Improved estimates of mass weighted fallspeeds and snowfall rates.

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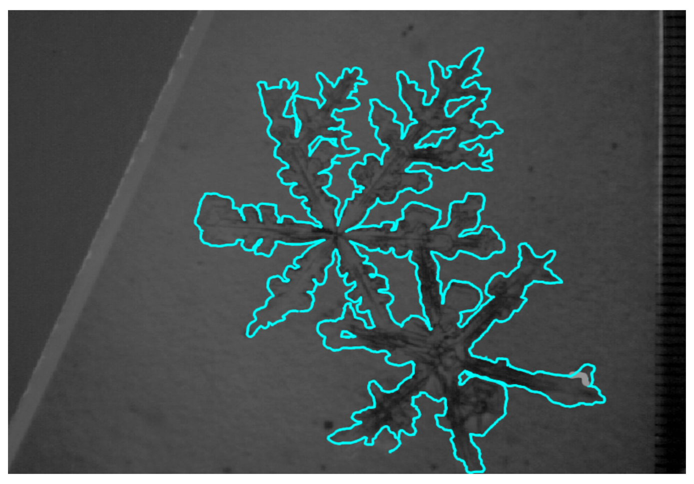
Cloud lifetimes and the Earth's radiation budget are strong functions of ice particle sedimentation velocities. Our long-term goal is to estimate these velocities from CloudSat and CALIPSO data and to use them as a basis for evaluating their representations in global climate models. **What is the current state of our knowledge of ice particle fallspeeds?**

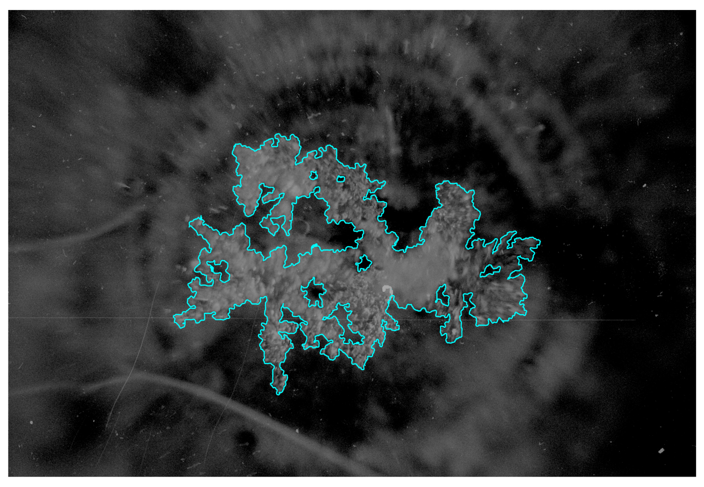
Fall velocity work

We have acquired historical raw data sets containing direct measurements of all of the properties of ice particles needed to derive ice fallspeeds. We have digitized photographs of particles to better calculate their dimensions. These data span particle sizes from tens of microns to centimeter sizes. Drag coefficients (C_d) for these particles are derived from

