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Interactive comment on "Shape dependence of snow crystal fall speed" *by* Sandra Vázquez-Martín et al.

Sandra Vázquez-Martín et al.

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Dear referee #1,

We sincerely appreciate your constructive feedback and time spent to read and evaluate this work. Please look at the lines at the end of this text that contain our responses to your comments.

Best regards,

Sandra et al.

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Discussion paper

Interactive comment on “Shape dependence of snow crystal fall speed” by Sandra Vázquez-Martín et al.

Anonymous Referee #1

Received and published: 2 December 2020

We sincerely appreciate the referee #1 for your constructive feedback and time spent to read and evaluate this work. Please see below our responses to your comments.

*General comments: ————————————-

1) One of the most interesting aspects of this paper is the examination of whether v vs D_max or v vs A do a better job of predicting particle fall speeds, but this aspect of the work isn’t highlighted in the abstract or introduction. I’d suggest adding this.

Thank you for pointing this out. We will add this finding to the Abstract and mention this aspect in the Introduction.

2) It is unclear to me how the method used to analyze images for fall speed in this work differs from the method presented in Kuhn and Vazquez-Martin (2020). The description in this paper (e. g., around lines 106 - 125) seems to suggest that an automated method is used when side-viewed particle exposures do not overlap, but a manual method is used when they do overlap. For example, at lines 109 - 110: "...whereas, in Fig. 1b, the particles are partly overlapping, which poses a limitation for an automated fall speed determination." But Kuhn and Vazquez-Martin (2020) say that fall speed determination is done using a manual method. It would be helpful to clarify (maybe succinctly describe the Kuhn and Vazquez-Martin (2020) method, then describe what is different in this work).

The method in this paper does not differ from Kuhn and Vázquez-Martín (2020). Thus, in both studies, the particle shape classification and the determination of fall speed are conducted manually.

We will clarify this in lines 106-111 by removing “which poses a limitation for an automated fall speed determination” and adding “In both cases, a manual procedure is carried out for the fall speed determination”.

3) The paper lacks some essential detail about how the power law fits were performed, stating for example, simply that the parameters are "determined from linear fits to the data expressed as ...". I assume the data were log-transformed, then a linear least-squares fit was applied. How were uncertainties in the data treated?

You assumed correctly that we have used linear least-square fits. Then, lines 164-169 will be modified for clarity. Doing the fitting, we have not considered uncertainties or spread in the data. See also our responses to your comment 15).

4) Starting in the paragraph just before section 3.2.3 and within section 3.2.3 itself, there seems to be some confusion and lack of clarity about the meaning of (RËĘ2)_a and (RËĘ2)_b when compared to how they are shown in Tables 3 and 4. This affects the interpretation of the results. Perhaps consider reorganizing this section to discuss separately the effects on RËĘ2 of binning and the effects on RËĘ2 of using D_max or A as the independent variable for fall speed parameterization.

We have already organized the discussions so that effects on R^2 of binning (Sect. 3.2.2) and the effects on R^2 of using D_max or A as the independent variable (Sect. 3.2.3) are in separate sections. Our inconsistent choice of names for R^2 and error in Tables 3 and 4 are the source of your confusion, we apologize for that. We will rename R_a to R_D since it refers to the v vs D_max relationships and R_b to R_A since it refers to v vs A. In Table 3 we will use the name R_D and in Table 4 R_A. To avoid ambiguity, we will also modify the text when we first mention R_D and R_A.

*Specific comments: ————————————-

1) Lines 2-3: Note that the influence of shape depends strongly on radar wavelength, with precipitation radar reflectivities (at S- and C-band) being much less sensitive to

shape than are cloud radars (at W- and Ka-band).

The influence, as you have pointed out, depends on radar wavelength and particle size. We will avoid mentioning radar as these details are not needed for our introduction. Accordingly, we will remove that sentence. In this way we will also address your comment 3) and a comment by referee 2 (general comment 1). In addition, we will edit Lines 26-32 in Introduction in order to make the text more concise and avoid ambiguities talking about remote sensing applications and precipitation retrievals that are not addressed in this work.

2) Line 6: It is unclear what "They" is referring to.

Line 6 will be corrected as follows:

They are Fall speed is also required for snowfall predictions . . .

3) Line 7-8: This seems to repeat the earlier statement at lines 2-3. Perhaps this should be removed?

