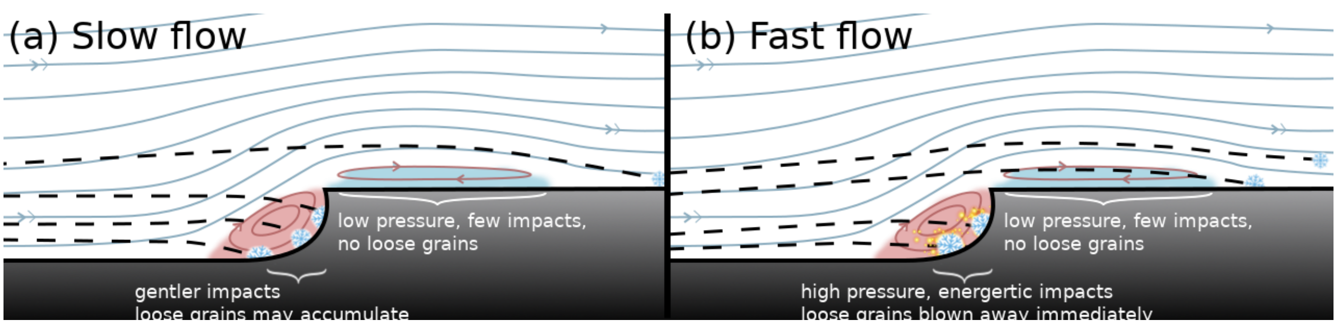
Author’s response to Reviewer #1

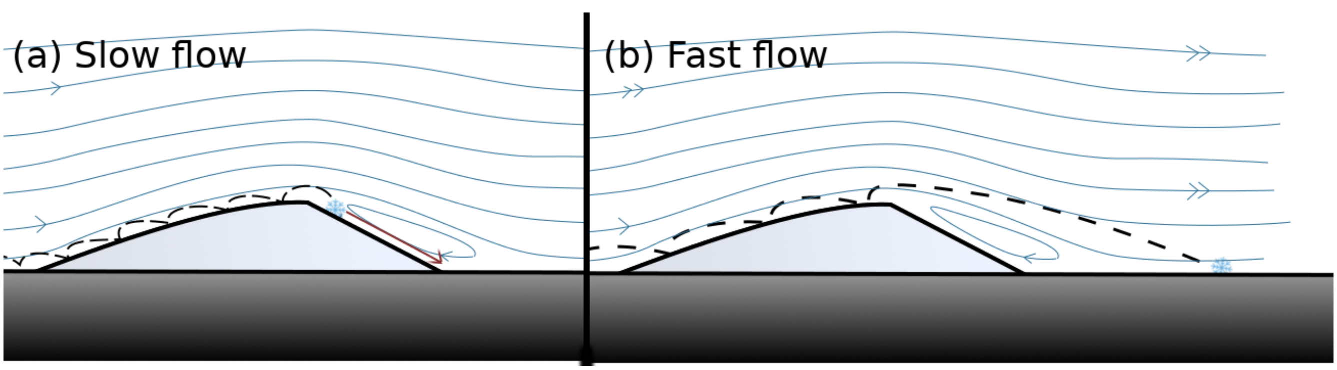
Review:
This manuscript provides excellent physical insights into snow bedform dynamics, built on qualitative and quantitative observations of the snow surface evolution in the Colorado Front Range. The authors attempted a comprehensive exploration of the main factors influencing formation and evolution of a number of snow bedforms. I particularly appreciated the effort that the authors made to provide physical interpretations of their observations, discussing the complex interplay among snowfall, drifting snow, and sintering. The discussion session is enlightening with respect to the dynamics of snow step erosion and the similarities/differences between sand and snow dunes. Moreover, the manuscript seems to identify a new type of snow features, the stealth dune.

I think this is a valuable contribution to our understanding of snow bedform evolution that advances well beyond previous work. I recommend publication after the authors consider the comments below.

Author’s comments
Thank you for the supportive review, and for the constructive comments included below.

We included a short response to your most technical comments concerning Figs. 14 and 15 in the interactive discussion. To recap, you pointed out that the wind speeds at our field site were too to create significant compression in the air. We confirmed that you were correct, and we adapted Figs. 14 and 15 to show that the lengths of the recirculation zones are constant with wind speed, as shown below:





Line-by-line comments
Page 1, line 2: Maybe replace warmth with heat- *Done.*

Page 1, line 8: the authors use the expression "retreating downwind" here and in other places. The verb retreat seems to me more suitable to describe an upwind movement. I would suggest to replace with advect to avoid confusion.-

This is a good point. We hoped that 'retreat' would imply mass loss and movement away from the force of the wind, but we can see that it may also confuse some readers who see 'retreat' as a movement opposite to the wind.
'Advect is a good suggestion', but it usually refers to an object that travels without changes to its mass or shape. Since we are describing a process of erosion, this might be misleading.

We have replaced 'retreat' with **'migrate [downwind]'**, which we hope will encourage readers to think of motion in the shape of the step, not in the mass that forms it.

Section 1.1: the authors differentiate between isolated dunes and close-packed dunes. However, the minimal distance at which dunes do not affect each others is not specified. I imagine that this distance is larger for dunes aligned with the wind direction, as the upwind dune can shed a wake several times its height. Conversely,side by side dunes can behave independently at reasonably short distance. Can the authors provide any estimations?-

We believe that the important distinction here is not the distance between dunes but the fraction of the surface which is covered by fresh snow. We have amended the text in Section 1.1 to make this clear:

> Barchan dunes are crescent-shaped, or two-horned, dunes. They have well-defined crests, with a gentle upwind slope and a steep downwind slope that curves into two forward-pointing arms \citep{Filhol2015, Petrich2012, Doumani1967, Kobayashi1980, Goodwin1986}.
> **In this paper, `barchan dune' (or `isolated dune') refers specifically to crescent dunes that do not cover the surface completely, but expose inter-dune areas of old snow, bare ground, or ice.**
>
> Close-packed dunes have defined crests. Unlike isolated barchans, they cover the surface completely.
> **We distinguish close-packed dunes from isolated barchans because they have different thermal properties and we expect them to follow different evolutionary trajectories.** First, fresh snow is more reflective and less thermally conductive than old snow, ice, or bare ground. Even small gaps in the snow cover create a positive feedback cycle that leads to rapid snowmelt in warm or sunny weather \citep{Petrich2012}. Second, fresh snow is usually less dense, and more erodible than old snow, ice, or dirt. Thus, exposed inter-dune areas make the snow surface inhomogeneous, which makes the dynamics of bedform evolution considerably more complex. We discuss this in \textsection 4 and \textsection 4.6.

Section 2.1: It would be useful to know the orientation of the ridge with respect to themain wind wind direction. This would tells us something more about the overall mass balance of the study site, such as the occurrence of snowfall preferential deposition and the relative importance of erosion and deposition.-

Good catch. Amended text:

> In winter the wind on Niwot Ridge blows almost without exception from the west-northwest, driven by temperature gradients over the Continental Divide. **The ridge also runs east-southeast to west-northwest, parallel to the prevailing wind. The saddle site is downwind of a gentle bump in the ridge, and collects deep snow during the winter although other parts of the ridge are occasionally scoured free of snow.**

Section 2.2: Additional information on the camera setup would be useful. Was the camera looking perpendicular to the main wind direction? What was the elevation from the surface? What are the errors on the estimations caused by the distortion by distance?-

Added:

> **The cameras were angled downwind or perpendicular to the prevailing wind to prevent snow from covering the lens; we indicate the wind direction for each image.**
> **The cameras were mounted on 2 m tripods. The distance between the cameras and the surface decreased as snow accumulated; we reset them on the surface once a month.**
> **The uncertainty in the camera elevation makes it difficult for us to estimate distance directly from the images.** We **therefore** measured bedform sizes and velocities both in-person, using meter sticks, and by reference to poles with 10-cm stripes placed in front of the cameras. **Where direct measurements are missing,** for example because the poles blew away, we convey sizes, speeds and intensities in non-dimensional units.

Page 6, line 6: "The falling snow that we observed often settled into plane beds". I imagine this was only the case for low wind speed conditions.-

Amended:

> The falling snow that we observed often **fell in still air** and settled into plane beds.

Page 6, line 16: I think that self-similarity is not exactly what the authors show. Self-similarity would imply that the surface features look similar across different length scales, but the range of distances here seems to be quite narrow. You could simply say that dune height and width scale linearly.-

Changed to:

> The dune heights and widths **scale linearly.**

Page 6, line 18: remove second 'of'.-
Done.

Page 6, line 26: It is not clear to me how you could track simultaneously blowing snow and dune evolution. Was the surface always visible from the camera during blowing snow? Or did you take manual measurements?-

The dune in this case was only about 2 m from the camera. Therefore, the dunes were clearly visible through the snow in perhaps 98% of the frames of the video. We included the footage in the supplementary video (Video S1, starting at 1:07); if you watch the footage both blowing snow and dune movement are quite clearly visible.

Added:

> **The dune was clearly visible through the snow in all but a handful of frames (see video S1 at 1:07).**

Page 6, line 33: "Instead of the other way around". What do you mean exactly? It is hard to imagine how blowing snow fluxes could be affected by dune velocities.-

You are correct. We removed confusing phrase:

> ~~"instead of the other way around"~~

Figure 2, caption: Please mention that panel (b) only shows to close-packed dunes and (d) only isolated barchan dunes.-

Added:

b) Time-lapse of **close-packed** dunes […]
d) Time-lapse of i**solated** barchan dunes […]

Figure 3: Can you assign units to the axes? Approximate distances are better than no units.-

For clarity, we have relabeled the axis with a unit ‘L’ that is approximately equal to 1 m. We have changed other figures that lack exact distances, such as Figure 9, to match. We hope that this will make things easier for readers while still accurately expressing our uncertainty in our estimates of the distances in these figures.

As the reviewer’s comment on Section 2.2 drew our attention to need to carefully address the uncertainties in our distance measurements, we hope that you will agree that we have chosen a reasonable presentation given the (unfortunately incomplete) distance data we have.

Page 8, line 13: the term "frequency" seems to indicate a cyclic process rather than a displacement. I think ’velocity’ would be more appropriate. Can you assign approximate distance units based on camera pixels and/or distance from the camera?-

We converted the units from frequency to time for clarity, and added an approximate velocity based on approximate distance units.

The crests advanced ~~with a frequency of 1.81 $\pm$ 0.16 min^{-1}~~ **by one wavelength every 33 ± 3 s. Although scale bars were missing from this image, if the ripples had typical 10–25 cm wavelengths, they would move at 11–27 m/hr.**

These high velocities are consistent with our other observations of ripples.

Page 8, line 18: What is your interpretation of the observation that sand-free ripples faded away? Is it related to larger sublimation?-

I suspect that the wind was blowing too fast for snow to be stable in bedload, and that the snow that was not armored by heavier sand grains blew away in suspension. Perhaps the sand-free ripples had lost their sand grains only recently and were in the process of blowing away.

Figure 4c: Can you plot the correlation coefficient rather than the cross-correlation? It would help to evaluate how important is the correlation peak.-

We use this plot to find the lag between the pulse of snow and the increase in dune velocity. Cross-correlations are a standard method for finding the lag between two signals, and so they are appropriate and relevant here.

Figure 9: I think you are expressing distances in too many different ways. Sometimes approximate distance units (figure 3), sometimes no units, sometimes fraction of image(here). The quality of the paper would improve if you could be consistent in the method used to quantify distances.

We changed the figure in question to be consistent with Figure 3. The paper now uses two self-consistent distance units: metres when distances are known with high confidence, and ‘L’ when real distances are not known, where ‘L’ is an arbitrary unit that equals one metre plus or minus some uncertainty listed in the figure caption.

This increases the consistency of the distance expressions, while endeavoring to make the systematic uncertainties in our distance measurements clear to readers.

Page 17, line 13: "snow dunes must somehow give way to snow waves and vicev-ersa". From Figure 11 there seem to be no transitions from snow waves to snow dunes.

Good catch. Amended to:

> “there [must be] path for **isolated barchans** to transition into snow waves and vice versa.”

Figure 11: In the text, you seem to describe region 2 and 3, but I didn’t notice anyreference to region 1 and 4. Why do you differentiate these two regions?-

These regions were drawn to be consistent with the loose-snow bedform, hardened-snow bedform, and mixed-surface bedforms categories that we use in the discussion. We have now made the motivation for the region-grouping clear in the text:

> “We have grouped together transitions that share similar characteristics. Transitions that involve a surface made of entirely loose snow are in Region I (yellow). Transitions from one type of hardened, erosional surface to another are in Region II (orange). Transitions between surfaces that expose a mix of loose snow and hardened snow, such as waves, are in Region (pink), and transitions in which hardened surfaces turn into mixed surfaces, or vice-versa, are in Region III (red). These groups of bedforms are discussed further in \textsection 4.”

We have also re-organized our discussion of Figure 11 so that all four regions are mentioned in order:

> “The transitions in **region I** and **region II** appear to be irreversible [...]
> […] the transitions in **region III** appear to drive cyclic evolution trajectories. […]
> […] we did not directly observe any transitions in **region IV** [...] “

Page 18, line 3: "The cyclic behavior is shown by the transition in region 3". Fromwhat you say earlier, all points laying below the 1:1 line are unidirectional. Then I think you are referring just to the part of region 3 above the 1:1 line in Figure 11?-

In mathematical terms, cyclicity is a property of an entire graph or matrix, not a particular transition within a graph.

For example, the transition from snow-waves to isolated barchans is currently above the 1:1 line. But, if I had decided to list the the snow-waves before isolated barchans on the graph, the snow-wave to barchan transition would fall below the 1:1 line, and instead the transition from isolated barchans to snow-waves, which is currently below the 1:1 line, would be above it.

I have amended the text to make this clearer, and to encourage readers to look for evidence of cyclicity in Fig 12 (where it is shown graphically) instead of Fig. 11 (where the same information is shown in matrix form, which is less intuitive):

> The cyclic transitions are shown graphically in Fig. 12. This graph contains the same information that is represented in tabular or matrix form in regions II, III, and IV. If bedform evolution were unidirectional, we would be able to arrange Fig. 11 such that all transitions lay on **the same side** of the 1:1 line, **or arrange Fig. 12 without any loops or repetition.**

Page 19, line 5: Why do you list isolated barchan dunes in mixed-surface bedforms only? Did you not observe isolated dunes in loose-snow conditions? And vice-versa, did you not observe close-packed dunes in mixed-surface conditions?-

This should now be clarified in the text by the updated definitions of isolated and close-packed dunes (see response to comment on section 1.1). We've updated the definition of isolated dunes to be dunes with exposed surfaces beneath them (old snow, bare ground, etc), so these dunes are mixed-surface features by definition.

