Author's response

Title: Snow Particle Fragmentation Enhances Snow Sublimation
ID: EGUSPHERE-2024-3218
Authors: Ning Huang, Jiacheng Bao, Hongxiang Yu, and Guang Li
Submitted to: Atmospheric Chemistry and Physics

The comments are in blue. Page and line numbers refer to the revised manuscript version with changes marked in italic.

Reply to comments of Anonymous Referee #1

The authors have carefully addressed the indicated points, which overall led to an improvement of quality and readability of the paper. Thanks a lot for these revisions.

The revised introduction gives a lot more background and refers to relevant past and recent studies in the domain of snow saltation and drifting and blowing snow. A new discussion section and updated and restructured conclusions present the findings of the study.

Nevertheless, there are still several points that need further attention and clarification (see the specific comments below). In addition, the paper (especially the new and revised sections) still needs a lot of editorial correction and revision to make it better readable from a language point of view. I started to list edits in the specific comments but then switched (again) to providing an annotated manuscript since this is more efficient and less tedious. Please refer to the annotated manuscript for language corrections and suggestions to improve clarity and readability. However, my editorial suggestions are not exhaustive.

The revised manuscript is suitable for publication in ACP but requires another round of revisions prior to acceptance. The following specific comments do not include major concerns but a few important points which need to be addressed. In general, they should be quite straight forward to be implemented.

Response: I would like to express my sincere gratitude for the reviewer's time and efforts in reviewing our manuscript and give us the constructive comments. We have revised the manuscript according to the comments carefully. Below is the point-to-point response:

Specific comments (numbers indicate lines in the revised manuscript):

1) 059-063: Here I would detail the physical cause for a changing sublimation rate, i.e., vapor pressure gradient related to particle geometry (curvature), temperature, ambient air vapor saturation, etc.

Response: Thanks for this valuable comment. We have added the content in lines 63-65: "*For sublimation rate is mainly driven by the pressure gradient between the surface saturation vapor and the ambient air, and the surface saturation vapor is influenced not only by air temperature, but also by particle curvature (Neumann et al., 2009).*"

2) 079-080: What is the applied threshold grain size? This should be mentioned here.

Response: The threshold grain size for suspension is calculated based on the Rouse Number (Scott et al., 1995), which is a mathematical model used to simulate suspension and saltation particles). The Rouse Number is defined as the ratio of fall velocity and friction velocity: $v_t/\kappa u_*$. We have added this information in lines 83-85: "*A threshold grain size was used to separate the saltating and suspended particles, **depending on the Rouse Number (Scott et al., 1995)***." The equation of Rouse Number is already shown as Eq. (18).

3) 080: On line 049 The Thorpe-Mason model has been "defined" as T&M model; this could be used here as well and throughout the manuscript.

Response: Thanks for suggestion. We have revised to T&M.

4) 130: It should be stated somewhere that the model is a 2-D approach, cf. "(r (x, z))".

Response: Thanks for suggestion. We have revised it in the beginning of the model description section as line 81-82: "*In our model, the saltation particles are described using a **2-D** Euler-Lagrangian tracking method, which captures the saltating motion of particles.*"

5) 140: Change order of variable definition (as they appear in Eq.7 and 8): first e_v and e_h, then v_ix, v_iy and v_ex, v_ey.

Response: Thanks for suggestion. We have revised the order of variable definition in lines 142-145:"*where $e_v=v_{ey}/v_{iy}$ is the vertical recovery coefficient, $e_h=v_{ex}/v_{ix}$ is the horizontal recovery coefficient, v_{ix} is the horizontal **velocity component** of the impacting grain, v_{iy} is the vertical **velocity component** of the impacting grain, v_{ex} is the horizontal **velocity component** of the ejected grain, and v_{ey} is the vertical **velocity component** of the ejected grain. n_e is the number of ejected snow grains.*"

6) 188: Make sure that the definition of w_s on this line and on line 150 are coherent. A description of (the physical meaning of) "delta" is missing.

Response: Yes, the definitions of w_s in these two lines are the same. We have deleted the second one. δ is the decreasing factor of the asymptotic diffusivity of heavy particles in the vertical direction refer to gaseous materials (Csanady, 1963). We have added it in lines 188-190: "*where q_s is the suspended snow particle mixing ratio, $K_s = \delta k u_* z$ is the diffusion coefficient of suspended particles, **δ is the decreasing factor of the asymptotic diffusivity of heavy particle in the vertical direction refer to gaseous materials, which can be expressed as** (Csanady, 1963):*"

7) 195: Do you want to say "consistent" or "inconsistent"? Maybe use "agree" or "disagree".