The sentence in line 2-3 will be removed (see specific comment 1 above).

4) Lines 15-17: Not sure that these methodology details belong in the abstract. Maybe focus more on principal results.

We will remove the methodology details and leave what is important: Relationships between particle size, cross-sectional area, and fall speed are studied for different shapes.

5) Line 93: It's not clear to what number the 23% reduction applies. The previously-mentioned count was 10,000 particles, and a 23% reduction would leave 7,700 particles.

Not all the mentioned >10,000 particle images have been analysed yet. As stated, we have selected part of these data. After excluding FOV and tumbling problems, we are left with about 3,200 images. Of these, 23% were measured at wind speeds >3m/s.

This will be clarified in the text.

6) Lines 104-105: It may not be apparent to the general reader why these quantities are more relevant (and more relevant to what?) when observed from a vertical rather than horizontal viewing geometry.

We will state why they are more relevant for drag, and thus fall speed, and for comparison with remote sensing data.

7) Lines 106-110: Are multiple particles ever side-view imaged? I'm wondering how the automated fall speed method deals with this. Since that could be a source of error to fall speed determination, it would probably be relevant to discuss that briefly.

Our fall speed measurements are determined manually not by an automated method. See also 2) in general comments.

8) Lines 112-113: And for the automated fallspeed method, how does the method find these matching points? This question ties back to my initial comments.

The matching points are found manually. Again, see 2) in general comments.

9) Line 125: How much impact did this have on the previously-mentioned (line 93) sample size of 2,461 particles?

Due to our manual analysis, this did not have any impact. See 2) in general comments.

10) Line 145-147: It seems like "shape" is being used somewhat inconsistently here. The "shape groups" mentioned in line 145 refers to the 3-dimensional characteristics of the particle, I think. But when it is said here (line 147, "shape does not change with size"), I think it's describing a 2-D property of the particle (the particle's projected area and area ratio). I suggest being more precise with the term - a particle shape can change with size while the area ratio remains constant.

You are right, the conclusion here was about "shape" in terms of area ratio. Lines 146-147 will be modified accordingly: Thus, apart from (15) Spherical, (12) Graupel is the

only shape group where Ar remains constant with increasing Dmax.

11) Table 1: It would be useful to also know the RMS error of the fitted line versus the measured area ratios for each shape group. This would be useful, for example, for assessing uncertainties in fallspeed parameterizations that use area ratios. Could these be added to Table 1?

Yes, we agree that including RMS errors is useful to show the uncertainty in each group. Then, we will add RMS errors for both calculated Ar and fitted A in that table as well as for v in Tables 3 and 4.

12) Line 152: This is more of a writing style comment, but I think it's usually not necessary to open with a statement of what the section contains. It's more engaging to proceed directly into the content (see for example, how you opened section 3.1).

Thank you, we agree. The opening statement in line 152 will be removed.

13) Lines 152-156: These four lines mostly restate information already provided in the caption for Figure 5. Perhaps this could be made more succinct with something like "Analysis of the shape dependence of fall speed (Fig. 5) shows that shape groups (7) Bullet rosettes ...". Also, note that the sentence "Followed by shape groups (4) ..." is an incomplete sentence.

Thank you, we agree and will change this part accordingly.

14) Figure 3 and 4 captions: Should be "length of the fit lines", I think.

Thank you, we agree. The captions have been corrected.

15) Line 183: It would be useful to comment on the source for this randomness in determining the fall speed of individual particles, either here or (maybe better) in the discussion section. Is it due to errors in determining matching points in the particle images? Air currents within the device? Variations in particle orientation that cause the horizontally-projected area to vary?

We have discussed the uncertainties of the measurement methods in our previous work (Kuhn & Vazquez Martín, 2020). While these certainly contribute to the spread in data, most of that is likely inherent to the type of data, i.e., fall speed that depends on particle drag, which in turn depends on shape and orientation. We will extend the sentence in Lines 189-190 to include a short discussion about this.

16) Lines 187-190: Does this method of fitting use the scatter of fall speeds within each bin as an uncertainty for the bin fall speed (the median value)? It seems with such significant scatter in the individual data points, it would be important to de-emphasize bins with a lot of scatter when fitting. Also, if the bin widths become large (e. g., due to the requirement that all bins contain equal numbers of particles), it may be necessary to also treat scatter in the particle sizes within each bin as an uncertainty on the median particle size for each bin. In cases with uncertainties in both the x- and y-values to be fitted, a method such as orthogonal distance regression is needed.

