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

General comments:

Given the scarce knowledge on these processes, this paper deals with a highly important and relevant question and makes a valuable contribution to further understanding drifting snow dynamics and associated sublimation, both important processes in large parts of the world, such as polar ice sheets, and high latitude regions in Alaska, Canada, Scandinavia, Eurasia, and High-Mountain Asia.

The model presented in this paper explicitly implements fragmentation of snow particles and is based on an otherwise established and validated model framework (Thorpe and Mason, 1966; Comola et al., 2017; Huang and Shi, 2017). The model is validated with two observational data sets (Schmidt, 1982; Pomeroy and Male, 1992) showing good agreement. A more comprehensive validation would have been desirable but is probably not feasible due to the lack of suitable validation data. Model simulations are performed in two configurations, (1) particle fragmentation disabled and (2) particle fragmentation enabled, both over a range of friction velocities which are used as proxies for different wind speed conditions. Then, results of the two series of simulations are quantitatively compared evaluating the effect of fragmentation on particle size distribution, saltation and suspension particle number, airborne mass concentration and mass flux, and most importantly the sublimation rate. These results clearly show the relevance and influence of particle fragmentation on the investigated quantities notably the increase of sublimation at all simulated wind conditions.

The paper nicely sheds light on processes of snow drift, particle fragmentation, and associated sublimation dynamics and therefore constitutes a valuable contribution in this domain. Below, I am suggesting some minor revisions necessary to clarify a few points and to fill in where small additions are needed. Major revisions though are needed for language, readability, and clarity of the paper. Instead of listing all these points, I am providing an annotated manuscript with corrections, suggestions, and language revisions for integration into a better readable and understandable manuscript.

Response: We sincerely appreciate the reviewer's insightful and constructive comments on our manuscript. We greatly appreciate the time and effort invested in providing detailed feedback, including the annotated manuscript with corrections and suggestions. These have been invaluable in helping us improve the quality, clarity, and readability of our work.

We provide a detailed, point-by-point response to each of the reviewer's comments below.

Specific comments:

Comment 1:

I suggest revising the abstract better focusing on the objectives and the results of the paper. In its present form, it does not fully reflect the content and contribution of the paper.

This paper addresses the dynamics and thermodynamics of drifting and blowing snow with a modeling approach. It emphasizes on the fragmentation of initially mainly dendritic ice crystals shattered to smaller rounded particles due to collision or impact on the surface during saltation and suspension processes. The consequences of such breaking mechanisms on snow sublimation dynamics are quantitatively assessed again from a modeling perspective.

Response: Thank you for your valuable suggestions. We have revised the abstract, introduction and conclusion to highlight the model and results.

The revised **Abstract** is as follows:

Abstract

Fragmentation of snow particles, where dendritic snowflakes transform into rounded shapes upon impact with surfaces and other particles during drifting and blowing snow events, plays a critical role in shaping snow dynamics. However, existing models of drifting and blowing snow often neglect the effects of snow particle fragmentation, introducing uncertainties in the prediction of flow dynamics and sublimation rates. In this study, we incorporate a snow particle fragmentation model into a well-developed wind blowing snow model to quantitively investigate the influence of fragmentation under varying wind conditions. Our results reveal that fragmentation within the saltation layer generates smaller particles, leading to an increase in mass flux and subsequently enhancing sublimation rates in drifting and blowing snow. Notably, the effects of fragmentation on sublimation are more pronounced for suspension particles than saltation particles, particularly under low wind conditions. This work highlights the critical role of collision-induced fragmentation, wherein dendritic snowflakes are shattered into smaller particles during transportation. This quantitative assessment of fragmentation impact on snow sublimation underscores its importance for improving the physical representation of drifting and blowing snow. These findings have important implications for improving the snow transport models, with potential applications in snow hydrology and climate modeling.

Comment 2:

The novelty of the paper, i.e., the new elements of the model and the relevance and implications of the results could be better highlighted (abstract, introduction, and conclusion).

Response: Thank you for your suggestion, we have revised the abstract, introduction, and conclusion to highlight the model and results. The modifications to the relevant sections are as follows:

Modifications in Abstract

In this study, we incorporate a snow particle fragmentation model into a well-developed wind blowing snow model to quantitively investigate the influence of fragmentation under varying wind *conditions. Our results reveal that fragmentation within the saltation layer generates smaller particles, leading to an increase in mass flux and subsequently enhancing sublimation rates in drifting and blowing snow. Notably, the effects of fragmentation on sublimation are more pronounced for suspension particles than saltation particles, particularly under low wind conditions. This work highlights the critical role of collision-induced fragmentation, wherein dendritic snowflakes are shattered into smaller particles during transportation. This quantitative assessment of fragmentation impact on snow sublimation underscores its importance for improving the physical representation of drifting and blowing snow. These findings have important implications for improving the snow transport models, with potential applications in snow hydrology and climate modeling.*

Modifications in Introduction

In this work, we introduce the snow fragmentation model into the drifting snow model, enabling a more realistic representation of the movement and dynamic size changes of individual particles in the air. This advancement allows for a more accurate prediction of snow particle sublimation rates, offering critical insights into the micro-scale processes that govern snow-atmosphere interactions.

