to values derived using a faster responding cloud imaging probe (CIP; Baumgardner et al., 2001). We also analyze the 2DC ice crystal interarrival times and investigate crystal shattering. Two data sets are analyzed. The first comes from Wyoming King Air flight data, acquired on 9 January 2011 during the Colorado Airborne Multi-Phase Cloud Study (CAMPS), and the second comes from the 80 downwind track-streamline intersections described in Sect. 3.5. Both the 2DC and CIP were operated with standard probe tips (Korolev et al., 2013).

Strapp et al. (2001) conducted laboratory studies that investigated a 2DC's ability to detect objects (circular dots) positioned away from the center of focus of the probe's laser. They demonstrated that the probe's finite response led to undersizing, counting losses and image distortion. At dot sizes smaller than 100 µm, undersizing and counting losses increased with the speed the dots transited through the probe's sample volume. Strapp et al. conducted their testing using dots deposited onto a glass disk. The dots were opaque, monodisperse, and regularly spaced on the disk along circular tracks. The disk was positioned with its rotational axis parallel to the 2DC laser beam. The position of the disk plane, relative to the center of focus of the beam, was varied. The largest dot speeds tested by Strapp et al. were comparable to the airspeed of the Wyoming King Air (~100 m/s).

A1 - 2DC and CIP Concentrations

A comparison of 2DC- and CIP-derived concentrations was made using Wyoming King Air data acquired on 9 January, 2011 (20110109). The comparison data was selected from three level-flight transits of an orographic cloud. The cloud was located over continental divide in northern Colorado. During the cloud transits the liquid water content was less than 0.2 g m^{-3} and temperature was between -23 and -25 ^{o}C. We processed the raw 2DC and CIP measurements the same way we processed the WAICO 2DC measurements (Sect. 2.2). Also consistent with the WAICO processing, the compared concentrations are five-second averages and are for crystals larger than 50 µm (sized along the aircraft track). The CIP/2DC comparison is shown in Fig. A1a. The vertical line at 5 L^{-1} marks the median of the 80 concentrations in our WAICO data set (Sect. 3.5), and its implication is discussed in the following paragraph.

Because of the undersizing and counting losses documented for a 2DC, especially at the low end of its range (D < 100 µm), and the fact these effects are attributed to the relatively slow time response of the 2DC's optical array (Strapp et al., 2001), it is expected that concentrations derived using the faster responding CIP (Baumgardner et al., 2001) should exceed 2DC-derived values. Contrary to that expectation, we found reasonable agreement (Fig. A1a). Measures of the agreement are as follows: 1) For concentrations larger than 5 sL^{-1}, all of the 2DC-derived values plot well within a factor of two of the CIP. 2) For concentrations smaller than 5 sL^{-1}, a large fraction of the 2DC values (87%) plot within a factor of two of the CIP. These findings, combined with the findings of Cooper and Saunders (1980) (also see Sect. 2.2), lend confidence to the concentration values we derived using 2DC measurements made during WAICO. However, this comparison does not completely lessen the concern that we biased the WAICO concentrations at D < 100 µm by assuming that the 2DC's optical depth of field was independent of crystal size and equal to the probes's sampling aperture (61 mm) (Vali et al., 1981 and Sect. 2.2).

A2 - Interarrival Time and Shattering

Representative CIP and 2DC size distributions, from CAMPS, are shown in Fig. A1b. It is evident that most of the detected crystals are smaller than 400 µm, especially in the 2DC measurement. A size distribution from one of the 80 WAICO downwind track-streamline intersections is shown in Fig. A2a. The largest crystal detected in this five-second interval is 400 µm. A histogram of crystal interarrival times for the same five-second interval is shown in Fig. A2b. Evident in the left tail of the histogram is a minimum, at interarrival time τ^* = 2x10^{-3} s, where we delineate between a fragment mode ($t < \tau^*$) and a mode corresponding to intact crystals ($t > \tau^*$). We note that 7% of the crystal counts classify as fragments and that this fraction is much smaller than the example presented by Korolev et al. (2013) for a 2DC with standard probe tips (their Fig. 14a).