Response: Thanks for suggestion, we mean "consistent". Have revised it as lines 198-199: "*The **simulation** results **for the range and trend of the size distribution agree with these field observations.***"

8) P.9: The caption of Fig.2 is insufficient. Please expand with a few more details, such that the figure is understandable as a stand-alone figure.

Response: Thanks for suggestion. We have revised the caption of Fig.2 as: "*Particle size distributions at 9 different heights above the surface: 1.13 m, 0.82 m, 0.77 m, 0.69 m, 0.12 m, 0.10 m, 0.06 m, 0.04 m, and 0.02 m. Blue bars represent simulation results with fragmentation considered, gray bars denote results without fragmentation. The red solid line represents field measurements.*

For heights below 0.1 m, simulated results are compared with observations from Nishimura and Nemoto (2005) at Mizuho Station, Antarctica; For heights above 0.1 m, comparisons are made with data from Gordon and Taylor (2009) in Manitoba, Canada."

9) 205: (and other instances) The term "total sublimation" should be defined upfront, i.e., explain that it is the sum of sublimation from the static surface plus sublimation from DBS, or whatever is meant with this term.

Response: Thank you for this comment. We have added the definition of total sublimation rate in lines 207-208: "*Here we defined the total sublimation rate as the sum of the sublimation rates of both the saltation layer and the suspension layer.*" And we also have added the definition of other terms.

10) 210: Maybe good to mention here these "other models" with name and reference.

Response: Thanks for suggestion. Have added it as lines 230-233: "*Suspension sublimation rates predicted by different blowing snow models are intercompared, as shown in Fig.5. The models generally give similar law, but the value of the bulk model PIEKTUK-B (Déry and Yau, 1999) predictions is smaller than those of the spectral models (WINDBLAST (Mann, 1999), SNOWSTORM (Bintanja, 2000), PIEKTUK-T (Déry et al., 1998)), which resolve particle size distributions across different bins.*"

11) 211-213: These lines should be part of the corresponding figure caption.

Response: Thanks for suggestion. We have moved it to the caption of Fig. 5 and revised it as:

*"**Figure 5.** Comparison of suspension sublimation rates predicted by different blowing snow models. The black line shows the sublimation rate of suspension when snow particle fragmentation is considered (this study), while the remaining curves represent simulation results without fragmentation from several existing models: PIEKTUK-T (Déry et al., 1998), PIEKTUK-B (Déry and Yau, 1999), WINDBLAST (Mann, 1999), SNOWSTORM (Bintanja, 2000), without fragmentation (Huang and Shi, 2017), and with fragmentation (This paper). ($u_* = 0.87$ m/s, $z_0 = 0.001$ m, $T_0 = 253.16$ K)."*

12) Figs. 3 and 4: Coherence of units: kg m^{-3} vs. kg/m^3

Response: Thanks for suggestion. We have unified the unit in the overall manuscript.

13) Fig. 4: Is it possible to provide an equation for the simulation results, e.g., mass concentration $C_m = f(z)$, where z is height.

Response: Yes, we have fitted it with the function: $C_m = \frac{58}{z} - 8$. C_m is mass concentration, z is the height above surface. We have added the description in lines 216 to 219: "*The mass concentration from the simulation (with fitting curve) and from field observations under the same friction velocity and temperature are compared in Fig. 4. The field data were measured by Pomeroy and Male (1992) near Saskatoon, Canada). The simulated and observed values show good agreement, and the mass concentration can be described by the function $c_m = 58/z - 8$ (unit: μg/m^3).*"

