Responses to the editor and each reviewer's comments

Title: Snow Particle Motion in Process of Cornice Formation
ID: EGUSPHERE2024-2458
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,

Based on your responses to referees' and community comments in the interactive discussion, you are invited to submit an appropriately revised version of your manuscript. Please make sure all issues raised in the reviews are effectively addressed in the revision. Note that the revised manuscript will be returned to the referees for further assessment before making a final editorial decision.

Best regards,
Guillaume Chambon / TC Topical Editor

Dear Editor,

We would like to thank you for the assessment of our manuscript. We have modified the manuscript accounting for all reviewer comments, which improved the quality of our work.

Based on the recommendations of reviewer 1:

- We have added the comparison of cohesive force of dendritic particles and spherical particles.

Based on the recommendations of reviewer 2:

- We have increased the particle number so that the analysis satisfies the requirements.
- We have analysis the vertical impact velocity of particles that adhere on edge and surface.
- We have reconsidered the static force analysis.
- We have clarified all the variables to increase the readability of this manuscript.
- We have highlighted the quantitative results in the manuscript.

Based on the above mentioned modifications, the manuscript has been improved. The discussion on the mechanism of particle adhesion on cornice edge and surface has been extended. Also, the revised mechanism model can be used to explain the experimental results, which increases the coherence of manuscript.

We have clarified all the variables to improve the readability of this manuscript. We hope these modifications adequately address all the comments by the reviewer. Please find a point-by-point reply to each of the comments below.

Sincerely,
Hongxiang Yu, on behalf of all authors

Responses to Reviewer #1:

General comments

This paper presents a detailed observation of snow particle motion in order to understand the process of snow cornice formation. It also investigates the conditions under which snow particles adhere to snow cornices through particle-level force analysis. There are few cases where snow cornice formation has been observed, so even though this is a very small-scale experiment in a wind tunnel rather than a full-scale snow cornice, this study is very informative. In addition, it is expected that the detailed force analysis will lead to the construction of a model for the snow cornice formation process, making this work worthy of publication.

Response: We sincerely thank the reviewer for the positive evaluation of our work and for recognizing the significance of our study in understanding the process of snow cornice formation. We appreciate the acknowledgment of the value of our wind tunnel experiments and the potential of our force analysis to contribute to modeling the snow cornice formation process.

Specific comments

Comment 1:

There is a big question about the force analysis, which is the main topic of this paper. The wind tunnel experiment in this paper uses dendritic snow particles. Although it is not clearly stated in the paper, my personal experimental experience and personal communications with researchers suggest that snow cornices can only form when dendritic snow particles are used, whereas they do not grow when spherical particles are used. The reason for this is not entirely clear, but it is thought that the large contact surface of dendritic particles makes it easier for snow particles to adhere to each other than for spherical particles. However, this paper discusses the balance of forces assuming that the particles are spherical, so it is possible that the contribution of the contact area of dendritic snow particles is sought in other forces when considering adhesion. To make this paper fruitfu**l, I recommend that the author re-examine whether there are differences in snow cornice formation and cohesive forces between spherical and dendritic particles.** Of course, it may not be easy to discuss cohesive forces between dendritic particles, but I expect that the contribution of dendritic shapes can be estimated from the parts that cannot be explained by considering spherical particles.

Response: Thank you for your valuable comment. We have tested the fresh snow particles and aged snow particles (by keeping the fresh snow for a few days, the particle shape becomes near spherical) and found that: 1) both of them can form a snow cornice; 2) fresh snow particles are much easier to form a snow cornice than the aged ones.

In the revised manuscript, we have added the description on snow particle type we use

in section 2 **Instruments and Methods**.
Lines 67 to 73:
Before conducting the experiment, we have performed preliminary tests on both fresh snow particles and aged snow particles. 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°C. 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, as they are much easier to consolidate into a stable structure compared to aged snow particles. Therefore, fresh snow particles were used in the subsequent experiments.*

Regarding the differences between dendritic particles and spherical particles, we add the following discussion in the section **3.4 Static force analysis of adhering particles on the cornice edge**.
Lines 260 to 266:
Dendritic snow particles, which have a cohesive force approximately 1.44 times greater than that of spherical particles (Eidevåg et al., 2022), exhibit a larger angle α*. This larger angle indicates a broader range of balanced positions at the edge, making dendritic particles more prone to adhering at the edges. This tendency explains the experimental phenomenon that fresh snow is more likely to form snow cornices.*

Additionally, smaller snow particles experience lower gravity forces. Consequently, the ratio of F_c *to* F_g *is higher, leading to increased values of* α *and enhancing their tendency to adhere. This finding aligns with the results of this experiment, that smaller snow particles are more likely to adhere at the edges.*

Technical corrections

Line 19: micr-mechanism -> micro-mechanism?
Response: Thanks for pointing it out. We have revised it in line 29: "*However, the micro-mechanism for particle adhesion to the cornice edge has not been studied in detail, due to the difficulty in observing the formation process at the particle scale*"

References:
Eidevåg, T., Thomson, E.S., Kallin, D., Casselgren, J., Rasmuson, A. Angle of repose of snow: An experimental study on cohesive properties. *Cold Reg. Sci. Technol*. 2022, 194, 103470. doi: 10.1016/j.coldregions.