Page 20, line 5: 'but much higher than the standard values for planar snow (0.5 mm)".0.2 mm is not much higher than 0.5 mm, or am I missing something?-

Good catch. That was meant to be 0.05 mm. Fixed.

Page 20, line 9-10: Readers may not be familiar with the interplay between shear velocity and settling velocity in setting the transport dynamics of particles. Please provide some references.-
Page 20, line 1-15: Overall, I find this paragraph not very well connected to the previous discussion. I suggest you clarify why this information is relevant for bedformdynamics.-

In response to this and a similar comment from Reviewer 2, we have restructured this paragraph so that it focuses clearly on the bedform-shaping processes in Fig. 13. We have also removed some of the less-well connected information, including the descriptions of Rouse numbers and shear velocities. This shortened the discussion by 300 words.

The section now reads:

> Fig.~13 illustrates the major snow processes that shape bedforms: snowfall, aeolian transport, erosion, and sintering. Here, we analyse the relative importance of these fluxes as a function of snow grain size and wind speed.
>
> Fig.~13a shows a wind too weak to move any snow grains. This occurs when the force that the wind exerts on the surface is insufficient to overcome gravity and friction and lift any grains.
>
> Fig.~13b shows loose-snow bedforms created by horizontal snow transport. We expect these bedforms to be created when the wind friction velocity is high enough to mobilize snow, but but not so high that all the snow is lifted away from the surface and into suspension. \citet{Li1997} found that dry snow is mobilized by winds higher than 7--14 m/s, measured at 10 m elevation. \citet{Clifton2006} found slightly higher thresholds that increased with particle density and size.
>
> Fig.~13 shows a hardened snow surface being eroded. The erosion rate of a solid surface is proportional to the energy of the impacting particles, minus a threshold energy that depends on the material hardness \citep{Anderson1986a}. Thus, erosion requires a supply of loose, high-speed snow particles.
> The threshold erosional energy of snow is not well documented in the literature, as most snow gets harder over time. This process, known as sintering, is accelerated slightly by humidity, warmth \citep{Colbeck1998}, small grain sizes, and wind action \citep{Colbeck1991}, and accelerated by orders of magnitude by the presence of liquid water \citep{Blackford2007}.
>
> Finally, Fig.~13d shows a surface in which sintering, transport, and erosion happen at comparable rates. The resulting bedforms are discussed in section 4.6.

Page 20, line 22: rather than "time-dependent" I would say that it depends on snowproperties such as grain size, grain shape, and sintering, which vary in time.-

Clarified:

> Most snow gets harder over time. This process, known as sintering, is accelerated slightly by humidity, warmth \citep{Colbeck1998}, small grain sizes, and wind action \citep{Colbeck1991}, and accelerated by orders of magnitude by the presence of liquid water \citep{Blackford2007}.

Page 20, line 27: Can you clarify why suspension is relevant to dune evolution? If suspended particles do not interact with the surface, how can they influence the dunes?

Particles can move from saltation to suspension either because the wind rises, or the particles become smaller due to sublimation or fragmentation.

Thus, under conditions of rapid sublimation or wind acceleration, the dunes will continuously lose mass as particles move into sublimation and cease interacting with the surface. This is a transient scenario that has not been discussed in detail in the sand literature, but is likely to have a significant impact on snow dune shape.

As part of the reorganization of section 4.1, we now explain this in the paragraph starting:

> Fig. ? shows loose-snow bedforms being created by horizontal wind-driven snow transport. We expect these bedforms to be created when the wind shear velocity is high enough to mobilize snow [...]

Page 21, line 3: How did you calculate the effective density?-
The effective values for snow grain density vary widely. Snowpacks usually have a density of 100-300 kg/m^3.

Page 21, line 30: Correct "grans" with "grains".- Fixed.

Page 22, line 1: In high Reynolds number flows, the length of the recirculation zone should not be sensitive to the wind speed. Can you provide any reference to previous studies that showed this?

You are correct, thank you for catching this error in our conceptual model. We worked with a colleague to check this using a fluid dynamics solver, Comsol, and we did not find any evidence that the length of the recirculation zone changed significantly at the pressures and wind speeds we expect to see at our field site.

We have updated Figure 14 as shown at the top of this review, and now note that the change in dune behavior between wind speeds will depend entirely on the saltation hop length of the grains, not the recirculation zone.

Page 23, line 7: Similarly to my previous comment, I'm not sure that the length of the stagnation zone changes with the wind speed - assuming the flow is Reynolds number independent, as I assume may be the case here. Please provide some additionalexplanation or references.-

You are again correct. We have updated Figure 15 as shown at the top of this review, and now explain the effect of wind speed on step erosion solely in terms of particle energy and armoring by loose grains.

Page 23, line 12: What is this threshold energy? Previous studies suggested that this threshold energy is that necessary to break cohesive bonds (e.g., Comola and Leaning2017, Gauer 2001). So this threshold depends on the conditions of the snow surface.

Added and re-organized the following discussion:

> **The threshold erosional energy of snow is not well documented in the literature. Most snow gets harder over time. This process, known as sintering, is accelerated slightly by humidity, warmth \citep{Colbeck1998}, small grain sizes, and wind action \citep{Colbeck1991}, and accelerated by orders of magnitude by the presence of liquid water \citep{Blackford2007}.**

We do not think that estimating a numerical value for this threshold energy in snow is within the scope of this paper, as we are certain that this value would vary in both space and time at our field site.

Author's response to Reviewer #2

Review:
This study uses an interesting set of pictures of the snow surface collected in a mountainous location to propose a comprehensive and original synthesis on snow bedform dynamics that undoubtedly contribute to improve our understanding on this quite undocumented subject. The manuscript is really well written, the semantics is appropriate and I really enjoyed reading it. The various and pertinent descriptions made from analysis of the footage and field measurement as well as the efforts put to physically relate and interpret them in terms of driving processes is really appreciable. Ways forward are provided and remaining gaps are identified. I recommend the paper as suitable for publication providing the authors can address the following minor comments.-

Author's comments:
Thank you for your supportive review. We're glad to hear that paper was an enjoyable read.

We appreciate the attention to detail you have given to our writing and references, and we have corrected all of the minor errors (typos, mis-spelled references, and unclear phrasing) that you identified.

In response to your most technical comments (on discussion paper P20 L1-15, the discussion of Rouse numbers and friction velocities), we have removed our estimates of numbers we could not measure in the field, as well as the introduction to friction velocities and Rouse numbers. This shortened the discussion by 300 words.

The section now reads:

> Fig.~13 illustrates the major snow processes that shape bedforms: snowfall, aeolian transport, erosion, and sintering. Here, we analyse the relative importance of these fluxes as a function of snow grain size and wind speed.
>
> Fig.~13a shows a wind too weak to move any snow grains. This occurs when the force that the wind exerts on the surface is insufficient to overcome gravity and friction and lift any grains.
>
> Fig.~13b shows loose-snow bedforms created by horizontal snow transport. We expect these bedforms to be created when the wind friction velocity is high enough to mobilize snow, but but not so high that all the snow is lifted away from the surface and into suspension. \citet{Li1997} found that dry snow is mobilized by winds higher than 7--14 m/s, measured at 10 m elevation. \citet{Clifton2006} found slightly higher thresholds that increased with particle density and size.
>
> Fig.~13 shows a hardened snow surface being eroded. The erosion rate of a solid surface is proportional to the energy of the impacting particles, minus a threshold energy that depends on the material hardness \citep{Anderson1986a}. Thus, erosion requires a supply of loose, high-speed snow particles.
> The threshold erosional energy of snow is not well documented in the literature, as most snow gets harder over time. This process, known as sintering, is accelerated slightly by humidity, warmth \citep{Colbeck1998}, small grain sizes, and wind action \citep{Colbeck1991}, and accelerated by orders of magnitude by the presence of liquid water \citep{Blackford2007}.
>
> Finally, Fig.~13d shows a surface in which sintering, transport, and erosion happen at comparable rates. The resulting bedforms are discussed in section 4.6.

Line-by-line responses:

P6, L8: "unsintered, unbroken snowflakes": Strictly speaking this sounds like idealized conditions since sintering starts naturally with vapour transfer as soon as snow is deposited and overburden pressure causes breaking of original crystal forms. Prefer simply loose snow or fresh snow layers.-

Reworded:

"They are the only surface type made from fresh snowflakes that have not saltated or broken during saltation"

P6, L32-33: "Instead of the other way round": Do you mean that your conclusion,which is self-sufficient and quite relevant to me, is less intuitive than the reversal involving an influence of dune velocities on blowing snow fluxes? Because it is actually the opposite.-

Your intuition is intriguing. We have added the following observation:

This positive correlation and positive lag is evidence of causation: high **incoming** fluxes of blowing snow drive high dune velocities ~~instead of the other way around~~. **Moreover, the dune movement must have contributed to the flux of blowing snow, because the dunes lost height during the observation. These blowing snow events appear to have create a positive feedback that turned snow dunes into wind-blown snow.**

P18, L13: "In the aeolian world": such a seductive phrase. I know rules are sometimes meant to be broken, but yet this is not suited for a scientific paper I'm afraid. Stop the sentence after "analogous" or replace with "among aeolian features"? I'm just suggesting.-

Thank you. Some unsuitable phrases are too pretty to remove before review.

Changed to:

"Other snow bedforms, such as snow-waves, are **not obviously analogous to other aeolian features**"

P20, L07 and elsewhere: Prefer "friction velocity" to "shear velocity".-

Sure. Changed all instances of "shear velocity" to "friction velocity". Added a note at first use of the phrases that "u_* is the friction velocity (sometimes called the 'shear velocity')".

P20, L4-6: Comparatively to the wide range of z0 values that have been reported for aerodynamically rough surfaces, 0.2 mm is not "much lower" than 1 mm.

Removed "much lower" comparison; now using only quoted values without evaluation.

See for instance Jackson and Carroll (1978) who reported centimetric z0 values for winds blowing perpendicularly to the sidewalls of high sastrugi (there seems to be a confusion in the actual value of z0 for planar snow since 0.5 mm is higher than 0.2 mm).

This is a typo; we have now corrected "0.5" to "**0.05**".

Note that changes in z0 of several orders of magnitude can also occurs depending on small shifts in wind direction without changes in wind speed, which may involve a few comments on the wind directional range at your study site. But, in line with my next comment, I don't see the added-value of this section.-

Following this comment, we have reworked this entire section to fit better within the text.

P20, L1-15: A bit of confusion here. Friction velocity intervenes for the lifting of particles of the surface and must overcome the cohesive and gravitational forces to trigger saltation. Once airborne, suspension of particles is ensured by a (wind) drag force high enough to compensate for the gravitational pull.

Moreover, there is no need to my opinion for such approximative calculations to finally state that smaller and lighter particles are preferably carried out by suspension than larger ones. Just evoking that the suspension transport mode is governed by a local dynamical balance between the downward gravitational force and the upward drag force due to turbulence logically permits such a statement without any quantitative illustration.

From this perspective the estimation of the friction velocity in the above paragraph is not needed anymore. In addition I don't see clearly the link of this paragraph with the rest of the text. Maybe consider removing it.-
P21,L3: Could you give references to support the values attributed to the effective density and diameter of saltating snow grains?-
We rewrote the section that sparked all of these comments. The new section was quoted at the top of this review.

P21,L27: How do you know? Any reference?-
Added references:

> "we know that dunes do not grow larger [than tens of centimeters] even in very cold locations, such as Antarctica (**Doumani, 1967)** and Alaska (**Filhol, 2015)**"

P21, L27-31: That final part of the discussion is not really convincing and does not shed light on anything. As you can't provide any measurements of grain size there is no need to speculate, even qualitatively, on suspension rates. You could remove it without altering the quality of the discussion, which is already quite long.-

Good point. Thank you for pointing out an opportunity for concision. We removed:

> ~~As for suspension rates, it seems likely that the fraction of loose snow in suspension increases over time as snow particles fragment and shrink.~~
> ~~The Rouse number calculations formed at the start of \textsection~\ref{sec:discussion} indicate that grains >0.1 mm are consistently transported in bedload; in our experience, grains of this size and larger are very common in dunes and bedload, but without quantitative measurements of grain size we cannot constrain the rate of change of typical grain sizes through time.~~

P25, L5: This generalization sounds a bit hasty. This is not necessarily true in windswept regions subject to quasi-unidirectional flows and relatively high snowfall rates and where erosional bedforms prevail, such as crest and/or windward slopes in mountainous regions, the accumulation zone of the Greenland ice sheet or a large portion of the Antarctic coast. That is, in many regions. Be more specific on the conditions required for your assertion to hold true.
Typo and misspelling: -
Good catch. We are used to thinking in terms of the net-depositional environment of our field site. We have reworded the paragraph to explain the range of possible effects:

> "When a region of snow erodes, it releases snow particles into the wind.
> Thus, the erosion of upwind bedforms may provide a snow flux that drives the evolution of downwind bedforms. **The effect of this snow flux will depend on the wind speed and the nature of the downwind bedforms. If the wind speed decreases, we expect blowing snow to be deposited in dunes, waves, or smooth drifts. In windswept conditions, we have seen blowing snow grains erode snow-steps, and remove mass from snow dunes."**

We corrected all the following typos:
P2, L20: You have reversed last and first names: "Bellot" is Hervé's last name. -
P2,L20: Spell Naaim-Bouvet instead of Naiim. -
P6, L32: "blowing snow" instead of "blowing slow" -
P10, L12: I guess "collected" must be used instead of"collect" -
P10, L12: "continuously" instead of "continuosly" -
P21, L30: "grains" insteadof "grans" -
P22, L3: "a too large number" instead of "too large a number" - Used simpler "too many"
P24, L4:C3"are they" must be removed

The evolution of snow bedforms in the Colorado Front Range and the processes that shape them

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Abstract. When wind blows over dry snow, the snow surface self-organizes into bedforms such as dunes, ripples, snow-waves, and sastrugi. These bedforms govern the interaction between wind, ~~warmth~~ heat , and the snowpack, but thus far they have far attracted few scientific studies. We present the first time-lapse documentation of snow bedform movement and evolution, as part of a series of detailed observations of snow bedform movement in the Colorado Front Range. We show examples of the movement of snow ripples, snow-waves, barchan dunes, snow-steps, and sastrugi. We also introduce a previously undocumented bedform: the stealth dune. These observations show that (1) snow dunes accelerate minute-by-minute in response to gusts; (2) sastrugi and snow-steps present steep edges to the wind, and ~~retreat~~ migrate downwind as those edges erode; (3) snow-waves and dunes deposit layers of cohesive snow in their wakes; and (4) bedforms evolve along complex, cyclic trajectories. These observations provide the basis for new conceptual models of bedform evolution, based on the relative fluxes of snowfall, aeolian transport, erosion, and snow sintering across and into the surface. We find that many snow bedforms are generated by complex interactions between these processes. The prototypical example is the snow-wave, in which deposition, sintering, and erosion occur in transverse stripes across the snowscape.