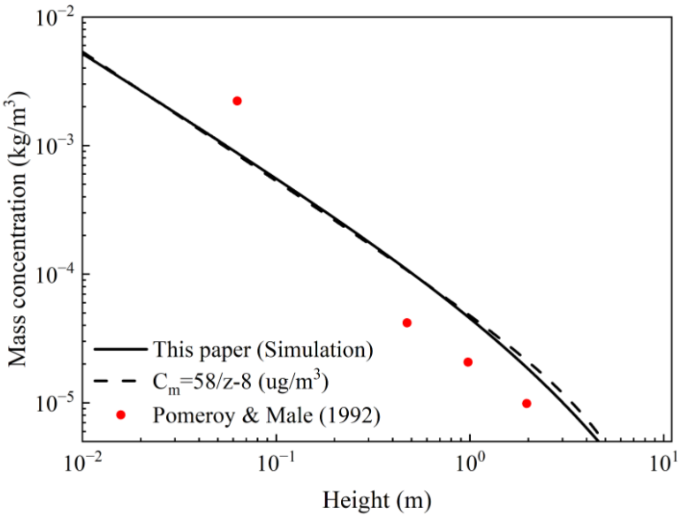

Figure 4. Comparison of simulated mass concentration (this paper, with fitting curve) and field observations (Pomeroy and Male, 1992), for u_* = 0.31 m/s, T = 265 K.

14) 214: the "most recent" or "the oldest" models?

Response: It means "the oldest" models. To make it clearer, we have deleted it and rewrite the overall paragraph as response in comment 15.

15) I think that Fig.5 contains a lot of interesting and valuable information, and it may be worthwhile expanding a bit more and discussing the underlying findings and implications.

Response: Thanks for this constructive suggestion. We have explored more and expanded a discussion as lines 230-244: "*Suspension sublimation rates predicted by different blowing snow models are intercompared, as shown in Fig.5. The models generally give similar law, but the value of the bulk model PIEKTUK-B (Déry and Yau, 1999) predictions is smaller than those of the spectral models (WINDBLAST (Mann, 1999), SNOWSTORM (Bintanja, 2000), PIEKTUK-T (Déry et al., 1998)), which resolve particle size distributions across different bins. This discrepancy arises because the bulk model average particle properties by integrating across sizes, thereby filtering out certain turbulence characteristics. Moreover, all the above models treat the saltation layer as a lower boundary - neglecting sublimation within this layer by assuming the RH of 100 %. In contrast, Huang and Shi (2017) considered the moisture transport within the saltation layer and calculated suspension sublimation initiating from the surface. This consideration of moisture transport results in continuous sublimation in both the saltation and suspension layers, enhancing the sublimation rate due to a higher lapse rate of water vapor. In our model, particle fragmentation further strengthens sublimation by modifying the particle size distribution. Notably, the peak of black curve occurs at a lower position (0.05 m) compared to other curves (0.1 m), indicating that accounting for fragmentation significantly alters the transport structure. In all, these finds suggests that particle size distribution plays a crucial role in DBS sublimation.*"

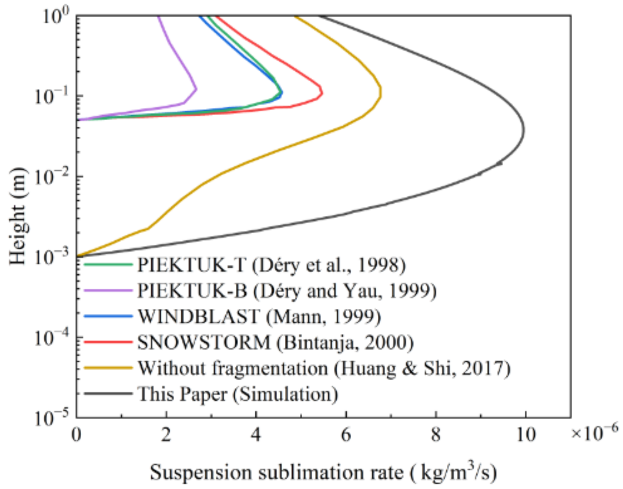

Figure 5. Comparison of suspension sublimation rates predicted by different blowing snow models. The black line shows the sublimation rate of suspension when snow particle fragmentation is considered (this study), while the remaining curves represent simulation results without fragmentation from several existing models: PIEKTUK-T (Déry et al., 1998), PIEKTUK-B (Déry and Yau, 1999), WINDBLAST (Mann, 1999), SNOWSTORM (Bintanja, 2000), without fragmentation (Huang and Shi, 2017), and with fragmentation (This paper). (u_* = 0.87 m/s, z_0 = 0.001 m, T_0 =253.16 K)

16) 231-235: This finding appears counter intuitive. Maybe emphasize that the observed increases are relative numbers and that there may be an "optimal" wind speed or friction velocity value for which the increase of saltation particles is maximal. Any thoughts or explanation? If so, it would be interesting to discuss this here.

