

Responses to Editor:

Title: Snow Particle Motion in Process of Cornice Formation

ID: egosphere-2024-2458

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Submitted to: The Cryosphere

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

Dear authors,

Having reviewed your responses to the referees and the amendments made to your manuscript, I am pleased to provisionally accept your paper for publication in TC. However, I suggest a number of minor, mainly technical, corrections, which are detailed in the attached file. These mainly concern typos, grammatical issues and areas that need clarification. More generally, I recommend thoroughly proofreading the manuscript, particularly the newly revised sections, before submitting the final version.

Best regards,

Guillaume Chambon / TC Topical Editor

Response:

Dear Editor,

We would like to thank you for your positive feedback on our revision. We greatly appreciate your time in reviewing the manuscript and for pointing out the errors. We have thoroughly proofread the manuscript, and we hope the modifications address all your concerns. Please find below a point-to-point reply to each of the comments.

Best regards,

Hongxiang Yu, on behalf of all authors

Comment 1:

Line 57: Problem with sentence: 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.

Respond: Thanks for pointing it out. We have revised this sentence as lines 45-47: “Previous field studies (Vogel et al., 2012; Eckerstorfer et al., 2013; van Herwijnen and Fierz, 2014; Hancock et al., 2020) mainly focused on the morphological variation, constrained by the limitations of observation equipment, making it difficult to observe how particles adhere to the mountain edges.”

Comment 2:

Line 94: Redundant: A ridge model with a fixed size (Fig. 2) is built with compacted snow before each experiment. 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. 2.

Respond: We have deleted the first sentence, and it has been revised as lines 82-83: “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. 2.”

Comment 3:

Line 114: What are these different cases? Do they correspond to different experiments, or were they all recorded during the same experiment?

Respond: Yes, they are different cases under the same experimental conditions. This sentence has been revised as lines 98-100: “*A total of 18 repeated individual experiments were conducted under the same experimental conditions. Each experiment lasted 4-5 seconds and produced 12455 images of particle trajectories.*”

Comment 4:

Line 115: Please indicate during which phase of cornice growth the images are taken. The introduction, as well as your responses to Reviewer#1, suggest that you only focus here on the initial stage of cornice formation. If so, this should probably be mentioned.

Respond: This sentence has been revised as lines 101-103: “*Here we concentrate on the initial stage (t_1 - t_3) of snow cornice growth, as described in Fig. 3(a) by Yu et al. (2022). Where particles accumulate at the edge to form a thin slab on the leeward side of the ridge model.*”

Comment 5:

Line 145: Notations (P_i , A_i) are not defined

Respond: Actually, notations (P_i , A_i) are P and A_p . This formula has been revised in line 132: “ $SSA = \frac{4P}{\pi A_p}$ ” and the notation has been added into the table NOTATION.

Comment 6:

Line 148: Which frames? Please clarify what is meant here.

Respond: The frames refer to the frames in which each particle is detected along its trajectory in the time-series. This sentence has been revised in lines 133-135: “*For each dendritic particle, the projected area A_p and perimeter P were averaged over the frames in which the particle was detected along its trajectory in the time-series, which effectively minimizes the influence of particle orientation on the calculated size.*”

Comment 7:

Line 175: Why giving the error on particle diameter here? It would make more sense to give it in 2.1. Furthermore, can you clarify what is meant by "visual observation", and how exactly these errors are estimated?

Respond: We have moved the error on particle diameter to section 2.1. Visual observation refers to the process of determining the position and size of a particle in each frame through direct human inspection, from which its velocity and radius are subsequently derived. The error is calculated as: $\frac{\phi_{pro} - \phi_{vis}}{\phi_{vis}}$, where ϕ_{pro} is the value (diameter/velocity/angle) from program recognition, ϕ_{vis} is the visual observation value.

We have incorporated the above explanation in section 2.1, lines 137-140: “*To assess the uncertainty of the shadowgraphy technique, particle diameter information was obtained through both visual identification, where the number of pixels occupied by the particle was counted by eye, and algorithmic recognition. By comparing the two methods, we found that the maximum relative error in particle diameter identification using the shadowgraphy technique is approximately 16%.*”

Meantime, in section 2.2, the sentence has been revised as lines 164-166: “*Similarly, we analyzed the differences between manual identification and particle tracking algorithm recognition and found that the maximum relative errors in particle velocity and angle identified by the algorithm are 5% and 18%, respectively.*”

Comment 8:

Line 234: What is meant by "retaining" here?

