Responses to the editor and each reviewer's comments

Title: Snow Particle Motion in Process of Cornice Formation
ID: egusphere-2024-2458
Authors: Hongxiang Yu, Guang Li, Benjamin Walter, Jianping Huang, Ning Huang, and Michael Lehning
Submitted to: The Cryosphere

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

Responses to Editor:

Dear authors,

I have received feedback from the two referees on your revised manuscript. Referee 2 is satisfied with the changes and has only pointed out a few minor corrections. However, Referee 1 remains much more critical, considering that the discussions still need improvement in several areas, particularly with regard to the study's relevance to real cornice formation and the quantitative evaluation of the proposed model against experimental data. I am also concerned that the referee mentions several discrepancies between your responses and the changes made to the paper. As your experimental results are highly novel and valuable to the snow community, I would like to give you another opportunity to address the referee's comments fully. Please consider all of their points and be sure to make the necessary amendments to your manuscript.

Best regards,
Guillaume Chambon / TC Topical Editor

Response:
Dear Editor,

We would like to thank you for providing us with another opportunity to revise our manuscript. Regarding the discrepancies mentions by the referee, we would like to clarify that the discrepancy may have arisen because the referee reviewed an earlier version of response file for discussion ("Reply to RC2" uploaded on Feb 11, accessible at: https://egusphere.copernicus.org/preprints/2024/egusphere-2024-2458/egusphere-2024-2458-AC4-supplement.pdf). However, an updated and more comprehensive response for review section was submitted on **March 24**, which can be found at: https://editor.copernicus.org/index.php?_mdl=msover_md&_jrl=25&_lcm=oc73lcm74a&_acm=get_authors_response_file&_ms=122384&id=2566119&salt=19379774151539860887. We apologize for any confusion that may have arisen and greatly appreciate your understanding and continued suggestions.

We fully understand the importance of robust quantitative analysis, as highlighted by Referee 1, and appreciate the reviewer's persistent efforts to improve the quality of our study. In response, we have further quantified the dendricity and specific surface area (SSA) of snow particles, and included more comprehensive quantitative analysis in the revised results. The model section has also been expanded and directly linked to experimental findings.

Based on the recommendations of **Referee 1**:

- We have provided a more detailed discussion of the study's relevance to real cornice formation, emphasizing its implications in natural environments.
- We have conducted and included additional quantitative analysis on the dendricity and SSA of both surface and edge particles, with further evidence showing the tendency of dendritic particles to adhere on edges.
- We have revised the model, which now can better explain the phenomenon that dendritic particles are more prone to adhere on edge, and we have derived the expressions for the cohesion force and threshold radius for dendritic particle, directly based on the experimental data.

Based on the recommendations of **Referee 2**:

- All minor corrections and suggested revisions have been carefully implemented.

We hope these modifications address all the concerns raised by the reviewers. Please find a point-by-point reply to each of the comments below.

Thank you again for your constructive feedback and for the opportunity to further improve our work.

Sincerely,
Hongxiang Yu, on behalf of all authors

Responses to Reviewer #1:

General comments

Comment 1:

As noted in my previous review, the experimental procedures presented in this manuscript are highly informative and will undoubtedly be valuable for researchers interested in particle motion. The authors' efforts to investigate the growth mechanism of the thin snow plate extending leeward from the edge are commendable, and the overall experimental procedure is well documented. However, as also noted in my earlier review, I still feel that the study falls short of clarifying the growth mechanism of natural snow cornices. The differences between this miniature experiment and real snow cornices found in nature cannot be explained solely by variations in terrain size, successive precipitation, and duration. The authors' explanations remain unsatisfactory in this regard. I would like to emphasize once again that the authors appear to be examining fundamentally different phenomena. If the authors wish to assert that the thin plate observed in this study is relevant to understanding natural snow cornice formation, they should provide a clear scenario— ideally illustrated with schematic figures—that shows how the thin plate would develop step by step into a real cornice, specifying the key mechanisms involved at each stage. Before addressing the detailed points within the manuscript, I must also point out several discrepancies between the authors' responses and the content of the revised manuscript:

Response: Thank you very much for your thoughtful and constructive comments, and for the considerable time and effort you have devoted to reviewing our work. We truly appreciate your critical insights, which have been invaluable in helping us improve the manuscript.

As is shown in Fig. 1, the growth of a snow cornice can be divided into several stages. In the initial stage, a thin slab forms at the mountain edge (highlighted in red in Fig. 1), primarily as a result of wind-driven accumulation and the adhesion of newly precipitated snow particles. In the subsequent stage, continued deposition from drifting and precipitation leads to further development of the cornice, which gradually increases in both length and height. As the cornice grows larger, gravitational forces cause the overhanging volume to bend downward. Eventually, when the volume of the cornice becomes excessive, or more specifically, when the shear stress at the base exceeds the strength of the snow cornice will break off.

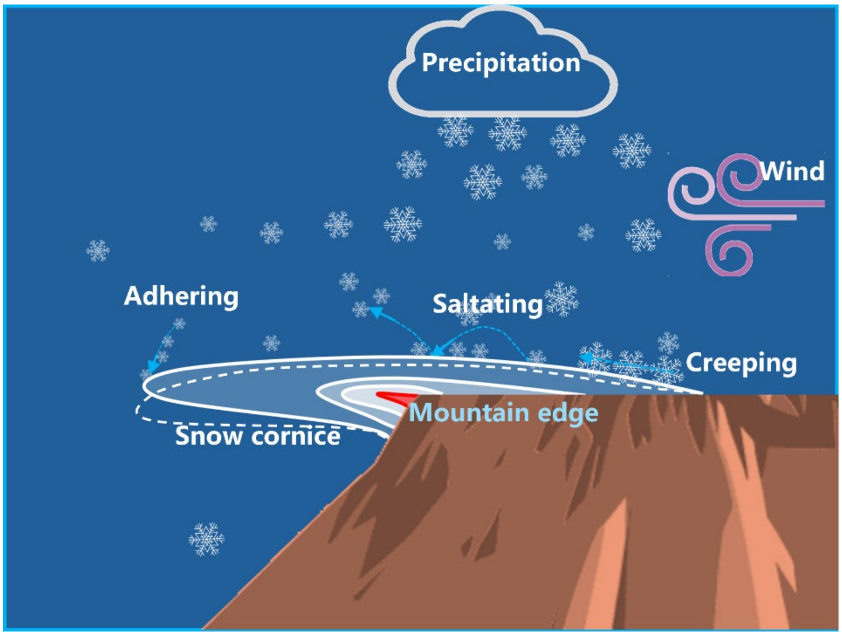

Figure 1. Schematic diagram of different stages in snow cornice growth.

The thin slab observed in our study corresponds to this initial stage of cornice formation, during which micro-scale adhesion mechanisms dominate. Clarifying these early mechanisms, as depicted in the schematic, provides important insight into how small-scale structures evolve step by step into much larger overhanging cornices found in natural alpine environments. We point out, however, that the principle mechanism should not be different between our small-scale model and the large-scale field.

