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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Captured Cirrus Ice Particles in High Definition" *by* Nathan Magee et al.

Nathan Magee et al.

magee@tcnj.edu

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The authors would like to thank the two referees for your thoughtful and detailed comments on this manuscript. Both reviews bring up important questions and considerations that should help to strengthen the final version of the paper. With respect to specific comments and questions from the referees, we convey our replies as follows:

In reply to RC1: 1. We agree that the results of the present manuscript are mostly descriptive rather than thoroughly quantified. We do think that these cryo-SEM images and the qualitative assessments thereof nevertheless present a novel view of cirrus ice particles that give insight to important questions, and suggest new avenues to pursue regarding cirrus microphysical research. In some senses, the inherently limited sam-

pling characteristics of this technique challenge the creation of quantifiable measures of large-scale cirrus properties, so we were reluctant to offer definitive statistics or parameterizations on a few samples that may not be broadly representative. However, our continuing work is pursuing several avenues to make ICE-Ball results more quantifiable and extendable to parameterizations for modeling: a) we have added a particle-vision system to be able to quantify cirrus particle densities coincident with particle captures, b) we are collaborating on a new project with PSU and DOE-ARM to fly ICE-Ball missions in different synoptic regimes and in conjunction with cloud RADAR and LIDAR remote sensing, and c) new research team members will focus on turning SEM micrographs of the ice particles into quantifiable statistics of several measures of complexity. In the final manuscript, we will add a paragraph to the conclusions highlighting potential paths forward toward improved quantification of cirrus ice particle complexity.

2. We think insights into aerosol roles in cirrus are a potential high-value contribution from ICE-Ball data in future work. We are confident that most of the small visible aerosol particles we see in the micrographs have adhered to the ice crystals in-cloud for several reasons: a) most aerosols are firmly attached or partially embedded in the ice surfaces (we can move and tilt the stage and partially sublimate surfaces to confirm this), b) CFD simulations and clear-sky flights both indicate that our system has a low collection efficiency for particles below 20 micron diameter, and c) collection tubes are normally sealed closed except when near or inside the cirrus clouds. New versions of the ICE-Ball sampling system will further address this question through a redesigned flow-path that aims to improve small-particle collection efficiency, in conjunction with the coincident particle vision system mentioned above. We are also planning for more complete imaging, counting, and compositional characterization of interstitial, surface-embedded, and residual aerosols in future missions.

3. - 21. (Technical comments, added references, and editing suggestions) Thank you very much for providing these detailed suggestions and additional references. All units will be formatted to SI standard notation. We look forward to incorporating each of

these additions and corrections in the final manuscript.

In reply to RC2: 1. Sampling Characteristic: We agree that a more through understanding and presentation of sampling characteristics of the ICE-Ball system is important to allow the measurements to be put in proper context relative to a single cirrus cloud, let alone to present measurements as characteristic to all cirrus or subtypes of cirrus. We have CFD simulations of the system geometry and streamlines that broadly appear to agree with the data from in-flight ice and aerosol particle collections. The CFD results and actual data both show collection efficiencies near 100% for particles over 60 micron max. diameter and efficiencies becoming quite small for particles under 20 microns. For example, the flight from April 18, 2019 (supplement 1E) mostly collected particles with diameters between 30-70 microns; most other flight collections were dominated by larger particles, with only a few below 50 microns. The regime between 20-60 micron diameter appears to be a transition where we capture a fraction of particles near the capture-tube inlets, but with higher fractions of the increasingly small particles following streamlines around the inlet tube. We aren't yet confident enough to assign exact collection efficiencies as a function of particle size because the collection characteristics appear to also be influenced by small-scale cloud turbulence, balloon-wake flow, and particle density. However, as discussed in our reply to RC1 above, we are adding an in-flight particle vision system to have an independent means to observe particle numbers, and we are slightly redesigning the capture aerodynamics to better sample smaller particles. Nevertheless, we would be happy to add some of the CFD results for the configuration used in this paper along with a sampling discussion. This could be included in the supplement, or if the editor prefers, we could add a figure and discussion to the methods section of the final version of the paper.

2. Mapping of microphysical properties to atmospheric conditions: This is a good point, and your description of the system's consecutive sampling of the cloud column is correct. As you described, in the case of a high-density collection of many particles (e.g. figure 2), it is very likely that collections from the bottom of the cloud are buried

under the top few layers of particles that we can image, and were captured only from the top of the cirrus layer. It is from several of these situations that we inferred high habit heterogeneity in the tops of these clouds, including the mix of sharp-faceted particles with others having high sublimation. We agree that the more sparse collections don't provide good insight into the distribution of habits through the cloud layer (except in a few cases where particle shapes are not highly heterogenous, e.g. supplement 1E). We do expect that future missions can provide significantly more insight into vertical distribution of ice particle habits and help unravel connections to cloud dynamics and thermodynamics. The planned missions over US Dept. of Energy-ARM RADAR and LIDAR are particularly exciting in this regard. In the case of a future flight through a relatively thick or dense cirrus layer, we will also plan to isolate captures by altitude, to sample the bottom, middle, and top of the cloud layer separately. In any case, we agree it is a good idea to revise and add detail to our current discussion in 4.1, and also point to the planned improvements in future work.

3. Sampling of different cirrus cloud types: We agree that we should explicitly point out that the focal data set in Fig. 2, Fig. 3, and table 1, and several of the additional data shown in the supplement (1A & 1D) constitute moderately thick frontal cirrus, although in none of the sampled cirrus were thick enough to be optically opaque. Several of the supplement data collections are from thin cirrus (1B,1E,1F,1G) or convective-origin cirrus (1C). We will look forward to including the insights from the papers you recommend in a revised discussion of the atmospheric and cloud-scale context of the cirrus particles described in Fig. 2, Fig. 3, and table 1. Overall, we very much agree that distinct cirrus types need to sampled more comprehensively, with a goal to connect detailed ice particle characteristics with the full range of cirrus altitudes, temperatures, dynamics, and nucleation modes.

Technical comments, suggestions, and references: Thank you very much for providing valuable additional references to include, and for several detailed editing corrections. We look forward to incorporating each of these additions and corrections in the final manuscript. We will revise to ensure all units are given in the SI standard. Finally, with regard to the question about the "rock" at upper left in figure 2: we think this is a steel burr (remnant from machining) that broke off from inside the collection tube. No such large mm-scale particles were observed in any other particle captures.

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