Respond: We have revised it to “*settling*”, in line 217.

Comment 9:

Line 236: Unclear statement.

Respond: The paragraph describing creeping particles has been revised as lines 218-223: *“Particles in creeping mode, predominantly larger particles, exhibit two distinct patterns of adherence to the snow cornice surface. One pattern involves particles slowly rolling forward and stopping at a certain point, referred to as ‘creeping’ (Fig. 8(a)), while the other involves particles rolling to the edge, where they are captured through interlocking with the dendritic structure, termed ‘hanging’ (Fig. 8(b)). These two patterns together account for approximately 14% of the total adhered particles and typically move slowly.”*

Comment 10:

Fig 8: The link between these "patterns" and the two "modes" (creep and saltation) described in the text, should be better discussed. In particular, the "hanging" pattern does not seem to be mentioned in the text.

Respond: We have rewritten section 3.2, lines 216-227:

“Near-surface moving particles were captured using a high-speed camera. Creeping (particles rolling or sliding over the surface before settling) and saltating (particles successively jumping over the surface before settling) (Bagnold, 2012) are the two primary modes contributing to cornice growth. Particles in creeping mode, predominantly larger particles, exhibit two distinct patterns of adherence to the snow cornice surface. One pattern involves particles slowly rolling forward and stopping at a certain point, referred to as ‘creeping’ (Fig. 8(a)), while the other involves particles rolling to the edge, where they are captured through interlocking with the dendritic structure, termed ‘hanging’ (Fig. 8(b)). These two patterns together account for approximately 14% of the total adhered particles and typically move slowly. In contrast, most of the adhered particles are transported primarily via saltation. Among these, approximately 82% of the total adhered particles deposit before reaching the front end of the snow cornice, which we refer to as ‘impact’ (Fig. 8(c)). About 4% of the total adhered particles are saltating particles that detach from the edge, move back, and are recaptured by the snow cornice edge, influenced by reflux vortex or the potential electric field, a process we term ‘back moving’ (Fig. 8d).”

Comment 11

Line 258: Problem with sentence: Here, we define the v_{im} is the impact velocity of the particle

Respond: We have revised this sentence in line 229: *“Here, v_{im} is defined as the impact velocity of the particle.”*

Comment 12

Line 271: “The relative frequencies of v_{im} and θ_{im} represent the probabilities of particle adhesion on the cornice with a certain impact velocity or impact angle.” Is this really a probability of adhesion, since only adhered particles are considered in the statistics?

Respond: To avoid misunderstanding, we have revised this sentence in lines 239-240: “*The relative frequencies of v_{im} and θ_{im} represent the probabilities of adhesion particles with a certain impact velocity or impact angle range.*”

Comment 13:

Line 274: edge particle velocities

Respond: We have revised this sentence to: “*Specifically, the relative frequency of impact velocities of edge particles follows the exponential function...*”, in lines 241 to 242. To be consistent in the whole manuscript, we have revised other places with the same expression.

Comment 14:

Line 282: Is this process (erosion or fracture induced by impacts) effectively observed in the experiments? If so, why not describing it earlier?

Respond: Yes, erosion or fracture induced by impacts is observed in the experiments. Erosion and fracture are one of the processes during cornice growth. However, this work only focuses on the particle adhesion mechanism during cornice growth, instead of providing a detailed introduction to the erosion and fracture processes. We mention it here to distinguish the adhesion mechanism between surface and edge particles.

Comment 15:

Line 300: Not very clear

Respond: This sentence has been revised, in lines 269-271: “*The differences in impact velocity and angle distribution between surface and edge particles are due to the variations in the fluid field caused by unique topography at the edge, where a sudden change in velocity and pressure (Yu et al., 2025).*”

Comment 16:

Line 304: "can be affected", or "is mainly affected"?

Respond: We have revised to “*is mainly affected*”, in 274.

Comment 17:

Line 310: topo

Respond: We have revised to “particle”, in line 278.

Comment 18:

Line 323: not defined:

Respond: We have added the definition in line 300: “where μ_f is the friction coefficient of the ice surface.”

Comment 19:

Line 337: What does this mean? I would think that the cohesive force is applied at the contact point between the two particles (here, the center of the bond).