Due to the limitations of field observation and equipment, it is difficult to observe the particle movement around a real-sized cornice on the mountain ridge. However, understanding the mechanism of snow cornice formation is still essential for avalanche prediction and simulation. Whether in the field or in the wind tunnel, the fundamental micro-scale processes-such as particle movement and adhesion-at the mountain top (top (plateau or ridge) are expected to be consistent. Therefore, we carried out a wind tunnel experiment specifically to observe the particle trajectories during the initial stage of cornice formation, focusing on when a cornice first appears as a thin snow plate at a ridge or plateau edge. The motivation for our study is precisely to address this observation gap by focusing on the very earliest stages of cornice formation-where a cornice begins as a thin snow plate at a ridge or plateau edge.

Although there are certainly differences between our small-scale laboratory setup and complex, evolving conditions in nature (including terrain size, weather variability, and duration of precipitation), we believe the fundamental physics governing particle motion, entrainment, and adhesion at the initial stage are directly relevant to the earliest moments of natural cornice development. In other words, the micro-scale processes we observe-how wind -driven snow particles move and adhere at the edge-must also operate during the formation of real cornices, even if the later stages involve further complexity.

In the revised manuscript, we will more explicitly outline the key mechanisms that are shared between the model system and full-size cornice formation and clarify the limitations and scope of our findings. We have revised the abstract in lines 2-3 to: *"Despite numerous observations and experimental simulations on their formation process, the microscopic mechanism of their* ***initial stage*** *of formation remains unclear.*" Lines 13-16: "*Overall, this research reveals the microdynamics underlying* ***initial*** *cornice growth, providing a theoretical basis for avalanche modeling and infrastructure protection in alpine environments, as well as offering a methodological and mechanical framework for studying snow and ice adhesion in both natural and engineered systems*"

In the Introduction, we have added Figure 1 that illustrates the various stages in cornice growth, and the explanation of the whole process of cornice growth in lines 29-47: "*The growth of a snow cornice can be divided into several stages (Montagne, 1980; Vogel et al., 2012; Eckerstorfer et al., 2013). In the initial stage, a thin slab forms at the mountain edge (highlighted in red in Fig. 1), mainly by adhesion of wind-transported snow particles. When more snow accumulates on the relatively flat surface above the edge, it can gradually be conveyed toward the slab tip—especially via wind-transported particles—thereby increasing the thickness at the cornice root. This sustained supply of snow from the platform region plays a key role in the transformation of a small slab into a fully developed cornice in nature. In the subsequent stage, repeated deposition from intermittent drifting and precipitation successively adds new layers of snow to the cornice. This layer-by-layer accumulation is accompanied by a gradual increase in both length and thickness of the cornice. As the cornice grows larger, the overhanging mass of snow is increasingly influenced by gravitational forces, which may cause it to bend downward (shown in the white dashed line in Fig. 1) and promote internal compaction near the edge. Eventually, when the cornice becomes too large and shear stress exceeds a critical threshold, it breaks off and collapses. The evolution of a wedge-shaped cornice—from initial slab formation to subsequent snow accumulation on the flat surface—has been experimentally investigated in our previous work (Yu et al., 2022), with particular focus on the relationship between cornice growth rate and air mass transport. However, the specific mechanisms governing the very initial stage, that is, how airborne snow particles first adhere and accumulate to form the incipient slab at the edge, remain unexplored.*

Previous field research mainly focused on the morphology variation due to limitations of observation equipment (Vogel et al., 2012; Eckerstorfer et al., 2013; van Herwijnen and Fierz, 2014; Hancock et al., 2020), for observing how particles adhering to mountain edges are hardly realized."

In Conclusions, we have added lines 376-379: "*Although this study focuses on the initial stage of snow cornice formation at the micro-scale, the fundamental processes of adhesion of wind-transported snow particles are consistent across all scales, from laboratory conditions to natural environments. The direct experimental observations of single particles help bridge the gap between theoretical models and natural phenomena.*"

Besides, we would also like to mention that there may be some confusion due to different versions of our response documents being available in the discussion system. It is possible that the latest version of our replies has not been reviewed. We sincerely apologize for any resulting misunderstanding and will address each of your comments point by point below to ensure that all concerns are fully resolved.

Discrepancies Between Author Replies and Manuscript
Contact Collision Explanation:
The authors state in their reply:

"For clarity, we will add the following sentences before introducing the maximum compression displacement of particles in Section 3.2: 'During contact collision, snow particles will be compressed and deformed, undergoing plastic deformation and brittle failure (Wang et al., 2020).'" However, neither the text nor the reference appears in the manuscript.

Sintering Force Description:
In the reply, the authors note:

"Sentences in lines 26–27 will be deleted, and we will add: 'In which, Fb is the sintering force, calculated as the product of the ice tensile strength and the contact surface area (Szabo and Schneebeli, 2007). Sintering begins upon particle deposition and plays a crucial role in stabilizing and preserving the cornice structure.'" Yet, this explanation and the notation for Fb are not included in the manuscript. The same applies to subsequent mentions of sintering effects—the manuscript still lacks these explanations.

Order of Magnitude Description:
The authors replied:

"The size of snow particles follows a distribution function, and different sized particles experience different magnitudes of force. Therefore, we present orders of magnitude rather than exact values." Yet the manuscript contains no mention or expression of "order of magnitude." Missing Reference: The following reference, cited in the authors' reply, does not appear in the manuscript: Enliang Wang et al., 2021, Cold Regions Science and Technology, 182, 103215.

Response: Thank you very much for your comments and careful review. We would like to clarify that the discrepancy may have arisen because the response file reviewed was an earlier version ("Reply to RC2" uploaded on Feb 11, accessible at: https://egusphere.copernicus.org/preprints/2024/egusphere-2024-2458/egusphere-2024-2458-AC4-supplement.pdf). However, an updated and more comprehensive response for review section was submitted on March 24, which can be found at: https://editor.copernicus.org/index.php?_mdl=msover_md&_jrl=25&_lcm=oc73lcm74a&_acm=get_authors_response_file&_ms=122384&id=2566119&salt=19379774151539860887.

We kindly invite you to refer to this updated response for the new revisions. We apologize for any confusion that may have arisen and greatly appreciate your understanding and continued suggestions.

Specific Comments

Comment 1:

Figure S1:
It seems the authors intended to show that shear stress becomes negligible, but it is difficult to interpret what is being presented. More detailed explanations are required, particularly regarding the reason for plotting two data series between 0.7 and 2 (x/H). Since computer simulations of airflow were conducted, I strongly recommend including a representative airflow pattern around the edge. This would be extremely helpful in explaining the particle movements discussed later.

