Interactive comment on "Mass of different snow crystal shapes derived from fall speed measurements" by Sandra Vázquez-Martín et al.

David Mitchell – Referee #1

Received and published: 23 April 2021

Dear David Mitchell,

We thank you for your constructive feedback. We sincerely appreciate that you took the time to read and evaluate our work. Please see below our response to your comments.

We are reporting our response (in blue italics) directly following each point that you have raised. Then, we are suggesting changes to the manuscript (still in blue).

- **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.

<u>One approach</u> is to define the Reynolds number Re in terms of a characteristic length L*, rather than maximum dimension Dmax, where $Re_{L^*} = V L^*/\nu$, where V = terminal fall speed and ν = kinematic viscosity of air = η/ρ_a where ρa = 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 (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

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

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 Dmax and Auer and Veal (1970, JAS). For columnar ice crystals, $L^* = (\pi/4)d\ [1 + (1/(1+e))]$ and

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

Notice here that Re_{L*} depends on the "diameter" or thickness of a column and not its maximum dimension Dmax (as was used in this ACPD paper). This indicates V is most related to d. By substituting ReDmax used in this ACPD paper with Re_{L*} in Eqn. 5 to calculate Best number "X", and substituting Dmax with L* in Eqn. 6 of this paper (while using this new calculation for X), the m-Dmax 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).

<u>The second approach</u> 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 C0 = 0.35 and δ0 = 8.0. However, in this case Re = ReDmax (as originally used in this paper) since this maintains consistency with HW2010. Then mass m is calculated by inverting the HW2010 definition of X*:

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

where m = ice particle mass, g = gravity constant and Ar = 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.

Response:
Thank you very much for suggesting these two approaches to modify and improve our methodology. The first approach seems to have much potential for better describing falling snow particles. Unfortunately, it is not easy to determine and add a characteristic length to all particles. This may be attempted after developing more automatic methods to retrieve particle properties from the image data. For a subset of shape group (3) we have performed a manual analysis to determine widths and lengths of hexagonal columns. From these dimensions, the characteristic length as defined by the study Jayaweera (1971, JAS) that you mentioned can be calculated and then used to determine Re and m. The results of this case study will be shown and discussed in our responses to RC2 general comment 1,

as referee 2 suggested such a case study to look at the X-Re relationship since m can be estimated directly from these dimensions without using X-Re.
For our current ACPD study, the second approach that you have suggested, i.e. using a modified Best number X as proposed by Heymsfield and Westbrook 2010 (H&W2010), can be easily added to our methodology as the needed area ratio is already part of our dataset. We are therefore implementing this, for more details please see our response to general comment from RC2.*

- **Major comments:**

1) 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.

Response:
The mass of each particle in our dataset is calculated based on measured maximum dimension, cross-sectional area, and fall speed as described in Sect. 3.1. All the relationships that we report in Table 1 are based on the fitting method described in Sect. 3.2. Table 2 contains both our results and previously reported results. Our results are the same as in Table 1 and are repeated for convenience. The previous results in Table 2 are shown as reported in literature, i.e., we did not use any of the analytical relationships described in Sect. 3.3 to convert any of those previous relationships. The derived relationships are reported in Sect. 3.3 for convenience in the case that a suitable dataset is not available, but existing relationships are. With our dataset we have the choice to use either method. By using the method outlined in Sects 3.1 and 3.2 we avoid issues with error propagation. We have clarified that in the manuscript.
Changes to the manuscript:
Line 149-150: "Note, that both methods for deriving the relationships given by Eq. 7–Eq. 9, described in Sect. 3.1 and in this section, are equivalent if they are based on the same dataset."
CHANGE TO: "Note, that both methods for deriving the relationships given by Eq. 7–Eq. 9, that is either the method described in Sect. 3.1 with fitting detailed in Sect. 3.2 or the alternative derivation from existing relationships described in this section, are equivalent if they are based on the same dataset."
Add at end of Sect. 3.3: "Thus, in this study, we have chosen to fit our data directly to Eq. 7–Eq. 9 (Sect. 3.2). This allows using environmental conditions individually for each particle and avoids the need to consider error propagation when deriving new relationships from existing ones."
Line 244: "Relationships from this work are further referred to as [VM]."
CHANGE TO: "Relationships from this work are further referred to as [VM] and are taken from Table 1. They have been determined as described in Sect. 3.2."
Caption Table 2: "The relationships found in this work are also shown as [VM]."
CHANGE TO:
"The relationships in this work have been found by fitting our dataset to Eq. 7–Eq. 9 as described in Sect. 3.2 and reported in Table 1. Those selected for comparison are also shown here as [VM]."