1 Introduction

Wind-blown snow self-organizes into bedforms, such as dunes, waves, and ripples, the most common of which are anvil-shaped sastrugi. These bedforms cover sea ice, tundra, alpine ridges, and almost all of Antarctica (Filhol and Sturm, 2015). They are formed by the interaction of wind, heat, and snow. After they form, bedforms govern the interactions between the snow surface and the atmosphere.

Snow bedforms increase the variability of snow depth on short (0.1–5 m) length scales. This variability increases the uncertainty on paleoclimate measurements of snow accumulation from ice cores (Leonard (2009) §2.5.3), and decreases the average thermal conductivity of the snow (Liston et al., 2018), while focusing heat flux in areas of thin snow (Petrich et al., 2012). Bedforms also increase the aerodynamic drag of the surface (Inoue, 1989a, b; Jackson and Carroll, 1978; Amory et al., 2017), and change the distribution of wind-blown aerosols (Harder et al., 2000). Finally, they increase the surface area of the snow, which decreases its reflectivity (Leroux and Fily, 1998; Warren et al., 1998; Corbett and Su, 2015). All of these effects are difficult to measure remotely.

Snow bedforms are commonly 0.1–5 m long. They are generally sub-pixel-scale for satellite imagery, and definitively sub-grid-scale for global and regional climate models. Moreover, bedforms align with the direction of the prevailing and/or most recent wind (Amory et al., 2016). Their effects on aerodynamic roughness and reflectivity are therefore anisotropic (Leroux and Fily, 1998; Corbett and Su, 2015), and cannot be conclusively measured by single satellites. Because of these difficulties, our understanding of the growth of snow bedforms and their thermal effects must begin on the ground.

Systematic field studies of snow bedform shapes and movement have, however, been separated by dozens of years and by thousands of miles. Cornish (1902) sketched snow bedforms, measured snow-wave wavelengths, and estimated the tensile strength of snow-mushrooms during a 3000-mile trip across British Columbia. Doumani (1967) photographed snow drifts, sastrugi, and barchanoids during two years' worth of traverses out of Byrd Station, Antarctica. Kobayashi (1980) used under-lit tables, photography, and meteorological stations to document the formation and advection of snow-ripples and snow-waves near their home institute of Sapporo, Japan. Finally, Filhol and Sturm (2015) collected photographs and descriptions of diverse snow bedforms, as well as LiDAR scans of dune fields near the University of Alaska, Fairbanks.

The past few years have seen a burst of new snow bedform research as several groups have deployed modern tools to document specific bedform behaviors. Kochanski et al. (2018) employed time-lapse imagery to detect bedform and sastrugi presence in the Colorado Front Range, and used this to predict the occurrence of snow bedforms as a function of weather. Amory et al. (2016) recorded the shift in sastrugi angle, and the resulting change in wind drag, during a storm in Adélie Land, Antarctica. Filhol et al. (2017) used a terrestrial LiDAR to capture fifteen images of an evolving field of snow dunes over the course of a 7.5 hour wind event in Finse, Norway. ~~Hervé et al., (2014)~~ Bellot et al. (2014) and ~~Naiim et al. (2017)~~ Naiim-Bouvet et al. (2017) noted that bedform evolution is rapid and difficult to capture with manual measurements, and have set up a terrestrial laser scanning system to automate the monitoring of sastrugi motion in the French Alps. These opportunistic observations have answered several basic questions about snow bedform evolution. For example, they have conclusively demonstrated that shifts in snow bedforms change surface wind drag (Amory et al., 2016), and that snow dunes merge and grow as they travel (Filhol et al., 2017).

None of the studies above, however, track the evolution of snow bedforms from one form to another. This makes it difficult to determine whether the observations represent rare events, or recurring patterns. Here, we aim to identify the overarching patterns of bedform evolution, so as to guide future monitoring studies. In particular, we seek to provide insight into the relationship between weather conditions and bedform evolution, so that, for example, future LiDAR studies can be deployed at the right times and places to capture the quantitative details of the most important events.

In this paper, we present the results of the longest-term observational study of snow bedforms that has been carried out to date: a three-year study on Niwot Ridge in the Colorado Front Range. Our observations are available at Kochanski (2018c). In this paper, we present detailed examples of the movement and formation of snow ripples, barchan dunes, snow-steps, snow-waves, and sastrugi. We analyze these observations in terms of the geomorphological processes that produce them (these processes are introduced in § S3). Finally, we outline a theoretical framework that describes the various evolutionary trajectories of snow bedforms in terms of the processes that drive their formation and growth.

1.1 Names and natures of snow bedforms

The study of bedforms is still very new, and the names used to describe bedforms are occasionally controversial. Here we define the names that we use to organize our results. Example images are provided in § 3.1. We discuss only bedforms that we observed in Colorado.

Plane beds (§ 3.1.1), or flat snow surfaces, occur when snow falls during periods of light wind (Kochanski et al., 2018). These beds are smoother than the underlying surface, and may sparkle. This surface type is rare at our field site.

Snow ripples (§ 3.1.3) are small transverse features (perpendicular to the mean wind) with wavelengths on the order of 15 cm. They are described in detail by Kobayashi (1980) and Kosugi et al. (1992). Filhol and Sturm (2015) refer to these features as 'ripple marks'.

Barchan dunes (§ 3.1.2) are crescent-shaped, or two-horned, dunes. They have well-defined crests, with a gentle upwind slope and a steep downwind slope that curves into two forward-pointing arms (Filhol and Sturm, 2015; Petrich et al., 2012; Doumani, 1967; Kobayashi, 1980; Goodwin, 1986). In this paper, 'barchan dune' (or 'isolated dune') refers specifically to ~~crescent dunes that are separated from neighboring dunes by wide stretches of hardened snow or ice~~ crescent dunes that do not cover the surface completely, but expose inter-dune areas of older snow, bare ground, or ice .

Close-packed dunes (also § 3.1.2) have defined crests. Unlike isolated barchans, they cover the surface completely. ~~They may be barchan dunes with arms melded into one another.~~ We distinguish close-packed dunes from isolated barchans because ~~snow surface thermal properties (Petrich et al., 2012) and evoluation are affected by exposed inter-dune snow.~~ they have different thermal properties and we expect them to follow different evolutionary trajectories. First, fresh snow is more reflective and less thermally conductive than old snow, ice, or bare ground. Even small gaps in the snow cover create a positive feedback cycle that leads to rapid snowmelt in warm or sunny weather (Petrich et al., 2012). Second, fresh snow is usually less dense, and more erodible than old snow, ice, or dirt. Thus, exposed inter-dune areas make the snow surface inhomogeneous, which makes the dynamics of bedform evolution considerably more complex. We discuss this in §4 and §4.6.

snow surface thermal properties (Petrich et al., 2012) and evolution are affected by exposed inter-dune snow.

Snow waves (§ 3.1.6) are large transverse features with 5–15 m wavelengths (Filhol and Sturm, 2015). They propagate parallel to the wind (Cornish, 1902; Kobayashi, 1980), but extend for tens to hundreds of meters in a perpendicular or oblique direction. They may or may not have visible crests.

Loose patches (§ 3.1.7) is a catch-all term. We found that, when a surface was mostly hardened, any remaining loose snow frequently travelled in patches 1–5 m long. Unlike dunes and waves, these patches lack crests, and they tend to fill depressions in the existing snow surface rather than organizing into persistent structures.

Sastrugi (§3.1.4) are the most widespread and well-developed erosional bedforms. Sastrugi are elongate features that present steep points into the wind (Filhol and Sturm, 2015; Amory et al., 2016). The points are regularly spaced, and the point of each feature is aligned with the gap between two neighboring sastrugi immediately upstream. The word 'sastrugi' has been previously used to describe a wide range of snow features (Leonard, 2009), but its usage has become more focused in recent years.

Snow steps (§3.1.5) are smaller, less regular erosional features (Kochanski et al., 2018). They present low (<2 cm) vertical faces to the wind, but lack the upwind-facing points that characterise sastrugi. Doumani (1967) called these features 'proto-sastrugi,' but we avoid using this name because it implies a pattern of evolution, from steps to sastrugi, that we did not observe (see § 3.2).

Finally, we introduce the *stealth dune* (§3.1.8). These are boomerang-shaped bedforms that resemble barchan dunes from afar, but their windward edges are vertical.

2 Methods

2.1 Field site

We surveyed bedforms on snow-crowned ridges and frozen reservoirs throughout the Front Range (§S2). Among the sites we visited, one stood out for its well-developed and undisturbed bedforms: the Niwot Ridge saddle site (Fig. 1, 40.054° N, 105.589° W). The site lies on the downwind end of a broad, treeless 3 km-long ridge, 5 km east of the Continental Divide, at an elevation of 3528 m. The ridge receives deep, dry snowfall ~~that is shaped by consistent west-northwesterly winds~~ . Snow falls from October through June, with the heaviest blizzards between January and March. Most blizzards bury the existing snow or ground surface. They deposit blank canvases on which bedforms evolve for a few days or weeks until they are buried by the next storm. The Colorado Front Range is a semi-arid region, with low humidity and famously dry snow. ~~The wind is primarily westerly, with local variations driven by temperature and altitude gradients over the Continental Divide.~~ In winter the wind on Niwot Ridge blows almost without exception from the west-northwest, driven by temperature gradients over the Continental Divide. The ridge also runs east-southeast to west-northwest, parallel to the prevailing wind. The saddle site is downwind of a gentle bump in the ridge, and collects deep snow throughout the winter, even while other parts of the ridge are occasionally scoured free of snow. We draw all but one of the observations in the main body of the text from the saddle site on Niwot Ridge.

We also present one set of observations made on the frozen surface of Barker Reservoir, Colorado, where we observed a type of bedform that did not appear on Niwot Ridge (§ 3.1.8). Barker Reservoir sits at the bottom of an elevated (2483m) post-glacial valley and, in winter, it becomes a 1800 m-long stretch of ice. The valley funnels the wind west-southwest across the long axis of the lake. Much of the incoming snow is blocked by the town of Nederland, which occupies the upwind edge of the reservoir.

2.2 Data collection

We observed bedforms on Niwot Ridge in person and through Day6 Plotwatcher Pro time-lapse cameras powered by cold-resistant Energizer Ultimate Lithium batteries. The cameras were angled downwind or perpendicular to the prevailing wind to prevent snow from covering the lens; we indicate the wind direction for each image. The cameras were mounted on 2 m

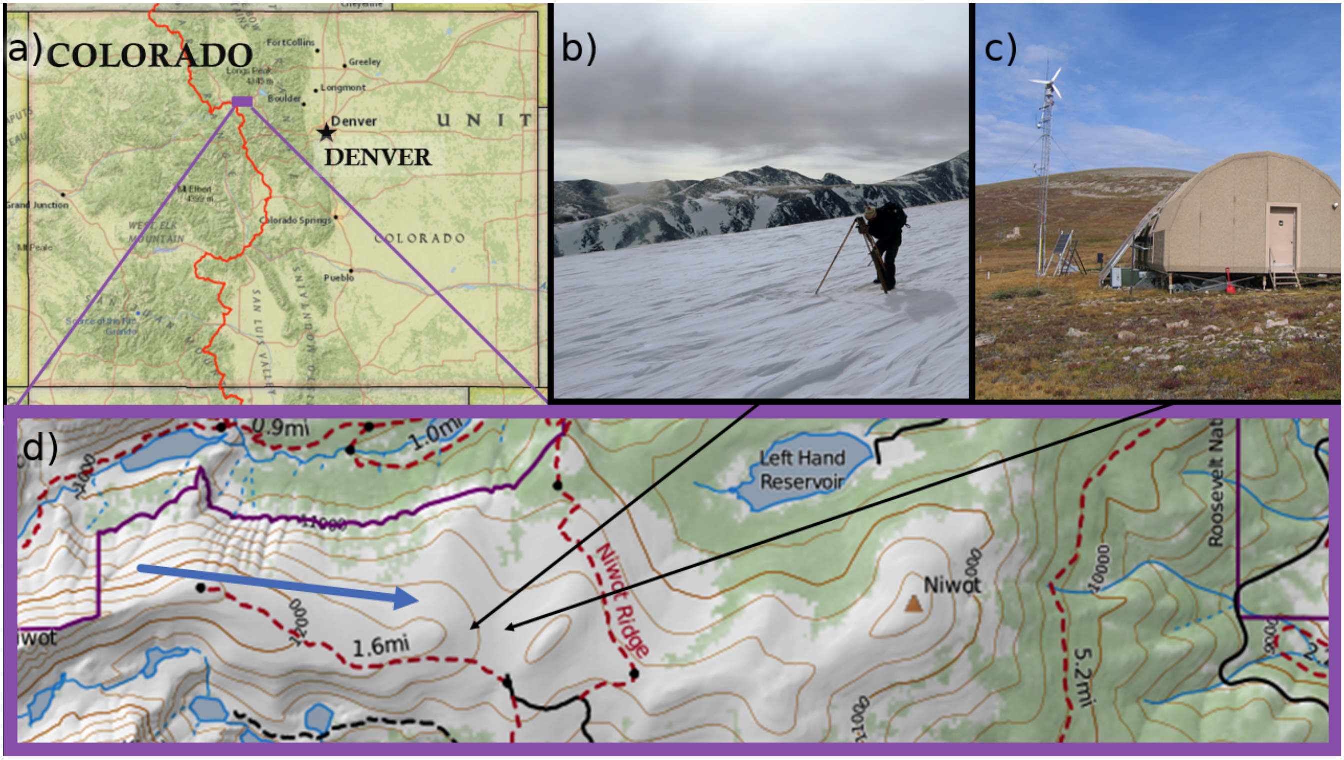

Figure 1. Field site on Niwot Ridge. a) Location of the field site within the state of Colorado. b) Installation of a time-lapse camera. c) Weather station. d) Close-up map of field site with arrows showing prevailing wind direction and locations of camera and weather station.

tripods. The distance between the cameras and the surface decreased as snow accumulated; we reset them on the surface once a month. The uncertainty in the camera elevation makes it difficult for us to estimate distance directly from the images.