Responses to Reviewer #2:

General comments

Comment 1:

I appreciate very much for the efforts to observe the particle motion carefully in the wind tunnel and investigate the growing mechanism of the thin snow plate which extends to leeward from the edge. However, according to my observations in the fields and the wind tunnel experiments, it is extremely fragile and always breaks down after growing several centimeters long at the maximum.

Response: Thank you very much for your time and valuable comments. The cornice growth on the mountain ridge and causes snow avalanches has been observed by Eckerstorfer et al. (2013b), Vogel et al. (2012), and Hancock et al. (2020). From the previous observation results, cornice growth experiences multiple times of collapses and extends. At each time of growth, it may break down after a few centimeters of growth. This phenomenon is also observed in our experiment. Due to the limited field observation, it is tough to observe the particle moving around a real cornice on the mountain ridge. However, understanding the mechanism of snow cornice formation is still essential for avalanche prediction and simulation. Therefore, we carried out a wind tunnel experiment to observe the particle movement surrounding a small cornice we produced, for no matter in the field or in the wind tunnel, the particle moving and sticking laws are the same.

Comment 2:

It never grows to the much larger one, such as, we find on the crest of a ridge along a mountain slope and occasionally causes the avalanche release.

Response: Thanks for pointing this out. This is due to the involved dimensions and timescales which are way smaller/shorter in the ring wind tunnel. However, the size of the crest of a ridge is a long-term result of multiple growth events, not one precipitation event. In our experiments, the cornice can grow to more than 10 cm, which is almost the size of the model base.

Comment 3:

The authors need to make clear at the outset that the authors are looking at completely different phenomena. Even though it is allowed to say this miniature as “cornice” as well in a broad sense, the following numerous points should be taken into consideration before the publication.

Response: Thanks for your suggestions. Although there are differences to real natural conditions, we are looking at snow particles that are transported by wind across a ridge while a fraction of the particles deposit on the lee edge resulting in horizontal and vertical snow slab (cornice) growth. As we mentioned above, no matter whether in the field or the wind tunnel, the particle moving and sticking laws are the same.

Specific comments

Comment 1:

Line 14: After "and snow cornice", Seligman et al. (1936) should be put as the reference.

Response: We agree with this and have revised this sentence in lines 21-23 to: *"Therefore, wind can shape the snow cover and produce special patterns by redistributing snow over various areas, such as sastrugi, snow dunes (Sommer et al., 2018), and snow cornices (Seligman et al., 1936).*"

Comment 2:

Line 29: " mechanical mechanism " sounds redundant and unnatural, although grammatically correct. I suppose only "mechanism" is fine.

Response: Thanks for your suggestion. We have revised this sentence in lines 36-37 to: "*However, the mechanism behind the wedge-shaped (Seligman et al., 1936) snow cornice has not yet been investigated.*"

Comment 3:

Line 53 to 54: 4 m/s is the wind speed at the center of wind tunnel? If the authors would like to analyze the experimental output physically, the friction velocity u_* should be used in the manuscript instead. Furthermore, the threshold wind speed needs to be specified.

Response: Thanks for your suggestions. The thickness of the boundary layer in this ring wind tunnel is estimated being very thin (~2 cm) (Sommer et al., 2017; Yu et al., 2023), and the wind speed inside the wind tunnel can be considered as uniformly distributed on the cross-section. Therefore, we used the center wind speed instead of friction velocity in the manuscript. We have added a sentence in Section 2 line 63: "*The wind speed inside the wind tunnel is nearly uniform with a very thin (around 2 cm) boundary layer (Sommer et al., 2017; Yu et al., 2023).*"

Reference:

Sommer, C. G., Lehning, M., & Fierz, C. (2017). Wind crust formation: snowMicroPen data. *Journal of Glaciology*. WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland. https://doi.org/10.16904/21

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 4:

Figure 1: 0.125 m on the side view corresponds to the height of snow on the floor?

Response: Thank you for pointing this out. This value represents the height of the ridge model made of snow. The height was measured from the lower floor. In section 2, we have revised the sentence which describe the snow model in lines 64-66 to: "*A ridge model with a fixed size (height 0.125 m, total length 0.4 m, flat surface length 0.1 m) is built with compacted snow before each experiment, and its side view is shown in Fig. 1.*"

Comment 5:

Line 118: "190 collision particles": Are these particles with the snow surface? Such careful explanations are lacking overall. Please check the manuscript again by standing at the place of the readers.

Response: Thank you for pointing this out. These 190 collision particles are moving particles in the air, and they also interact with the surface. This sentence has been revised in lines 136-139 "*By maintaining the wind speed in the experiment at a constant (4 m/s), the study analyzed 655 collision particles interacting with the snow surface. These interactions included particles that rebounded, impacted, or deposited on the snow bed, as determined through an image post-processing method. Among these particles, 186 adhered to the cornice edge, while 469 adhered to the cornice upper surface.*"

Comment 6:

Figure 4 (b): Although it is described that the size of points shows the particle diameter, no explanation are found in the figure caption. Further, the corresponding specific size should be added as well.