We have not used the scatter within each bin as a measure of uncertainty in the fitting method. Instead, we have selected our simpler fitting method. When we started fitting after binning the data, we first tested equally-spaced Dmax or A bins, however, frequently observed issues with the first and/or last bin when only one or two particles were included in the bin. Changing bin sizes would then affect the fitted relationships. We could resolve these issues by requiring an equal number of particles in each bin. The number of bins, ten, was a compromise we have selected between many bins but too few particles per bin and many particles in each bin but too few bins for a good fit.

17) Lines 191-193: I'm not sure I agree completely with this assertion. Imagine an extreme case of fitting using M_b with only two bins. I wouldn't expect the results to match those from a M_a fit. Is there a reason that 10 bins were selected?

As explained in 16), the number is a compromise to have enough bins to build a regression, but few enough so that there are enough particles in each bin to get a representative median to decrease the spread in data within each bin. With this compromise,

we expect Mb and Ma to agree reasonably well, and in the following, we discuss for which shape groups this is the case and for which not. We will change the text to make this clearer.

18) Line 201-208: This is saying that (RËĘ2)_a is for v vs D_max, and (RËĘ2)_b is for v vs A. Is this what is intended? That doesn't seem consistent with what is shown in Tables 3 and 4. Instead, Tables 3 and 4 show that (RËĘ2)_a corresponds with M_a, and (RËĘ2)_b corresponds to M_b. My understanding, then, is that you want (RËĘ2)_b to be better than (RËĘ2)_a in order to believe that M_b provides a valid fit. Or do you want both correlations to be high? I think it is necessary to review the discussion in these lines to make sure it says what you intended. See my opening comments.

Yes, that was what we intended. And you are right it is inconsistent with Tab 3 and 4. See our response to 4) in general comments. In addition to the changes mentioned there, we will rephrase a few sentences here to make our intentions clearer, i.e. that we are looking at Rˆ2 for Method b to check for which of the shape groups the fitted relationships for v vs Dmax and v vs A are reliable.

19) Line 211-212: Given the data in Tables 3 and 4, it's not clear to me how binning improved both (RËĘ2)_a and (RËĘ2)_b for capped columns. (RËĘ2)_a doesn't represent binned fits. See my opening comments.

The confusion should be resolved by our response to 4) in general comments. Rˆ2 for v vs Dmax improved from 0.12 (Ma) to 0.42 (Mb). For v vs A the improvement is from 0.10 to 0.49.

20) Lines 213-214: Similarly here, binning doesn't impact (RËĘ2)_a, so I'm not sure what is meant by "improved their correlation coefficients (RËĘ2)_a...". See my opening comments.

See again our response to 4) in general comments.

21) Line 223: Isn't cross-sectional area an aspect of particle size? Do you mean that fall

speed depends more strongly on cross-sectional area than on maximum dimension? Figure 7 caption: Again, this usage of (RËĘ2)_a and (RËĘ2)_b seems inconsistent with how they are represented in Tables 3 and 4.

We use particle size and maximum dimension interchangeably. For clarity, we will change “particle size” here to “maximum dimension” or change the text to make the interchangeability clearer. Regarding Fig. 7 caption, please see the answer to 4) in general comments.

22) Lines 242: Does the "(15) Spherical" shape group then represent solid ice spheres?

Shape group (15) Spherical includes frozen small raindrops and liquid raindrops. These particles have spherical shape and morphology but are solid or liquid particles as shown in Fig. 1 attached as a pdf (see more details in Vázquez-Martín et al., 2020 “Shape Dependence of Falling Snow Crystals’ Microphysical Properties Using an Updated Shape Classification”). H1c are ice particles and H4a are liquid droplets. If the particle is a perfect sphere, it is assumed to be liquid and thereby considered a raindrop, whereas if the particle has a popping bubble on the edge, it is considered as an ice particle.

23) Lines 272-274: For me, the most interesting aspect of this is that the vertically-oriented particles do not fall *much* faster than the horizontally-oriented particles. Per, for example, Mitchell and Heymsfield (2005), fallspeed should depend on the ratio of mass to horizontally-projected area. It would be interesting to see the comparisons shown in Figure 11, but resolved by particle shape. Do vertically-oriented plates fall faster than horizontally-oriented plates of the same D_max? I’m not suggesting that this be included in this paper, of course, but perhaps for future work.