We therefore measured bedform sizes and velocities both in-person, using meter sticks, and by reference to poles with 10-cm stripes placed in front of the cameras. Where measurements are missing, for example because the poles blew away, we convey sizes, speeds and intensities in non-dimensional units.

We used Tracker video analysis software (Brown, 2018) to extract high-resolution position-velocity data from several of our images. In one analysis we used the video to make a frame-by-frame visual estimate of the variations in the flux of blowing snow. We only attempted these analyses when the features moved perpendicular to the camera view, to avoid distortion by distance. The cameras were active from February to March 2016, from October 2016 to March 2017, and from November 2017 to March 2018. They captured a total of 1082 hours of good visibility footage, with photos taken every 10 s. Footage is missing at night, during white-outs, on days when clouds enveloped the ridges, when cameras were buried, and during equipment failures. Sample time-lapse videos are shown in video S1 and all videos are archived in (Kochanski, 2018b).

Weather and precipitation data are available from the Niwot Ridge Long Term Ecological Research Program station 200 m downwind of our cameras (Losleben, 2018a, b). Temperature measurements were collected with a Campbell Scientific CS500 mounted in a Stevenson Screen 1.5 m above ground, and wind speed was measured with an RM Young 501D mounted 7.5 m above ground. The recorded wind speeds from November through March average 10.5 m/s. The gusts average 14.4 m/s and reach as high as 29.7 m/s. The highest winds that we have seen sustained for an hour or more were 23.0 m/s. Winter temperatures average -7.5°C and vary from -28–11°C. Melting temperatures occur in every month.

~~We have endeavored to convey all sizes, speeds, and intensities in the most useful units that are available to us. The quality of these measurements varies, unfortunately, between data sets; for example, in many 25 of our images the measurement poles have blown away.~~

We analyzed the resulting data with Matplotlib (Hunter, 2007) and NumPy (Oliphant, 2007). We previously presented a statistical analysis of the relationship between snow bedforms and weather conditions on Niwot Ridge in Kochanski et al. (2018). In this paper we focus on bedform dynamics.

3 Results

3.1 Bedform movement

Here, we illustrate the movement of each bedform with examples from time-lapse footage: planar snow surfaces (§ 3.1.1) barchan dunes and close-packed dunes (§ 3.1.2), ripples (§ 3.1.3), snow-waves (§ 3.1.6), sastrugi (§ 3.1.4), snow-steps (§ 3.1.5), and stealth dunes (§ 3.1.7). For each example, we include still frames in the text. These still frames have been selected for their clarity. The frames are taken from the videos provided in 5 minute supplementary video S1 (Kochanski, 2018a). As this paper focuses on the motion of snow bedforms, video S1 is the most important figure.

3.1.1 Plane beds

The falling snow that we observed often fell in still air and settled into plane beds. These snow surfaces were smoother than the ground, or older snow, that they covered, and were unmarked by corners, edges or organized bedforms. They are also the only surface type made from ~~unsintered, unbroken snowflakes~~ fresh snowflakes that have not saltated or broken during saltation, and thus the only surfaces that sparkle in the sun. These surfaces did not persist once any perceptible amount of snow began to blow. Kochanski et al. (2018) determined that the snow on Niwot Ridge was likely to be flat only if the wind speed was less than 6.4 ± 2.2 m/s and the snow was fresher than 1.4 ± 3.3 days.

3.1.2 Snow dunes

The biggest dune that we saw was 54 cm tall (Fig. 2a, in a field of 30–50 cm dunes). The smallest dune (Fig. 2c) was no more than 7 cm tall and 40 cm long.

Fig. 2b shows a field of close-packed dunes. These advected downwind, but they also interacted with one another. They rapidly merged, calved, and changed height. We tracked the heights, widths (measured horizontally from the dune crest to the downwind foot of the dune), and velocities (measured at the crest) of the dunes in Fig. 2b; the results are shown in Fig. 3. The

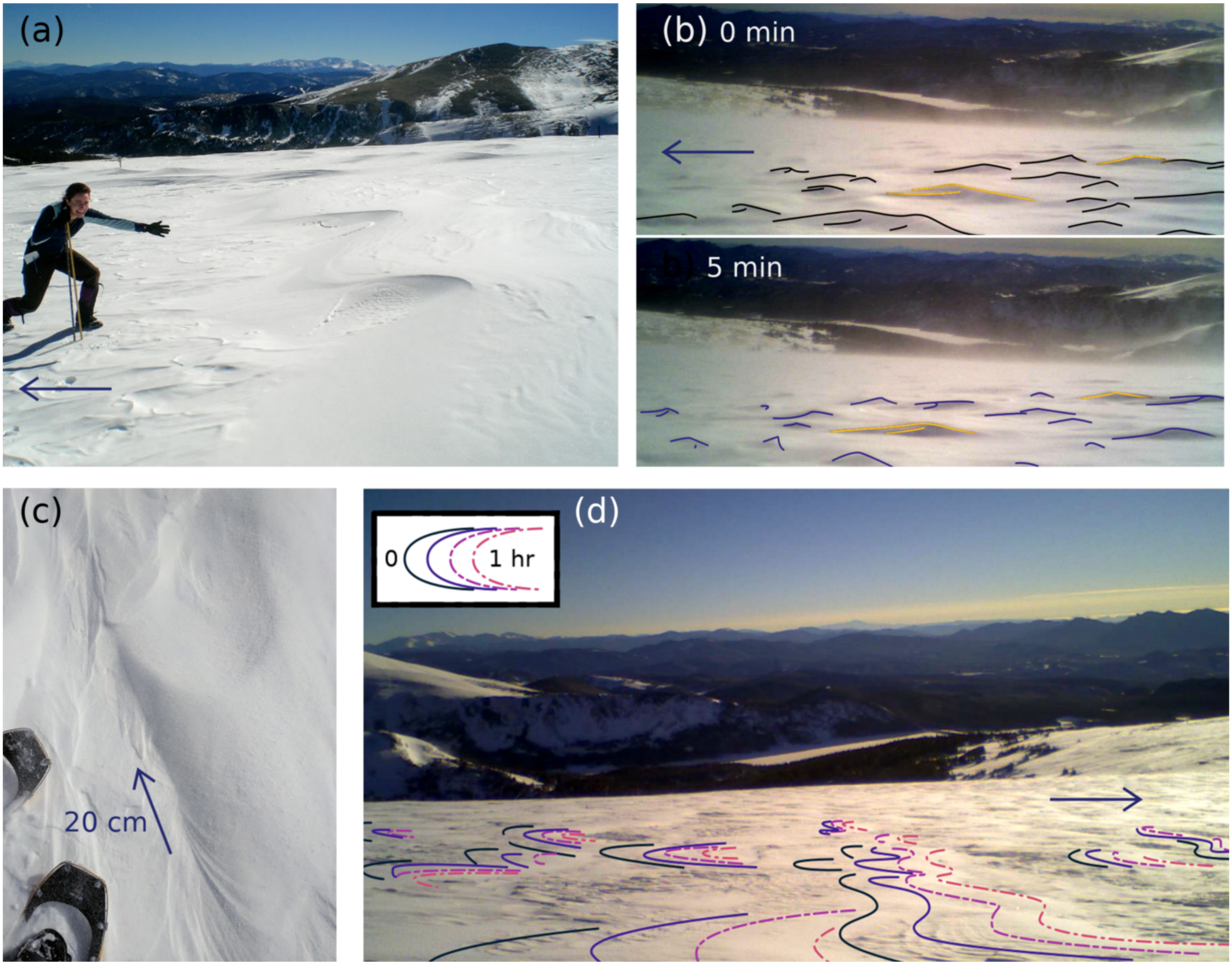

Figure 2. Snow dunes on Niwot Ridge, CO. a) 30–40 cm tall stationary barchan dunes on 03/03/2018. Temperatures are near freezing. The snow between the dunes, which has been marked by erosional bedforms, is now unmarked by the author's weight. b) Time-lapse of close-packed dunes travelling downwind on 22/01/2018 from 13:29–13:34 (video S1, 0:08). No hard or eroded snow is visible between the dunes. c) Smallest barchan dune observed on Niwot Ridge, seen moving downwind at 11:25 09/11/2017 at 1–2 cm/min. <1–5 mm wide snow grains creep across the crest (video S1, 0:57). d) Time-lapse of isolated barchan dunes from 07:20–08:20 on 17/01/2017 (video S1, 0:39). Lines track the positions of the dune crests.

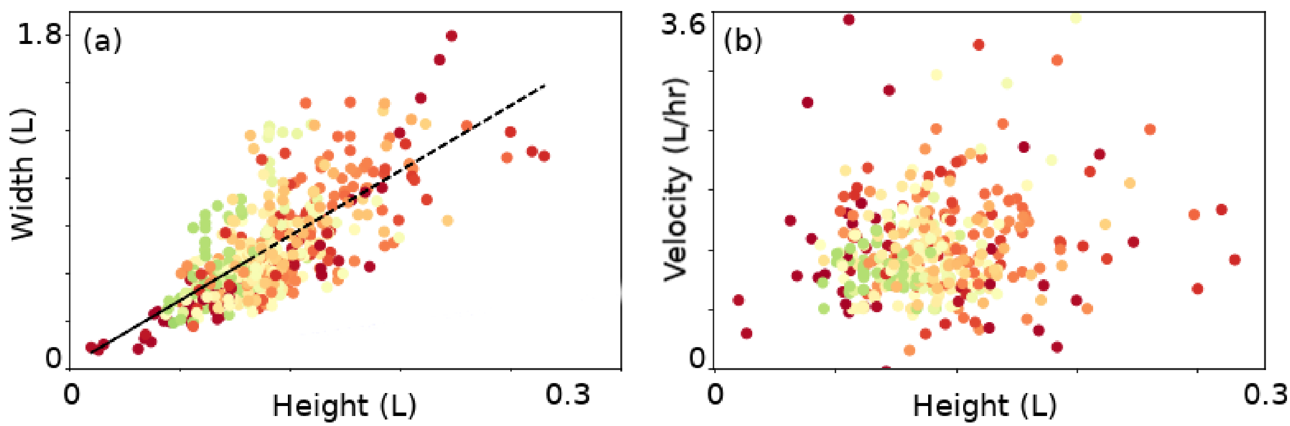

Figure 3. Scaling relationships for dunes observed on 22/10/2018. Length is measured in an arbitrary unit $L = 1 \pm 0.5$ m. Colors indicate the distance of the dune from the camera (dark red is close, pale green is far) which should be independent of the measured quantities.

dune heights and widths scale linearly. Their velocities, unlike the velocities of sand dunes (see § 4.2) were not correlated with their sizes.

Fig. 2d shows the motion of a field of barchan snow dunes. These dunes are not close packed, and do not interact with one another. They maintain their shapes as they move downwind (see video S1, 1:07).

We tracked the position of the barchan dunes in Fig. 4 through time. The tracked points on the dunes moved an average of 0.63 m in the first fifteen minutes of observation, for an average velocity of 2.52 m/hr, after which they decelerated until sunset. The dunes lost about a third of their height during this period.

Neither the weather that drove the dunes nor their speeds were constant. The dunes were subject to frequent gusts. The instantaneous velocities of the dunes, observed over 10s intervals, varied from 0 to 15 m/hr. The dune arms (A1 and A2) accelerated and decelerated at the same times as the peaks (C1 and C2), which indicates that the dunes moved as a whole in response to changes in the wind. Although our wind data measurements were not of sufficient resolution to resolve these gusts, the gusts were associated with pulses of blowing snow. We evaluated the blowing snow flux visually in our camera footage at 10 s intervals, and indicate them with gray shading in Fig. 4b. The shading varies from white (no visible snow—though in our experience, the flux of blowing snow can be quite intense before it is opaque enough to appear on camera) to dark gray (whiteout). The dune was clearly visible through the snow in all but a handful of frames (see video S1 at 1:07).

We cross-correlated the intensity of blowing snow (on a normalized scale from 0 (white, no blowing snow) to 1 (dark grey, whiteout)) with the instantaneous velocities of the dunes (Fig. 4c). This revealed that the velocities of C1, C2, and A2 lagged the pulses of blowing snow by 30 ± 5 s, though the velocity of A1 did not correlate with the blowing snow.