Modifications in Conclusion

In this study, we developed a drifting snow model that incorporates the snow particle fragmentation process. This model simultaneously accounts for both the dynamic processes, including the movement of saltation and suspension particles, and the thermodynamic processes, such as snow sublimation. The model was validated using experimental data from previous studies, ensuring its reliability. This integrated approach, the model offers a comprehensive understanding of snow particle dynamics and sublimation during transport in DBS events.

Based on this model, this work investigates the significant role of snow particle fragmentation in DBS. We find that fragmentation not only alters the particle size distribution but also increases the number, concentration, and mass flux of particles in DBS. Subsequently, this phenomenon affects the sublimation rate of airborne snow particles. Specifically, fragmentation reduces the average particle size, creating smaller particles that are more prone to sublimation. The effects of fragmentation on sublimation are more pronounced for suspension particles than saltation particles, particularly under low wind conditions.

Investigating the effects of particle size distribution on sublimation rates, we find that the sublimation rate is enhanced for particles with a larger average diameter and a higher proportion of larger particles. These results underscore the importance of accurately representing fragmentation and size distributions in snow transport models.

Our simulation results are consistent with previous observational data, suggesting the validity of the model. Furthermore, a comparison of simulation results considering or ignoring fragmentation of snow particles, shows that our sublimation rates are 2 – 4 times higher than other previous model results. This is because fragmentation reduces the snow particle's size, and increases the number of airborne particles, which are more susceptible to sublimation. By integrating fragmentation into the numerical model, this study marks a significant step forward in understanding and quantifying the effects of particle dynamics on snow sublimation.

Our work provides insights into the complex dynamics of DBS. It provides a deeper understanding of the physical process of snow particle fragmentation during saltating/suspending in the air. This indicates the importance of fragmentation in the numerical models of DBS. However, the used model is a two-dimensional numerical model, which could not be applied to larger regions, especially for complex terrains. Therefore, the expansion of this model into a three-dimensional drifting snow model in the future is necessary. Moreover, crystal habits is another important factor in influencing the sublimation rate of snow particles, such as density, size, and specific surface area. Future numerical simulation should be carried out regarding crystal habits factors.

The simulation results provide detailed insights into the physical processes of particle-atmosphere momentum transfer, heat, and mass transfer, from a single particle perspective. This work provides the theoretical foundation and prediction method for accurately assessing the accurate amount of snow sublimation during DBS. These findings have important implications for improving the representation of snow transport and sublimation processes in atmospheric and climate models, which can enhance predictions of snow mass balance and its broader environmental impacts.

Comment 3:

The introduction is rather minimalist. A bit more background on past and current drifting snow models would be desirable and useful, including a brief discussion of some fundamental studies, e.g., Thorpe and Mason, Pomeroy et al., Dery and Yau, etc. Also, the specific objectives of the paper and the applied methodology to address the research questions could be put in evidence more prominently.

Response: Thank you for your valuable suggestion. We appreciate your recommendation to expand the introduction by including a discussion of key studies such as those by Thorpe and Mason, Pomeroy et al., Dery and Yau, etc. We have revised the introduction accordingly to provide more background on past and current drifting snow models, as well as to highlight the specific objectives of the paper and the applied methodology more prominently.

The revised **Introduction** is as follows and the specific objectives and the applied methodology in this work are shown in bold:

Introduction:

Snow plays an important role in Earth's climate system because of its wide coverage and seasonal variation, leading to variable surface conditions. Sublimation is a significant process for snow surface to exchange the heat, mass, and energy with the atmosphere. Snow sublimation includes static surface sublimation and dynamic airbrone particle sublimation. The latter process usually happens in drifting and blowing snow (DBS), in which snow particles follow the air flow, driven by the wind. Water vapor transport created by snow sublimation has a significant influence on the local hydrological cycle and distribution, especially in polar and high alpine regions. For example, in the coastal area of Antarctica, ice sheet mass loss caused by DBS reaches 18.3 % of the whole DBS amount each year (Pomeroy and Jones, 1996). In Antarctica, snow sublimation depleted approximately 17 - 20 % of its annual precipitation (Déry and35 Yau, 2001). In Mongolia, snow sublimation depleted 20.3 - 21.6 % of annual snowfall (Zhang et al., 2008). On the Tibetan Plateau, *due to its extremely dry, cold, and windy environmental condition, the sublimation amount is very high, up to about 50 % of the amount of snow cover every year (Ueno et al., 2007).*

DBS sublimation fluxes (40 - 60 W/m^2) are more than twice as high as surface sublimation fluxes (20 - 30 W/m^2) (Pomeroy and Essery, 1999). Drifting and blowing snow sublimation is obviously stronger than surface snow sublimation for: 1) The turbulence is stronger during drifting and blowing snow events. 2) Aerodynamically entrained particles from the surface enlarge the contact surface with air. 3) The relative humidity decreases during drifting/blowing snow, which promotes a faster sublimation process. Therefore, ***investigating the role of sublimation in drifting/blowing snow is the forehead to accurately assess the water equivalent and understand the interaction between land surface and atmosphere in cold areas, especially for polar regions.***