Response: Thank you for pointing it out. We have re-plotted this figure and used color variation to represent the size difference, as is shown in Fig. 4(b). The explanation has been added in the figure caption: "*Figure 4. (a) Cornice edge and surface, with the dashed box indicating the regions of edge and surface. (b) Impact velocity and impact angle of snow particles of different sizes (deeper color represents larger size) on edge (in blue points) and surface (in red points).*"

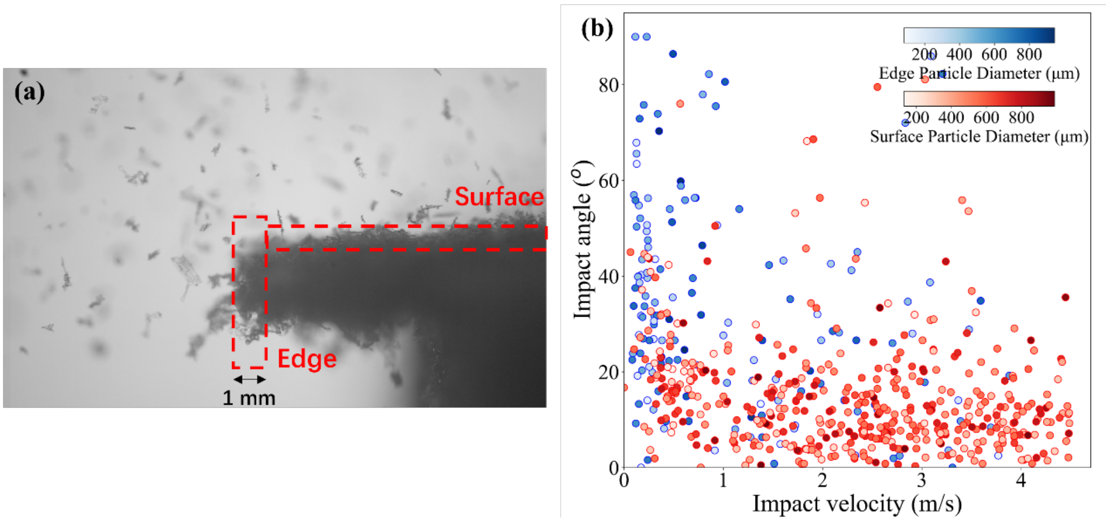

Figure 4. (a) Cornice edge and surface, with the dashed box indicating the regions of edge and surface. (b) Impact velocity and impact angle of snow particles of different sizes (deeper color represents larger size) on edge (in blue points) and surface (in red points).

Comment 7:

Line 137: Although Stokes number: *St* is introduced, no explanations about the parameters are shown. Probably, ρ_p is particle density, *d* is particle diameter, *U* is wind speed, *m* is kinematic viscosity and *L* is the characteristic length scale. Specify each value you used, particularly *L*. It looks the difference of St between the surface and the edge is caused by the particle diameter only. If it is the case, I am wondering it is needed to take the trouble to introduce *St*. As you see, *St* is a dimensionless number that characterizes the behavior of particles suspended in a fluid flow. It represents the ratio of the particle's inertial forces to the viscous forces exerted by the fluid. When *St* is much smaller than one, the particle closely follows the fluid flow, whereas *St* is much larger than one particle's inertia dominates, and it is less affected by the fluid flow, tending to maintain its original trajectory. On the other hand, at $St \approx 1$ the particle behavior lies between these extremes, showing partial coupling with the fluid flow. In this case, both 1.8 and 3.1 are close to one and the difference is quite small; correspond to the third case together. Consequently, I have to say the discussions here are almost meaningless.

Response: We agree with this and have added a notation for all variables existing in this manuscript. The discussion on the Stokes number has been deleted from the revised manuscript. The notation is shown below.

NOTATION

Symbol	Definition and units
A	Constant [$=3.18\times10^{-7}$]
A_p	Projected area of one particle [m^2]
D	Diameter of particle [m]
v_p	Particle velocity [m s^{-1}]
v_{px}	Particle velocity component in x direction [m s^{-1}]
v_{py}	Particle velocity component in y direction [m s^{-1}]
v_{imv}	Vertical impact velocity of particle [m s^{-1}]
F_c	Cohesive force [N]
F_f	Frictional force [N]
F_g	Gravity force [N]
F_s	Supporting force [N]
M_s	Torque [Nm]
x	Radius of contact surface [m]
t	Current time [s]
Δt	Time step [s]
T_{air}	Air temperature [°C]
θ_p	Particle moving angle [°]
θ_{im}	Particle impact angle [°]
θ	Cornice angle [°]
μ_f	Friction coefficient of ice surface
ρ_p	Particle density [kg/m^3]
σ	Tensile strength at failure [kPa]
α	Angle between direction of gravity and cohesion [°]

Comment 7:

Figures 5 and 7: Generally, the number of particles you analyzed is extremely small. If the authors would like to induce concrete and statistically significant conclusions, at least more than 300 particles data for edge and surface each should be corrected and examined.

Figure 7: Authors are looking at the impact velocity and the angle separately. I suppose the combination of two factors for the particles on edge and surface reveals interesting findings, supposing the enough data exists.