$$C_d=2mg/(\rho_f V_t^2 A) \qquad (1)$$



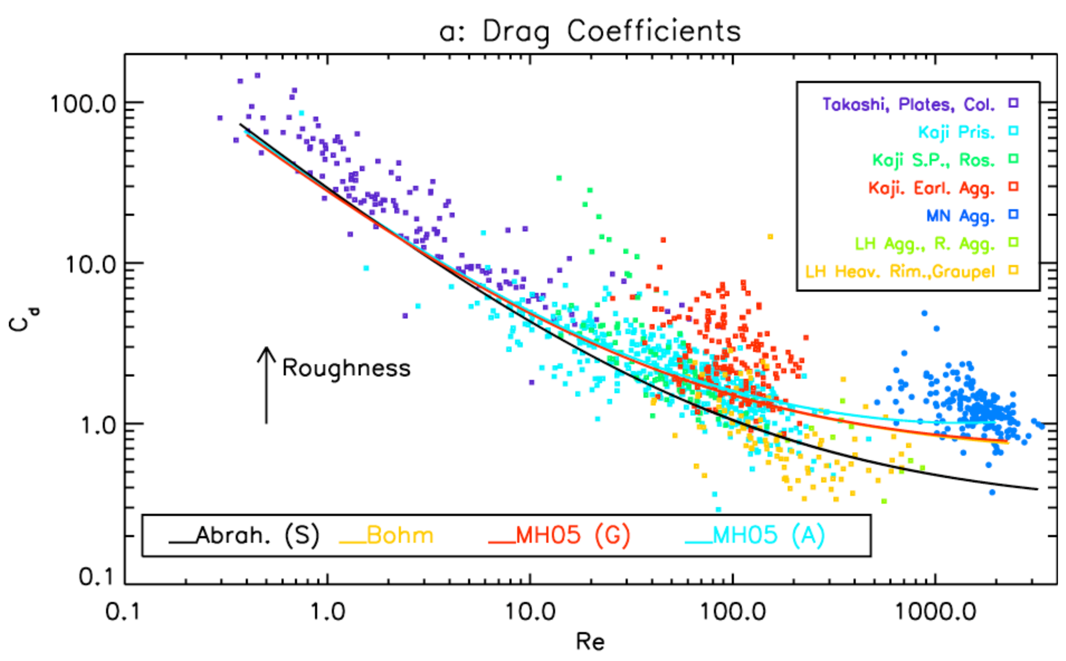
Kajikawa "early aggregate"

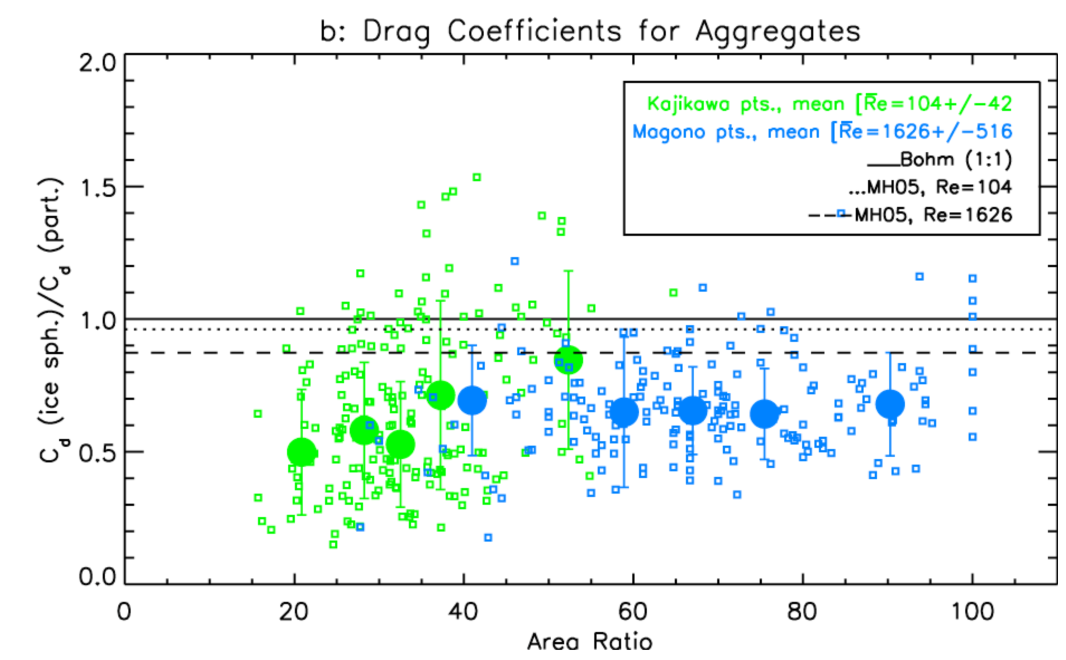


Locatelli and Hobbs "aggregate"