In DBS, mass, momentum, and energy are transferred between the surface and atmosphere accompanied by snow particle movement. Snowfall is the initial source of snow particles on the ground. Once the snow particles deposit on the surface, they either start rolling on the ground, saltating near the surface entrained by the wind force, or suspension in high air when wind speed exceeds a threshold value. During particle saltating, they jump on the ground surface and may bring up more particles to start to move, which is called splash. The above processes have been well described in the current numerical model of DBS (Pomeroy and Male, 1992; Taylor, 1998; Lehning et al., 2008; Vionnet et al., 2014; Yu et al., 2022; Sigmund et al., 2021; Melo et al., 2022a). Early saltation models are usually empirical mass transport equations, which are functions related to surface shear stress (Pomeroy et al., 1993; Dery and Yau, 2001). These models are susceptible to empirical parameters. JDoorschot et al. (2004) developed a numerical model for steady-state saltation by considering the aerodynamic entrainment and rebound processes, which shows a more physical picture. Nemoto and Nishimura (2004) developed a new numerical model for saltation and suspension that considers aerodynamic entrainment, grain-bed collision, and wind modification processes with a distribution of grain sizes. Based on their model, a few improved works by Zhang and Huang (2008), Yu et al. (2022), Wang and Huang (2017), Hames et al., 2022, and Melo et al. (2022) are carried out. ***However, the role of sublimation in drifting snow has not been demonstrated in these models.***

For a single snow particle sublimation process, the sublimation rate is well described in the model proposed by Thorpe and Mason (1966), in which the sublimation rate is related to the particle size and environmental conditions. This T-M model has been implemented in the current snow model to estimate the sublimation in drifting and blowing snow, to assess the amount of sublimation amount caused by DBS on a small scale (meters) (Groot Zwaaftink et al., 2011; Huang and Shi, 2017; Dai and Huang, 2014; Vionnet et al., 2014; Sharma et al., 2018), middle scaled (kilometers) (Sharma et al., 2023; Gadde and Berg, 2024). The numerical simulation results from the above models all show that snow sublimation is an important snow physical process that cannot be ignored in drifting and blowing snow. In these small-scaled snow models, they track each single snow particle's trajectory, by considering particle diameter is unchanged. Also, the parameterization of sublimation in those middle-scaled snow models is from these small-scaled snow models, based on the same assumption.

In fact, snow particles, one of the most easily deformable and fragile granular systems, inevitably undergo fragmentation - a process that occurs during saltating, where particle-particle and particle-surface collision cause snowflakes to break apart and deform into smaller particles. This fragmentation not only alters their dynamic behavior by changing particle size (Sato et al., 2008; Walter et al., 2024) but also significantly impacts the sublimation rate, as the sublimation of snow particles is closely linked to their size, shape, and specific surface area (Domine et al., 2009). For a moving particle in the air, the reduction in size of a moving particle in the air is a joint effect of breakage and sublimation. In turn, the dynamically varying size of snow particles will affect their moving rules such as changing their trajectories, which further influences the mass flux and sublimation rate. ***However, this mutual physical feedback caused by fragmentation in drifting and blowing snow has never been reported, and the relevant model is still lacking.***

To date, there is only one model (Comola et al., 2017) considering the fragmentation of snow particles during drifting snow. That study, using a statistical mechanics model, calculates the fragmented number of particles from the perspective of energy and mass balance and analyzes the effect of fragmentation on the particle size distribution. However, it did not explore the impact of fragmentation on drifting snow flux or the subsequent sublimation of snow particles.

In this work, ***we introduce the snow fragmentation model into the drifting snow model, enabling a more realistic representation of the movement and dynamic size changes of individual particles in the air.*** *This advancement allows for a more accurate prediction of snow particle sublimation rates, offering critical insights into the micro-scale processes that govern snow-atmosphere interactions.*

Comment 4:

Section 2 should clearly distinguish between the existing model components and the new additions to better identify the innovations in the modeling process.

Response: Thank you for your insightful comment. We have added a comparison of our model and the existing model in Section 2 (Model description).

Model description

The model by Huang and Shi (2017) is a simulation framework for DBS, which is able to simultaneously describe the behavior of both saltation and suspension particles. In our model, the saltation particles are described using an Euler-Lagrangian tracking method, which captures the saltating motion of particles. For suspension particles, which are typically smaller in size, we employ a dispersion function to characterize their movement dynamics. A threshold grain size was used to separate the saltating and suspended particles. The Thorpe and Mason model (Thrope and Mason, 1966) is used to calculate the sublimation of DBS. The feedback of particle motion and particle sublimation to the wind field, air temperature, and air humidity are also considered.

Comola's model, as the only one drifting model that consider snow particle fragmentation, is a one-dimensional, non-CFD (computational fluid dynamics) statistical approach. While it incorporates particle fragmentation, it does not couple the particles with the wind field. As a result, the effects of fragmentation on the wind field cannot be evaluated in their framework.

Building on the previous model developed by Huang and Shi (2017), we incorporated the fragmentation model proposed by Comola (2017) and set up a comprehensive DBS model. This new model addresses the limitations of Comola's (2017) model and provides a more comprehensive description of the interactions between particle fragmentation and the wind field. The particle fragmentation is now newly taken into consideration in the saltation splash process.

Here, we reintroduce them briefly.