Response: Thanks for your suggestions. We have increased 383 surface particles and 121 edge particles from the experimental data. 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 updated Fig. 5 and Fig. 7 are shown below. In the updated Fig. 5, the size distribution of particles follows the same trend as the previous one, with the same distribution function but different parameters. In the updated Fig. 7(a), the impact velocity distribution of edge particles maintains the same trend as before, while the distribution pattern of surface particles changed to a Gauss distribution function. In the updated Fig. 7(b), the impact angle distribution of edge particles also follows the same trend as before, but the distribution of surface particles changes to an Exponentail distribution function.

Furthermore, we combined the impact velocity and the angle to plot the vertical impact velocity, as shown in Fig. 7(c). The vertical impact velocity of both surface particles and edge particles follows the same trend.

We have revised the relevant paragraphs in Section 3.1.

Section 3.1 Particle size distribution

Lines 150-164:

The size distribution of particles adhering at different positions on a dynamically evolving cornice is analyzed, as is shown in Fig. 5. For all particles adhering to the cornice, their size distribution follows the log-normal distribution described by $\theta \sim N(\mu = 5.94, \theta = 0.36)$*. For particles adhering at the edge, their size distribution follows the log-normal distribution described by* $\theta \sim N(\mu = 5.76, \theta = 0.43)$*. For particles adhering on the surface, their size distribution follows the log-normal distribution described by* $\theta \sim N(\mu = 5.74, \theta = 0.47)$*. It can be concluded that particles with smaller sizes adhere more likely on the edge, and larger particles adhere more likely on the cornice surface.*

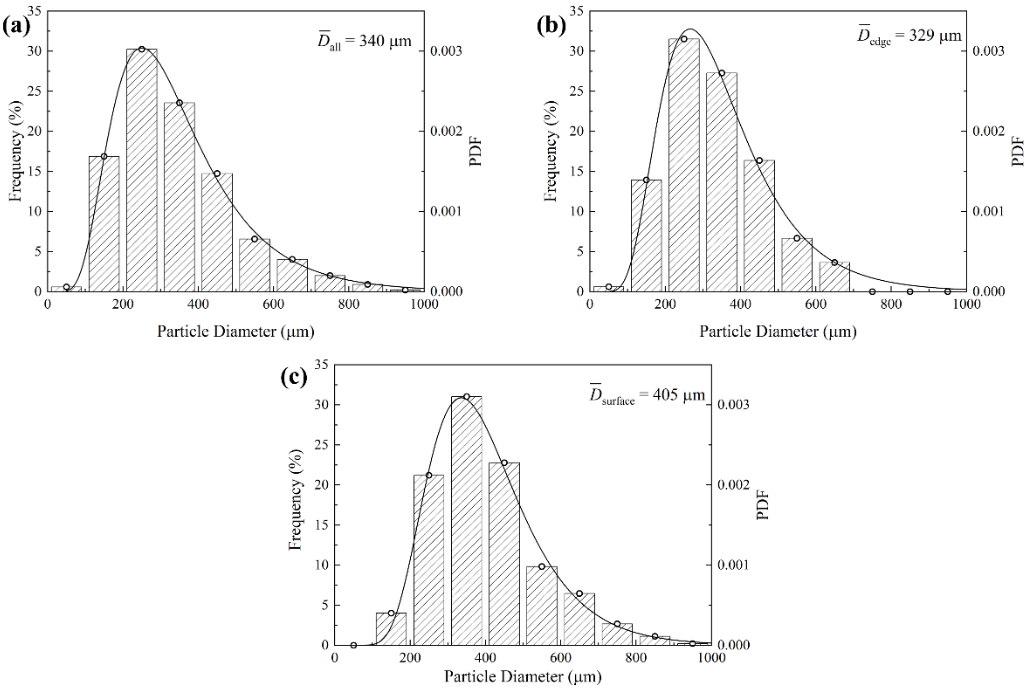

Figure 5. Size distribution of particles at different positions. (a) All particles. (b) Adhesion particles at the edge. (c) Adhesion particles on the surface. The grey shadow represents the existence frequency of particles with different sizes.

The observed differences in particle size distribution across various locations suggest that environmental conditions, such as fluid field and gravitational effect, play an important role in influencing the adhesion of particles of different sizes. The flow on surface is a boundary layer flow, which provides a more stable environment with less turbulence, facilitating the deposition of larger particles. In contrast, the flow on the edge is a separation flow, where the ability to counteract particle gravity differs. On edge, larger particles are more likely to fall due to gravity, while smaller particles can stay on edge under cohesive forces. Moreover, smaller particles, with better followability with the wind, are more likely to stay on edge under the influence of reflux vortex behind the edge.

Moreover, we have revised the relevant paragraphs in Section 3.3.

Section 3.3 Particle impact velocity and angle

Line 183-185:

Here, we define the impact velocity/angle of the particle that deposits on the cornice surface as particle adherence velocity/angle (PAV/PAA). We first analyze the PAV and PAA of 469 particles deposited on the surface and 186 particles deposited on the edge.