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 = π r2 k r = π k r3 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 bD is too high since bD 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.

Response:
The argument presented in Mitchel et al. 1990 Sect 4a applies to plates or columns with constant aspect ratio. While, presented in this way, it is very clear, we chose to express it in a more general way since we were referring to shape groups 6 stellar and 11 spatial stellar. For stellar particles one would, as you are pointing out, not expect a high exponent (steep relationship) as we are observing for shape groups 6 and 11. Instead you would expect a decreasing density, or area ratio, with increasing size. However, in Vazquez Martin et al. 2020 (Figure 5 Bottom) we showed that, unexpectedly, the area ratio in this group is almost constant. This may be caused by a particular mix of shapes in shape group (6). Besides pristine stellar shapes, the group contains other shapes, such as for example rimed stellar and split stellar crystals. These two shapes (rimed stellar and split stellar crystals) account for 15 out of 43 particles in shape group (6) and excluding them results in a reduced exponent (less steep slope). These numbers, however, also highlight that the shape group suffers from bad statistics due to a low number of particles. Thus, it will be interesting to revisit this issue later, when more pristine stellar particles will have been added to our dataset. We will highlight these issues more clearly in the manuscript.

Changes to the manuscript:
Line 187-188:
"However, a slope similar to spherical particles indicates that in these groups the morphology remains similar independent of size, i.e. during growth the ice particles grow equally in all three dimensions."
CHANGE TO:

"However, a slope similar to spherical particles may indicate that in these groups the morphology remains similar independent of size, i.e. ice particles scale equally in all three dimensions. An example for this would be hexagonal plates or columns that all have the same aspect ratio. For pristine stellar particles one may not expect such a steep slope similar to spherical particles, but rather a decreasing area ratio with increasing size. Shape group (6), however, contains other shapes besides pristine stellar particles, such as rimed stellar and split stellar crystals. A particular mix of shapes may cause an apparently steep slope. Indeed, the area ratio in this shape group is approximately constant (Vazquez Martin et al., 2020). Our dataset does not contain a sufficient number of stellar particles yet to analyse this further, by for example regrouping particle shapes. Additionally, the low number of particles in this group also results in a relatively high uncertainty ($\tilde{b}_d = 2.60 \pm 0.69$)."

3) 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 Dmax 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 Dmax, indicating the formulation of Eqns. (2) and (5) in terms of Dmax are flawed based on ReL*. This is indeed the case for hexagonal columns.

For our response, see Response to your major comment 4)

4) 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.

Response (to major comments 3) and 4) together):
In Vazquez Martin 2021 (ACP) we showed that fall speed is very poorly correlated to Dmax for shape groups (1) Needles, (2) Crossed Needles, and (3) Thick columns. This supports the point that you are highlighting, i.e. that Dmax is not suitable to describe relationships. As we have described there, and as you are pointing out, a characteristic length that is similar to the width of columnar particles would be more suitable as it should be used to determine Reynolds number. Since we are using Reynolds number (together with the X-Re relationship), this has consequences for the resulting mass. For these three shape groups, related to columnar particles. Using Dmax will result in unreliable and/or incorrect mass. As you have suggested, replacing Dmax with the width (diameter) and using Re based

on that, should result in a better relationship between size (now width) and derived mass. Indeed, for a subset of 75 particles in shape group (3), for which column width can be easily defined, b_D is 2.4. This seems consistent with b_D = 2.6 by Mitchell et al. 1990 (Tab. 1), who, however, have used column length (if we interpreted L in that paper correctly) rather than width.
We will include these arguments to improve the discussion and conclusions.