We analyzed interarrival times obtained from each of the 80 WAICO downwind track-streamline intersections. Histograms were binned as in A2b (3.5 bins per decade) and all particle images, including those that did not pass the rejection criteria of Pokharel and Vali (2011) (Sect. 2.2), were used. We developed a procedure that searches the histogram for a minimum between $t = 10^{-6}$ s and the histogram mode. In our set of 80 there are 16 cases that do not exhibit a minimum and 21 with a provisionally significant minimum. The provisional cases were characterized by a cumulative fraction, evaluated at the minimum, greater than 20%. The example shown in Fig. A2b is not a provisional case because the cumulative fraction at $\tau^{*} = 2\text{x}10^{-3}$ s is less than 20%. All of the provisional cases exhibited a minimum that was within an order of magnitude of the histogram mode. Because order-of-magnitude separation is substantially less than the minimum-to-mode separation seen Korolev et al. (2013) (their Fig. 14), we concluded that a fragment mode could not be discerned. Thus, we ignored the effect of shattering. Twenty six of the remaining 43 cases (43=80-16-21) had a minimum more than an order of magnitude smaller than the histogram mode; Fig. A2b is an example. For these we ignored the effect of shattering because the fraction affected was less than 20% and because the rejection criteria of Pokharel and Vali (2011) removes some of the affected crystals from the population used to evaluate the concentration.