Respond: Yes, the cohesive force is applied at the contact point. To avoid misunderstanding, we have deleted this sentence and reorganized the whole section 3.4.

Comment 20:

Line 340: Please better explain this expression.

Respond: This sentence has been revised as lines 295-297: “The friction force F_f acts at P through moment arm $R\cos(\arcsin(x/R))$, which is the perpendicular distance from the line of action of F_f to the point P , projected along the particle-center line.”

Comment 21:

Line 344: What is relation between this equation and Eq. (8)? Furthermore, what is the point of Eq. (8), since it does not seem to be used in the following analysis?

Respond: To make it more concise, we have deleted Eq. (8) and the relevant description, and have revised the whole section 3.4 as:

“To investigate the effect of dendricity on the particle adherence at the edge, forces acting on a particle adhering to the edge are analyzed in this section.

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. 10, 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 bond 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 (Shehadi, 2018; DeBonis, 2022; Yu et al., 2025), allowing the drag and lift forces acting on particle i to be neglected compared to other forces (Schmidt, 1980).

The force and moment balance equations for particle i can be expressed as:

$$F_g \cos \alpha + F_c - F_s = 0 \quad (5)$$

$$F_g \sin \alpha - F_f = 0 \quad (6)$$

$$(F_s - F_c)x + F_g R \sin \beta - F_f R \cos(\arcsin \delta) = 0 \quad (7)$$

where α is the angle between the line connecting the centers of the two particles and the direction of gravity, x is the radius of the bond (blue shadowed area). The radius of

the bond can be assumed to vary linearly with particle radius $x=\delta R$, with ratio $\delta=0.1-0.25$ (Golubev and Frolov, 2001). The gravity force F_g acts at point P through the moment arm $R\sin\beta$, with the angle between F_g and line OP given by $\beta = \alpha - \arcsin\delta$. The friction force F_f acts at P through moment arm $R\cos(\arcsin\delta)$, which is the perpendicular distance from the line of action of F_f to the point P , projected along the particle-center line. F_s is the support force exerted by particle j on particle i . The frictional force F_f is given by:

$$F_f = \mu_f F_s \quad (8)$$

where μ_f is friction coefficient.

Substituting Eq. (5), Eq. (6) and Eq. (8) into Eq. (7) yields:

$$\frac{F_c}{F_g} = \frac{\delta \cos\alpha + \sin(\alpha - \arcsin\delta) - \mu_f \cos\alpha \cos(\arcsin\delta)}{\mu_f \cos(\arcsin\delta)} \quad (9)$$

The bond cohesive force F_c for a spherical particle is given by (Szabo and Schneebeli, 2007):

$$F_c = \pi x^2 \tau_b \quad (10)$$

where 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. Previous study shows that the presence of sharp edges of particles can lead to an increase in cohesion via interlocking (Vivacqua et al., 2019). Thus, here we introduce a weighting parameter A into Eq. (10) for dendritic particles:

$$F_c = \pi x^2 \tau_b (1 + A(dd - 1)) \quad (11)$$

where dd is the dendricity of non-spherical particles. For spherical particles, $dd=1$, Eq. (11) is equivalent to Eq. (10). The weighting parameter A for snow should be determined by the experiment. For those particles that adhere on the edge in our experiment, the average value of dendricity $dd = 1.9$, as is shown in Fig. 7.”

Comment 22:

Line 346: This definition is already provided in line 324. Is "sigma" the same quantity as "tau_b"? Please better define this quantity.

Respond: We have deleted the repeated definition. Yes, they are the same quantity. We have unified the quantity with the τ_b in the manuscript.

Comment 23:

Line 351: Can you provide a better justification for this expression? Is it supported by previous studies?

Respond: We have added the reference for this expression, in lines 308-309: “Previous study shows that the sharp edges of particles can lead to an increase in cohesion via interlocking (Vivacqua et al., 2019). Thus, here we introduce a weighting parameter A into Eq. (10) for dendritic particles.”

Comment 24:

Line 363: A division seems to be missing here.

Respond: We have revised Eq. (14) to:

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

Comment 25:

Line 386: unclear

Respond: have revised this sentence in line 342: “*For each δ , the threshold radius R_{th} increases linearly with dendricity, as is shown in the Fig. 12.*”