Changes to the manuscript:

Line 192-199:

"We have seen in Vázquez-Martín et al. (2020b) that an increase in Dmax (needle length) is directly proportional to A, indicating that the diameter of these needle-shaped particles (needle width) remains similar, whereas Dmax, and consequently A is growing. Thus, these shapes are clear examples of a size-dependent morphology, i.e. as size increases, not all three dimensions grow at the same rate. In this case, since Dmax is approximately proportional to A, one would expect both values of $\tilde{b}$D and $\tilde{b}$A ≃ 1, which most of them are for these three shape groups. Only $\tilde{b}$D for shape groups (1) and (2) are smaller than 1, indicating a decreasing width as the particle length increases. This seems inconsistent, which might be due to the X–Re relationship given by Eq. 5 not being accurate for these shapes. However, this may also be related to the very low correlation in these two cases."
CHANGE TO:
"We have seen in Vázquez-Martín et al. (2020b) that an increase in Dmax (needle length) is directly proportional to A, indicating that the diameter of these needle-shaped particles (needle width) remains similar, when Dmax and consequently also A are growing. Thus, Dmax is approximately proportional to A, and one would expect both values of $\tilde{b}$D and $\tilde{b}$A to be close to 1, which most of them are for these three shape groups. Vázquez-Martín et al. (2020b), observing the very poor correlation between Dmax and measured fall speed, argued that Dmax is not suitable to determine the Reynolds number. Therefore, a more suitable characteristic length should be used, rather than Dmax, to determine Reynolds number and derive mass from it. Otherwise, the derived mass, and consequently bD, are likely not useful. Jayaweera (1971, JAS) suggested a characteristic length for hexagonal crystals for which the dimensions of the basal facet and the aspect ratio are known. Unfortunately, this information is not readily available for all particles in our dataset (or is not defined in case of more complex particles). Therefore, determined mass and relationships based on it should not be used."

Conclusions:

Add a disclaimer about groups (1)-(3) to first bullet point or add a new second bullet point about that.

5) 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.

Response:

The shape group (5) Plates contains planar and plate-like shapes such as simple hexagonal plates but also stellar plates, rimed plates, split plates, and double plates. This mixture, and in particular the inclusion of shapes other than pristine plates, is likely responsible for bD in this study being below 2, which is the theoretical limit for planar particles approximated by spheroids (Chen and Lamb, 1994).

While we only have a handful simple hexagonal plates, rimed, skeletal, and double plates are represented with 39 or more particles, and for these shapes bD is 1.9 for skeletal plates and 2.1 for the other two shapes. We will discuss this better in Sect 4.4.1.

Changes to the manuscript:

Add to the end of Sect 4.4.1:

"Our relationship [VM] for shape group (5) has a lower slope bD than any of the other relationships from previous studies. Chen and Lamb (1992) approximated hexagonal plates with spheroids and found a theoretical lower limit of 2 for bD of plates, which bD = 1.76 of [VM] seems to violate. While the selected previous studies with bD values larger than 2 looked at particular shapes, [VM]'s shape group (5) represents a mixture of plate-like shapes such as rimed plates, split plates, and double plates. Two of the shapes are represented with more than 40 particles, namely rimed plates (R1c) and double plates (P1o), sufficient to determine their own relationships. Both have steeper relationships with bD of approximately 2.1. Double plates are composed of two plates with a small gap in between, so that they resemble almost thicker plates. They are most similar to the thick plates (C1h) by [H] within they their size range. Most rimed plates in our dataset are thinner plates with light to moderate riming. They are most similar to hexagonal plates by [M]."

