

Title: Measurement report: Mass and Density of Individual Frozen Hydrometeors

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General Comments:

This paper analyzes measurements from a new instrument, the Differential Emissivity Imaging Disdrometer (DEID) to obtain continuous measurements of ice particle mass and effective size D_{eff} . The DEID data are combined with photographic imagery obtained using a Multi Angle Snowflake Camera (MASC) to obtain estimates of particle density. Results for three ice particle shapes are presented; graupel, densely rimed crystals and aggregates, where the number (N) of ice particles sampled in the latter two categories exceeds 15,000 (for each category). For graupel, $N = 34$. Mass- D_{eff} and density- D_{eff} power law relationships are presented for each shape category. The paper is well organized and well written with high-quality figures. It should be acceptable for publication after minor revisions. There are some concerns however that need to be addressed before publication, mentioned below and under Major Comments.

More information is needed for the ice particle shape categories of “densely rimed” and “aggregates”. What is densely rimed; columnar crystals, planar crystals, or both? Does this include densely rimed aggregates? For aggregates, please indicate the type of primary component ice crystal, whether it is columnar or planar, and if columnar, whether it is short or long columns (or needles). This information may help explain why the power term b is so large in the aggregate relationship $M = a D^b$ where M is ice particle mass and $D = D_{\text{eff}}$.

Figure 12 in Chen and Lamb (1994, JAS) compares theoretical and observed values of the inherent ice crystal growth ratio Γ^* , from which b can easily be calculated. Theory assumes prolate spheroids for columns and oblate spheroids for planar crystals, with the latter being relevant for hexagonal plates, broad branched dendrites and rimed planar crystals. Since there is reasonable agreement between theory and observations, their results provide constraints for likely values of b . For short and long columns/needles, $1.8 \leq b \leq 2.7$, while for the above noted planar crystals, $2.3 \leq b \leq 2.5$. While the DEID b value for “densely rimed” conforms well with these ranges, the aggregates (DEID $b = 2.75$) would need to be comprised mostly of short columns to conform with the expected b range, and short columns tend not to aggregate well. Thus, it is difficult to reconcile the b value for aggregates with both theory and observations.

The authors compare their aggregate b with aggregate b values from Locatelli and Hobbs (1974), ranging from 1.4 (unrimed dendrites or side planes) to 1.9 (containing either side planes, columns & bullets or densely rimed dendrites). Given the component crystals, it makes sense that the latter value is larger (i.e., the increase in mass per unit size increase is larger). But it is hard to imagine packing the crystals so densely in an aggregate that $b = 2.75$.

Taking this a step further, Westbrook et al. (2004, “Theory of growth by differential sedimentation, with application to snowflake formation”, Phys. Review E) presents a model of columnar particle aggregation based on the differential sedimentation of the particles. A condensation of these results are reported in Westbrook et al. (2004, “Universality in snowflake aggregation”, GRL, **31**, L15104, doi:10.1029/2004GL020363, but the paper is difficult to understand due to missing information. They state that “The structure of the aggregates produced by this process is found to feed back on the dynamics in such a way as to stabilize both the exponents controlling the growth rate, and the fractal dimension of the clusters” (i.e., the value of b). Their model predicts $b = 2.05 \pm 0.1$, with theory giving $b = 2$. This is either close to or the same as the measured value of b reported for all seven types of observed aggregates in Table 1 of Mitchell et al. (1990, “Mass-Dimensional Relationships for Ice Particles and the Influence of Riming on Snowfall Rates”, JAM).

Overall, the evidence appears compelling for rejecting 2.75 as a plausible b value for aggregates. Nonetheless, these are new and interesting measurements, and the community can decide how seriously to take them. But to make that decision, all of the above studies should be described and cited.

Major Comments:

1. Line 104: While this identity appears plausible, it is not convincing mathematically. Can this identity be demonstrated mathematically? Seems important since it is used to derive Eq. 3 below.
2. Table 1: Please add N (# samples) to this table.
3. Figure 7: It might be of interest that “heavily rimed dendrites” in Mitchell et al. (1990) have $m = 0.068 D^{2.2}$ in mg-mm units. This snow-type probably has more riming than the “densely rimed” category here (hence the larger prefactor), but b is quite consistent with the Locatelli and Hobbs b range. Erfani and Mitchell (2017, ACP) present evidence that riming changes the prefactor but not b .
4. Lines 189-191: This statement seems to contradict the findings of Chen and Lamb (1994, JAS) who show theoretically and observationally that the mass exponent for long columnar ice crystals is < 2 and lies between 2 and 2.5 for planar ice crystals.
5. Line 220: Please also provide the standard deviation values here.

6. Figure B3: Can this be understood as a 3-D volume showing the distribution of ice particles within that volume? If so, can it be used to evaluate the PSD post-processing algorithms based on interarrival times, which are designed to reduce the contribution of shattered ice particles to the number concentration measured by optical probes? The science question that might be addressed is whether “inertial clustering” of ice particles occurs naturally as it does for cloud droplets (Ray Shaw’s work). If ice particles tend to naturally cluster with relatively little space between particles, then interarrival algorithms may be “throwing the baby out with the bathwater” more often than is currently known. While this is outside the scope of this paper, perhaps it might be worth looking into?

Minor Comments:

1. Line 74: Eq: 2 => Eq. 2?

With best wishes for this paper,
David Mitchell