Comment 5:

Section 3.4, lines 198-202: Numbers or content of this paragraph seem wrong. Please verify and correct.

Response: We appreciate the reviewer pointing out. The numbers are right, but in a wrong expression. We have revised these sentences in Section 3.4 as:
When the wind speed is 0.3 m/s, the average sublimation rate of saltation particles increases by 20 % due to fragmentation, from 1.56×10^{-2} kg/m^2/s to 1.87×10^{-2} kg/m^2/s. However, as the wind speed increases to 0.5 m/s, this increase drops to 3 %, from 4.37×10^{-2} kg/m^2/s to 4.49×10^{-2} kg/m^2/s, indicating that the impact of fragmentation on the sublimation rate diminishes under stronger wind conditions. This trend can be attributed to the fact that higher wind speeds enhance particle transport and mixing, which reduces the relative contribution of fragmentation to the overall sublimation process.

A similar trend is observed for suspension particles at higher altitudes. At a wind speed of 0.3 m/s, the average sublimation rate of suspension particles increases by 8 times, from 1.09×10^{-6} kg/m^2/s to 9.8×10^{-6} kg/m^2/s when fragmentation is considered. As the wind speed increases to 0.5 m/s, this growth decreases to 50 %, from 3.7×10^{-6} kg/m^2/s to 5.7×10^{-6} kg/m^2/s. While the effect of fragmentation on sublimation remains significant at higher wind speeds, the reduction in growth indicates that other factors, such as increased turbulence and particle dispersion, may play a more prominent role in driving sublimation under these conditions.

Overall, snow fragmentation has a more pronounced effect on sublimation rate of suspension particles than for saltation particles. This difference can be attributed to the longer residence time and greater exposure of suspension particles to the airflow, which amplifies the impact of fragmentation on their sublimation rates. In contrast, saltation particles, which are closer to the surface and are subject to more frequent impact and splash processes, experience a relatively weaker influence from fragmentation as wind speed increases.

Comment 6:

Has the behavior for longer simulations (beyond 10 seconds) been investigated? What are the expected implications? Is consolidation expected and if so at which level and after how much time?

Response: Yes, we have conducted simulations for different cases extending up to 100 seconds to investigate the behavior over longer durations. As is shown in the Fig. R1, the results indicate that the particle number stabilizes after approximately 10 seconds, suggesting that the system reaches a steady state beyond this point. After stabilization, no significant changes in particle number occurred, confirming that the transient phase is largely completed within the first 10 seconds. This implies that simulations beyond 10 seconds are sufficient to capture the key dynamics and steady-state behavior of the system.

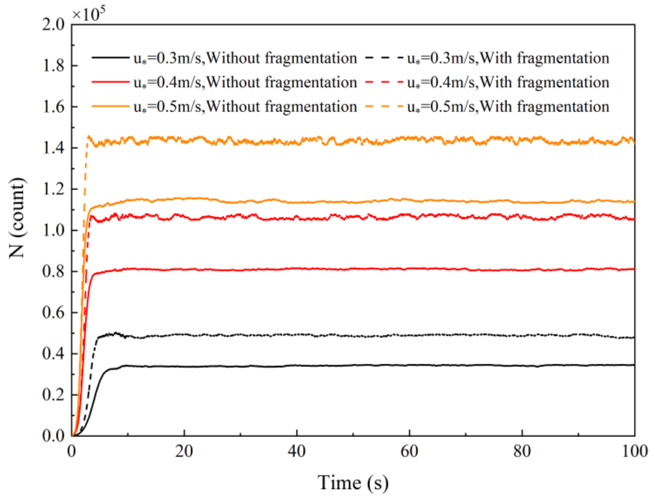

Fig. R1 Saltating particle number variation with time.

Comment 7:

Section 3.5.2, lines 212-213: Message not clear – please try to clarify.

Response: We have revised this paragraph as line 285-287: "*We set up three cases with the same mean diameter* $\bar{d}$ *= 200 μm but different* α *and* β*, parameters. These differences in* α *and* β *result in particle systems with varying size distributions. In these three cases, the proportion of particles with diameter larger than the threshold diameter is 73 % (blue), 85 % (green), and 96 % (purple), respectively.*"

Comment 8:

I would suggest a short Discussion Section before the conclusions in which the following points are briefly addressed: (1) Coherence of obtained results: Some of the results with particle fragmentation implemented are rather obvious, e.g., a modified particle size distribution, enhanced sublimation due to an increased specific surface area of more and smaller transported particles, etc. Other results are less intuitive and could be further discussed. (2) I would also appreciate a paragraph elaborating on how the results and findings can be used in spatially distributed surface energy balance studies. What are the implications for snow surface properties, e.g., albedo, snow microstructure, and for seasonal totals of sublimation, and finally snowpack mass balance? A few points are already mentioned at the end of the conclusion section but are not discussed earlier.

Response: Thanks for this valuable suggestion. We have added a Discussion Section before the Conclusion and incorporated your comments.