Fig. 4a and Tab. 2:

We are adding two relationships with the labels 1R. and 1P. In Tab. 2 they will be inserted after 1. [VM], in Fig 4a as black dashed lines:

Rimed plates	44	0.37--0.6 mm	1.2--17 µg	0.11--0.6 m s^{-1}	1R. $m/(\mu g) = 21.1 \cdot (D/mm)^{2.06}$	0.66	[VM]
Double plates	55	0.21--0.9 mm	1.7--58 µg	0.11--0.6 m s^{-1}	1P. $m/(\mu g) = 31.3 \cdot (D/mm)^{2.15}$	0.88	[VM]

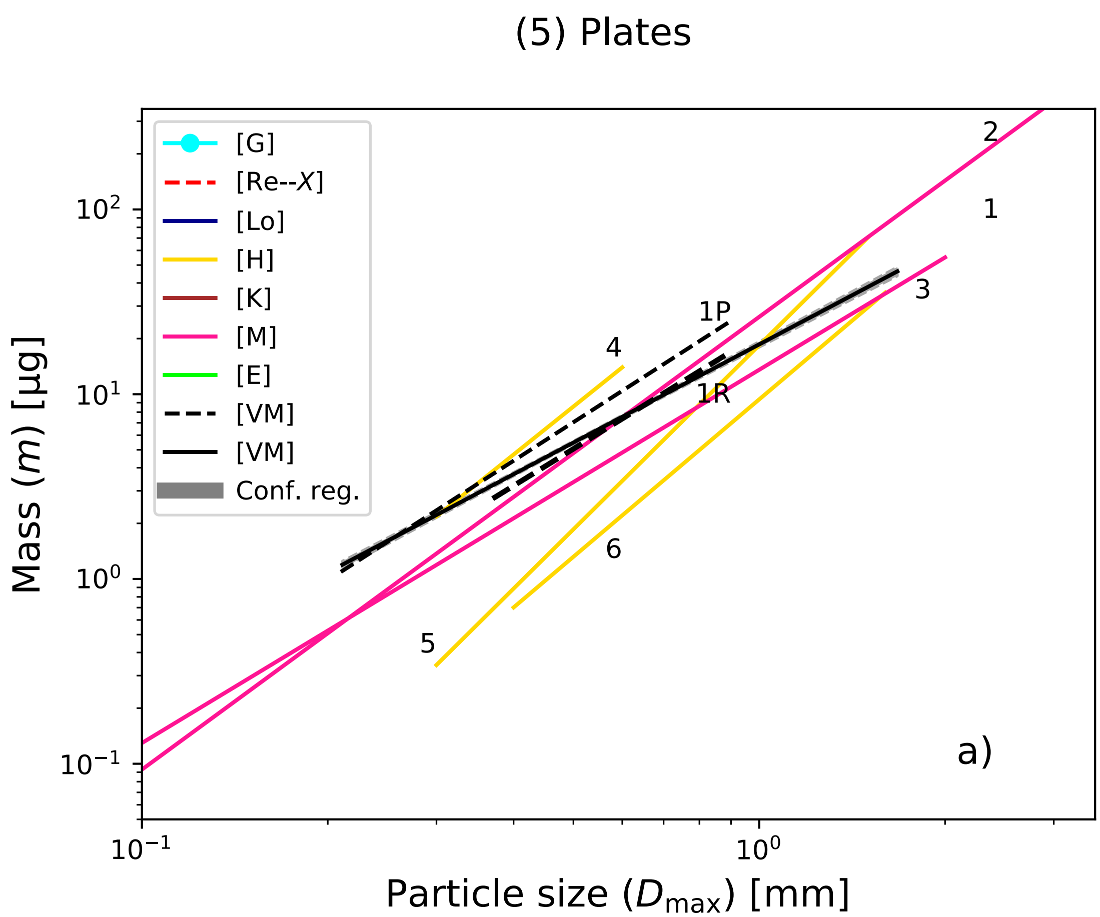

Fig 4a

6) 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.

