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Atmos. Chem. Phys. Discuss., referee comment RC1
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Comment on acp-2021-203

David Mitchell (Referee)

Referee comment on "Mass of different snow crystal shapes derived from fall speed measurements" by Sandra Vázquez-Martín et al., Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2021-203-RC1, 2021

General Comments:

This paper is the first to demonstrate the calculation of ice particle mass from measurements of ice particle maximum dimension, projected area and fall velocity, and in doing so, it represents a test of hydrodynamic flow theory. However, as argued below, the method appears successful for graupel and quasi-spherical ice particles, but less successful for planar ice crystals (e.g., stellars or dendrites) and definitely not successful for needles and columnar ice crystals. Similar findings were reported by Heymsfield and Westbrook (2010, JAS; henceforth HW2010), where the fall speed treatment of Mitchell (1996, JAS; henceforth M96) worked well for ice crystals having aspect ratios closer to unity (e.g., graupel, short columns, thick plates) but not well for stellars and needles having more extreme aspect ratios. Therefore, two new approaches are offered for modifying the methodology described in this study.

One approach is to define the Reynolds number Re in terms of a characteristic length L*, rather than maximum dimension D_{max}, where $Re_{L*} = V L^*/v$, where V = terminal fall speed and v = kinematic viscosity of air = η/ρ_a where ρ_a = air density and η = dynamic viscosity of air. This L* was found to describe the vapor mass and heat transfer from a ventilated ice crystal well and hence captures the flow effect on ice crystal growth. L* is defined as

$$L^* = A/P \quad (1)$$

where A = total surface area of an ice particle and P = ice particle perimeter projected to the flow. See Pruppacher and Klett (1997), *Microphysics of Clouds and Precipitation*,

Kluwer Academic Publishers, p. 552, for more details.

Fortunately, Jayaweera (1971, JAS) has formulas describing L* for planar and columnar ice crystals. For planar ice crystals, L* = (d/2) (1 + 2e) and

$$Re_{L*} = 0.5(1 + 2e)\ Re_d \quad (2)$$

where subscript d on Reynolds number Re indicates that Re is evaluated using the diameter d of a circle having the same area as the basal face of the ice crystal. For hexagonal plates, d = 0.910 D, where D = maximum dimension of the basal face. Moreover, e refers to the ratio of minor to major axis. Reasonable estimates for e can be obtained from D_{max} and Auer and Veal (1970, JAS). For columnar ice crystals, L* = (π/4)d [1 + (1/(1+e))] and

$$Re_{L*} = (\pi/4)\ [1 + (1/(1+e))]\ Re_d\ . \quad (3)$$

Notice here that Re_{L*} depends on the "diameter" or thickness of a column and not its maximum dimension D_{max} (as was used in this ACPD paper). This indicates V is most related to d. By substituting Re_{Dmax} used in this ACPD paper with Re_{L*} in Eqn. 5 to calculate Best number "X", and substituting D_{max} with L* in Eqn. 6 of this paper (while using this new calculation for X), the m-D_{max} power laws found here for columnar and planar ice crystals may be improved, having greater consistency with the body of theoretical and empirical knowledge (discussed below under Major Comments).

The second approach is to calculate the "modified Best number" X* from Eqn. 5 of this ACPD paper (as described in HW2010) by redefining the constants used to calculate

X^*, where $C_0 = 0.35$ and $\delta_0 = 8.0$. However, in this case $Re = Re_{Dmax}$ (as originally used in this paper) since this maintains consistency with HW2010. Then mass m is calculated by inverting the HW2010 definition of X^*:

$$m = \pi \eta^2 X^* A_r^{1/2} / (8 g \rho_a) \quad (4)$$

where m = ice particle mass, g = gravity constant and A_r = area of ice crystal normal to the flow divided by area of circle having same maximum dimension (referred to as the area ratio).

However, if the "thick columns" shape category in this study corresponds to short, thick columns, the M96 fall speed scheme should work fine for this shape category, and this second approach may not address the problem for this shape.

It is possible that neither of these alternative approaches will render improved results, but it seems worth a try. If there is no improvement, the limitations described below will need to be mentioned in the paper.

Major Comments:

- Lines 149-150: Please indicate which relationships in Tables 1 and 2 are based on the approach described in Sect. 3.3 vs. the approach given in Sect. 3.2. Since this approach involves empirical relationships already having considerable uncertainty,

m(D), m(A) and v(m) from this approach may have greater uncertainty than the previous approach (Sect. 3.2) due to the propagation of uncertainties in the empirical expressions used here. This knowledge may be helpful for interpreting the results in Tables 1 and 2.