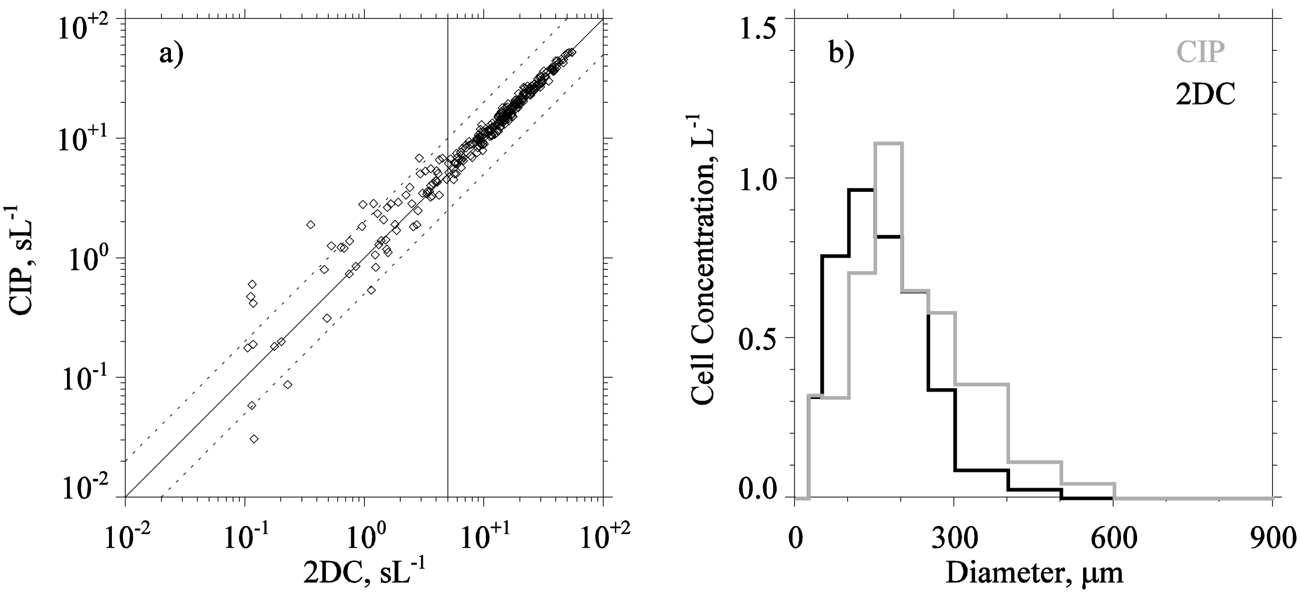

Fig. A1 – a) The CIP/2DC concentration comparison. Compared values are five-second averages and are for crystals larger than 50 µm. Comparison data is from 20110109 during the Colorado Airborne Multi-Phase Cloud Study (CAMPS). Wyoming King Air data shown here was selected from three along-wind level-flight cloud transits: 1) 221200 to 222200 UTC, 2) 223900 to 224800 UTC, and 3) 230600 to 231600 UTC. The vertical line at 5 sL^{-1} is drawn at the median value for our set of 80 WAICO 2DC-derived measurements. b) 2DC and CIP size distributions from a representative five-second subset (224646 to 224650 UTC) of the CAMPS cloud transits on 20110109.

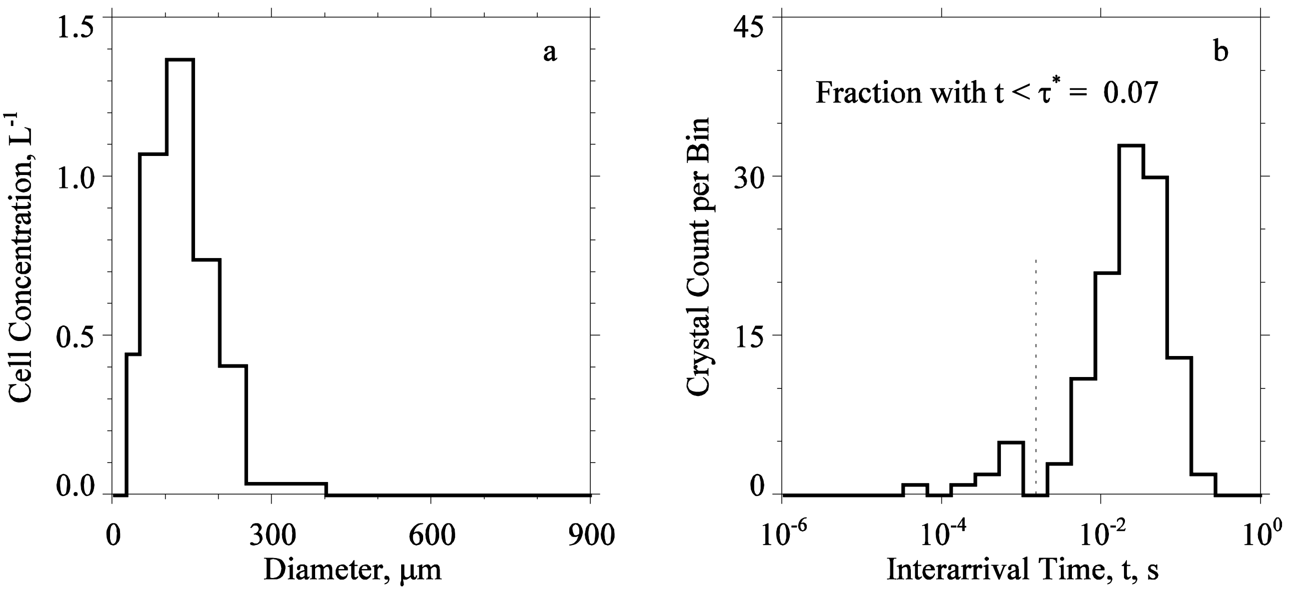

Fig. A2 – a) The 2DC size distribution derived for the WAICO 181933 to 181937 interval on 20080227. This interval corresponds to the downwind track-streamline intersection at x=15 km in Fig. 1c. b) The interarrival time histogram for the 181933 to 181937 interval on 20080227. The vertical dashed line marks a minimum between a fragment mode ($t < \tau^*$) and a mode corresponding to intact crystals ($t > \tau^*$).

References

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