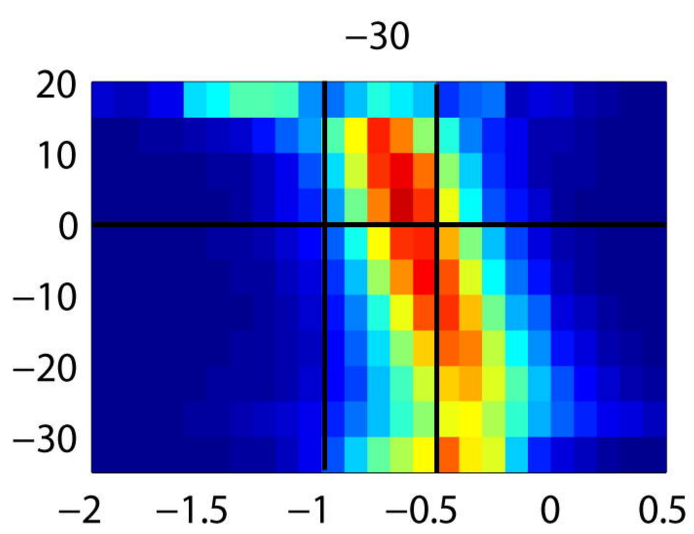
Drag coefficients, for a given value of the Reynolds Number, $Re=V_t D/\varpi$, vary widely and are a function of the number of particles in the aggregate (see Kajikawa, "early aggregates"), the type of component ice crystals (see Fig. 2a-b), and the degree of riming. Because the spread noted in C_d is inversely proportional to $(Vt)^{0.5}$, aggregates (and other particle types) of the same Re have factor of two or more differences in fallspeeds. Representations of their drag coefficients to account for turbulence are inadequate

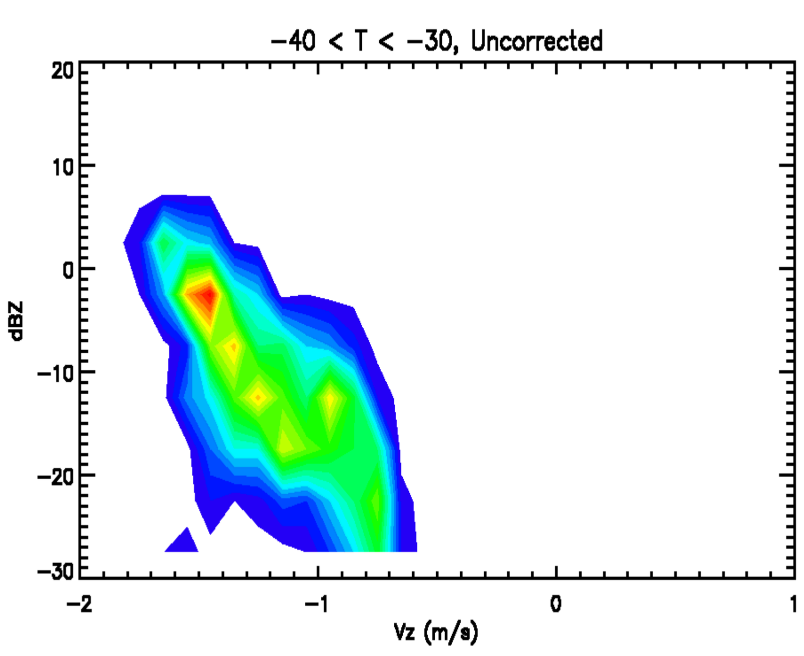
a: Drag coefficients derived from particle properties as a function of the Reynolds number from reanalyzed data sets.
b: For each aggregate in the Kajikawa and Magono and Nakamura (1965) data sets, C_d (particle) has been derived given its properties (as in panel a) and C_d (ice sphere) from the Bohm relationship for the particles' Reynolds number. The ordinate shows the ratio of the two drag coefficients and the abscissa the particle area ratio. Mean ratios and the standard deviations are shown.
Also shown are horizontal lines indicating that the ratio would be using the MH05 correction for aggregates at the mean value of the Reynolds number for each data set.