Thanks for your comment and suggestion, very interesting. We had investigated what you mention for different shapes individually, i.e., for shape groups (1) Needles, (5) Plates and (6) Stellar. However, probably due to the small sample size, the results were not conclusive showing larger uncertainties than differences between the two

falling orientations. We will certainly look at these questions again in future studies when more data will be available.

24) Line 285: I'm not sure what is meant by "overlapping somewhat in D_max and A".

We will rephrase to make this clearer:

As can be seen in Fig. 12, these relationships are spread out in a way, so that for a given. . .

25) Lines 293-319: This analysis is highly interesting, but it took several read-throughs to follow the development. Since mass, area and area ratio can all be expressed succinctly using power laws as functions of D_max, I wonder if it might be clearer to develop, for example, the resulting power law relationships for mass and area as functions of area ratio then show, by substituting in the appropriate exponents for elongated particles, that mass increases more rapidly than does A as A_r increases. Is there a reason this approach wasn't used?

The purpose of this section is to investigate the Ar dependence observed in Fig 12. For that, we are considering the special case of a subset of the data with constant Dmax. Because of that, we cannot use normal power laws as a function of Dmax to do this investigation. If one would use them, then the particle mass was constant. We will modify the text slightly to improve clarity. See also our response to your comment 26), where we correct an error.

26) Lines 308-311: If I look at prior studies like Mitchell (1996), it seems more common for other shapes to have mass power laws where the exponents are in the range of 1.7 to 2.4, rather than 3. Does this alter the interpretation presented here?

We examine here the special case of constant Ar. For this A is proportional to Dˆ2 as stated. However, it was wrong to state that m would then be proportional to Dˆ3. There could, of course, be shapes such as simple plates where Ar is constant and where thickness (not seen on image) does not increase proportionally to D. In an extreme

case, m would then be proportional to Dˆ2. So, in general, in a dataset with constant Ar, m would be proportional to anything between Dˆ2 to Dˆ3. We will change the text to correct this. It does not alter the interpretation presented.

27) Figure 13 caption: Please also describe the purpose of the numbers labeling each line.

The purpose of labelling each line was to easily connect the fit lines to the power laws displayed in Table 6. We will mention this in both captions of Table 6 and Fig. 13.

28) Table 6: For comparison purposes, I suggest that you consider converting all the relationships reported here to consistent units. I know it will affect only the leading coefficients, but it would make it easier to quantify the differences between the relationships.

The reason why we have shown the relationships in different units was to be consistent with the power laws used from the literature. However, we agree that for comparison it would be more convenient if all used the same reference units. Therefore, we will be adding such information in the text, for instance, by adding “The power laws from the literature have been converted to the same units.” Consequently, we will change the relationships shown in Table 6.

*We made some text edits: ————————————

1) Line 102 has been corrected as it follows:

“cross-sectional are” has been replaced by “cross-sectional area”

2) Replace versus ‘vs.’ by ‘vs’.

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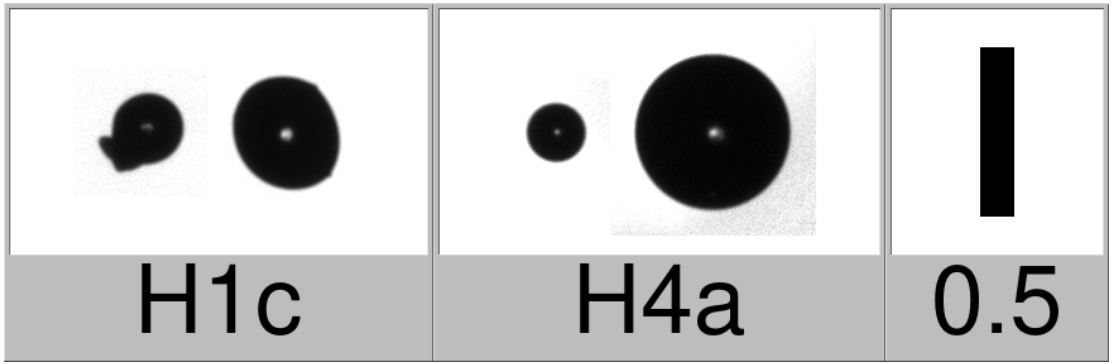

Fig. 1. Specific comment, #22)

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