The added **Discussion** section is as follows:

Discussion:

In this study, we investigated how particle fragmentation affects snow transport and sublimation processes. We found that when fragmentation is considered, the particle size distribution is modified, leading to an expected increase in snow sublimation during drifting and blowing snow. This occurs because fragmentation generates a greater number of smaller-sized particles, which increases the average specific surface area of transported snow. Since the sublimation rate is directly *proportional to the specific surface area, the presence of smaller particles enhances sublimation. Additionally, the smaller particles produced by fragmentation reduce the averaged diameter of surface snow particles, leading to a lower threshold velocity of aerodynamic entrainment. As a result, more particles are lifted from the surface and transported by wind, further increasing the number of particles available for sublimation during transport. Moreover, the sublimation rate is directly proportional to the mass concentration of drifting snow particles, amplifying the overall sublimation effect.*

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 but primarily contributes to the mass in the suspension layer. This is because smaller fragmented particles are more easily transported by wind forces, exhibiting greater flowability in air and reaching higher altitudes.

Moreover, the fragmentation of the snowflakes produces smaller-sized particles that remain in saltation and suspension, while deposited particles alter the surface size distribution. These changes in particle size distribution influence snow surface properties, such as albedo (Manninen et al., 2021), snow microstructure, static snow cover sublimation rate (Albert and Mcgilvary, 1992), and surface roughness. Larger snow particles reduce multiple scattering events because light travels longer paths within larger particles, leading to increased absorption, particularly in the near-infrared spectrum. Thus, larger snow particles have a low snow albedo. Smaller snow particles, with their higher specific surface area, allow light to undergo more scattering events within the snowpack and reduce the absorption of solar radiation, typically having a high albedo, especially in the visible spectrum. The variation of snow surface size distribution due to fragmentation in drifting and blowing snow influences the surface energy balance by changing the snow surface albedo. Additionally, smaller grains affect the snow thermal conductivity, mechanical stability, and the retention of impurities, which can further reduce albedo and accelerate snowmelt. Therefore, this variation of snow surface properties plays a critical role in determining the energy exchange between the snowpack and the atmosphere.

These findings highlight the importance of incorporating particle fragmentation processes into spatially distributed surface energy balance models. This can improve the accuracy of snowpack mass balance assessments, enhance predictions of seasonal snow dynamics, and better represent snow transport and sublimation processes in atmospheric and climate models.

Reference:

Albert MR, Mcgilvary WR. Thermal effects due to air flow and vapor transport in dry snow. *Journal of Glaciology*. 1992;38(129):273-281. doi:10.3189/S0022143000003683

Manninen T., et al. Effect of small-scale snow surface roughness on snow albedo and reflectance, The Cryosphere, 15, 793 – 820, https://doi.org/10.5194/tc-15-793-2021, 2021.

Comment 9:

Conclusion: At the beginning and before the discussion of the results, the model and the methodology used should be summarized.

Response: Thanks for your suggestion. We have added the summary of our model and methodology before the discussion of the results.

The revised **Conclusion** is as follows:

Conclusion

In this study, we carried out a numerical simulation to investigate the snow particle fragmentation and sublimation during DBS. The model is based on an Euler-Lagrangian method to track the trajectories of individual snow particles. To account for sublimation processes, we implemented the T-M model, which calculates the sublimation rate of snow particles based on their size, temperature, and the surrounding environmental conditions.

The simulation incorporates key physical processes in drifting and blowing snow, including particle-particle interactions, fragmentation due to collisions. The model was validated with experimental data from previous studies. This integrated method provides a detailed understanding of the dynamics of snow particles and their sublimation during snow particle transport.

Comment 10:

The author contributions appear inconsistent with the order of authors.

Response: The author contributions has been revised as follows:

Author contributions

N H designed the conception, JC B contributed to the programming and numerical calculation, HX Y contributed to the conception, first draft and revision, G L designed the conception and revised the manuscript.

Minor comments (with line no. reference):

(Sub-)Section title style: incoherent capitalization, adapt to journal style.

Response: Thanks for your notice, the (Sub-)Section title style has been changed to adapt to journal style.

2. "…transformation from dendritic to spherical shapes…"; rather use "rounded", spherical suggests too much a regular geometry.

Response: Thanks for your notice, we will replace spherical shapes with rounded. This sentence has been revised as line 1-3: "*Fragmentation of snow particles, where dendritic snowflakes transform into* ***rounded*** *shapes upon impact with surface and other particles during drifting and blowing snow events, plays a critical role in shaping snow dynamics.*"

3. 17/18: what is the difference between DSS and BSS? The abbreviations are not used anymore in the manuscript after their introduction.

Response: DSS is drifting snow sublimation (near the surface), BSS is blowing snow sublimation (in higher space). We have deleted the definition of DSS and BSS and revised this sentence to lines 18-19: "*The latter process usually happens in drifting and blowing snow (DBS), in which snow particles follow the air flow, driven by the wind.*"

4. 100: what is “turbulence velocity variance”? Please clarify.

Response: Turbulence velocity variance refers to the fluctuations in velocity caused by turbulent eddies, which value is proportional to the square of the friction velocity. We have revised this sentence as line 149-150: “where $\sigma^2 = 2.5u_*^2$ *is the turbulence velocity variance which refers to the fluctuations in velocity caused by turbulent eddies (Stull, 1988).* w_s *is the settling velocity of snow particles.*”

References:

R. B. Stull. An introduction to boundary layer meteorology, volume 13. Springer Science & Business Media, 1988.

5. 120: what exactly is meant with “vertical grid” here? Please explain.