Response: Thanks for suggestion. Although the relative increase in particle number appears larger under low friction velocity (u_* = 0.3 m/s, 42%) compared to high friction velocity (u_* = 0.5 m/s, 26%), this is primarily due to the much smaller absolute particle number at low u_* values. When the initial particle concentration is low, even a modest absolute increase translates to a high percentage increase, whereas at higher friction velocities, the baseline number of particles is already larger, so similar or larger absolute increases correspond to lower relative growth. This means that the observed increases are indeed relative, not absolute.

The observed percentage increase in particle number with increasing friction velocity does not necessarily indicate the existence of an 'optimal' or peak wind speed at which the relative increase is maximized. Instead, the percentage increment tends to decrease monotonically as friction velocity increases. This is because, at low friction velocity, the baseline particle number is small, so even a moderate absolute increase results in a high percentage increment. As friction velocity rises, the absolute particle number grows, and similar or even greater absolute increases yield lower percentage growth. Therefore, the relationship between percentage increase and friction velocity is generally characterized by a monotonic decline, rather than an optimum value.

We have added lines 260-261: *"This is because, at lower friction velocities, the baseline number of particles is relatively small; therefore, even a modest absolute increase due to fragmentation leads to a larger relative increase ratio."*

17) 246-248: Confusing and unclear sentence. Please revise, clarify and simplify.

Response: Thanks for suggestion. We have revised as line 268-271: *"**When the friction velocity is 0.3 m/s, the relative increment proportion of fragmentation mass concentration is 19 %; While when the friction velocity is 0.5 m/s, it is 3 %,** which means the fragmentation has stronger effects on the mass concentration under weak wind conditions."*

18) 259-260 and 265/267: Is it "wind speed" or "friction velocity"?

Response: It is "friction velocity". Have revised as "friction velocity".

19) Fig.10 and 259-268: the vertical axes of 10a and 10b are labeled with 12x10e-3 and 3x10e-4, respectively. Numbers in the text are of the order of 10e-2 and 10e-6, respectively. I am confused and a bit lost here. Also, I don't see the factor 8 in the numbers given on line 266.

Response: Sorry for the misunderstanding we may cause. In the text, the sublimation rate is the overall value along the height (in unit of kg $m^{-2}s^{-1}$), while in Fig. 10, it is the volume sublimation rate in a certain height (in unit of kg $m^{-3}s^{-1}$), thus their orders are different, and correct 10^{-2} to 10^{-5} for our mistake. We have revised it as line 282-286: "*To evaluate the overall effect, we calculate the height-integral sublimation rate of saltation particles, and find that for a friction velocity of 0.3 m/s, the average sublimation rate of saltation particles increases by 20 % due to fragmentation, from* ***1.56×10⁻⁵ kg/m²/s to 1.87×10⁻⁵ kg/m²/s****. However, for a friction velocity of 0.5 m/s, this increase drops to 3 %, from* ***4.37×10⁻⁵ kg/m²/s to 4.49×10⁻⁵ kg/m²/s****, indicating that the impact of fragmentation on the sublimation rate diminishes under stronger wind conditions.*", as well as in line 289-293:

"*A similar behavior is observed for suspension particles at higher altitudes. For a friction velocity of 0.3 m/s, the average sublimation rate of suspension particles increases by 8 times, from* ***1.09×10⁻⁶ kg/m²/s*** *to* ***9.83×10⁻⁶ kg/m²/s*** *when fragmentation is considered. For a friction velocity of 0.5 m/s, this growth decreases to* ***54 %****, from* ***3.70×10⁻⁵ kg/m²/s*** *to* ***5.69×10⁻⁵ kg/m²/s****.*"

20) 277: If 'alpha' and 'beta' refer to the Gamma distribution, please include a cross-reference to Equation 5 here.

Response: Thanks for suggestion. We have revised in lines 301-302: *"Size distribution of particles obeys the Gamma distribution function, characterized by the parameters α (shape factor) and β (scale factor), as defined in Eq. (5)."* And include a cross-reference to Equation 5 in line 119-120: "*The particle size distribution f(d) follows a gamma distribution (Schmidt, 1982):*"

21) 282-283: What is a "higher fragment extent"? Please explain.