Response: Thank you for your valuable suggestion regarding the inclusion of numerical simulation results and the airflow pattern around the edge. In fact, conducting such simulations has required considerable effort and has been comprehensively addressed in our recent publication (Yu et al., 2025), which has been accepted and will be available online soon. To avoid repetition and ensure the focus of the present manuscript, we have not included those simulation details here, but we have cited relevant numerical simulation results from previous studies on the flow around steps to support our discussion regarding the airflow structure near the edge in the last response: "*Moreover, from the previous simulation and experiment studies on the fluid field of backward-facing step (DeBonis, 2022; Shehadi and Edmond. 2018), as is shown in Fig.R1, the skin friction coefficient* $C_f=\tau_w/0.5\rho U_{ref}^2$ *drops to a very small value at the edge (x/H=0). In which,* τ_w *is the wall shear stress,* ρ *is the fluid density,* U_{ref} *is the freestream velocity. It can be concluded that the drop in* C_f *at the edge of the backward-*

facing step is caused by boundary layer separation due to sudden geometric discontinuity. This separation creates a recirculating region with low or negative wall shear stress, leading to a significant reduction in C_f. Similar with our case, the edge of a cornice is the flow separation point, with a wall shear stress approximately equal to zero. Therefore, the drag force of particles on the edge can be ignored."

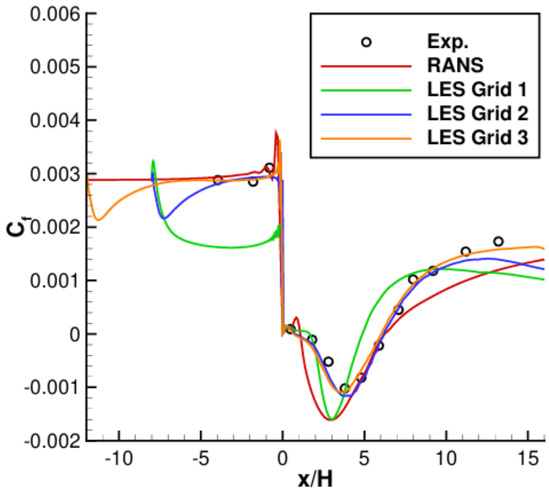

Figure R1. Skin friction coefficient (DeBonis, 2022)

Correspondingly, we have added the relevant description in lines 206-207: "*Such particles therefore preferentially deposit on the edges—where the wind speed is near zero and accompanied by a reflux vortex (DeBonis, 2022).*"

And lines 278-280: "*Due to the separation of flow, the wind velocity and surface shear stress near the edge of the cornice are close to zero (DeBonis, 2022; Shehadi, 2018), allowing the drag and lift forces acting on particle i to be neglected compared to other forces (Schmidt, 1980).*"

References:

Schlichting, H., & Gersten, K. (2016). Boundary-Layer Theory. Springer.

DeBonis, J.R. A Large-Eddy Simulation Of Turbulent Flow Over A Backward Facing Step. In Proceedings of the AIAA SCITECH2022 Forum, San Diego, CA, USA, 29 December 2022; p. 0337

Shehadi, Edmond. (2018). Large Eddy Simulation of Turbulent Flow over a Backward-Facing Step. 10.13140/RG.2.2.17703.24480.

Yu, H., Li, G., Jafari, M., Lehning, M., Huang, J., & Huang, N. (2025). Effect of snow cornice formation on wind fields and snow deposition: Insights from numerical simulations. Journal of Geophysical Research: Atmospheres, 130, e2024JD042702. https://doi.org/10.1029/ 2024JD042702

Comment 2:

Line 58 & Figure 1: The description of the wind tunnel setup is inadequate. Please include key specifications such as the length and size of the working section

Response: Thank you for your comment. The specifications of the wind tunnel, including the length and size of the working section, were described in detail in our previous work (Yu et al., 2022). To provide a clear description, we have added the main parameters and cited the previous study. The sentences have been revised in lines 73-76: "*The experiment setup is shown in Fig. 2. The working section of the wind tunnel is 1 m in length, with a cross-section area of 0.2 m(width)×0.5 m(height), and has been successfully used for several drifting snow experiments (Wahl et al., 2024; Walter et al., 2024; Yu et al., 2022; Sommer et al.,2017, 2018a). Further details of the wind tunnel can be found in Yu et al. (2022).*"

Comment 3:

Line 67:

The authors mention preliminary tests comparing two types of snow and concluding that dendritic snow is more suitable. Were the particle sizes of both types the same? Since the manuscript later emphasizes particle size as a key factor, it's important to clarify this point.

Response: Thank you for your comment. Regarding the comparison between the two types of snow, we used artificial fresh snow (dendritic) and aged snow that stored for 2-3 days (rounded). Due to snow metamorphism, it was impossible to keep the particle sizes identical. Aged snow tends to have smaller, rounded particles, while fresh snow forms larger, dendritic grains.

We acknowledge that this makes it impossible to strictly separate the effects of particle size and grain shape. Nonetheless, our experiment aimed to reflect realistic changes that occur in snow exposed to aging. Our results indicate that fresh, dendritic particles are considerably more conductive to cornice formation. Thus, we used the dendritic particle in the experiments.

We have clarified this point in lines 86 to 90: "*Fresh snow particles, characterized by their highly dendritic shapes, were compared to decomposed snow particles, which are characterized by small, rounded shapes after being stored for several days at a constant temperature of T_{air} = -10 ºC. The results show that both types of snow particles are capable of forming a snow cornice. However, fresh snow particles exhibit a significantly higher propensity for cornice formation and are much easier to consolidate into a stable structure. Therefore, fresh snow particles were used in the subsequent experiments.*"

Comment 4:

Line 80: The phrase "for 4–5 s during cornice growth" would be clearer if supplemented with figures showing the time evolution of the thin plate's length and thickness.

Response: Thank you for this comment. The cornice evolution in length and thickness has been already reported in the previous work (Yu et al., 2022). In this work, only short time periods (4-5 s) were selected in each experiment to capture particle movement. In our experiments, a total of 18 cases were conducted, each lasting 4-5 seconds, due to memory limitations of our high-speed camera. These short-duration cases were distributed over the entire cornice growth process.

To address the reviewer's suggestion, we have clarified this point in the revised manuscript, lines 100-102: "*A total 18 cases were conducted during the cornice growth, with each case lasting 4-5 seconds and yielding 12455 images to record the particle trajectories. The duration of each case was limited by the camera memory. A sequence of the different growth steps is illustrated in Fig. 3 (a) of Yu et al. (2022).*"

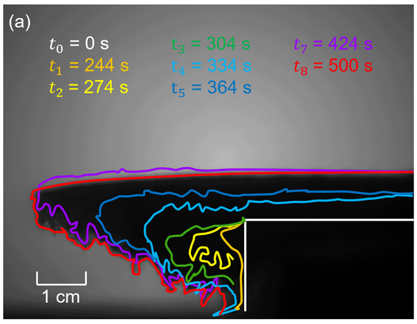

Figure. 3(a) Cornice profiles in the growth process (Yu et al., 2022)

Reference:

Yu, H., Li, G., Walter, B., Lehning, M., Zhang, J., and Huang, N.: Wind conditions for snow cornice formation in a wind tunnel, The Cryosphere, 17, 639–651, https://doi.org/10.5194/tc-17-639-2023, 2023.

Comment 5:

Line 109:

Since fresh dendritic snow tends to orient perpendicular to the wind to maximize resistance, particle size might be underestimated when viewed from the side. This effect would be negligible for rounded particles but should be considered for dendritic ones.