Line 191-207:

The relative frequency of PAV/PAA represents the probability of particle adhesion on the cornice with a certain impact velocity or impact angle. As is shown in Fig. 7(a) that for edge particles, the PAV of edge particles follows the exponential distribution function $f_s(v_{im}) = 4.3+30e^{-0.9v_{imp}}$ (R^2=0.96), with values mainly concentrated at below 1.5 m/s. While the PAV of surface particles follows the Gaussian distribution function of $f_s(v_{im}) = -2.8+\frac{79}{3.4\sqrt{\pi/2}}e^{-2((v_{imp}-2.9)/3.4)^2}$ (R^2=0.91), with values mainly concentrated at 3 m/s. This indicates that particles deposited on the surface normally have a higher impact velocity than the edge. The low number of particles adhering to the surface at low impact velocities can be attributed to the wind speed in the wind tunnel, which is set at 4 m/s. At this wind speed, the majority of particles are entrained and transported at higher velocities, leaving only a small fraction of particles moving at very low velocities near the cornice's surface.

As is shown in Fig. 7(b) that the frequency of PAA of surface particles follows the Exponential distribution function $f(\theta_{im}) = -0.8+80.6e^{-0.1v_{imp}}$ (R^2=0.97), with values mainly concentrated below 17°. While the PAA of edge particles follows the Gaussian distribution function $f(\theta_{im}) = 7.1+\frac{448.8}{45.7\sqrt{\pi/2}}e^{-2((v_{imp}-18.1)/45.7)^2}$ (R^2=0.72), with values distributed more uniformly in range. The average PAA of surface particles is 13°, which is consistent with the previous experimental results of Nishimura and Hunt (2000), as is shown in the red dash in Fig. 7(b).

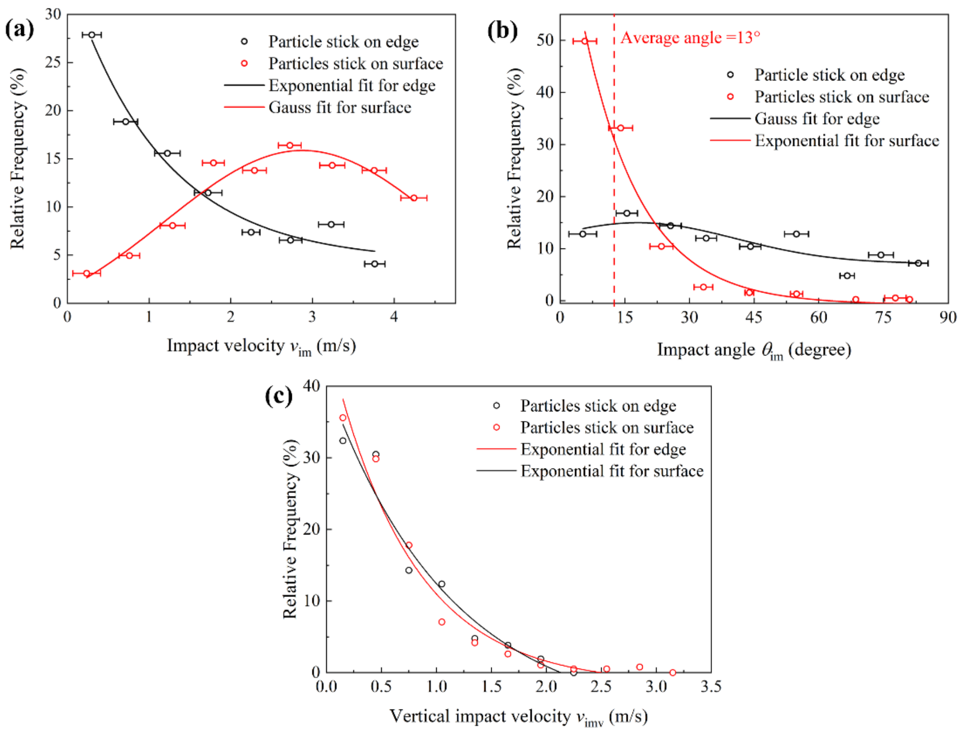

Figure 7. Relative frequencies of (a) PAV, (b) PAA, and (c) vertical impact velocity of particles on edge and surface.

Furthermore, we combined the impact velocity and angle by analyzing the vertical *impact velocity ($v_{imv}=v_{im}\sin\theta_{im}$) in Fig. 7 (c).The relative frequency of both surface particles and edge particles follow the exponential distribution, with surface particles $f_s(v_{imv})= 0.5e^{-v_{imv}/0.7}$ (R^2=0.96), and edge particles $f_s(v_{imv})$=-0.1+0.5$e^{-0.9v_{imp}}$ (R^2=0.95). Particles adhere at low vertical impact velocities, whether on edges or surfaces. For both edge and surface particles, the threshold vertical impact velocity ranges from 2-2.5 m/s, with edge particles having a lower threshold velocity compared to surface particles.*

It is noted that the vertical impact velocity distributions of surface particles and edge particles are in the same trend, although the impact velocity and impact angle distributions of edge particles and surface particles are different. It indicates that particle adhesion to the surface is mainly determined by the vertical impact velocity, and the differences in impact velocity and angle distributions between surface and edge is due to the fluid field differences caused by topographic changes.

Comment 8:

Further, here, authors set focus on saltating particles only. How do you estimate the contribution of the creep particles?

Response: The samples we analyzed also include creep particles (rolling over the surface). We concluded four adhering patterns of snow particles, and one of them is creep. The creep particles contribute ~13.6% of the particles (using the number ratio) that stick on the cornice, which is mentioned in Section 3.2 Particle movement pattern.