Response:

You are correct, it is valid in general regardless of shape. We will correct it in the manuscript.

Changes to the manuscript:

Last sentence in caption Fig 3:

"The green solid line represents a reference for spheres, which corresponds $\tilde{b}D/\tilde{b}A = b$."

CHANGE TO:

"The green solid line corresponds to the general relationship between the slopes, $\tilde{b}D/\tilde{b}A = b$ (derived from Eq. 7, 8, and 10)."

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

Response:

Yes, this could be said. We should then also mention that the fit line [VM] fits well our data at masses below 10 µg*. The only two particles heavier than 10* µg *would be overpredicted by the fit line (see Fig. A3, panel for shape group 15).*

Changes to the manuscript:

Line 289-290:

"The straight line for the shape group (15) of [VM] is at somewhat lower fall speeds below approximately 10 µg and at higher speeds above that mass. It represents …"

CHANGE TO:

"The straight line for the shape group (15) of [VM] is at somewhat lower fall speeds below approximately 10 µg. All data but two particles in shape group (15) have m below that mass. For those two particles heavier than 10 µg the fit line [VM] overpredicts mass (see Fig. A3 in the Appendix). While [VM] represents …"

Line 291:

"…, whereas the two curved lines of [G] and [Re–X] represent only liquid droplets."

CHANGE TO:

"…, the two curved lines of [G] and [Re–X] represent only liquid droplets, and, thus, an upper limit in fall speed."

8) 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.

Response:

Yes, thank you for pointing this out. We have already mentioned this in the last sentence in Sect. 4.1. We will repeat a similar statement in the Summary and conclusions.

Changes to the manuscript:

Line 310, add a last sentence to this bullet point:

"The fact that m is derived from v contributes to a stronger correlation between both quantities."

9) 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.

Response:

This point is related to your major comment 1), so please also look at our response to that comment. If the same data is used to derive first a v-D relationship and then a m-D relationship from that, or to derive a m-D relationship directly m values that have been added to the data (Sect 3.1), then the resulting m-D are identical (as long as the same X-Re relationship is used. With our dataset we have the choice to use either method. By deriving m-D directly (the method outlined in Sects 3.1 and 3.2) we avoid having to consider error propagation, we can use Eq 5 (instead of a power-law approximation of Eq. 5). In addition to changes in response to your major comment 1) we will also modify the text in this bullet point to make this clearer.

Changes to the manuscript:

Lines 311-314:

“When deriving the m vs Dmax, m vs A, and v vs m relationships analytically from A vs Dmax (see Section 3.3), the results are equivalent to fitting to measured data. The analytical relationships Eq. 13–Eq. 15 can be used if power laws are available instead of data. However, fitting to data has the advantage that Eq. 5 can be used rather than power-law approximations required for the analytical derivation of relationships (see B in Appendix).”

CHANGE TO:

“When deriving the m vs Dmax, m vs A, and v vs m relationships analytically from A vs Dmax, v vs Dmax, and v vs A given from a suitable dataset (see Sect. 3.3), the results are equivalent to fitting to the same dataset after adding m for individual particles derived from v (See Sect. 3.1). On the one hand, fitting m vs Dmax, m vs A, and v vs m relationships to data has the advantage that the X-Re relationship from Eq. 5 can be used rather than power-law approximations required for the analytical derivation of the same relationships (see B in Appendix). On the other hand, if a suitable dataset is not available but power-law relationships for A vs Dmax, v vs Dmax, and v vs A are, the analytically derived mass relationships Eq. 13–Eq. 15 can be used.”

10) 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.

Response:

Thank you for pointing this out. As the reason for these high slopes of groups (6) and (11) is uncertain (see also our response to your major comment 2), we will remove that statement.

Changes to the manuscript:

Lines 315-319:

“Their values are highest for the shape groups (6) Stellar, (11) Spatial stellar, (12) Graupel, and (15) Spherical, close to the values for spheres, i.e. $\tilde{b}_D = 3$ and $\tilde{b}_A = 3/2$. While this is as expected for shape groups (12) and (15), for groups (6) and (11) it indicates that the morphology in these shape groups remains similar independent of size, i.e. during growth the ice particles grow equally in all three dimensions.”