Response: Thank you for raising this important point regarding the potential influence of dendritic particle orientation on measured particle size. Although fresh snow tends to orient perpendicular to the wind to maximize resistance, this generally occurs for freely suspended particles moving steadily in the air (without colliding with the surface). In our experiment, most particles collided with the surface and exhibited rotation， resulting in varying projected areas across consecutive frames. To account for this, we recorded multiple frames as each particle rotated and averaged the projected areas to estimate particle size. This approach effectively minimized the influence of particle orientation on the measured size. Therefore, we consider the effect of dendritic particle orientation on particle size estimation is considered negligible in our results. This clarification has been added to the revised manuscript, lines 133 - 135: "*For dendritic particles, the projected area A_p and perimeter P were averaged across these frames for each particle, which effectively minimizes the influence of particle orientation on the calculated size.*"

Comment 6:

Line 137:

Are any particles ejected by collisions with saltating particles? If so, they might move slowly and contribute to edge growth. Please clarify this point.

Response: Thank you for this insightful comment. Yes, we have observed that particles ejected by collisions with saltating particles can indeed contribute to edge growth, and we have included these into creeping particles in our analysis. These ejected particles typically move as creeping particles. We have added a description of this particle type in lines 214-218: "*Creeping particles (Fig. 8(a)), which account for about 14% of the observed particles, represent the minority of larger-sized adhered particles, and they typically move slowly. These particles are mainly entrained from the surface under the ejection of other particles. Most of them retain on the cornice surface, and only a small fraction—with elongated dendrites—are able to interlock and remain adhered at the edge (Fig. 8(b)).*"

Besides, those observed saltating particles might also come from the ejection particles, therefore, we added the description in lines 219-220: "*In addition, saltating particles observed near the cornice originate either from airborne trajectories or from ejection off the surface.*"

Comment 7:

Line 143: The statement "smaller particles, with better followability with the wind" suggests that their impact speed should be higher, which conflicts with Figure 7. Additionally, larger dendritic particles typically have more branches, potentially increasing their likelihood of being trapped at the edge. I recommend introducing quantitative parameters such as specific surface area to strengthen this discussion.

Response: Thank you for your insightful comment. We appreciate your suggestions regarding the relationship between particle size, followability with the wind, and impact velocity, as well as the value of introducing quantitative parameters such as specific surface area (SSA) to strengthen our discussion.

To further address your suggestions for adding quantitative morphological parameters, we have included descriptions of how dendricity and specific surface area are calculated in the revised manuscript.

2.1 Particle recognition

Lines 124-135:

"*During image processing, the particle's area and perimeter are saved in a numerical matrix in binarized format. Thus, the particle's projected area A_p can be estimated by calculating the sum of all the connected component labels, and the particle's perimeter P is the sum of all the boundary labels. The particle's equivalent diameter is calculated based on the value of its projected area:* $d_e = \sqrt{4A_p/\pi}$. *The dendricity of each particle was quantified using the method proposed by (Bartlett et al., 2008), based on two-dimensional image analysis. Specifically, dendricity was calculated as* $De = \frac{P^2}{4\pi A_p}$. *The specific surface area (SSA) of particles was estimated from two-dimensional images by measuring the perimeters and areas of particles, following the stereological approach proposed by (Ren et al., 2021). According to this method, SSA is calculated as* $SSA = \frac{4\bar{P}_i}{\pi \bar{A}_i}$. *This approach enables the statistical analysis of SSA distribution based on 2D image data, and its validity and limitations have been demonstrated in comparison with three-dimensional and conventional measurement methods. For dendritic particles, the projected area A_p and perimeter P were averaged across these frames for each particle, which effectively minimizes the influence of particle orientation on the calculated size.*"

Additionally, in the Section 3.1, we conducted a comparative analysis of the dendricity and SSA of edge and surface particles.

3.1 Particle size and shape

Lines 186-197:

"*In addition to particle size, dendricity and specific surface area (SSA) are important indicators of particle morphology and surface characteristics. As illustrated in Fig. 7(a), the average dendricity of edge particles is 1.9, higher than that of surface 1.4. Meanwhile, the distribution range of the edge particles (1 to 4.7) is broader than that of the surface particles (1 to 3.1). These results indicate that the edge particles have more fragmented or branched morphologies, while particles on the surface are generally more regular and compact.*

However, the SSA values of edge particles and surface particles are similar, with the average value of 20 mm^2/mm^3, as is shown in Fig. 7(b). This similarity arises because both edge and surface particles originate from the same snow source. Therefore, dendricity is a more critical factor in determining whether a particle can adhere to an edge or the surface. In particular, edge particles with high dendricity have more contact points with neighboring particles on the cornice, which may lead to a greater cohesion force Fc—the force counteracts the gravity force Fg and allows the edge particle to adhere. In contrast, surface particles may experience less cohesion force, and their *gravity acts in the same direction as the cohesion force, making gravity either irrelevant or even beneficial for particle adherence.*

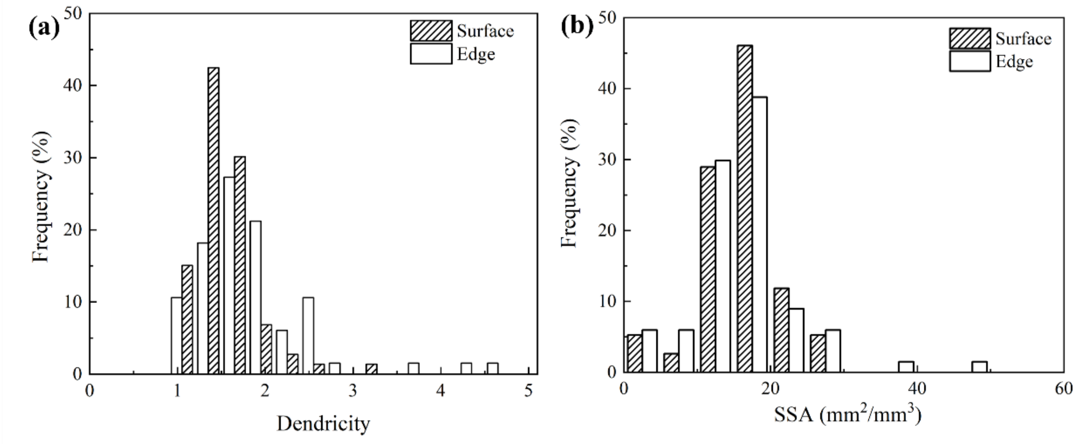

Figure 7. *Frequency distributions of (a) dendricity and (b) specific surface area (SSA) for particles adhering to the edge and surface.*