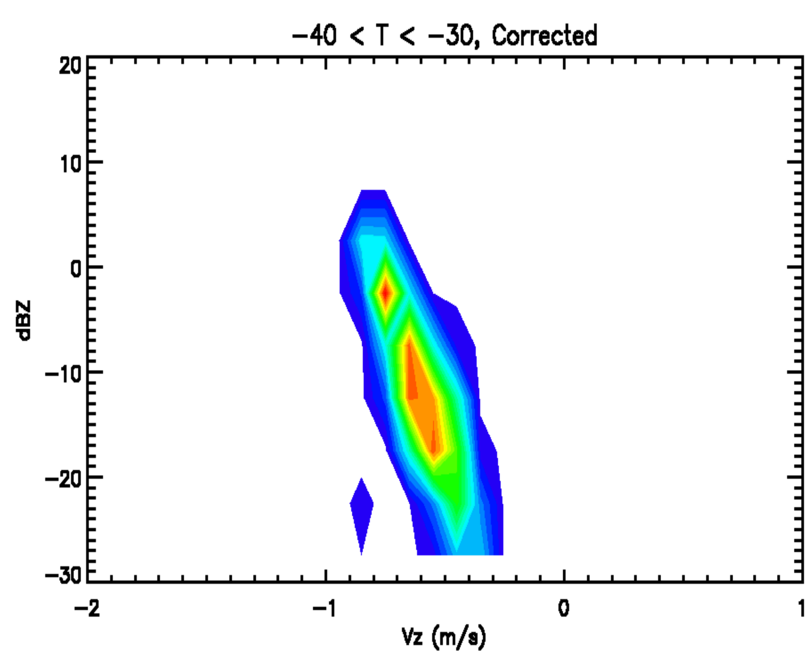




Averages of three years of data from Chilbolton, England X-band Doppler radar observations. The radar is in a vertically-pointing mode. Colors represent frequency of observations, in a normalized format. Data and figures courtesy of Chris Westbrook.



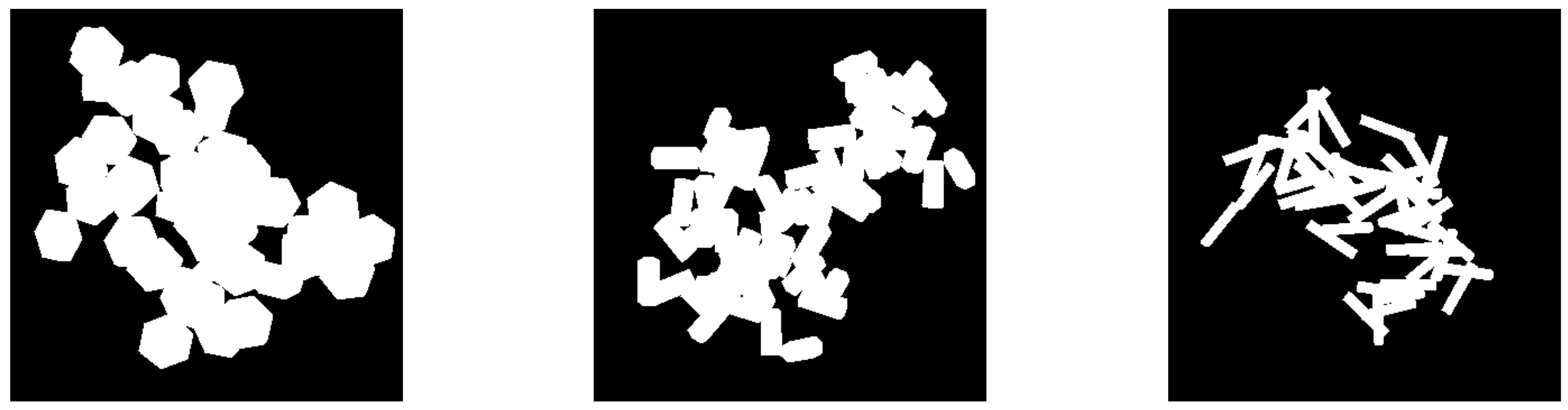




Doppler fall speeds are estimated from aircraft microphysical data for the ARM IOP in 2000. The conditions for the flight were typical mid-latitude conditions and should compare reasonably to the Chilbolton data. The left panel show the doppler radar values calculated assuming the MH05 parameterization while the right panel shows the corrected values based on the uncertainties found.