Comment 9:

Figure 8: Please make the figure clearer. Though many parameters are introduced, it is hard to recognize what they mean and indicate, such as, a. In addition, preferably, make the right and left sides reverse to align with Figures 4 and 6.

Response: Thanks for your suggestions. To address the concerns raised, we have added a notation to clearly define and explain the parameters as we mentioned in Comment 7. Moreover, Fig. 8 has been adjusted by reversing the right and left sides to align with the structure of Fig. 4 and 6.

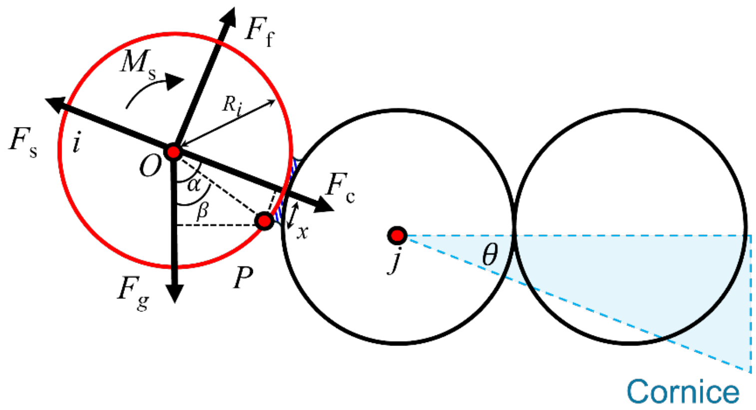

Fig. 8 Schematic diagram of force analysis of particles adhering to the edge

Comment 10:

Line 190-191: In fact, the wind speed near the surface is getting smaller. However, you cannot neglect the wind shear stress acting there.

Response: Thank you for this suggestion. There are two methods of calculating the drag force on a particle. First method calculates the drag force with the relative velocity between the particle and the flow:

$$F_d = 18\pi D^2 C_D (u - u_p)^2$$

where u_p is the particle velocity, u is the air wind speed, C_D is the drag coefficient, and D is the particle diameter. For particle at the edge, the air wind speed u and particle velocity are both equal to zero, therefore, the drag force is zero and can be ignored.

The second method calculates the drag force with the surface shear stress τ [N/m^2]:

$$F_d = \tau A$$

where A [m^2] is the wind-affected surface area of a particle. However, the equation $\tau = \rho u_*^2$ is most suitable for flat surface and long-term averaged fluid field (Schlichting and Gersten, 2016). Thus, this calculation method for cornice edge is not suitable here.

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.

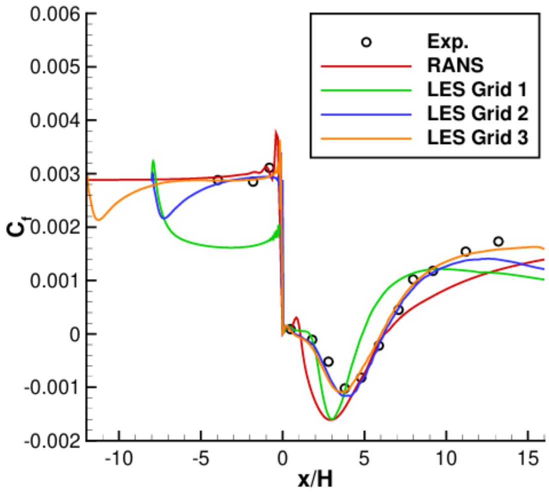

Figure R1. Skin friction coefficient (DeBonis, 2022)

In summary, no matter using which method of calculating the drag force of particles at the edge, its value can be considered negligible.

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.

Comment 11:

Line 191: According to your data, particle speed is quite low (nearly 0.5 m/s), thus, the compression deformation due to the collision is unlikely.

Response: Thank you for pointing out this important aspect. We agree that the particle speed at the edge of the snow cornice is relatively low, which makes significant compression deformation unlikely. In our analysis, we primarily focus on the role of the static balance of forces in particle accumulation at the edge. The compression deformation is expected to be minimal and negligible in this context. We have revised the relevant sections to clarify this point and ensure that the role of compression deformation is not overstated.

The revised Fig. 8 and the corresponding paragraph are shown as below:

Considering the differences in particle size distribution between the edge particles and surface particles, we conducted a static analysis of the particles at the edge. As shown in Fig. 8, a newly deposited particle i adheres to the foremost particle j at the edge of the cornice. Particle i is subjected to gravity F_g, the cohesive force F_c exerted by particle j, and the frictional force F_f at the contact surface. 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 and Edmond. 2018), allowing the drag and lift forces acting on particle i to be neglected compared to other forces (Schmidt, 1980).*

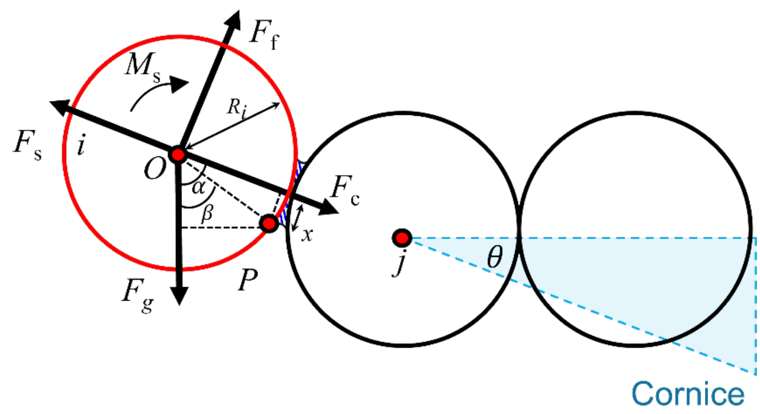

Figure 8. *Schematic diagram of force analysis of particles adhering to the edge.*