Response: "Higher fragment extent" refers to the ability of larger particles to undergo more extensive fragmentation, resulting in the production of a greater number of smaller snow particles. To clarify, we have revised the sentence as follows in line 318-319: *"Overall, both a higher average particle diameter (increasing α) and a broader size distribution (increasing β) enhance the extent of fragmentation and increase the production rate of small particles during drifting snow."*

22) 285: A small table presenting the selected combinations of alpha and beta values in the simulations would be helpful here.

Response: Thanks for suggestion. We have added a table describing all the cases. And lines 305-306: *"To investigate the effects of average particle diameter and size proportion on the results, we have set up 9 cases, whose parameters are shown in the Table 1."*

Table 1. Parameters of α and β settings for all simulation cases.

Parameter	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
α	5	8	10	5	5	5	2	4	10
β	40	40	40	40	50	60	100	50	20

23) Fig.11: Positioning the inset figures in panels a, b, and c in the upper left corner and the legend in the upper right would allow to increase the size of the insets, which are currently rather small. The figure caption needs correction as indicated in the annotated manuscript.

Response: Thanks for suggestion. We have revised Fig. 11 by repositioning the insets to the upper left corner and the legend to the upper right corner in all panels. The revised figure provides better visibility of the inset details. In addition, we have corrected the figure caption as indicated in the annotated manuscript.

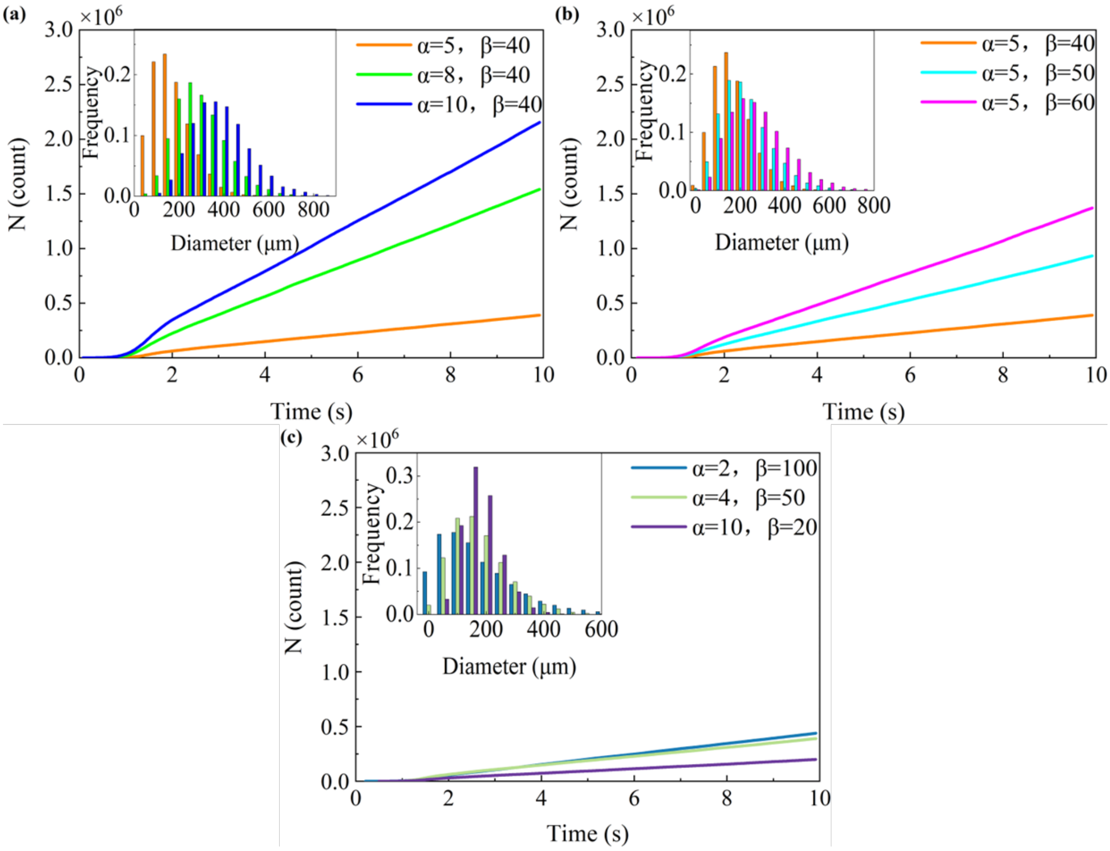

Figure 11. Number of snow particles as a function of time. (a) variation of shape parameter α, scale parameter β = 40, const. (b) variation of **scale** parameter β, **shape** parameter α = 5, const. (c) **α × β** = Average diameter $\bar{d}$ = 200 μm.