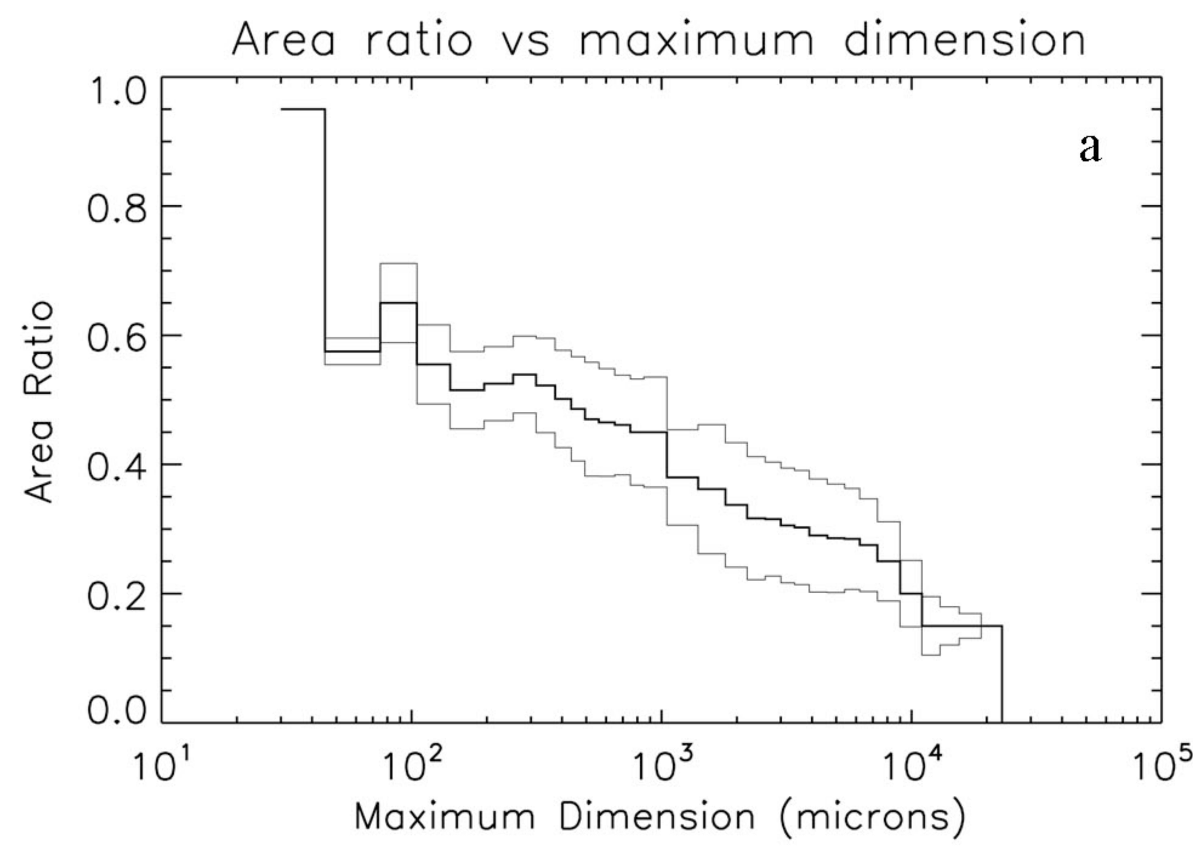
A self-consistent method to link ice particle area to mass using fractal geometry.

Accurate terminal velocity calculations require accurate particle area and particle mass estimates. For ice crystal aggregates, fractal geometry can be a powerful tool to relate particle area and mass. Aircraft microphysical probes measure the projected area of cloud particles. From these measurements it is possible to calculate the 2D fractal dimension which relates the particle projected area to the particle maximum dimension. The challenge is to determine the 3D fractal dimension based on the calculated 2D fractal dimension. This is important because 3D fractal dimension is the power in the common power law mass dimensional relationship. To investigate particle fractal properties we constructed theoretical ice crystal aggregates from hexagonal plates and columns.