To better explain the reason for larger particles sticking to the surface preferentially and smaller particles to the edge, we have added a paragraph in lines 198-210: "*Combining the analysis of particle size, dendricity, and SSA distribution, we find that smaller particles and dendritic particles are more prone to adhere to the edge, while larger and more spherical particles tend to deposit on the surface. This phenomenon is closely related to the aerodynamic behavior of particles in the air. Specifically, the pattern of particle deposition is primarily governed by the Stokes number (Comola et al., 2019), a dimensionless parameter that compares the inertial response time (particle relaxation time) of a particle to the characteristic time scale of the fluid flow. In general, particles with smaller sizes, as well as large particles with irregular shapes, tend to have lower relaxation times than spherical particles of the same size (Loth, 2008). As a result, for such small particles and large, highly dendritic ones, viscous forces dominate over inertia, enabling the particles to quickly respond to changes in local fluid velocity and closely follow the streamlines. Such particles therefore preferentially deposit on the edges —where the wind speed is near zero and accompanied by a reflux vortex (DeBonis, 2022). In contrast, for spherical particles, especially those with larger size, inertial forces become more significant relative to viscous drag, making these particles less responsive to fluid velocity changes and more likely to deposit on the main surfaces —which are generally characterized by a stable boundary layer and low turbulence.*"

Comment 8:

Lines 158–164:

These descriptions are speculative and qualitative. As noted earlier, it would greatly improve the discussion to include airflow patterns around the edge. If direct measurements using a hot-wire anemometer were not conducted, simulated streamlines or vortex separations would be very helpful.

Response: Thank you for your valuable suggestions. We agree that inclusion of simulated streamlines or vortex separation would enhance the discussion of airflow patterns around the cornice edge. Conducting detailed flow simulations for the given geometry has been an effort in its own and covered in our recent publication (Yu et al., 2025), which paper has been accepted and will be online soon.

In this revision, we have clarified that the location of cornice growth corresponds to a step-flow, and we have referenced relevant numerical simulation results from previous research to support our interpretations. The revised paragraph is shown in lines 206 to 207: "*Such particles therefore preferentially deposit on the edges—where the wind speed is near zero and accompanied by a reflux vortex (DeBonis, 2022).*"

Besides, in the conclusion, we have added a sentence in lines 383-385: "*Numerical simulations will be essential for a more comprehensive understanding of the coupling between the flow field and snow cornice dynamics, and investigate the effects of mountain morphology on cornice growth.*"

Reference:

DeBonis, J.R. A Large-Eddy Simulation Of Turbulent Flow Over A Backward Facing Step. In Proceedings of the AIAA SCITECH2022 Forum, San Diego, CA, USA, 29 December 2022; p. 0337

Yu, H., Li, G., Jafari, M., Lehning, M., Huang, J., & Huang, N. (2025). Effect of snow cornice formation on wind fields and snow deposition: Insights from numerical simulations. Journal of Geophysical Research: Atmospheres, 130, e2024JD042702. https://doi.org/10.1029/ 2024JD042702

Comment 9:

Lines 169–170:

There's an inconsistency here. The authors state that creeping particles (about 14%) are larger and settle near the front end of the cornice, but later conclude that smaller particles are more likely to adhere at the edge. This contradiction needs to be resolved.

Response: Thank you for your attention to this point, which may cause misunderstanding for readers. We would like to clarify that the creeping particles refer to larger particles, which only represent a small proportion of the particles able to adhere to the edge. When we state smaller particles are more likely to adhere at the edge, it is compared to all the particles. To avoid confusion, we have revised this sentence as lines 214-216: "*Creeping particles (Fig. 8(a)), which account for about 14% of the observed particles, represent the minority of larger-sized adhered particles, and they typically move slowly.*"

Comment 10:

Lines 176–181 & Figures 6–7:
How many particle trajectories were analyzed to derive the appearance ratios in Figure 6? Is the sample size sufficient for quantitative conclusions? Also, how were impact speeds and angles in Figure 5 determined under the complicated particle movement? Were these captured at time step 4? If so, negative angles should appear in Figure 7 as well.

Response: Thank you for helping us improve the clarity and rigor of presentation. We have clarified this question regarding the particle number in Comment 7 in the last response uploaded on Mar 24th. We have increased 383 surface particles and 121 edge particles from the experimental data. Therefore, there are 655 collision particles in total. We used Kolmogorov-Smirnov test to evaluate whether the observed data significantly deviate from the fitting function. The p-values for both surface and edge particles being higher than 0.05 suggest that the sample size is sufficient to support the analysis results.

The impact speed and angle are both defined as relative to the horizontal axis, as is shown in Figure below:

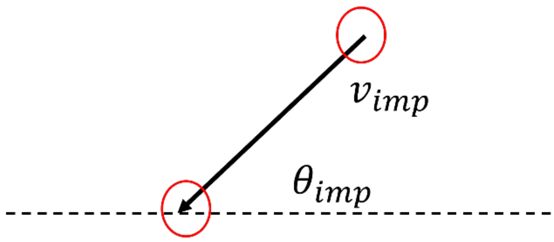

Figure. Schematic figure of impact speed and angle definition

Back-moving particles indeed result in negative angles, which are not included in the PAV in Fig. 9. Firstly, the number of particles adhering via back-moving is extremely small and does not significantly affect the overall statistical trends. Secondly, since these recaptured particles tend to attach at positions deviating from the horizontal surface of the cornice, it is impossible to define their impact angles in a manner consistent with the other particles. Therefore, the collision parameters of these few particles were not included in the statistical analysis presented in this study. Although this model of back-ward moving adhesion was not included in the main statistical analysis, it is worth noting that such process may be caused by the possible electric field and fluid field, which needs further investigation in future studies.

We have added the clarification in lines 227-231: "*Here, we define the v_{im} as the impact velocity of the particle θ_{im} is defined as the angle of particle incidence on the horizontal cornice surface, ranging from 0^o (parallel to the surface) to 90^o (perpendicular to the surface), and this angle measures how steeply a particle approaches the surface or edge before sticking. Only particles impacting the cornice surface from above (incidence angle 0-90^o) are considered, while particles with trajectories suggesting backward-moving (θ_{im} >90^o) are excluded.*"

Comment 11:

Moreover, Figure 7's horizontal axis is labeled "impact velocity or angle," while the figure caption refers to "particle adherence velocity or angle." This should be unified for clarity.

Response: Thank you for pointing this out. We have revised the caption of Figure 9 (Figure 7 in the previous version) and unified the terminology throughout the manuscript.