The force balance equations for particle i can expressed as:

$$F_g \cos\alpha + F_c = F_s \tag{5}$$

$$F_g \sin\alpha \leqslant F_f \tag{6}$$

$$F_f = \mu_f F_s \tag{7}$$

Here, F_g is the gravity force on particle i, F_c is the cohesive bond force, given by $\pi x^2 \sigma$ (Szabo and Schneebeli, 2007), where σ is the tensile strength at failure and x is the radius of the bond (blue shadowed area). F_s is the supporting force, and α is the angle between the direction of gravity and cohesive force. R_i is the radius of particle i.

When snow particles adhere to the surface, both the gravity force F_g and the adhesive force F_c are in the vertical direction, resulting in an upward support force from the surface that maintains their stationary position. However, when snow particles adhere to the edge, the gravity force F_g and the adhesive force F_c are not in the same direction. The component of the cohesive force in the direction of the gravity force is balanced by the support force generated by the edge, while the component of the gravity force perpendicular to the adhesive force needs to be balanced by friction force F_f. Once this component exceeds the frictional force, the particles will fall.

By substituting Eq. (5) and Eq. (7) into Eq. (6), we can derive the condition for particle i to maintain mechanical equilibrium if:

$$\frac{F_c}{F_g} \geq \frac{sin\alpha}{\mu_f} - cos\alpha \tag{8}$$

To analyze the stability of particle i, overturning moments are calculated around point P (at the edge of the bond). The supporting force F_s and cohesive force F_c act through the center of particle i and operate on point P through the moment arm x. The gravity force F_g acts on point P through the moment arm $Rsin(\alpha - arcsin(x/R)$, where the *angle between F_g and line $\overline{OP}$ (distance from particle center to point P) is $\beta=\alpha-\arcsin(x/R)$. The friction force F_f acts on point P through the moment arm Rcos(arcsin(x/R). The condition for the particle to remain in equilibrium is $M_s \leq 0$. Therefore:*

$$(F_s - F_c)x + F_g R sin(\alpha - \arcsin\left(\frac{x}{R}\right)) - F_f R cos(\arcsin\left(\frac{x}{R}\right)) \leq 0 \qquad (9)$$

Substituting Eq. (5) and Eq. (7) into Eq. (9) yields:

$$\frac{F_c}{F_g} \geq \frac{x/R \cdot cos\alpha + sin(\alpha - \arcsin(x/R)) - \mu_f cos\alpha \cos(\arcsin(x/R))}{\mu_f cos(\arcsin(x/R))} \qquad (10)$$

For the bond radius x<<R (Gubler, 1982), $x/R \sim 0$, $\arcsin(x/R) \sim 0$. Thus, we can simplify the Eq. (10) to:

$$\frac{F_c}{F_g} \geq \frac{sin\alpha}{\mu_f} - cos\alpha \qquad (11)$$

Eq. (11), derived from the momentum equilibrium analysis, is consistent with Eq. (8), which is derived from the force balance analysis. This equation indicates that particles adhering to the edge within the range of [0, α] can remain stable. The ratio of cohesive force (F_c) to gravity force (F_g) is proportional to the upper limit of angle α, indicating that a higher cohesive force or lower gravity force results in a wider stable angle range for α.

Dendritic snow particles, which have a cohesive force approximately 1.44 times greater than that of spherical particles (Eidevag et al., 2022), exhibit a larger angle α. This larger angle indicates a broader range of balanced positions at the edge, making dendritic particles more prone to adhering at the edges. This tendency explains the experimental phenomenon that fresh snow is more likely to form snow cornices.

Additionally, smaller snow particles experience lower gravity forces. Consequently, the ratio of F_c to F_g is higher, leading to increased values of α and enhancing their tendency to adhere. This finding aligns with the results of this experiment, that smaller snow particles are more likely to adhere at the edges.

References:

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Comment 12:

Line 216: Authors say that the sintering time is much longer than the collision time in the manuscript at lines 26-27 and exclude the mechanism to create the wedged-shaped form. I do not understand why it appeared again. It looks contradictory statements. Furthermore, the static electric forces have been observed in the specific cases so far, and not always.

Response: Thank you for pointing out the unclear point in the manuscript. I understand the concern about the seemingly contradictory statements regarding the role of sintering in the formation of snow cornices. I would like to clarify that in lines 26-27, it was stated that the sintering time is much longer than the collision time when a particle impacts the cornice surface. This means that on the timescale of particle sintering, the drifting snow aerodynamic process dominates the redistribution of snow particles and the patterns of snow cornices. However, the intention was not to imply that the sintering force is unimportant in maintaining the shape of snow cornice. Rather, the point is that during the initial stage of cornice formation, the drifting snow aerodynamic process is the primary driver of the distribution of snow particles. After these particles are deposited on the edge, the sintering force then dominates the main place in keeping the particle stationary, thus shaping and preserving the cornice structure.