Response: Sorry for the confusing expression. Here “vertical grid” means the whole calculation domain. We have revised this sentence as line 167-171:

“*To consider this effect, the equivalent body force on one grid is calculated as:*

$$f_p = -\frac{1}{V}\sum_{i=1}^{N} f_{di}$$

“*V is volume of the grid, N is total number of airborne particles in the grid,* f_{di} *is the drag force of the* i_{th} *particle in the grid.*”

6. 205: what does “steep extent” mean? Please clarify.

Reply: “steep extent” means the slope of the curve. Since we have already introduced the Gamma function in Section 2, Eq. (5), we will add the description of α and β there and delete it here in the revising version of this manuscript. We have revised this sentence as line 277-279:

“*The averaged particle diameter* $\bar{d} = \alpha \times \beta$, *where α and β are shape and scale parameters, respectively. α adjusts the peak position and the slope of curve, β controls the width of distribution (the higher the value, the wider the distributes).*”

Reply to comments of Anonymous Referee #2

General comments:

Comment 1:

Observations show a variety of crystal habits that can contribute to blowing snow, and even dendritic crystals can have various amounts of riming on them. How can this be factored into your model? How may this impact the validation to prior work?

Response: We appreciate the reviewer's comment regarding the variety of crystal habits and their contribution to blowing snow. Different crystal habits can indeed exhibit aerodynamic and sublimation process. However, our study focuses specifically on the fragmentation of snow particles on sublimation, rather than considering all influencing factors on blowing snow. While the diversity of crystal habits is an interesting aspect, our simplified assumptions in our model, which exclude snow growth processes such as riming, are designed to isolate the effects of fragmentation on sublimation. We believe that this approach does not compromise the validity of our main conclusions.

Riming is one of the main growth processes of snow crystal by collecting supercooled cloud droplets. It plays a significant role in the formation of precipitation in cold clouds. It can change crystal habits such as density, shape, size, and deposition velocity. Riming normally occurs in a high-humidity environment, thus is less important in blowing and drifting snow with dry air environment. Blowing and drifting snow primarily involves sublimation, resuspension and fragmentation of snow particles, rather than their growth process.

We have added the above into the Conclusion section in the revised manuscript: "*Crystal habits is another important factor in influencing the sublimation rate of snow particles, such as density, size, and specific surface area. Future numerical simulation should be carried out regarding crystal habits factors.*"

Comment 2:

The validation of the model is limited and not thoroughly explained/discussed. Did you consider comparing your model results to other blowing snow observation studies such as those conducted in Franklin Bay (Gordon et al. 2009) or at Mizuho station, Antarctica (Nishimura and Nemoto 2005)? Think about this from the perspective from an observer… what observations do we need to validate the model? I would elaborate on what your results mean. Figure 5 suggests it is critical that our observations are capable of detecting particles < 100 um in diameter. It's unclear how this relates to height above ground. Overall, the presentation of results is more limited than what it should be.

Response: Thank you for pointing out this point. We have compared our model results to field observation studies of Gordon et al. (2009) and Nishimura and Nemoto (2005), as is shown in Fig

2. Our simulation results are consistent with the field observation results. Particle sizes are smaller at higher altitudes, exhibiting a narrow range of 0-90 μm. In contrast, within the saltation layer (up to 0.1 m in height), particle sizes display a broader distribution, ranging from 50-450 μm. Furthermore, we have added more descriptions on Fig. 2.