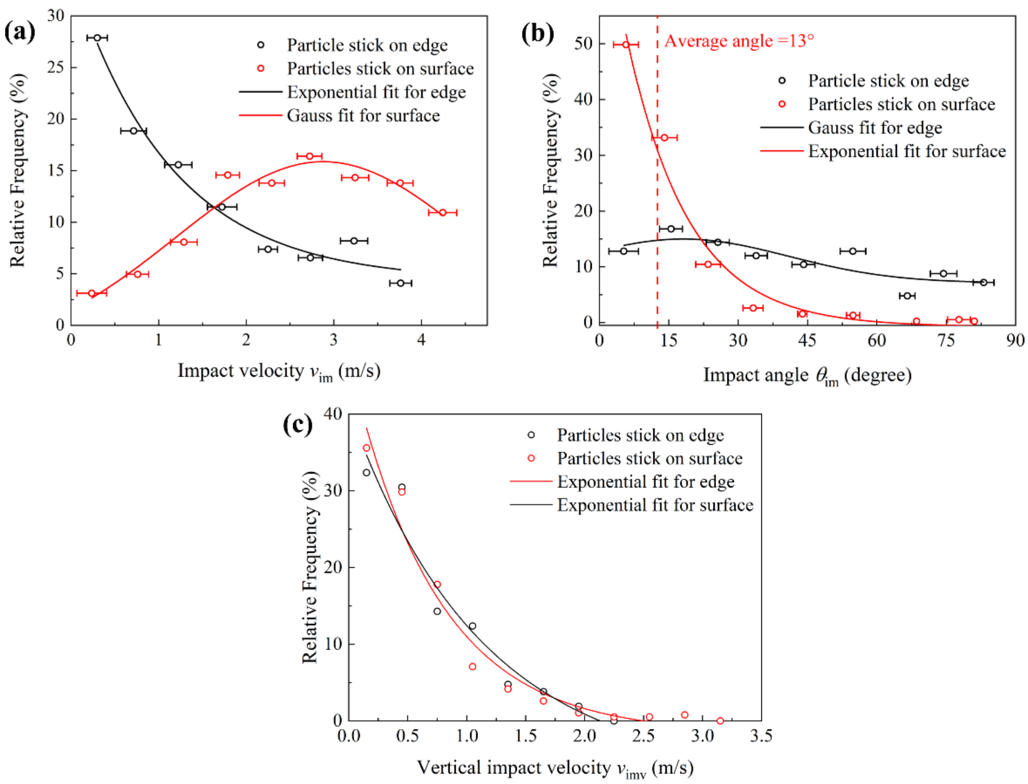

Figure 9. Relative frequencies of (a) impact velocity, (b) impact angle, and (c) vertical impact velocity of particles adhering to the edge and surface.

Comment 12:

Lines 182–218 & Figure 7:

The explanation for why higher-speed particles adhere at certain positions but not near the edge remains unclear. Generally, high-speed, low-angle impacts would result in rebound. Further, do you have evidence that the vertical component of velocity predominantly dictates particle behavior? A clearer discussion is needed

Response: Thank you very much for this comment. We agree that the explanation for particle adhesion in different regions requires clarification. In our experiments, we focused on the particles that adhered to the surface after impact, and did not specifically analyze those that rebounded, as the rebound has been extensively studied in the previous works (e.g., Sugiura and Maeno, 2000).

Generally, on the thicker surface region, the snowpack can absorb more impact energy via longer force chains, allowing some particles (especially those with sufficient vertical velocity component) to adhere. In contrast, the snowpack thickness of edge is thin and cannot effectively dissipate the kinetic energy through force chains. The impact of high-speed particles will cause the edge break. We have added the descriptions in lines 245-248: "*This is because the snowpack on the surface is thicker than at the edge, as the cornice has a wedge shape. As a result, the surface can absorb more impact energy through longer force chains, allowing particles with higher impact velocities to adhere. In contrast, the thinner snowpack at the edge cannot effectively dissipate kinetic energy, so high-speed particle impacts often leads to erosion or fracture at the edge.*"

Concerning the role of the vertical velocity component, the conclusion that whether a particle can adhere or rebound on the surface is determined by the vertical velocity is consistent with the well-established knowledge. We have added the discussion in lines 269-271: "*This is because only the vertical kinetic energy provided by the normal velocity can be used to overcome the adhesion energy barrier of the surface, whereas the tangential velocity cannot assist the particle in detaching from the surface in the vertical direction (John, 1995)*"

References:

Sugiura, K., Maeno, N. Wind-Tunnel Measurements Of Restitution Coefficients And Ejection Number Of Snow Particles In Drifting Snow: Determination Of Splash Functions. *Boundary-Layer Meteorology* **95**, 123–143 (2000).

Walter, John. Particle-Surface Interactions: Charge Transfer, Energy Loss, Resuspension, and Deagglomeration, Aerosol Science and Technology, 23:1, 2-24, (1995).

Comment 13:

Lines 218–266: The model describing forces between particles at the edge feels redundant, as all subsequent discussions are qualitative. As noted previously, quantitative validation using experimental snow and environmental data is essential. The claim that smaller dendritic particles adhere more readily due to a higher Fc/Fg ratio can be easily speculated without introducing the model.

Response: Thank you for your valuable comments. We have added more quantitative results in the model and directly using experimental snow data. We have further added detailed explanations for the phenomena that smaller dendritic particles adhere more readily. Furthermore, based on the mode, we have derived the cohesion force of dendritic particles, and derived the threshold radius of particles that can adhere on the edge.

3.4 Static force analysis of adhering particles on the cornice edge

Lines 307 to 355:

$$\frac{F_c}{F_g} = \frac{x}{R} cos\alpha + sin(\alpha - arcsin(\frac{x}{R})) - \mu_f \ cos\ \alpha\ cos(arcsin(\frac{x}{R}))\ \mu_f\ cos(arcsin(\frac{x}{R})) \tag{10}$$

In which F_c is the cohesion force, which can be expressed as:

$$F_c = \pi x^2 \tau_b \tag{11}$$

where x is the contact radius of ice bridge, assumed here to vary linearly with particle radius $x = \delta R$, with ratio δ=0.1-0.25(Golubev and Frolov, 2001). τ_b is the bond shear stress. While for non-spherical particles, particularly those with dendritic structures, the cohesion force is higher than that of spherical particles, due to the stronger geometrical interlocking between particles. Thus, dendricity should be considered in the calculation of the cohesion force for non-spherical particles. Here, we introduce a weighting parameter A into the cohesion force equation for dendritic particles, and its value will be derived later.

$$F_c = \pi x^2 \tau_b (1 + A(De - 1)) \tag{12}$$

where De is the dendricity value of non-spherical particles. For spherical particles, dendricity is a constant: De =1 and cohesive force is only determined by the contact radius, $F_c = \pi x^2 \tau_b$. For those particles adhere on the edge, the average value of dendricity De = 1.9, as is shown in Fig. 7.

The gravitational force of the particle is:

$$F_g = \frac{4}{3} \pi R^3 \rho_i g \tag{13}$$

By substituting Eq. (12) and (13) into the left side of Eq. (10), we obtained the expression for the ratio of F_c/F_g:

$$\frac{F_c}{F_g} = \frac{\pi x^2 \tau_b (1 + A(De - 1))}{4/3 \pi R^3 \rho_i g} \tag{14}$$

Meanwhile, the right side of Eq. (10) can be defined as a function φ, which is affected by the ratio δ, angle α, and friction coefficient μ_f:

$$\varphi = \delta cos\alpha + sin(\alpha - arcsin(\delta)) - \mu_f cos\alpha cos\,(arcsin\,(\delta)) \mu_f cos\,(arcsin\,(\delta)) \tag{15}$$

In which the friction coefficient μ_f ranges from 0.2 to 0.7 (McClung and Schaerer, 2006), and the angle α varies from 0 to 90^o according to the experiment result. The resulting values of ϕ are illustrated in the contour plot shown in Fig. 11. Notably, ϕ decreases with increasing μ_f at all α, which indicates that higher friction reduces the need for a strong cohesive force to maintain stability. For a given μ_f, ϕ increases at larger angles, meaning that higher cohesion is required to keep the particle stable at the edge. When angle α=90^o, the cohesion force is perpendicular to the gravity force; under this condition, the particle is most difficult to adhere to the edge. The bottom-right blank areas correspond to the instability status for particles where adhesion doesn't happen.