This positive correlation and positive lag is evidence ~~that high fluxes of blowing slow cause high dune velocities, instead of the other way around~~ of causation: high incoming fluxes of blowing snow drive high dune velocities. Moreover, the dune

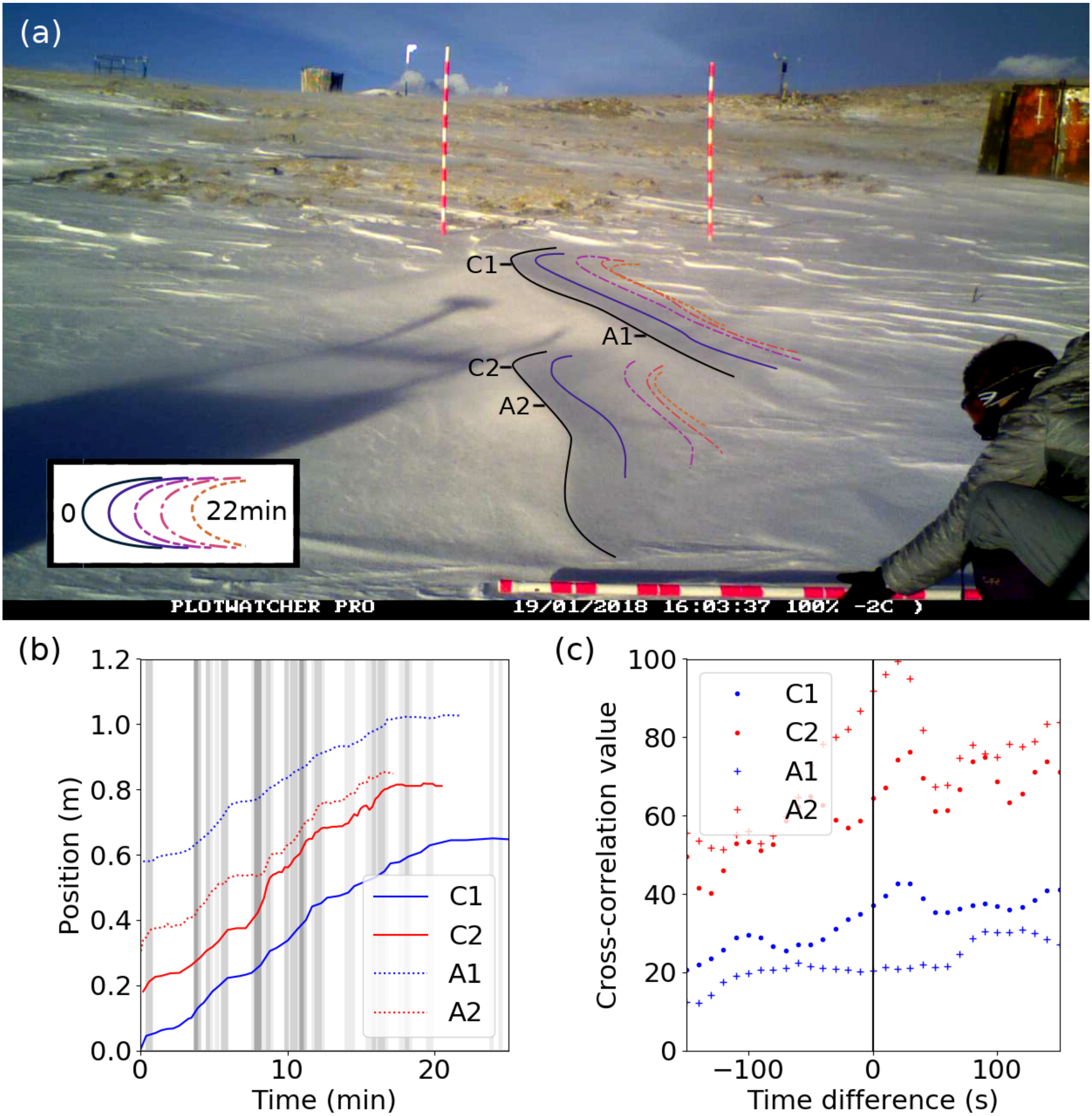

Figure 4. Movement of two barchan dunes on Niwot Ridge, Colorado, from 16:03 to 16:28 19/01/2018, and analysis of the effect of pulses of blowing snow on dune movement. See video S1 1:07. a) Dunes at 16:03. Colored lines show the crest position through time, taken from time-lapse imagery. Poles have 10cm stripes. Horizontal pole is held 2m in front of vertical poles, which are 2m apart. b) Horizontal (left to right) positions of the dune crests at points C1, A1, C2 and A2 at 10s intervals. Background is shaded when blowing snow is visible in the footage. c) Cross-correlation of the presence of blowing snow with the instantaneous velocities of the dunes.

movement must have contributed to the flux of blowing snow, because the dunes lost height during the observation. These blowing snow events appear to have created a positive feedback that turned snow dunes into wind-blown snow.

The snow on the moving dunes that we observed demonstrated all three major types of aeolian snow movement. Saltating snow is clearly visible in the time-lapse footage used for Fig. 2b. Snow grains crept, with halting movements, across the crest of the dune in Fig. 2c. Finally, the images used to make Fig. 2a were often obscured by blowing snow that was suspended to at least the height of the 2 m camera. Although blowing snow is not always visible on the cameras, in person we observed moving snow dunes, ripples, and waves only during ground blizzards, and never on days without blowing snow.

3.1.3 Snow ripples

Ripples appeared at our study site both as a primary features, covering wide swaths of ground (Fig. 5c), and as a secondary feature that adorned dunes and snow waves (§ 3.1.3). The ripples that we observed were 0.5–2 cm tall with wavelengths of 10–25 cm.

Fig. 5a shows ripples covering the snowy portion of partially snow-covered ground in the early part of the snow season. The ripples advected downwind. Dislocations propagated across the bed, leading individual ripples to merge and separate from one another. The velocity of the ripples was consistent throughout the observation. The crests advanced ~~with a frequency of 1.81 ± 0.16 min^{-1}~~ by one wavelength every 33 ± 3 s. Although scale bars were missing from this image, this allows us to estimate that snow ripples with typical 10–25 cm wavelengths move at 11–27 m/hr. These high speeds are consistent with our observations of ripples in §3.1.6. The movement of the ripples did not advance the snow over the rocky part of the ground, implying that the mass transported by the ripples was either buried or lost to suspension at the edge of the rocks.

The photos in Fig. 5b were also taken on a day when both snow and bare ground were exposed on the ridge. They formed from a mix of wind-blown snow and sand. The sand (dark) was concentrated on the crests of some of the ripples. Over the course of this 3-minute observation, the ripples without sandy crests faded away, leaving mostly sand-covered ripples. The sand-covered ripples travelled at 4 ± 1 m/hr, which is slower than snow ripples alone.

Fig. 5c shows snow ripples emerge from a flat snow surface. They advected downwind by many wavelengths between photos, and their amplitudes grew gradually over time.

3.1.4 Sastrugi

Our study site, Niwot Ridge, frequently held sastrugi that were 14–40 cm deep and spanned 45–90 cm between points. The largest observed sastrugi (at the downwind end of Niwot Ridge) were 90–120 cm deep, and spanned 120–180 cm. The troughs between those sastrugi resembled meandering slot canyons.

Fig. 6 shows two erosion events in which sastrugi travelled downwind. We tracked the shapes of the twenty best-defined points in Fig. 6a for two hours, and found that five became more overhung, seven became less overhung, and eight ~~retreated~~ migrated downwind without changes to their profile. The majority of the sastrugi in Fig. 6b maintain straight vertical edges, but two became more gently sloped and one became steeper during the 30 minute observation.

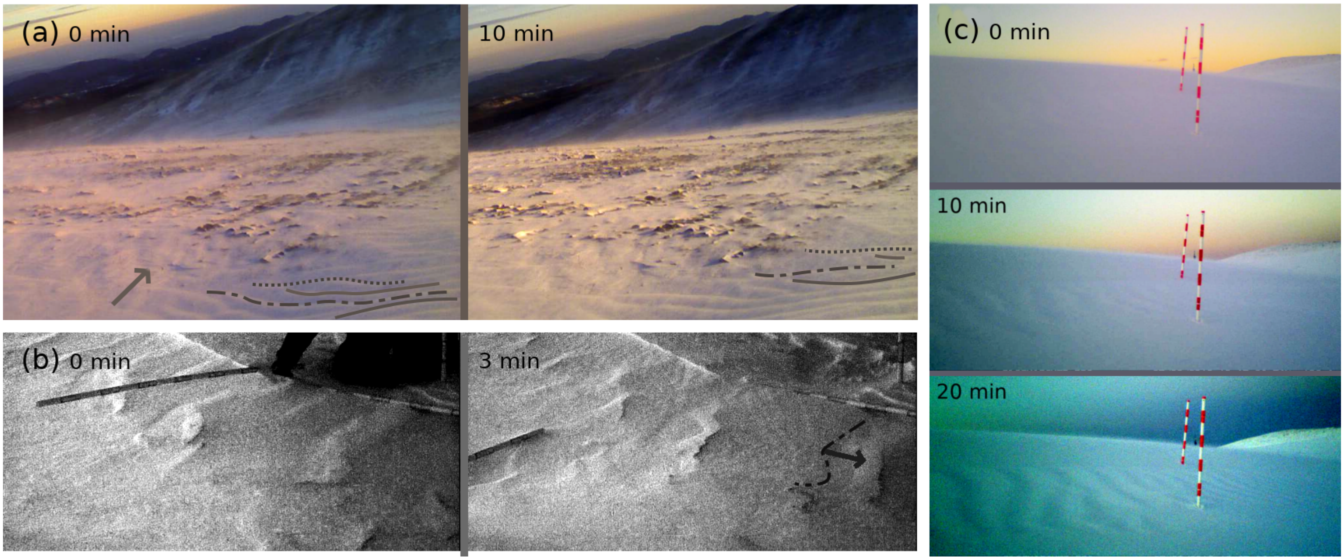

Figure 5. Time-lapse images of snow ripples on Niwot Ridge, Colorado. (a) Ripples advect from 7:28—7:38 on 19/11/2016, video S1 1:32 (b) Sand covers the crests of advecting ripples from 17:23:33–17:26:33 on 18/01/2018, video S1 2:06. Pole has 10 cm stripes. (c) Ripples emerge from a previously flat snow-covered surface on Niwot Ridge between 18:05 and 18:25 on 27/03/2018, video S1 2:23. Poles are 2 m apart and have 10 cm stripes. Ripples travel many wavelengths between photos.

When we observed sastrugi in person, during high-wind events, loose snow collected at the bottoms of their points. These loose snow grains moved continuously, such that the loose snow sparkled with motion while the sastrugi themselves appeared dull. Up close, we saw that large grains collected at the base of the sastrugi, then crept downwind along both sides of the point. This creep moved the grains in an oblique downwind direction, without moving them vertically over the sastrugi. These patches of loose snow disappeared momentarily in strong gusts.

We did not observe sastrugi formation. Our video observations therefore provide evidence that sastrugi are stable enough to ~~retreat~~ migrate horizontally by several times their height without significant changes of form, but they do not show direct evidence of the mechanisms of sastrugi formation.

3.1.5 Snow-steps

Fig. 7a shows a row of slowly moving snow-steps left in the wake of a traveling snow-wave (snow-step formation behind waves is discussed in § 3.1.6). The steps ~~retreat~~ migrate downwind over the observation period. When they first form, at the beginning of the observation, they are relatively straight and soft-looking. Over the following two hours, they become more crenulated and sinuous in plan view. The density of the snow-steps on the surface also increases; Fig. 7a shows all of the steps visible at the start of the observation (dashed blue lines), which is not all of the steps visible at the end (photo, select steps traced in black).

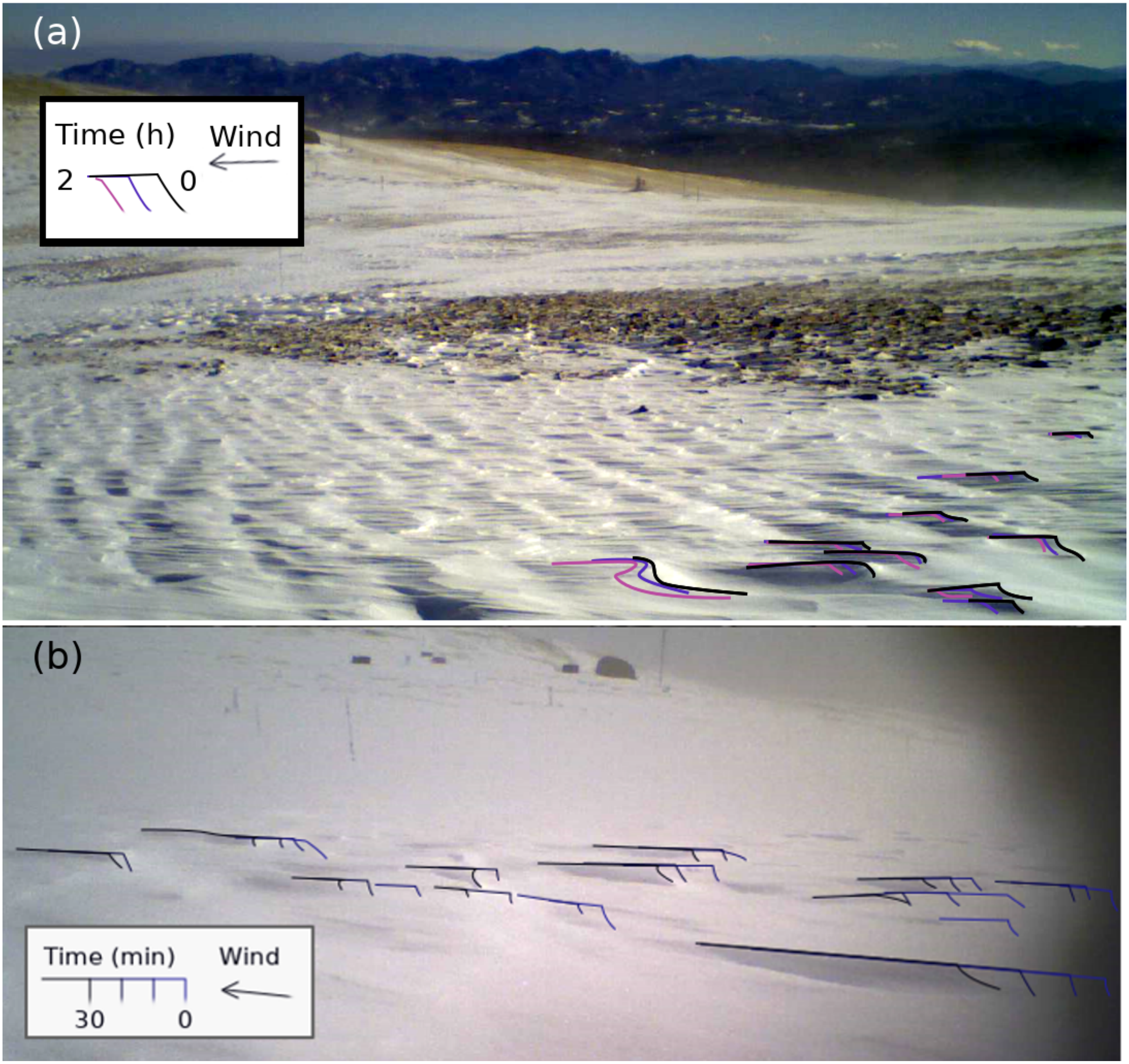

Figure 6. Time-lapse of sastrugi crests (a) from 15:30 (pictured) to 17:30 on 18/11/2016, video S1 2:51, and (b) from 10:23 to 10:53 (pictured) on 25/03/2016, video S1 3:05.