24) 303-309: Here it is stated that the mass flux increases mainly in the first 1 cm above the surface which is typically within the level which is saltation dominated. However, it is concluded that that this increase is primarily due to an increased number of particles in suspension since "smaller fragmented particles are more easily transported by wind forces, exhibiting greater floatability in air and reaching higher altitudes". While I agree with the first point, I don't consider 1 cm as "higher altitudes". I think there is an important message here, but it may need to be a bit disentangled.

Response: Thank you for your comment. We have clarified this distinction in the revised manuscript to avoid misunderstanding, as lines 340-346: "*However, fragmentation has a limited impact on the overall mass flux profile, with notable changes primarily observed in the near-surface layer. Specifically, when fragmentation is considered, the mass flux below 0.01 m increases. This increase is mainly attributed to changes in mass concentration of suspension particles, for the mass concentration of saltation particles remains largely unchanged. This indicates that fragmentation predominantly occurs within the saltation layer and primarily contributes to an increased concentration of suspended particles within this near-surface region. This is because smaller fragmented particles are more easily entrained and maintained in the airflow within the near-surface layer.*"

25) 346-348: Fig.10a and 10b show that the sublimation rate is increased at almost all vertical levels when fragmentation is implemented. Fragmentation however suggests that the air-borne particles are smaller than without fragmentation. This is not coherent with the conclusion presented here.

Response: Sorry for the confusing description. We have revised the sentences in line 384-386:

"*We analyzed the impact of particle size distribution on the results and found that when the average particle size is larger, or when the proportion of large particles is higher, fragmentation in the air becomes more significant, generating more small particles. Consequently, the overall sublimation rate increases.*"

26) Author contributions: I am reiterating. From the indicated author contributions, it is not clear who coded the model, performed the simulations, carried out the analysis and finally wrote the paper draft.

Response: We have revised author contributions as: "*N H, G L, and HX Y designed the conception, and revised the manuscript, JC B coded the model, performed the simulations, and draw the figures, HX Y carried out the analysis and wrote the paper draft.*"

Reply to comments of Anonymous Referee #2

Summary: The paper is now in better shape, and I only have minor comments. Regarding my comment on crystal habit, I did not imply that growth mechanisms should be considered. Rather, my question is whether the crystal habit impacts the fragmentation process. For example, I would expect dendritic snow vs. snow with significant riming to have different characteristics regarding their ability to fragment.

Model simulations with and without fragmentation should be shown for several of the figures.

Paper still needs another run through for grammar. I tried to find some of the larger issues.

Finally, the paper still lacks some general comments about the observations we need to improve modeling efforts. This is important for observationists such as myself, because it helps with justification either for field work or to develop new instrumentation.

Response: Thank you very much for your constructive comments and positive feedback. We agree that the crystal habit likely influences the fragmentation process, and different types of snow crystals (e.g., dendritic vs. heavily rimed) should have different mechanical properties relevant to fragmentation. However, appropriate mechanical parameters for different habits remain difficult to obtain experimentally at present. In future work, we are interested in parameterizing such differences (e.g. by setting up parameterization scheme for fragmentation ability of different types of snow particles) with the available supporting data.

Besides, simulation with and without the fragmentation process are now directly compared in Fig. 2 and 5-10, as suggested. We also checked overall of the manuscript and revised all the grammar mistakes carefully.

Regarding the observations that we need to improve modeling efforts, field and laboratory measurements characterizing how different crystal habits fragment under wind and collision would provide crucial data for improving and validating model parameterizations. We have now added a corresponding statement to the conclusions, line 400-404: "*Besides, there is a lack of observational data on the evolution of particle size distributions during drifting and blowing snow processes. Furthermore, the influence of crystal mechanical properties on the fragmentation process is still unclear. To further improve the model, detailed observations exploring how various crystal habitus affect fragmentation and subsequent particle size distributions are needed.*"

Below is the point-to-point response:

Minor comments:

Line 5: strike 'wind' prior to blowing snow model (wind is implied)

Response: Thank you for this comment. The sentence now has been revised as lines 5-7: *"In this study, we incorporate a snow particle fragmentation model into a well-developed blowing snow model to quantitatively investigate the influence of fragmentation under varying wind conditions."*

Line 9: qualify low wind with a value (e.g. < X m s-1)

Response: Thank you for this comment. The sentence now has been revised as lines 8-10: "The *effects of fragmentation on sublimation are more pronounced for suspension particles than for saltation particles, particularly* ***when friction velocity is less than 0.3 m/s***".