Considering the most challenging condition for a particle to adhere to the edge occurs when the angle α= 90^o and the friction coefficient μ_f = 0.2. The corresponding $\phi \approx 5$. Therefore, by combining Eq. (10), (14) and (15), we can obtain:

$$\frac{F_c}{F_g} = \frac{\pi x^2 \tau_b (1+A(De-1))}{4/3\pi R^3 \rho_i g} = 5 \tag{16}$$

Based on the experimental results shown in Fig. 6(b), the maximum radius of particles adhering on edge is 325 um. Therefore, we have:

$$\frac{4\delta^2 \tau_b (1+A(De-1))}{15\rho_i g} = 325 \times 10^{-6} \tag{17}$$

with δ *= 0.1,* τ_b *= 1 kPa (Jamieson and Johnston, 1990), De = 1.9, and* φ_{max} *= 5, we can derive the value of parameter A* $\approx$ *0.07.*

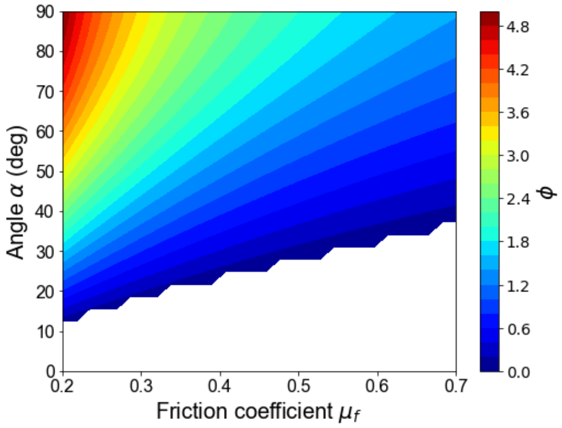

Figure 11. *Variation of* ϕ *as a function of friction coefficient* μ_f *and angle* α*.*

Therefore, in general, the cohesion force for edge particles, considering the shape effects, can be expressed as:

$$F_c = \pi x^2 \tau_b (1 + 0.07(De - 1)) \tag{18}$$

and the threshold radius R_{th} *for particles that can adhere to the edge can be estimated by:*

$$R_{th} = \frac{4\delta^2 \tau_b (1+0.07(De-1))}{3\rho_i g \varphi_{max}} \tag{19}$$

The threshold radius R_{th} *linearly increases with the increasing dendricity, in different* δ *values, as is shown in Fig. 12. With the higher value of ratio* δ*, it means a larger contact surface, therefore it allows larger particles adhering to the edge.* δ *is mainly dependent on the air temperature and relative humidity (Colbeck, 1982). Furthermore, we divided the radius into different bins based on the dendricity values. By comparing the averaged radius of various dendricity, we found that the experimental result is in good agreement with the model-predicted results. The experimental data lie between the theoretical curves for* δ*=0.15 and* δ*=0.25. It can be concluded that the maximum particle size capable of adhering to the edge increases with increasing dendricity. Which means greater dendricity enables larger particles to remain attached, suggesting that the complexity of the particle shape helps counteract gravity.*

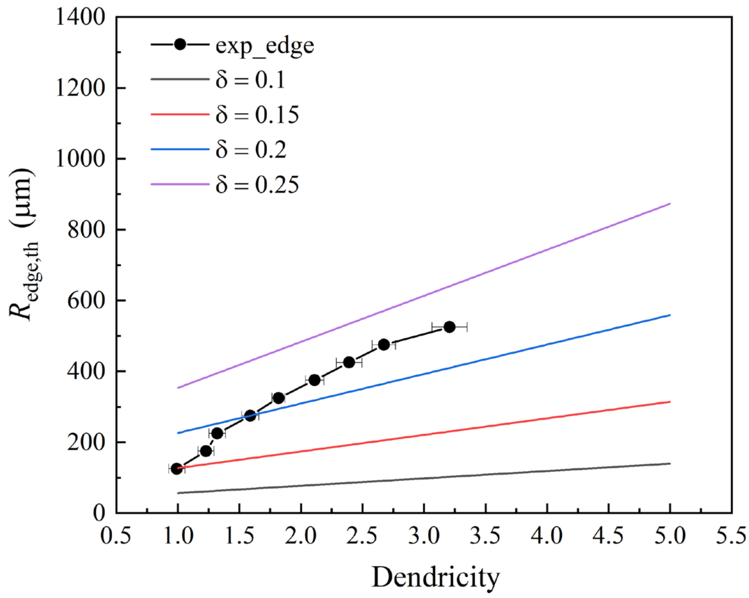

Figure 12. *Experimental and theoretical threshold radius of edge-adhering particles as a function of dendricity for various δ values.*

References:
McClung, D., & Schaerer, P. (2006). The Avalanche Handbook (3rd ed.), Table 9.1.

Colbeck, S. C. (1982), An overview of seasonal snow metamorphism, *Rev. Geophys.*, 20(1), 45–61, doi:10.1029/RG020i001p00045.

Jamieson JB, Johnston CD. In-Situ Tensile Tests of Snow-Pack Layers. *Journal of Glaciology*. 1990;36(122):102-106. doi:10.3189/S002214300000561X

Golubev, V. N. and Frolov, A.: On the correlation between tensile strength and stress wave velocities of dry coherent snow based on its structural model, Annals of Glaciology, 32, 70 – 74, https://doi.org/10.3189/172756401781819562, 2001.

Comment 14:

Given the complexity of dendritic particle shapes, factors such as branching and interlocking likely have greater influence. Additionally, the dependence of Fc/Fg on particle size is unclear. If the authors wish to explore particle size effects more rigorously, I strongly recommend analyzing the cornice structure post-experiment to measure particle size distributions and dendricity. This would greatly enhance the study's credibility.

Response: We thank the reviewer for this valuable suggestion. We have updated our model to account for the complex effects of particle shape. Specifically, we now derive the cohesive force expression explicitly for dendritic particles and have refined the relevant parameters in the cohesion force equation using our experimental data.

Regarding analysis of post-experiment cornice particle size distributions and dendricity, we have examined both the size and morphology of snow particles on the cornice surface and edge. The particle size distribution observed is consistent in trend with the results reported in our manuscript. However, collecting snow particles from the cornice surface and edge post-experiment is easy to break the dendritic snow shape, making post-experiment measurements of their size and dendricity potentially unreliable. For this reason, we did not adopt this method for data analysis in the current study, as it could introduce significant uncertainties.

Comment 15:

Line 224: The authors state that wind velocity and shear stress near the cornice edge approach zero. Please provide clear evidence for this. Figure S1 is unsatisfactory and hard to interpret. Moreover, since the ridge model differs from natural terrain shown in the reference, the airflow at the edge may not reduce to zero but instead decrease rapidly on the leeward side.