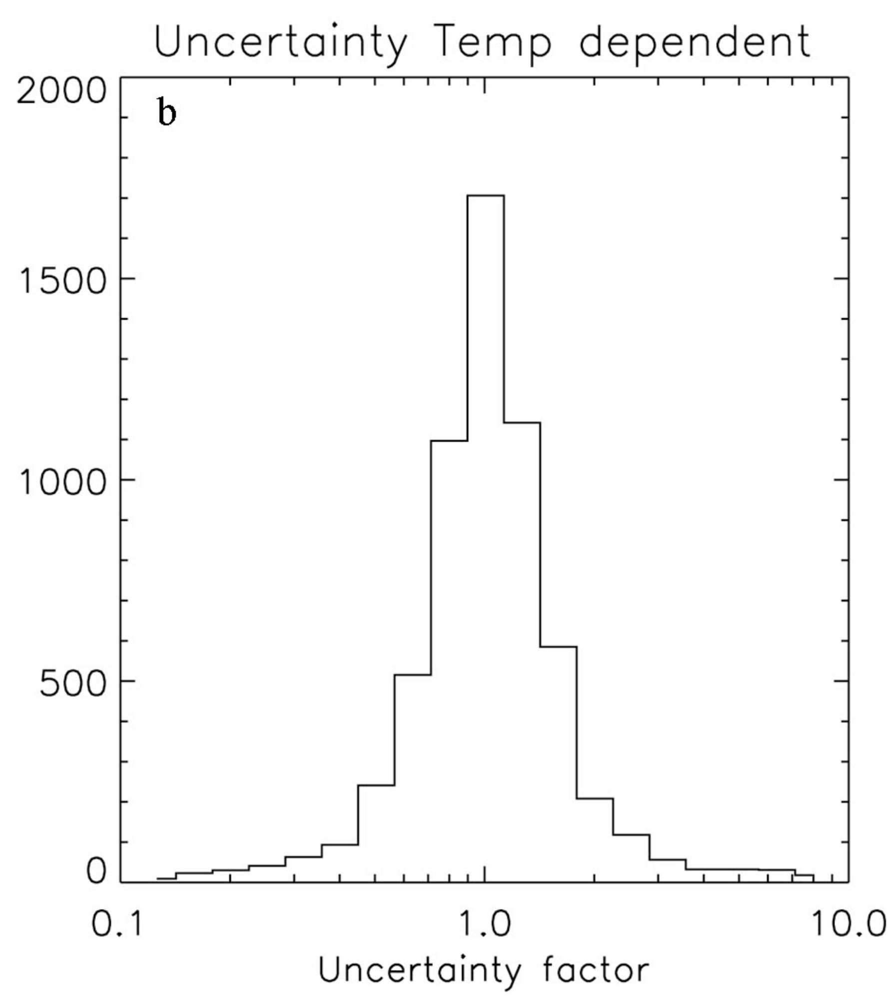


Theoretical aggregates made from different shaped seed crystals.

For the theoretical aggregates we calculated the 2D fractal dimension based on the project area that would be measured by an aircraft imaging probe and compared that to the 3D fractal dimension of the particle. Two dimensional and three dimensional box counting methods were used to calculate the fractal dimensions. The relationship between the 2D fractal dimension and the 3D fractal dimension was found to be constant for most theoretical aggregates composed of 25 or more hexagonal crystals.



To test the relationship we used data from the CRYSTAL-FACE field project. The UND Citation took measurements of particle properties through low latitude convective clouds composed mostly of aggregate ice crystals. The above plot shows the relationship between the particle maximum dimension and the particle area ratio. From this plot, a relationship was calculated for particle area ($A=\alpha D^{\beta}$). The βvalue is the 2D fractal dimension. From the relationships determined using the theoretical aggregates, the 3D fractal dimension was determined and entered into the common form ($m=aD^b$) of the mass dimensional relationship as the 'b' value. With α, β, and 'b' known, the only remaining unknown is the 'a' value. To find 'a' the α, and β values were used to identify the particle size that would have an area ratio of 1.0. By assuming that a particle with an area ratio of 1.0 would be a solid spherical ice particle we were able to determine a mass for the particle and solve for 'a'.



For the CRYSTAL-FACE dataset, the 'a' value and the 3D fractal dimension (the 'b' value) were found to have a temperature dependence. A temperature dependent form of the mass dimensional relationship was developed and used to test the theory. The particle mass estimates calculated from the new temperature dependent mass-dimensional relationship were combined with the measured particle size distribution to estimate the total ice water content. These ice water content values were then compared to the directly measured IWC and was found to agree well. A probability distribution function of the uncertainty is shown to the left. The result is surprisingly good given that the mass dimensional relationship was developed from fractal theory and did not require any pre-knowledge of the ice water content.