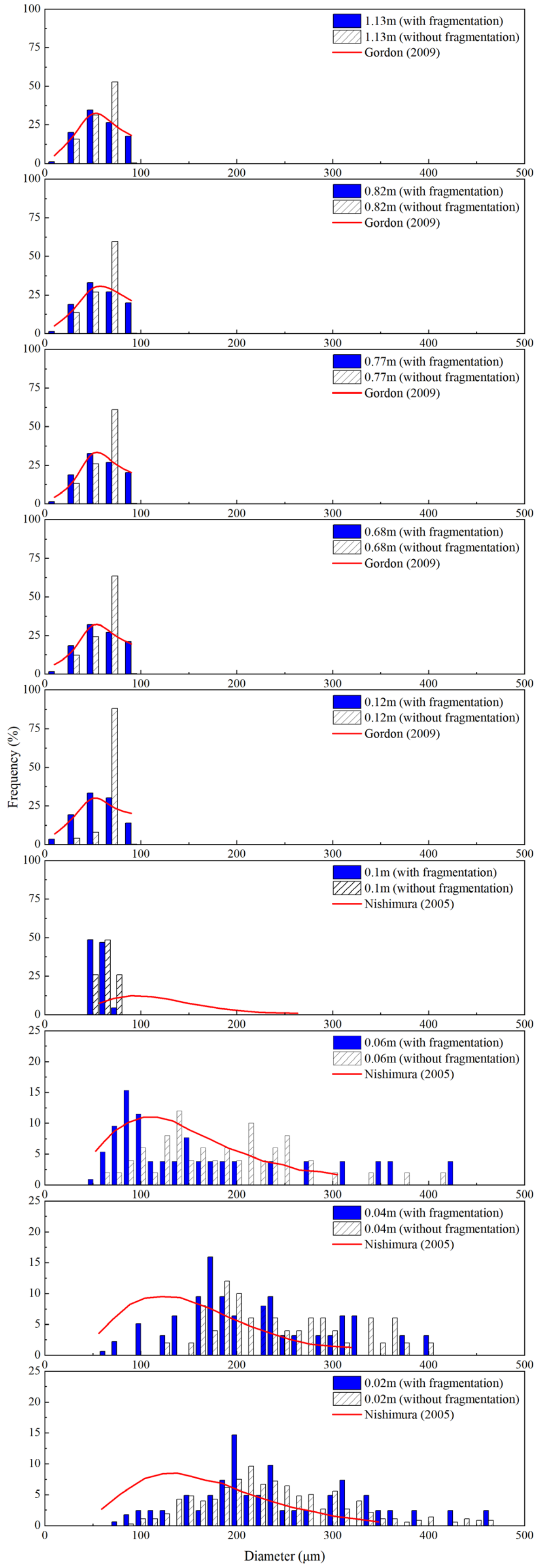

Figure 2. Particle size distribution along the height.

The revised Model verification is as follows:

Model verification

To verify the model, we compared simulated particle size distribution, sublimation rate, and mass concentration to observational data. We first compare the particle size distribution at all heights with the field observation data of Gordon (2009) and Nishimura (2005), shown in Fig. 2. The simulated results are consistent in the size distribution range and variation trend, compared to field observation. Overall, the size distribution variation with height deviates more significantly in the near-surface (0.02 m to 0.1 m), compared to that in higher space (0.12 m to 1.13 m). The proportion of smaller-sized particles increases when considering the fragmentation (blue columns in Fig. 2), which is closer to the observation results (white columns in Fig. 2). For particles in height between 0.12 m to 1.13 m, particle size is in a narrow range of 0-90 μm. In contrast, within the saltation layer (up to 0.1 m in height), particle sizes display a broader distribution, ranging from 50-450 μm, and the simulated average particle size decreases with increasing height. However, this trend is not evident in the field, which might be due to the complexities of the field environment compared to ideal simulation, as well as limitations in the accuracy of measurement sensors.

Fig. 3 shows the comparison of the total sublimation rate between the numerical simulation and the field observation data (Schmidt, 1982). Comparing these two curves, we see that the sublimation rate is the same order of magnitude, which shows that the model is suitable for calculating the sublimation rate of blowing snow. The mass concentration from the simulation and field observations for the same friction velocity and temperature is shown in Fig. 4 (measured by Pomeroy and Male (1992) near Saskatoon).

The suspension sublimation rate from this paper and from other sublimation models under the same conditions are compared (Fig. 5). The black line is the sublimation rate of suspension in the case of fragmentation of snow particles, and the other five curves are the simulation results of suspension sublimation of jump without fragmentation of snow particles (Xiao et al., 2000; Huang and Shi, 2017). The results demonstrate that drifting snow sublimation is important, particularly in the near-surface saltation layer. However, most previous models underestimate the sublimation rate near the surface, which significantly impacts the assessment of the drifting snow sublimation. Accounting for fragmentation increases the sublimation rate by approximately 1.3 times, which suggests that it is necessary to conclude snow particle fragmentation in drifting snow and blowing snow models.

Specific comments:

Comment 1:

Line 30: Strike ‘the’

Response: Thanks for mentioning it, we have revised this sentence as line 66-67: “*To date, there is only one model (Comola et al., 2017) considering the fragmentation of snow particles during drifting snow*”.

Comment 2:

Line 31-32: Sentence reads weird. Perhaps: This work used a statistical mechanics model to calculate the fragmented number of particles from the perspective of energy and mass balance and simply analyzed the effects of fragmentation on the particle size distribution.

Response: Thanks for your suggestion, we have revised this sentence as line 67-68: "*That study, using a statistical mechanics model, calculates the fragmented number of particles from the perspective of energy and mass balance and analyzes the effect of fragmentation on the particle size distribution*".

Comment 3:

Line 50: reintroduce

Response: Thanks for your suggestion, we have revised this sentence as line 91: "*Here, we **reintroduce** them briefly*".

Comment 4:

Line 101: Had some trouble understanding this sentence. Is this what you mean?···Equation 10 is used to determine whether it is broken. The number of snow particles N is calculated and λ represents the ratio···

Response: Sorry for the misunderstanding. Yes, it is what we mean. This sentence has been revised as line 150-153: "*When a snow particle falls back to the ground (initial velocity v_i > 0.5 m/s), Eq. 10 is used to determine whether it breaks and then the number of snow particles N is calculated by Eq. 11, and λ is the ratio of particle size before and after fragmentation, again following Comola et al. (2017), by Eq. 12*"

Comment 5:

Line ~10: crushing = shattering or fragmenting?

Response: Sorry for the misunderstanding, here we want to express fragmenting. This sentence has been revised as line 157-158: "*The velocity and the direction angle of the newly produced snow particles is kept same as that of the original snow particles.*"

Comment 6:

Figure 3: Move the legend a bit to the right or put a box around it. At first glance the legend symbol for P&M 92 could be interpreted as a data point.