Additionally, the duration of a particle's contact time on the surface is not particularly significant. It only needs to be sufficient for the sintering force and gravity to overcome the shear and rebound forces, ensuring the particle remains stationary. Besides, the impact time is strongly influenced by surface roughness and particle morphology. The rougher the surface, the more likely the particle gets caught and stay long enough so that sintering can make it ultimately sticking at the cornice edge.

To be clear, sentences in lines 26-27 have been deleted. Besides, we agree on the point that the static electric force is only important in specific cases, such as low wind speeds and high charge on particles. Therefore, we have deleted the definition of electricity force and the electric field.

Comment 13:

Although authors tried to introduce all the conceivable forces which may act between particles on edge, time scales are not always consistent. Furthermore, all the discussions are qualitative from beginning to end and no quantitative estimates, which is enough to keep the thin plate growing, are shown. To say the least, quantitative approval of their idea, based on the snow and environmental data obtained in the experiment, is essential to make the manuscript reasonable and worthwhile.

Response: We sincerely thank the reviewer for their thoughtful feedback. We understand the concern regarding the lack of quantitative estimates and the consistency of time scales in our manuscript. Below, we address these points in detail and outline the revisions we have made to strengthen the manuscript. Regarding the time scale consistency, this concern has been answered in Comment12 (the main point is the duration of a particle's contact time on the surface is not particularly significant. It only needs to be sufficient for the sintering force and gravity to overcome the shear and rebound forces, ensuring the particle remains stationary). Regarding the quantitative estimates, we have addressed the reviewer's request to highlight the quantitative results more explicitly in the abstract and conclusion sections and added additional explanations in the relevant sections.

Abstract:

Snow cornices are a common snow pattern in cold regions, and their fracture and collapse can easily trigger avalanches. Despite numerous observations and experimental simulations on their formation process, the microscopic mechanism of their formation remains unclear. In this paper, based on wind-tunnel experiments and high-speed photography, experimental studies on the trajectory of particles surrounding the snow cornice were carried out. The experiment results reveal the distinct differences in particle size, impact velocity, and impact angle between the surface and edge of a cornice. The findings show that the edge of a cornice is primarily composed of small snow particles, with saltation being the dominant movement pattern for particle adhesion. The distributions of impact velocity and angle of particles differ between the edge and the surface. The relative frequency of particle adhesion on the edge exponentially decreases with increasing impact velocity, while surface adhesion follows a Gaussian distribution. These differences are primarily attributed to topographic effects. Analysis of vertical impact velocity distributions reveals that both edge and surface particles follow the same exponential trend, with threshold velocities ranging from 2 to 2.5 m/s, indicating a similar adhesion mechanism. To further explain the observed differences in particle size between the edge and surface, the forces acting on particles adhering to the edge were analyzed. The results show that smaller or dendritic particles are more likely to adhere to the edge due to a higher cohesive-to-gravity force ratio (F_c/F_g). This study quantitatively provides insights into the micro-mechanism of snow cornice formation, offering a theoretical foundation for improving avalanche prediction.

Conclusion:

Our findings reveal that near-surface saltation and creeping are the primary modes for particles to adhere to the cornice. Among the adhered particles, the majority are saltating particles that settle on the surface, while only a few deposit directly at the front end. Additionally, some creeping particles interlock and hang with others at the cornice edge, and a small number of particles may detach from the edge and move *backward due to opposing forces acting against the flow. These varying movement patterns of particles contribute to the increase in both the thickness and length of the cornice, which is essential for its structural growth.*

The experiment results show that although the distributions of the size, impact velocity, and impact angle of particles on surface and edge are different, the vertical impact velocity distribution is consistent, with threshold velocities ranging from 2 to 2.5 m/s for adhesion. Quantitative analysis demonstrates that the relative frequency of edge particle adhesion decreases exponentially with impact velocity, while surface adhesion follows a Gaussian distribution. This indicates that the particle adhesion is dominated by the vertical impact velocity. The variations in particle size, impact velocity, and impact angle distributions arise from the distinct fluid field generated by sudden topographic change.

Moreover, the cornice edge is primarily composed of lightweight snow particles compared to the cornice surface. This phenomenon can be attributed to the mechanics of particle adhesion, where the ratio of cohesive forces to gravity forces plays a critical role. Smaller particles, particularly dendritic ones, are more likely to adhere to the edge due to their favorable physical properties (with higher F_c/F_g *ratios), which enhance their stability in the presence of wind and other forces.*

Overall, this research provides valuable insights into the micro-mechanisms of snow cornice formation, emphasizing the critical roles of particle size, movement patterns, and environmental conditions. The findings have important implications for avalanche prediction and management, as understanding snow cornice dynamics can help mitigate risks associated with their fracture and collapse in cold regions. Furthermore, these insights may extend to related phenomena, such as the formation of snow bridges in ice crevasse, wire icing, and snow accumulation on train bogies, highlighting the broader relevance of particle adhesion mechanisms. Future studies should continue to explore the interactions between environmental factors and particle behavior to refine our understanding of snow cornice dynamics.