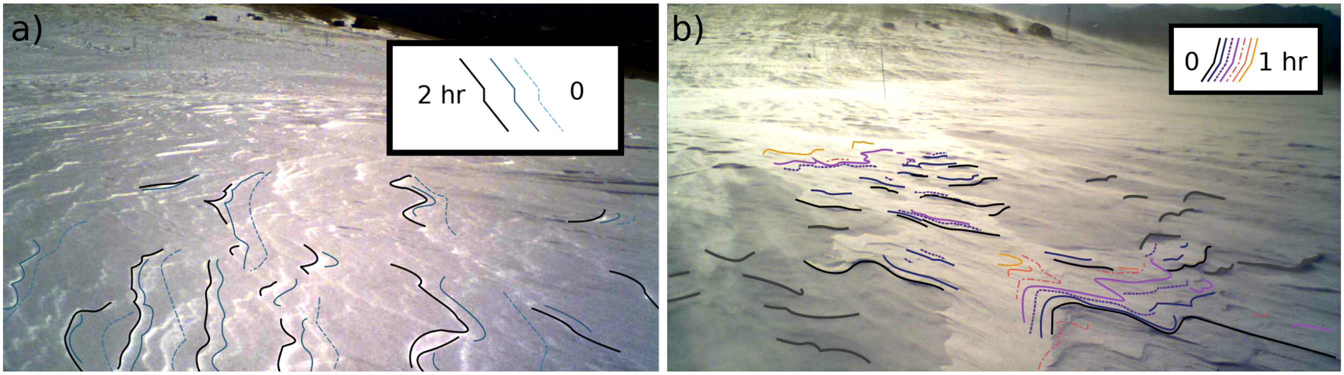

Figure 7. The movement of snow-steps on Niwot Ridge, Colorado (a) 21/03/2016 12:06–14:06 (video S1 3:35, photo at end of observation) and (b) 13/03/2016 07:09–08:09 (video S1 3:57, photo at beginning of observation).

Fig. 7b shows differential step motion in a case where an old, hardened snow layer (duller white) lies under a relatively new and soft layer (brighter white). The newer steps eroded during the day, but the older steps did not move visibly. At the end of the day the newer steps were entirely removed. Their removal revealed a subtle landscape of older snow-steps that had apparently been buried and persisted under the snow.

3.1.6 Snow-waves

Snow-waves appeared frequently on Niwot Ridge. The waves we observed were 1–3 m long parallel to the wind , with crests separated at wavelengths of 10–20 m. Fig. 8a shows a field of snow-waves extending for tens of meters in a direction oblique or perpendicular to the wind.

Fig. 8d shows a section of a wave. The wave has several separated crests, joined by low, rippled sections of the wave. The crests point directly downwind, but the overall orientation of the wave is oblique.

Snow waves move by advecting downwind, but they also interact with the snow surface beneath them. We document this interaction in Figs. 8b, c and 9. Fig. 8b shows time-lapse imagery of the movement of a snow-wave, and nearby snow-steps. As the video progressed, the visible steps ~~retreated~~ migrated downwind, and new steps appeared behind the wave.

Fig. 8c shows this process close-up. The travelling wave in this photo buried the snow-steps to its left. It also genererated the snow-steps to its right. The right-hand steps parallel the wave crest, and the steps further from the crest are slightly more crenulated than the steps at the top. The snow surface behind the wave was several centimeters higher than the snow in front, implying that the new steps formed in newly-deposited snow.

Fig. 9 further illustrates the interaction between snow-waves and the underlying snow surface. The wave started as a low rippled section. The ripples occasionally appeared, disappeared, and merged, which was consistent with a side view of ripple dislocation (e.g. Fig. 5a). The ripples travelled about ten times as fast as the bulk of the wave. After about 60 minutes, the last ripple caught up to and merged with the previous ripples, forming a single crest. The velocity of the wave did not appear to change as it shifted from a rippled section to a crest. The crest deposited a layer of new snow, which was noticeably higher r

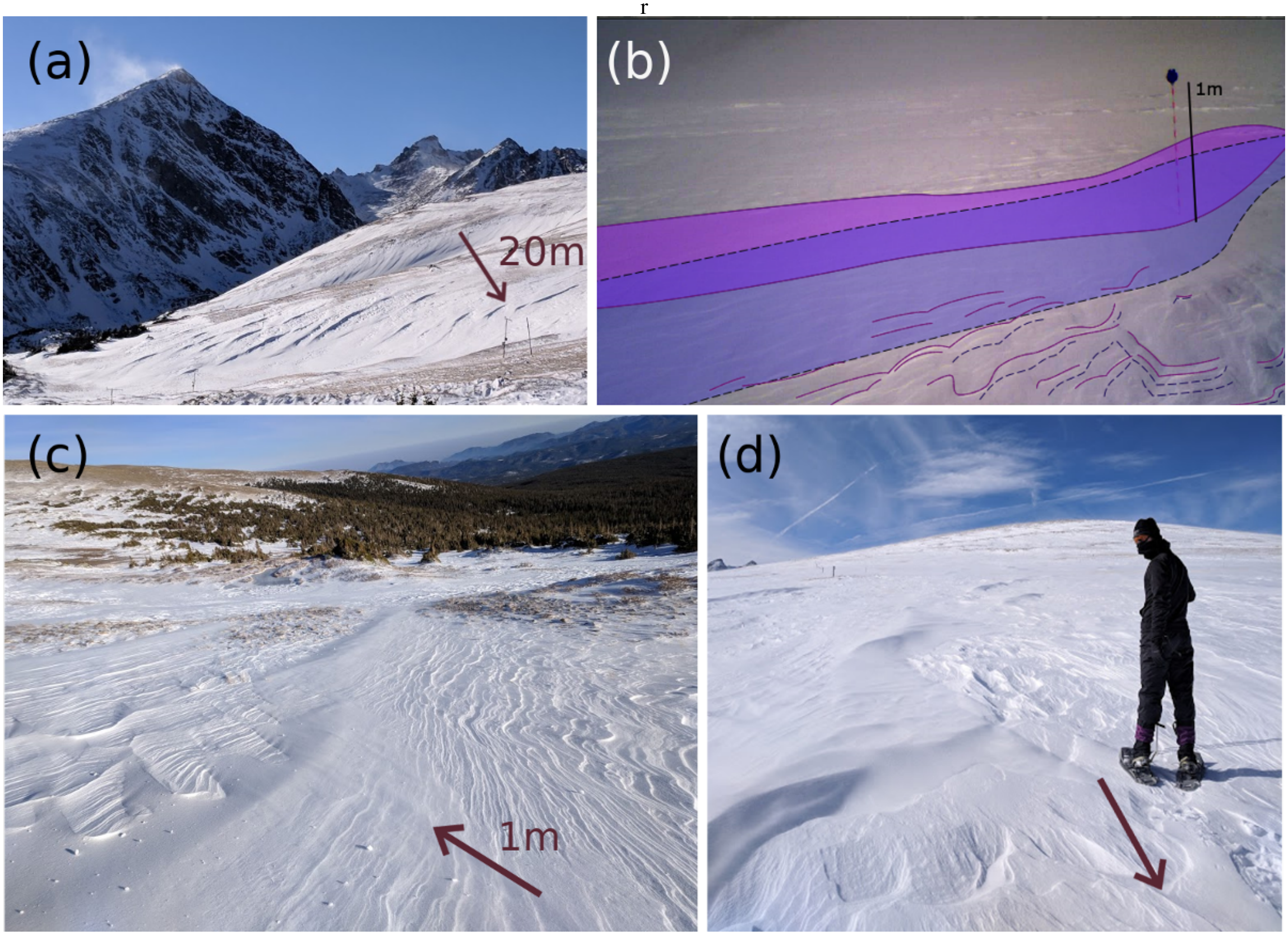

Figure 8. Snow-waves on Niwot Ridge, CO. (a) long-distance view on 9/11/2017 with estimated wind direction and scale (b) time-lapse image showing motion of wave (shaded) and small erosional features (lines) away from the camera from 12:20 (blue, dashed) to 13:00 (purple, solid) on 24/02/2017, video S1 4:19 (c) parallel snow-steps in the wake of a wave on 9/11/2017 (d) alternating wave crests and ripples on 12/11/2017.

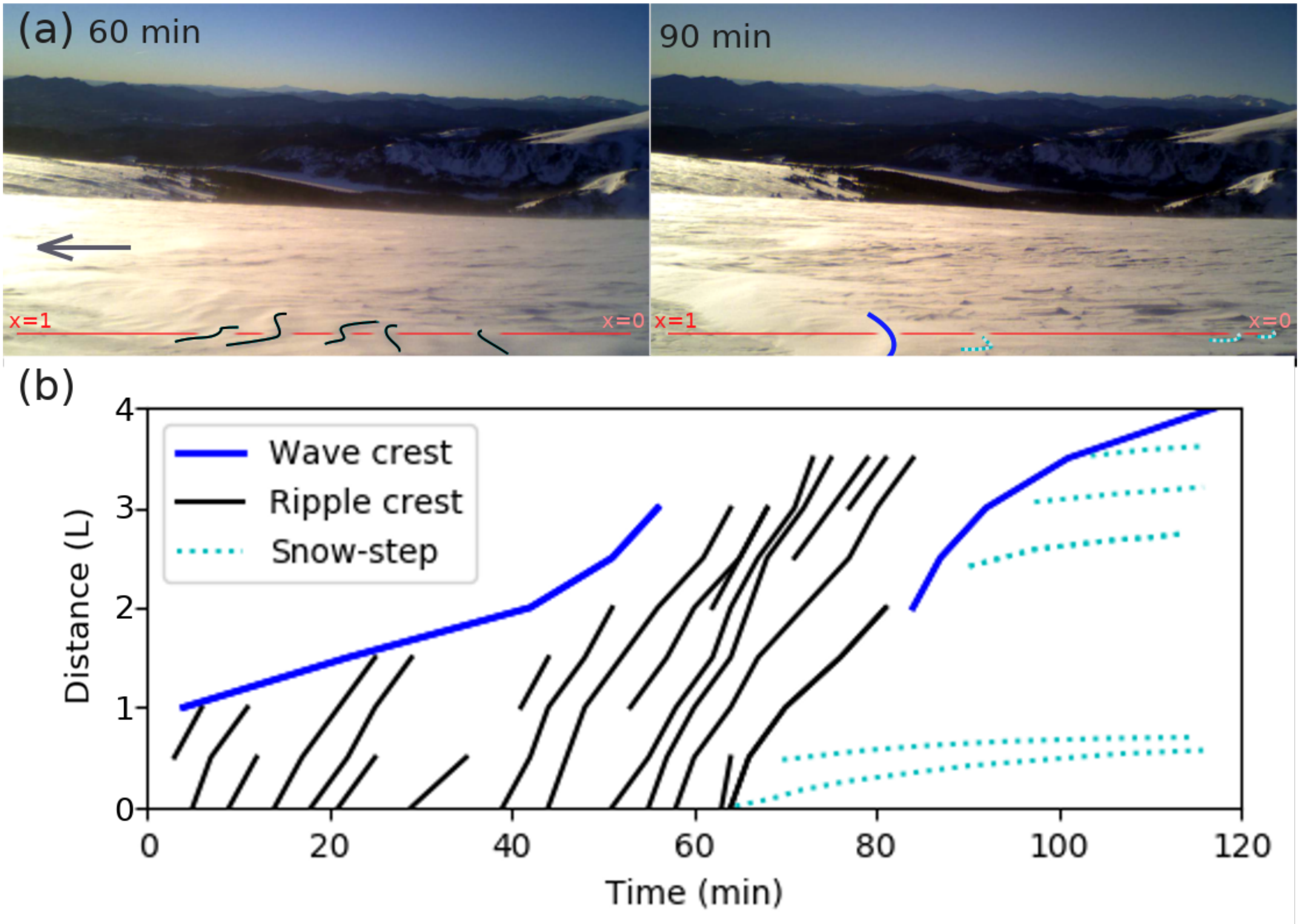

Figure 9. A rippled wave travels across Niwot Ridge from 6:40–8:40 on 01/19/2017, video S1 4:40. The wave is covered by ripples, which eventually collapse into a single crest, and deposits fresh snow as it passes. This in turn develops snow-steps. ~~Length is measured in an arbitrary unit of approximately 30 cm~~ Distance is measured in arbitrary unit $L = 1 \pm 0.3$ m.

and fresher-looking than the previous snow surface. Several snow steps formed in this freshly deposited snow. They ~~retreated~~ migrated downwind and decelerated over time. Fig. 9b tracks the peaks of the ripples, crest, and snow-steps at 5–10 minute intervals.

3.1.7 Loose snow patches

Small quantities of loose snow on deeply eroded surfaces collected into longitudinal “patches” a few centimetres thick. They flowed between underlying sastrugi and do not have persistent forms. The patches that we observed were 25–300 cm wide and

0.5–10 m long. On one occasion, a set of otherwise stationary snow-steps began to ~~retreat~~ migrate downwind when a patch of snow passed by.

3.1.8 Stealth dunes

Finally, we observed an extreme erosional bedform that we propose to call the *stealth dune* for its low profile and its rarity (Fig. 10). These dart-shaped dunes sit on ice and resemble barchans from afar, but their slopes are inverted: the upwind edges of the dunes are hard and vertical, while their lee sides are nearly flush with the ice. Figs. 10a–c show three dunes from a field of mixed size. The wing spans of the stealth dunes in that field ranged from 0.15–3 m, and their heights ranged from imperceptible thinness (likely due to scouring by wind after the dune formed) to a maximum of 10 cm. Fig. 10d shows an idealized stealth dune, emphasizing the vertical upwind slope. We observed stealth dunes only on the frozen mile-long surface of Barker Reservoir, and we did not see them move.

3.1.9 Bedforms in spring

We observed snow bedforms from first snowfall through late March. When week-long periods passed without snowfall, suncups appeared on the snow surface. These surfaces were consistently covered by sastrugi. The suncups appeared to be symmetric around the sastrugi, including the underhung sides of lanceolate sastrugi: they were not visibly larger on the sunny south sides, nor eroded on the upwind sides.

From April or May through July, the surface of the snow on Niwot Ridge deflates due to melting and sublimation. We are missing observations in April and May, but in June 2016 and 2017 the surface of the snow was soft, wet, and marked by suncups without other bedforms.

The rate of sublimation on the ridge is slow compared to bedform formation. We observed the snowpack on Niwot Ridge shrink in above-freezing temperatures from 19/06/2017–01/07/2017. The snow depth decreased by 1.1 m during this 12-day period (0.092 m/day). As many bedforms that we observed grew in periods of hours, it seems unreasonable that they are erased by sublimation in spring. We therefore infer that spring conditions prevent bedforms from forming in the first place. This agrees with other authors' observations that bedforms grow best in dry snow.