Response: Thank you for mentioning it. We have moved the legend to the left corner to prevent interpreting data points.

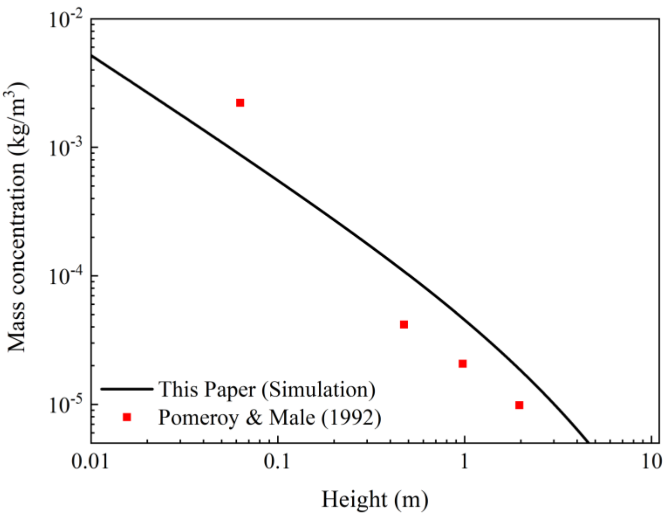

Figure 4. Comparison of mass concentration for this paper and field observations. (Pomeroy and Male, 1992) (u_* = 0.31 m/s, T = 265 K)

Comment 7:

Figure 4: In legend, should read 'snowstorm' Caption: 'Comparison of suspension sublimation rates with other blowing snow models. I think it would be better to put height on the y-axis. I would also go to a higher height. Practically, we are only going to have observations at heights z > 0.1m.

Response: Thanks for your suggestions. We have switched the x-axis and y-axis and revised the caption to: "*Comparison of suspension sublimation rates with other blowing snow models. (u_* = 0.87 m/s, z_0=0.001 m, T = 265 K)*".

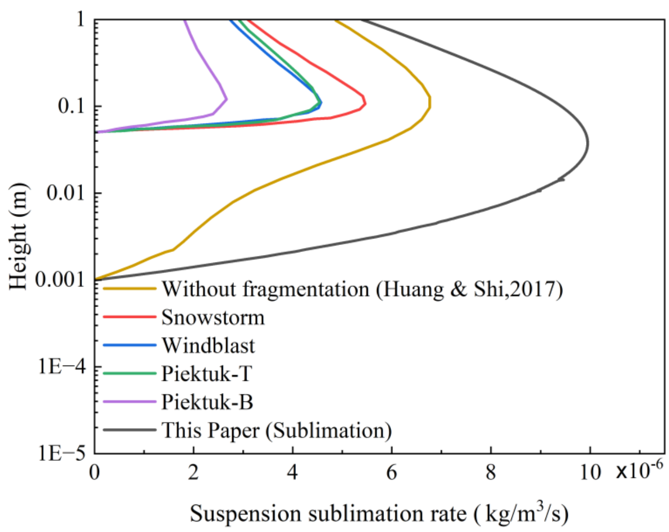

Figure 5. Comparison of suspension sublimation rates with other blowing snow models. (u_* = 0.87 m/s, z_0=0.001 m, T = 265 K)

Comment 8:

Figure 6: How do the PSDs change with height? Once again, I'm thinking about this with my observer hat on.

Response: Thanks for pointing it out. Fig. 2 shows the PSDs at different heights. The particle size becomes more concentrated at higher height levels. Particle size decreases on average with the increasing height. When considering fragmentation, the PSD switched left on the x-axis, which means a lower value on average.

Comment 9:

Line 161: Not a complete sentence. How do results change by mean particle size which will vary depending on location and environmental conditions?

Response: Thank you for pointing it out. This sentence has been revised as line 222-223: "*Simulations are conducted with a friction velocity* u_* *= 0.45 m/s, and an initial mean particle size* $\bar{d}$ *= 200 μm*." The effects of the mean particle size on simulation results are discussed in Section 3.5. In Section 3.5, we investigated the effects of the average particle diameter and the size proportion on the number of fragmented particle numbers. We found that the larger the average particle diameter of the granular system, the greater the extent of particle fragmentation. For granular systems with the same average particle diameter, a higher proportion of larger particles leads to a greater extent of particle fragmentation. A greater extent of particle fragmentation, in turn, results in a higher sublimation rate of snow particles.

Comment 10:

Line 212: strike the 2nd 'the'

Response: Thanks for mentioning it, we have revised this sentence as line 286-287: "*In these three cases, the proportion of the particles larger than the threshold diameter is 73 % (blue), 85 % (green), and 96 % (purple).*"

Comment 11:

Friction velocity: there are various comments that discuss how properties change with wind speed although results are for friction velocity. While friction velocity is directly related to wind speed, you also have roughness length and stability considerations to think about so, I'd be careful with how section 3.4 is worded.

Response: Thanks for pointing it out. In this work, we consider neutral boundary layer conditions for drifting and blowing snow mainly happen in near surface area. The roughness length is kept as constant ($z_0 = 3\times10^{-5}$ m). We have changed all the "wind speed" to "friction velocity" in section 3.4.