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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Ice particles in the upper anvil regions of mid-latitude continental thunderstorms: the case for frozen-drop aggregates" *by* J. L. Stith et al.

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We thank this reviewer for the helpful suggestions for improving our paper. Our responses to the reviewer's comments are as follows:

General Comments. The reviewer suggests that the principal aim of our paper is to show that the conditions for FDA production may be more widespread than has previously been suggested, including possible production at temperatures warmer than the homogeneous freezing temperature and that these points should be emphasized more in the introduction and the evidence presented for warmer production of FDAs should

be bolstered. Generally, we agree with this interpretation of the intent of our paper and we expand the introduction slightly to emphasize these points. However, because there have been so few previous observations of FDAs and chain-aggregate FDAs, there is little in the way of an existing inventory in the literature to use as a starting point. This paper aims to expand this inventory and to call attention to this category of ice which is in need of further study. As far as bolstering the evidence for warmer production of FDAs, we are somewhat limited by having only a few observations at warmer temperatures. We expand this section somewhat, in line with the available data, to include imagery of FDAs observed at warmer temperatures with appropriate discussion of these images added to the paper.

p. 27023 line 24. The reviewers asks us to comment on the extent to which shattering may impact our data due to the fact that particle inter-arrival time correction software is not completely effective at eliminating the effects of particle shattering. We believe that the effects of shattering are minimized in the data presented here because both anti-shattering tips for the 2DC and software corrections using particle inter-arrival time are implemented. The combination of the two techniques offers the best change of minimizing the effects due to shattering artifacts (Korolev et al., 2013). Furthermore, particles must shadow at least three diodes (75 microns) to be included in the total concentration data. As suggested in Korolev et al. (2013), it is probably not possible to completely know the residual effects of shattering even with the three methods used here to reduce these effects. While there may still be some residual shattering impacts on the total 2DC concentration, impacts on higher moments of the size distribution, such as total particle volume/mass concentration, are likely to be minor (Korolev et al, 2013). We have expanded the description of the shattering impacts in the paper to better cover this topic.

p. 27025, line 7. The reviewer asks us to confirm that our treatment of current data follows that of Davis et al. The measurement technique and data processing steps follow that of Davis et al. (2007 a, b).

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p. 27025/6, Figs. 1/3. The reviewer asks if it is possible to give a simple presentation of electrical activity in these clouds. Because the DC3 project had a major focus on NOx-production by lightning, nearly all of the storms chosen for sampling exhibited significant or intense lightning activity, so the charge separation process was certainly present in these clouds. As a part of the next phase of our study we intend to examine the Lightning Mapping Array data to determine if it can help explain the occurrence of the chain-aggregate FDAs in these storms. Thus, we have expanded the explanation in the paper to make it clear that the charge separation process is likely in these storms, but will save more detailed presentations of electrical activity in these storms for future research.

p.27029, line 13. The reviewer suggests that the bulk IWC from the CLH-2 is not independent of the measured size distribution. This is a valid point and we have changed the text to be clearer. It is more correct to say that the measured IWC is only weakly dependent on the particle size distributions at the typical high altitude and high airspeed conditions where sampling typically occurred. Unpublished computational fluid dynamics calculations done specifically for the CLH-2 on the G-V sampling conditions suggest that the particle aspiration efficiency was within 4.6 % of the inertial enhancement ratio (ratio of air velocities) for diameters greater than 25 microns. A similar result for the CLH-1 instrument is shown in Figure 4 of Davis et al. (2007a). For the DC-3 sampling conditions, we estimate that particle size distribution effects to be less than 2% of the measured IWC.

p. 27029. Line 14. The reviewer recommends looking more closely at the mass-diameter power-law relationship and suggests some possible dimensional relationships. We agree with the reviewer's comments that the existing relationship is adequate for showing the dominant contribution to total IWC by small particles on the fringes of the cloud, and that was the primary intent of the analysis presented here. However, we believe that the suggestion by the reviewer to look for mass proportional to D-squared (differential settling) versus mass proportional to D (chain aggregation) is an excellent

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method to use in further studies.

p. 27029, Fig 12. The reviewer suggests that the figure is not clear whether it represents a horizontal cross section or a vertical cross section through the anvil. We have changed the figure caption to clarify this point.

p. 27030, Fig.13. The reviewer suggests that the -38 C isotherm should be added to the figure. We have added the isotherm to the figure and updated the text in accord with this suggestion.

p. 207030, line 21. The reviewer suggests that the weaker updraft may however be a means by which pristine crystals might lofted to higher altitudes where they might aggregate with FDAs produced higher up. We agree that it is worth mentioning this possibility in the paper.

p. 27034, line 25. The reviewer asks if Table 1 is to be interpreted as saying that FDAs were observed throughout the full range of temperatures given, some images of FDA from warmer temperatures should be included, and suggests some ways in which the discussion of warmer FDA encounters may be improved. We have changed the text from "The sampling times provided in Table 1 are intended to identify clouds that contained FDAs, but FDAs were not necessarily found throughout the cloud as discussed below." to "The sampling times and temperatures provided in Table 1 are. . ." We have also expanded the discussion of warmer FDA encounters and included some images from warmer FDA encounters. We do not, however, subscribe to the use of the term "proto-graupel" (i.e. "first-graupel") as we have no way of knowing when these FDA images were formed in relationship to other graupel in the storms. Graupel densities as low as 0.05 g cm-3 have been reported in the literature (Locatelli and Hobbs, 1974), which is within a factor of two of the average density reported here for FDAs, so it is reasonable that some of the FDA's might be indistinguishable from low-density graupel. We hope that the role of riming versus electrical aggregation can be better established as more in depth studies are done of FDAs and FDA forming regions of the storms.

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Detail points. These have been corrected. Our usage of the umlaut appears to follow the usage in the original paper, although we defer to the editor concerning the proper usage here.

We also note that, since the discussion paper was written, CLH-2 data have been updated to reflect an improved understanding of the particle enhancement factor based on a recent series of test flights of the instrument alongside the NCAR counterflow virtual impactor (CVI). This resulted in a slightly lower computed effective density for the FDAs, but does not change the paper significantly otherwise. We have added a short note to point out that the inlet enhancement factors used to convert water vapor signals into IWC (and which assume spherical particles) may return somewhat low values for the highly non-spherical FDAs observed in this study. Future studies will investigate this possibility, although it does not alter the basic conclusions of this study.

References.

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Interactive comment on Atmos. Chem. Phys. Discuss., 13, 27019, 2013.