Response: Thanks for this suggestion. Regarding the wind velocity and shear stress from numerical simulation, we have interpreted in Comment 1 in the specific comment.

There are two principal types of mountain terrain where snow cornice is commonly formed, the plateau type, characterized by relatively flat mountaintop areas with abrupt edge, and the ridge type, which refers to elongated, narrow mountain crest exposed to prevailing winds. In this work, we specifically investigate the plateau-type setting, where cornices form along the abrupt edges of relatively flat mountaintops, as is shown in Figures below. We have tested these two types of snow model and showed the plateau type mountain in this work.

Figure. Snow fences to the left and wind baffles to the right in use in Switzerland (photos: Stefan Margreth).

Figure. Snow cornices. (photo by Lea Frye in Buena Vista, Colorado, United States of America. Source: Smithsonian Magazine Photo Contest.) [https://photocontest.smithsonianmag.com/photocontest/detail/snow-cornice-while-snowmobiling-near-cottonwood-pass-colorado/]

Figure. Snow cornices overhanging Gruvefjellet. (photo by Holt Hancock et al., 2022) [https://www.ntnu.no/blogger/richard-hann/2022/05/18/monitoring-the-snow-cornices-for-avalanche-risks/]

Moreover, the effect of mountain terrain on cornice growth is needed to be discussed in the future work. We have added the sentence in lines 383-385: "*Numerical simulations will be essential for a more comprehensive understanding of the coupling between the flow field and snow cornice dynamics, and investigate the effects of mountain morphology on cornice growth.*"

Comment 16:

Line 275:

The claim about increases in both the thickness and length of the cornice should be supported by time-series data. If such data were obtained, please present them. **Response:** We appreciate the reviewer's suggestion. As reported in Yu et al. (2022), we have previously published the time-series data illustrating the temporal evolution of cornice thickness and length. However, the present study focuses on particle motions by observations with high temporal resolution and short time period, during which such macroscopic changes are not as evident. To avoid potential misunderstanding, we have deleted this sentence in Conclusion and added lines 100-102: "*A total 18 cases were conducted during the cornice growth, with each case lasting 4-5 seconds and yielding 12455 images to record the particle trajectories. The duration of each case was limited by the camera memory. A sequence of the different growth steps is illustrated in Fig. 3 (a) of Yu et al. (2022).*"

References

Yu, H., Li, G., Walter, B., Lehning, M., Zhang, J., and Huang, N.: Wind conditions for snow cornice formation in a wind tunnel, The Cryosphere, 17, 639–651, https://doi.org/10.5194/tc-17-639-2023, 2023.

Additional Comment:

Looking at Figures 4 and 6, it appears that snow accumulation on the flat surface at the model's right end increased. This area may play a key role in conveying rolling particles toward the edge and increasing the cornice root's thickness. This process could be crucial to understanding how thin plates evolve into full cornices in nature. This process deserves attention in future discussions and analyses.

Response: We appreciate this comment concerning the accumulation at the root of the cornice and its role in subsequent cornice growth. This area indeed plays a key role in conveying not only rolling particles but also saltating particles toward the edge. The relationship between air mass transported and the growth rate of cornice has been studied in our previous work of Yu et al. (2022). To be clear, we have incorporated a relevant description of the cornice growth process in the Introduction of the current paper. As lines 29-44: "*The growth of a snow cornice can be divided into several stages (Montagne, 1980; Vogel et al., 2012; Eckerstorfer et al., 2013). In the initial stage, a thin slab forms at the mountain edge (highlighted in red in Fig. 1), mainly by adhesion of wind-transported snow particles. When more snow accumulates on the relatively flat surface behind the edge, it can gradually be conveyed toward the slab tip—especially via wind-transported particles—thereby increasing the thickness at the cornice root. This sustained supply of snow from the platform region plays a key role in the transformation of a small slab into a fully developed cornice in nature. In the subsequent stage, repeated deposition from intermittent drifting and precipitation successively adds new layers of snow to the cornice. This layer-by-layer accumulation is accompanied by a gradual increase in both length and thickness of the cornice. As the cornice grows larger, the overhanging mass of snow is increasingly influenced by gravitational forces, which may cause it to bend downward (shown in the white dashed line in Fig. 1) and promote internal compaction near the edge. Eventually, when the cornice becomes too large and shear stress exceeds a critical threshold, it breaks off and collapses. The evolution of a wedge-shaped cornice—from initial slab formation to subsequent snow accumulation on the flat surface—has been experimentally investigated in our previous work (Yu et al., 2022), with particular focus on the* *relationship between cornice growth rate and air mass transport. However, the specific mechanisms governing the very initial stage, that is, how airborne snow particles first adhere and accumulate to form the incipient slab at the edge, remain unexplored.*"

References

Yu, H., Li, G., Walter, B., Lehning, M., Zhang, J., and Huang, N.: Wind conditions for snow cornice formation in a wind tunnel, The Cryosphere, 17, 639–651, https://doi.org/10.5194/tc-17-639-2023, 2023.

Responses to Reviewer #2:

General comments

Comment 1:

An explanation of the effect of particle shape (spherical/dendritic) on snow cornice formation has been added. The discussion of the balance of forces has been simplified without introducing excessive parameters, resulting in increased reliability, and consistency with the experimental results has also been noted. Other explanations of the experimental results have also been revised for clarity, and as a result the paper is now acceptable for publication with some corrections.

Response: Thank you very much for your time and efforts in reviewing our manuscript and for your constructive comments that have helped us improve the quality of this work. We appreciate your positive assessment and are grateful for the opportunity to address the reaming corrections.

Specific comments

Equation (3): Although this notation is understandable, it would be clearer to write the expression within the square root as (vpx(t))^2 + (vpy(t))^2.

Response: Thank you for pointing this out. We have revised the equation (3) to:

$$v_{\mathrm{p}}(t) = \sqrt{(v_{\mathrm{px}}(t))^2 + (v_{\mathrm{py}}(t))^2} \tag{3}$$

Line 248: Rcos(arcsin(x/R) A bracket is missing.

Response: Thank you for pointing this out. We have added the bracket and the sentence have been revised to: "*The friction force F_f acts on point P through the moment arm Rcos(arcsin(x/R)).*"

Lines 293-294: …and snow accumulation on train bogies… It is unclear which state of accumulation is considered. If the accumulation is not due to natural wind, but rather to the movement of the train, additional factors such as different speed ranges and mechanical heat generation would have to be considered.

Response: We agree on this point. We have deleted the description on the train bogies. This sentence has been revised as lines 379-381: *"Our experiments and findings enhance predictions of cornice growth and avalanche risk, with broader implications for understanding snow adhesion on both natural features and infrastructure, such as ice crevasse formation and wire icing.*"

Lines 327-330: The same paper by Eckerstorfer is listed as 2013a and 2013b. Line 351: The author Seligman is listed twice.

Response: Thank you for pointing this out. We have deleted the repeated reference.