Line 13: strike ‘the’

Response: Thank you for this comment. Incorporating both referees’ suggestions, the sentence has been revised as lines 11-14: “*This quantitative assessment of fragmentation impact on snow sublimation underscores its importance for improving the physical representation of drifting and blowing snow in snow transport models, and for potential applications in snow hydrology and climate modeling.*”

Line 27: How about: ‘DBS sublimation is stronger than surface snow sublimation due to several reasons: 1) …’

Response: Thank you for this comment. Incorporating both referees’ suggestions, the sentence has been revised lines 28: “*DBS sublimation is **larger** than surface snow sublimation for several reasons:*”

Line 30: forehead should be ‘at the forefront’?

Response: Thank you for this comment. We agree with you the word “forehead” is not suitable here. Incorporating both referees’ suggestions, the sentence has been revised as lines 31-33: “*Therefore, investigating the role of sublimation in DBS is **a requirement** to accurately assess the water equivalent and understand the interaction between land surface and atmosphere in cold areas, especially for polar regions.*”

Line 34: Don’t like the word ‘either’. Particles can saltate then end up in the suspension layer. Reword.

Response: Thank you for this comment. This sentence has been revised as lines 35-37: “*Once the snow particles deposit on the surface, they **may undergo surface creep, be entrained into saltation by wind, and, under sufficiently strong wind conditions, transition from saltation into the suspension layer.***”

Line 53: Scaled = scale

Response: Thank you for this comment. The sentence now has been revised as line 53-54: *“… and intermediate **scale** (kilometers) (Sharma et al., 2023; Gadde and Berg, 2024).”*

Line 57: How about: ‘Snowflakes are fragile, granular systems that can undergo fragmentation’

Response: Thank you for your valuable comment. To improve the precision and consistency of terminology through the manuscript, we have replaced all instances of “snowflakes” with “snow crystal” in the revised version. And this sentence has been revised as lines 59-61: “*Snow particles are fragile granular systems that can undergo fragmentation - a process that occurs during saltation, where particle-particle and particle-surface collision cause **snow crystals** to break apart and transform into smaller particles.*”

Line 63: How about: ‘their moving rules such…’ = ‘their movement such…’

Response: Thank you for your valuable comment. This sentence has been revised as lines 66-68: “*In turn, the dynamically varying size of snow particles will govern their **motion** such as changing their trajectories, which further influences the mass flux and sublimation rate.*”

Line: 118: Gamma Distribution = gamma distribution

Response: Thank you for your valuable comment. This sentence has been revised as lines 119-120: *"The particle size distribution* $f(d)$ *follows a* ***gamma distribution (Schmidt, 1982)****:"*

Line 167: Check grammar on 2nd sentence.

Response: Thank you for your valuable comment. This sentence has been revised as lines 169-170: "*To consider this effect, we use an equivalent body force* ***in those grids containing particles****, which can be calculated as:*"

Line 196: Should read: '…compared to these field observations.'

Response: Thank you for your valuable comment. This sentence has been revised as lines 198-199: "*The simulation results for the range and trend of the size distribution* ***agree*** *with these field observations.*"

Figure 2: More explicitly state what this is showing in the caption. I would put the heights as a subtitle on the plots vs. in the legend.

Response: Thank you for your valuable comment. We have revised the caption of Fig.2 as:

"***Figure 2.*** *Particle size distributions at 9 different heights above the surface: 1.13 m, 0.82 m, 0.77 m, 0.69 m, 0.12 m, 0.10 m, 0.06 m, 0.04 m, and 0.02 m. Blue bars represent simulation results with fragmentation considered, gray bars denote results without fragmentation. The red solid line represents field measurements. For heights below 0.1 m, simulated results are compared with observations from Nishimura and Nemoto (2005) at Mizuho Station, Antarctica; For heights above 0.1 m, comparisons are made with data from Gordon and Taylor (2009) in Manitoba, Canada.*"

Line 205: Elaborate on the stated measurement capabilities from the included papers.