- Lines 185-188 on stellar ice crystals: This same argument is expressed more quantitatively in Mitchell et al. (1990, Sect. 4a), where hexagonal crystal volume V is approximated by using a circular basal face so that aspect ratio k = c/a = c/r, where r = radius of this circle having the same area as the basal face. Moreover, c and a are the semi-axes corresponding to the prism and basal faces of an ice crystal. Thus, $V = \pi r^2 k r = \pi k r^3$ for this approximation, and for constant density and constant k, the m-D relationship has a power of 3.

However, constant k is an invalid assumption for a stellar ice crystal that only forms between ~ -14 and -16 °C. As described in Chen and Lamb (1994, JAS), k is rarely constant (definitely not at these temperatures), and depends on the ratio of condensation coefficients for the basal and prism crystal faces. This is referred to as the inherent growth ratio (IGR), and IGR is related to m-D power laws in Sect. 7 of their paper. I strongly recommend that the authors read this paper and then revise this commentary accordingly. This information is also in the cloud physics text book by Lamb and Verlinde, Physics and Chemistry of Clouds (2011, Cambridge Univ. Press). In addition, Jerry Harrington's group at Penn. State Univ. has greatly extended this work through several publications (e.g., Harrington et al., 2013, JAS, "A method for adaptive habit prediction in bulk microphysical models. Part I: Theoretical development).

Physical intuition also informs us that slope b_D is too high since b_D is a measure of the increase in mass with respect to size. A large (i.e., steep) slope indicates a relatively large mass increase per unit size increment, but this is not true for stellar or dendrite ice crystals since their ice density decreases with increasing size.

- Lines 190-196: These shapes are all columnar, which may be a clue to the problem here. Reynolds Number Re is expressed by (2) in terms of D_{max}, but due to hydrodynamical considerations, some argue that D_{max} should be replaced by a "characteristic length" L* defined in Pruppacher and Klett (1997) as: L* = A/P, where A = total ice particle surface area and P = particle perimeter normal to the flow. For needles, changes in A and P will be roughly proportional, with L* changing much less than D_{max}.

As shown by Jayaweera (1971, JAS), L* is strongly related to the column radius (or basal face semi-axis) and weakly related to D_{max}, indicating the formulation of Eqns. (2) and (5) in terms of D_{max} are flawed based on Re_{L*}. This is indeed the case for hexagonal columns.

- Lines 196-199: Note that b_D < 1.0 also for thick columns (C1e; group 3), with b_D = 0.81. Compare this with Tables 1 & 3 in Mitchell et al. (1990, JAM)), where C1e b_D =6 is found to be consistent with other studies based on dimensional-density relationships. Moreover, b_D = 2.6 is very consistent with the theoretical prediction of Chen and Lamb for C1e b_D (see their Fig. 12). This is strong evidence that the C1e b_D in this current study suffers from some limitation. Please expose this issue for the readers.

- Section 4.4.1 on plates: Chen and Lamb (1992) provide theoretical limits for columnar and planar ice crystals regarding b_D, where b_D for hexagonal plates lies between 2.0 and 3.0. In this current study for plates, b_D = 1.72, indicating its value should be treated with caution; please make readers aware of this. Since side planes grow diffusionally through a different mechanism (Furakawa, 1982, J. Meteor. Soc. Japan), it is not clear whether these limits apply to side planes. Please mention this.

- Figure 3 caption, last sentence: The text indicates that this should be valid for all ice particles and not just spheres; please make this clear.

- Lines 290-291: Can it be said that Re-X represents the fall speed upper limit?

- Summary and conclusions; 1st bullet: Will the fact that m is derived from v produce a co-variance that contributes to the stronger correlation between v and m? If so, please mention this wherever it is most appropriate.

- Summary and conclusions; 2nd bullet: Will not the power-law approximations have greater uncertainty than the relationships based on Eq. 5? Please address this concern wherever it is most appropriate.

- Summary and conclusions; last sentence of 3rd bullet: But we know this is not true based on Chen and Lamb (1994, JAS) and other m-D measurements for stellar crystals. Please remove this last sentence.

- Line 328-330: I don't see this relationship plotted (spherical ice having a density of 0.12 g cm^{-3}). If it is not shown, then please add in parentheses, "not shown".

Minor Comments:

- Line 150: Apparent typo; Sect. 3.1 => 3.2?

- Lines 248-9: It appears that Ma has not been defined.

- Line 329: The second comma is not needed.

Best wishes for a successful study,

David Mitchell

Please also note the supplement to this comment:
https://acp.copernicus.org/preprints/acp-2021-203/acp-2021-203-RC1-supplement.pdf