3.2 Bedform evolution

In § 3.1 we showed three examples of transitions from one type of bedform to another. In § 3.1.1 we discussed the deposition of flat snow surfaces during heavy snowfall events with gentle winds. In Fig. 5c, we showed ripples emerging from a flat snow surface. Finally, Figs. 8b–d and 9 showed snow waves burying existing snow steps and leaving new snow steps in their wakes. The sum of all the transitions that we observed are presented in Fig. 11. These include transitions that we observed directly (●), as in the example cases above, plus changes in the surface that happened overnight or during other $<$12 hr gaps in our observations (○). ~~Some of the observed transitions appear to be irreversible. For example, we saw flat surfaces turn into ripples (Fig. 5c), but did not see rippled surfaces return to flat. We also saw moving snow-steps and sastrugi stop moving (region II)~~

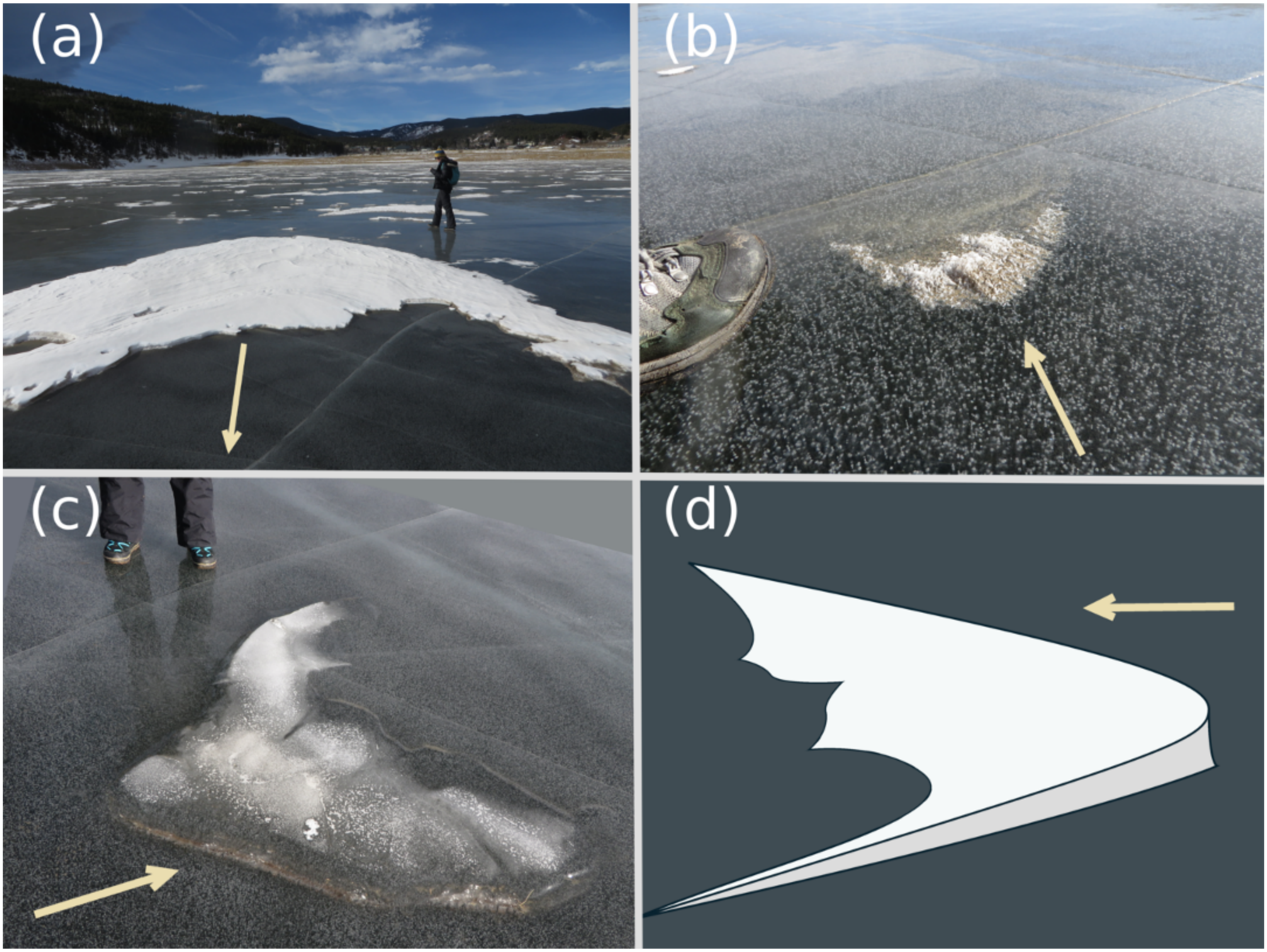

Figure 10. Stealth dunes viewed from several angles on Barker Reservoir, Colorado, on 16/01/2016. (a) Large stealth dune (b) Remnant of small stealth dune (c) Marks left on ice beneath a dune; surface is raised by 1.5 cm (d) Schematic of stealth dune.

~~but did not see them start moving again. Moreover, at least some of the snow-steps that we observed above decelerated continuously (Fig. 9b) with no obvious outside influence, implying that they stop spontaneously. The indirect transitions imply that ripples, close-packed dunes, and flat surfaces must turn into various combinations of snow-waves, barchan dunes, loose patches, snow steps, and sastrugi, and that snow dunes must somehow give way to snow- waves and vice versa. We did not observe any of these transitions directly. Moreover, we did not observe the formation of close-packed dunes, although we did once observe an indirect transition in which they appeared shortly after snowfall and a brief camera whiteout. These results demonstrate that bedform evolution is cyclic. The diagonal line in Fig. 11 represents 1:1 transitions. If bedform evolution were unidirectional, we would be able to arrange the table such that all observed transitions, both direct and indirect lie below the diagonal line. Our observations, however, cannot be organized so tidily. The cyclic behavior is driven by the transitions in Region III (shown graphically in Fig. 12). We saw snow-waves, snow patches, and barchan dunes bury snow steps (such as in Fig. 8c) and sastrugi. Sometimes, the snow-waves or loose patches moved on without changing the surface, and revealed the buried bedforms, apparently unchanged. On one occasion, existing snow steps were re-mobilized by a passing loose patch. Barchan snow dunes always deposited a new snow layer in their wakes, and snow waves sometimes did. These new layers eroded into either sastrugi or snow-steps.~~ We have grouped together transitions that share similar characteristics. Transitions that involve a surface made of entirely loose snow are in Region I (yellow). Transitions from one type of hardened, erosional surface to another are in Region II (orange). Transitions between surfaces that expose a mix of loose snow and hardened snow, such as waves, are in Region (pink), and transitions in which hardened surfaces turn into mixed surfaces, or vice-versa, are in Region III (red). These groups of bedforms are discussed further in §4.

The transitions in regions I and II appear to be irreversible. For example, we saw planar surfaces turn into ripples (Fig. 9), but rippled surfaces never became planar, and we saw snow-steps and sastrugi decelerate (Fig. 9) and stop moving but did not see them re-start. In contrast, the transitions in region III appear to drive cyclic evolution trajectories. We saw snow-waves, snow patches, and barchan dunes bury snow steps (such as in Fig. 8c) and sastrugi. Sometimes, the snow-waves or loose patches moved on without changing the surface, and revealed the buried bedforms, apparently unchanged. On one occasion, existing snow steps were re-mobilized by a passing loose patch. Barchan snow dunes always deposited a new snow layer in their wakes, and snow waves sometimes did. These new layers eroded into either sastrugi or snow-steps. These transitions are shown graphically in Fig. 12. This graph contains the same information that is represented in tabular or matrix form in regions II, III, and IV. If bedform evolution were unidirectional, we would be able to arrange Fig. 11 such that all transitions lay on one side of the 1:1 line, or arrange Fig. 12 without any loops or repetition. Finally, we did not directly observe any transitions in region IV. We suspect that these transitions only occur by way of the transitions in region III; for example, we have seen a surface covered by isolated barchans, then snow-steps, then snow-waves.

4 Discussion and directions for future work

Many snow bedforms are analogous to other self-organized aeolian features. Barchan snow dunes, close-packed dunes, and snow ripples resemble sand dunes and ripples. Snow-steps and sastrugi find their analogues in scoured bedrock: the scalloped

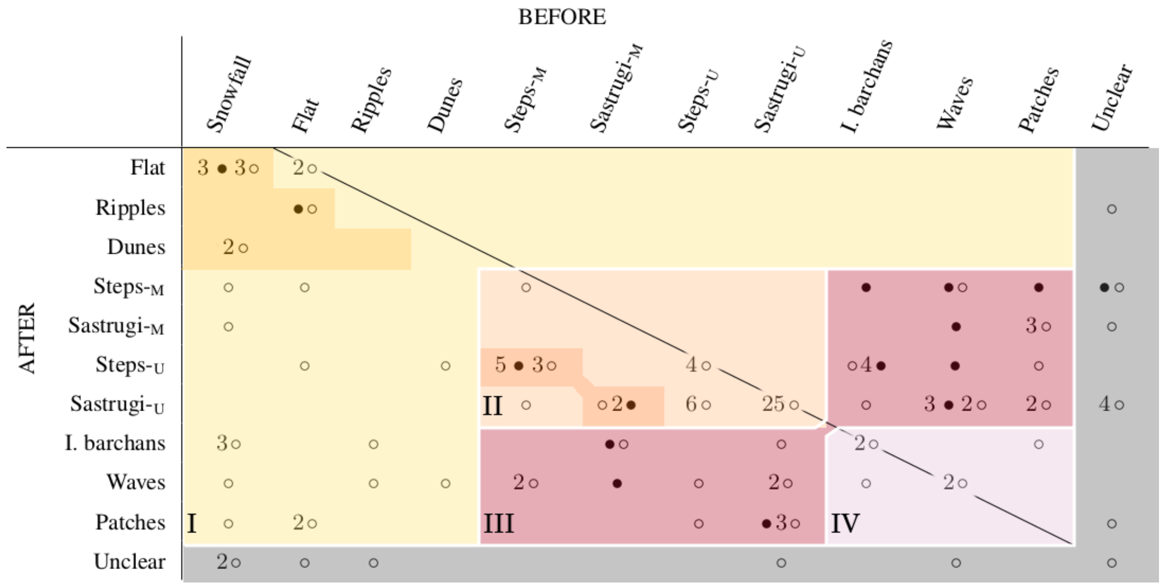

Figure 11. Transitions from one type of bedform to another, either observed directly (•) or implied during a <12 hr gap in footage (○, e.g. overnight). Snow-steps and sastrugi may be moving (M) or un-moving (U) when observed. 'Dunes' are close-packed (as in Fig. 2b), 'I barchans' are separated (as in Fig. 2d).

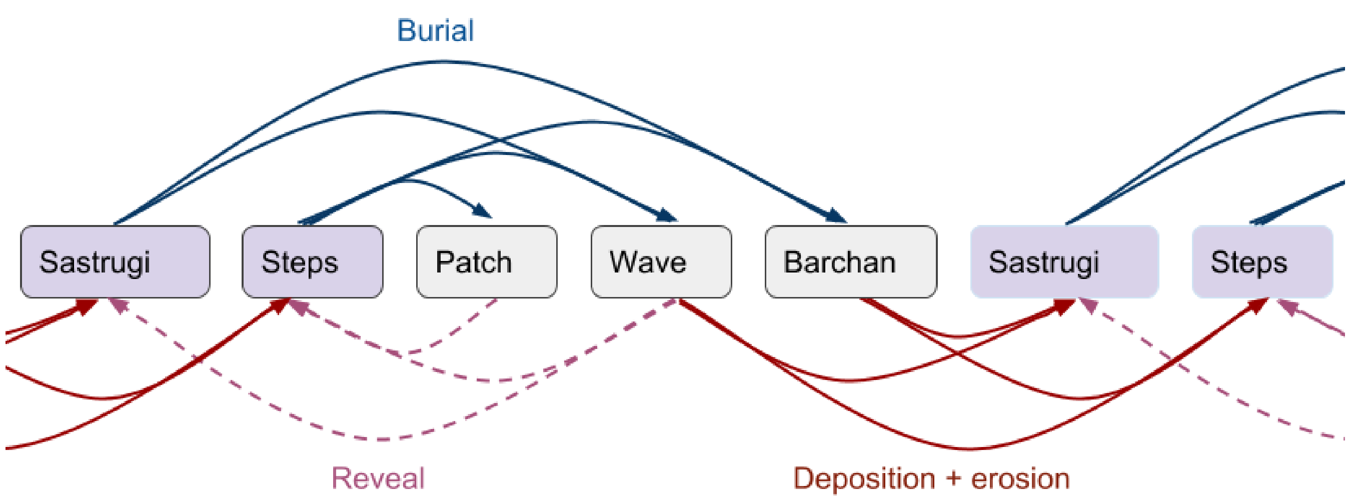

Figure 12. Observed interactions between erosional bedforms and bedforms made of loose snow. Left-to-right interactions result in the net deposition of new snow on the surface. Burial (blue): a wave, dune, or patch advects onto an eroded surface and covers the existing bedforms. Reveal (dashed): the wave, dune, or patch continues traveling, and leaves the observed area without modifying the surface. Deposition + erosion (red): a wave, dune or patch deposits a layer of freshly-accreted snow onto the surface. Erosional bedforms are carved immediately in the fresh snow.

edges of snow-steps loosely resemble bedrock fluting, and the aerodynamic points of sastrugi resemble yardangs. Other snow bedforms, such as snow-waves, ~~do not have obvious analogues elsewhere in the aeolian world~~ are not obviously analogous to other aeolian features , but mediate the transitions between the sand-like and bedrock-like bedforms.

We use these observations to place snow bedforms into three categories that we use in the remainder of this discussion:

– *Loose-surface bedforms* consist entirely of granular snow, which creeps or saltates downwind and slips when over-steepened. The bedforms on these surfaces resemble aeolian sand features. These include close-packed dunes and ripples.

– *Hardened-surface bedforms* are cohesive, solid, and shaped by erosion. These include snow-steps and sastrugi.

– *Mixed-surface bedforms* consist of loose snow traveling over a hardened-snow surface. Loose-surface and hardened-surface bedforms alternate in patches or stripes. These include isolated barchan dunes and snow-waves.