Response: Thank you for your valuable comment. We have added the measurement capabilities of each paper as lines 220-229: "*In the field observation of Schmidt (1982) in Wyoming, they tested 10 min data. In which SPC is used for measure vertical profiles of blowing snow concentration, number flux, particle size and particle speed at 6 heights of 0.05, 0.10, 0.20, 0.35, 0.50, and 1.00 m above the surface; Anemometers is used for measure wind speed at 5 heights of 0.16, 0.5, 1.0, 1.6, and 2.4 m above the surface; Thermocouple psychrometer is used for measure air humidity. In the field observation of Pomeroy and Male (1992) in Saskatoon, they tested 7.5 min data. In which wind speed was measured with anemometers at six levels, logarithmically spaced from 0.35 to 3.0m above the snow surface; Air temperature was measured by thermistors at five levels from 0.1 to 2 m above the snow surface. Humidity was measured by lithium-chloride electro-chemical hygrometers at five levels in tandem with the thermistors; The flux of blowing snow particles was measured with optoelectronic snow particle detectors located at five levels, spaced logarithmically from 0.01 to 2 m above the snow surface, the particle flux is converted to a mass flux.*"

Line 209: List Saskatoon, Canada. On that note, locations should be provided for the studies shown in Fig. 2.

Response: Thank you for your valuable comment. We have revised as line 217:

"… (measured by Pomeroy and Male (1992) near Saskatoon, ***Canada****)."*

And for the capture of Fig.2: *"... observations from Nishimura and Nemoto (2005) at* ***Mizuho Station, Antarctica****; For heights above 0.1 m, comparisons are made with data from Gordon and Taylor (2009) in* ***Manitoba, Canada****."*

Figure 3: After digging into this more, this looks extremely familiar to your 2017 paper on vertical moisture diffusion. Why not include your prior model simulations in here without fragmentation (as in Fig. 2). Include in additional figures.

Response: Thank you for this constructive comment. We have added the result of Huang & Shi (2017) to Fig. 3 for comparison. Meanwhile, we have added the description in lines 207-215: "*Here we defined the total sublimation rate as the sum of the sublimation rates of both the saltation layer and the suspension layer. Fig. 3 compares the total sublimation rate profiles obtained from the numerical simulation with field observation data (measured by Schmidt (1982) near Wyoming, USA). The sublimation rates in both profiles are of the same order of magnitude, demonstrating that the model can reasonably predict the sublimation rate of blowing snow. While Huang and Shi (2017) shows good agreement with observations at higher elevations, their results underestimated the sublimation rate near the surface. By incorporating fragmentation, the model not only performs well near the surface but also shows better agreement with the observed sublimation rates. This indicates that the modified model can more accurately capture the near-surface snow particle dynamics, especially the particle-surface interaction.*"

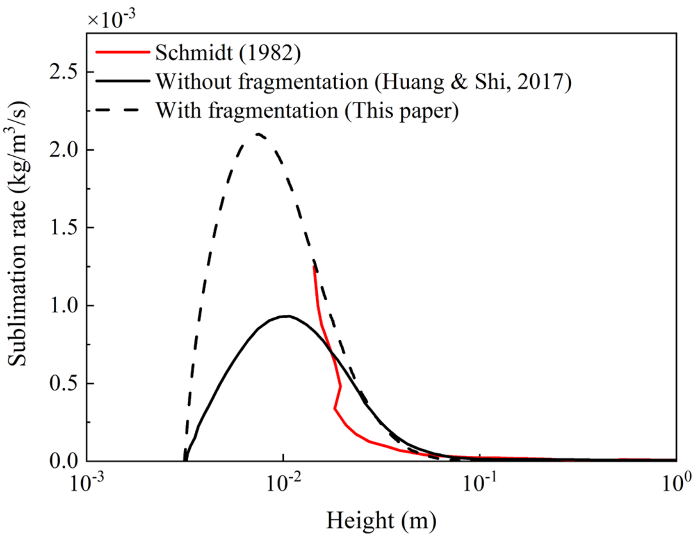

Fig 3. Comparison of sublimation rate profile for this paper, result of Huang & Shi (2017), and field observation (Schmidt, 1982), for ($u_* = 1.1$ m/s, $z_0 = 3.2 \times 10^{-4}$ m, T = 265.65 K).

Line 255: Should read: 'at lower friction velocities'

Response: Thank you for your valuable comment. We have revised as line 280: "*This enhancement is more significant at lower* ***friction velocities****, indicating that snow particle fragmentation has a more profound effect on sublimation under such conditions."*