CHANGE TO:

“Their values are highest for the shape groups (6) Stellar, (11) Spatial stellar, (12) Graupel, and (15) Spherical. For groups (12) and (15) they are close to the values expected for spheres, i.e. $\tilde{b}_D = 3$ and $\tilde{b}_A = 3/2$.”

11) 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".

Response:

Thank you, we agree. Accordingly, we will modify this conclusion as well as the corresponding sentence in the discussion (Sect. 4.4.3).

Changes to the manuscript:

Lines 329-330:

"…, and it is well approximated, by the mass of spherical particles with a density of 0.12 g cm−3.
CHANGE TO:
"…, and it is well approximated by the mass of spherical particles with a density of 0.12 g cm−3 (not shown in Figure 4-d)."

Line 275:

"It is well approximated, by the mass of spherical particles with a density of 0.12 g cm−3, which …"
CHANGE TO:
"It is well approximated by the mass of spherical particles with a density of 0.12 g cm−3 (not shown in Figure 4-d), which …"

- **Minor comments:**

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

Response:
Thank you for pointing this out. The method is actually described in Sections 3.1 and 3.2. This line will be changed in response to your major comment 1).
Changes to the manuscript:
Line 150:
CHANGE TO "…described in Sect. 3.1 with fitting detailed in Sect. 3.2…"

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

Response:
Thank you for finding this oversight on our side. [Ma] corresponded to a study that we are not displaying, it will be removed.
Changes to the manuscript:
Lines 249-249:
"For [VM], as well as for [H], [E], [K], [M], and [Ma], D corresponds to Dmax."
CHANGE TO:
"For [VM], as well as for [H], [E], [K], and [M], D corresponds to Dmax."

3) Line 329: The second comma is not needed.

Response:
Thank you. The comma will be removed in response to your major comment 11).

- **Other changes:**

1) We will change the numbers of equations (10)-(12) as follows:

$$A(D_{max}) = a \cdot \left(\frac{D_{max}}{1mm}\right)^{b} \text{ (10-a) }, D_{max}(A) = a' \cdot \left(\frac{A}{1mm^2}\right)^{b'} \text{ (10-b)}$$

$$v(D_{max}) = a_D \cdot \left(\frac{D_{max}}{1mm}\right)^{b_D} \text{ (11-a) }, D_{max}(v) = a'_D \cdot \left(\frac{v}{1ms^{-1}}\right)^{b'_D} \text{ (11-b)}$$

$$v(A) = a_A \cdot \left(\frac{A}{1mm^2}\right)^{b_A} \text{ (12-a) }, A(v) = a'_A \cdot \left(\frac{v}{1ms^{-1}}\right)^{b'_A} \text{ (12-b)}$$

2) References used in Table 2 and Figure 4 and mentioned in the text will be modified and adapted to ACP style and for consistency with "*Shape dependence of snow crystal fall speed*, S. Vázquez-Martín et al., Atmos. Chem. Phys., 21, 7545–7565, 2021":

- Locatelli and Hobbs (1974) [Lo] → L74
- Heymsfield and Kajikawa (1987) [H] → H87
- Kajikawa (1989) [K] → K89
- Mitchell (1996) [M] → M96
- Erfani and Mitchell (2017) [E] → E17
- The relationships found in this work will be shown as VM21 instead of as [VM].

3) The author contributions Lines 340-342 will be modified and completed as follows:

Author contributions. TK and SVM performed the conceptualization; TK prepared the resources and the instrumentation; SVM and TK performed the experiments and data collection; SVM and TK prepared the formal analysis; SVM and TK carried out the data curation; SVM prepared the original draft; SVM, TK and SE contributed to changes and writing during review and revisions; SVM prepared the visualization that includes tables and figures; TK and SE carried out the supervision of the research project.