4.1 The processes that shape snow surfaces

~~Fig. 13 illustrates the major snow fluxes that shape a representative bedforms from each category. Bedforms are shaped by at least four major processes: snowfall, aeolian transport, erosion, and sintering. When snowfall dominates (Fig. 13a, 4.1), snow settles flat. When snow is granular and blown by the wind, it forms loose, sand-like bedforms (Fig. 13b, 4.2). When snow is hardened, the surface evolves by erosion (Fig. 13c, 4.3). When snow rests in place (not pictured) it sinters and becomes more cohesive (Blackford, 2007). Finally, many snow bedforms are shaped by more than one of these processes (Fig. 13d, 4.6).~~ Fig. 13 illustrates the major snow processes that shape bedforms: snowfall, aeolian transport, erosion, and sintering. Here, we analyse the relative importance of these fluxes as a function of snow grain size and wind speed.

Fig. 13a shows a wind too weak to move any snow grains. This occurs when the force that the wind exerts on the surface is insufficient to overcome gravity and friction and lift any grains.

Fig. 13b shows loose-snow bedforms created by horizontal snow transport. We expect these bedforms to be created when the wind friction velocity is high enough to mobilize snow, but but not so high that all the snow is lifted away from the surface and into suspension. Li and Pomeroy (1997) found that dry snow is mobilized by winds higher than 7–14 m/s, measured at 10 m elevation. Clifton et al. found slightly higher thresholds that increased with particle density and size. Snow transport shapes all bedforms except planar surfaces.

Fig. 13 shows a hardened snow surface being eroded. The erosion rate of a solid surface is proportional to the energy of the impacting particles, minus a threshold energy that depends on the material hardness (Anderson, 1986). Thus, erosion requires a supply of loose, high-speed snow particles. The threshold erosional energy of snow is not well documented in the literature, as most snow gets harder over time. This process, known as sintering, is accelerated slightly by humidity, warmth (Colbeck, 1998), small grain sizes, and wind action (Colbeck, 1991), and accelerated by orders of magnitude by the presence of liquid water (Blackford, 2007). This process occurs for hardened and mixed-surface bedforms.

Finally, Fig. 13d shows a surface in which sintering, transport, and erosion happen at comparable rates. This forms mixed-surface bedforms, as discussed in § 4.6.

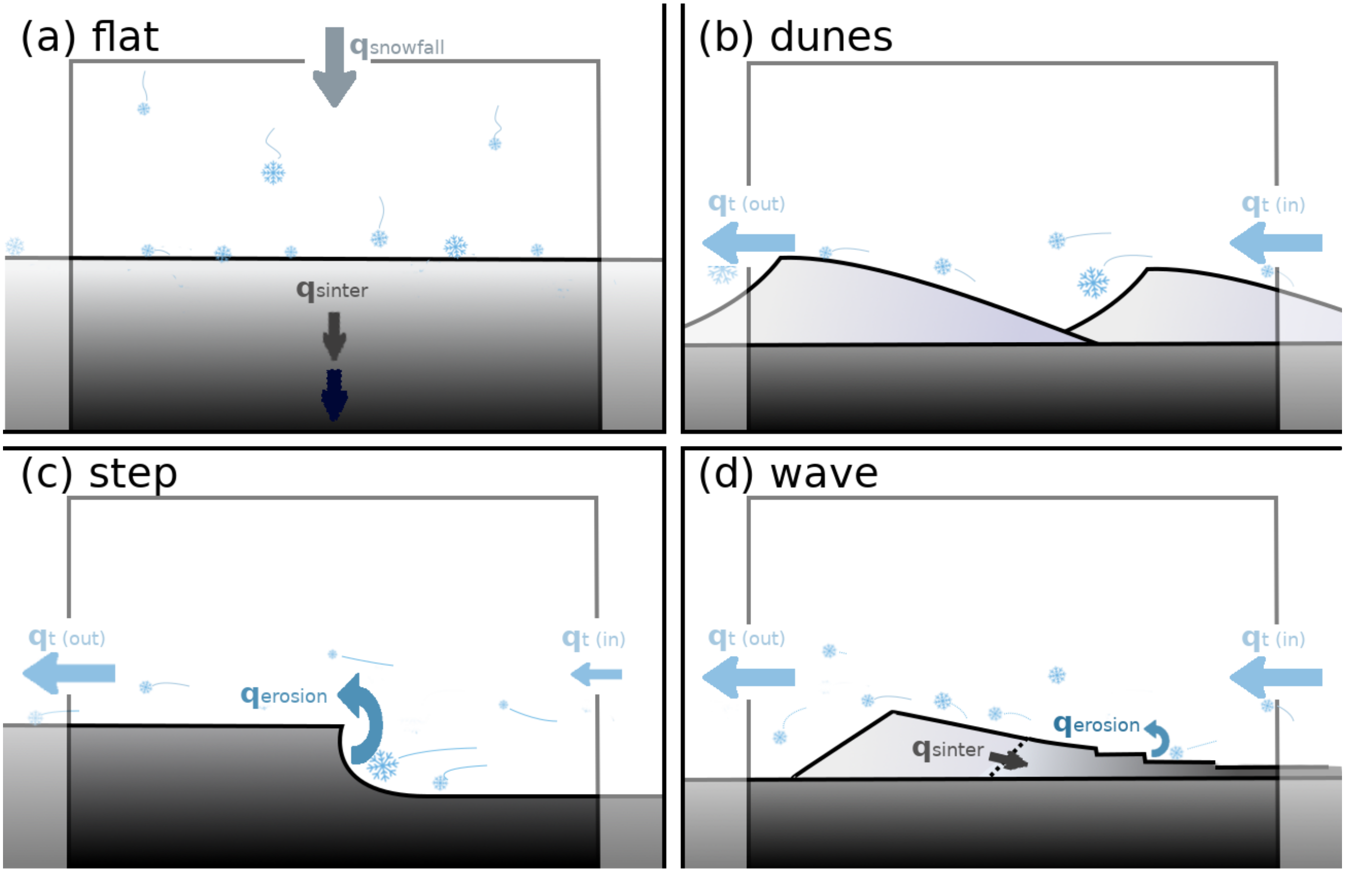

Figure 13. Expected self-organization of snow in environments dominated by (a) snowfall, (b) aeolian transport, (c) erosion, or transport on a cohesive surface, and (d) a mix of processes. Here, q refers to the total flux of snow, and q_t refers to aeolian transport by creep or saltation.

~~The horizontal flux of snow is distributed between bedload and suspended load. Suspension rates depend on the shear velocity of the wind, u , which is a function of the wind speed and the surface roughness length z 0 . Assuming a logarithmic wind profile, the wind speed u measured at height z is $u = uln(z/z0)$, where = 0.4 is the Von constant. We assume the roughness length z 0 is 0.2 mm; this is a typical value for wind blowing perfectly parallel to a sastrugi field (Inoue, 1989b) or for freshly fallen snow with small drift features (0.24 mm, Gromke et al. (2011)), but much higher than the standard values for planar snow (0.5 mm), and much lower than the values for wind blowing perpendicular to sastrugi (1 mm, Inoue (1989b)). For our field site, this gives us a shear velocity of u = 0.4 m/s in the average 10.5 m/s measured wind, and u = 0.9 m/s in a high 23 m/s measured wind. Particles begin to be suspended when the shear velocity is greater than their settling velocity, and they are transported fully in suspension when the shear velocity is twice their settling velocity (these thresholds are equivalent to Rouse number thresholds of 2.5 and 1.25). The settling velocity of fresh snow is m/s (Barthazy and Schefold, 2006), although saltating snow tends to break into ice fragments (Comola et al., 2017); assuming these fragments are spherical and move much like~~

~~water droplets, their settling velocities increase non-linearly with their size, and range from 0.1 m/s (0.05 mm diameter) to 0.3 m/s (0.1 mm) to 1.1 m/s (0.5 mm) (Anderson, 2008). We therefore expect that large snow particles (0.1 mm) are consistently transported as bedload, and that particles of 0.1 mm diameter and smaller are often suspended.~~

~~4.1 The rarity of flat snow surfaces~~

~~Flat snow surfaces are rare on Niwot Ridge, and occur only when flat snow falls during periods of gentle winds. We never saw snow blow across a flat snow surface, and suspect that any wind that lifts snow grains from the surface also initiates bedforms in the snow. We therefore hypothesize that flat snow surfaces occur only when the shear velocity of the wind is below the entrainment threshold for the snow. Li and Pomeroy (1997) estimated that for dry snow this threshold is equivalent to a 7.7 m/s wind speed, measured 10 m above the ground. Kochanski et al. (2018) found that flat snow on Niwot Ridge occurs at wind speeds at or below 7.3 m/s measured at 7.5 m above the ground, though the threshold is time-dependent.~~

4.2 Snow dune dynamics

Loose-snow bedforms bear many similarities to sand dunes and ripples. Here, we focus on snow dunes. For a thorough and quantitative analysis of snow ripples, see § 3.3 of Kobayashi (1980). Our observations show that sand dune motion provides a moderately useful analogue for snow dune dynamics. Many of the processes that shape sand dunes appeared around the snow dunes that we observed, including saltation, suspension, creep (§ 3.1.2), and grain sorting (Fig. 5b). In the following paragraphs we discuss three major differences between sand dunes and snow dunes, and present conceptual models to explain these differences.

First, snow dunes are small. The dunes we observed varied from approximately 7–55 cm in height (see examples in Fig. 2). We saw at least one well-formed dune barely longer than my snow-shoes (about 40 cm, see 2c). Other reports from Antarctica (Doumani, 1967) and Alaska (Filhol and Sturm, 2015) have also documented snow dunes only tens of centimeters high ~~(Doumani, 1967)~~ , even in snowy, cold environments where dunes should have considerable time to grow. Some but not all of the size difference may be attributed to known scaling laws. The fundamental length scale for sand saltation and sand dune growth is $\lambda_{\max} = 50 d \rho_s / \rho_f$, where d is the grain size, ρ_f is the fluid air density, and ρ_s is the solid grain density (Elbelrhiti et al., 2005). Saltating snow grains on Niwot Ridge have an effective density of perhaps half the density of ice (450 kg/m^3, noting that the density of snow grains is bounded by the density of ice and the), occur at low air density due to altitude (0.860 kg/m^3 at -5^{o}C), and are perhaps 0.2 mm in diameter, leading to a value of $\lambda_{\max} \approx 5.2$ m. For contrast, a typical value of $\lambda_{\max}$ for Sahara sand is 20.4 m (Elbelrhiti et al., 2005). The snow dunes that we observed, however, were not even a quarter the size of Sahara sand dunes. We therefore infer that at least one process that is present in snow but not in sand limits the size of dunes.

Second, sand dunes have downwind slip, or avalanche, faces, but not all of the snow dunes that we saw were steep enough to slip. The dunes in Figs. 2a and c clearly have steep slip faces, but the dunes in Fig. 2d appeared to be nearly flush with the snow. The dunes in Fig. 2b and Fig. 4 are indeterminate.

Third, the speeds of sand dunes are inversely proportional to their heights (Bagnold, 1937; Vermeesch and Drake, 2017). We do not observe this relationship in snow dunes. Although Fig. 9 clearly snows small ripples moving faster than the larger bedform that they cover, when we explicitly tracked the velocities and heights of a field of dunes (Fig. 3), we did not find a systematic dispersion relationship.

These three features — dispersion, size, and avalanching — are all manifestations of the pattern of mass flow around a dune. The dispersion relationship for sand dunes is a direct function of the conservation of sand flux (Bagnold, 1941; Vermeesch and Drake, 2017). If all dunes in a field are exposed to the same flux of blowing sand, and all of them trap this same flux on their lee slopes, then their velocity will be inversely proportional to their height. Thus, as we document that snow dune velocities are not inversely related to the dune heights, we infer that snow flux is not conserved within individual snow dunes. Lack of snow conservation within a dune might occur when (1) a dune loses mass to sublimation (2) gains mass from snowfall, (3) the driving wind speed varies rapidly, or (4) a dune exchanges mass with its neighbors.

Our observations indicate that sintering is the primary limit on dune size on Niwot Ridge, although we cannot discount the removal of particles into suspension. Snow dune size could plausibly be limited by three processes: sublimation, suspension and sintering. We have considerable evidence that snow sinters in dunes. We saw several hardened barchan dunes; the dunes in Fig. 2a were hard enough to support the author's weight. We also saw hints of a snow stratigraphy and cohesive snow-steps in the wakes of the mobile dunes in Fig. 2c and Fig.2d. In contrast, we did not find evidence that sublimation limits the size of snow dunes. The sublimation rates on Niwot Ridge are very slow relative to the speed of snow dunes (§ 3.1.9), and we know that dunes do not grow larger even in very cold locations, such as Antarctica (Doumani, 1967) and Alaska (Filhol and Sturm, 2015), where sublimation rates are yet lower than on Niwot Ridge.

We hypothesize that low-lying, non-avalanching, non-flux-conserving dunes could be formed by rapid changes in the wind speed. In order for a dune to have a downwind avalanche face, many wind-blown grains must fall out of the air onto the avalanche face. In sand dunes, grains fall out of the air in the recirculation zone downwind of the dune and land on the avalanche face (as in Fig. 14a). If the wind rises, however, the hop lengths of saltating grains will lengthen. Saltating grains may then miss the slip face entirely and collect in a drift downwind of the dune (Fig. 14b). ~~The recirculation zone in turn is generated by the strong negative step in the bed formed at the brink of the dune. If the wind rises, however, the recirculation zone will lengthen, and the hop lengths of saltating grains will lengthen, while the length of the slip face stays the same. Saltating grains may then miss the slip face entirely and collect in a drift downwind of the dune (Fig. 14b).~~ This is only possible in small dunes whose slip faces are similar in length to the saltation hop length. ~~If too large a number of grains miss the slip face, the dune will lose mass and dwindle.~~ Small, non-avalanching dunes are likely transient features, because if too many grains miss the slip face the dune will lose mass and dwindle away. The final shape of a snow surface, however, is usually set within one or two days of snowfall (Filhol and Sturm, 2015), so even short-lived features may play important roles in the surface evolution.

4.3 Snow-step erosion

All of the hardened-snow bedforms that we have observed are characterized by steep windward edges. We hypothesize that these steep edges hold the key to a general understanding of snow surface erosion. Our observations have shown that snow-

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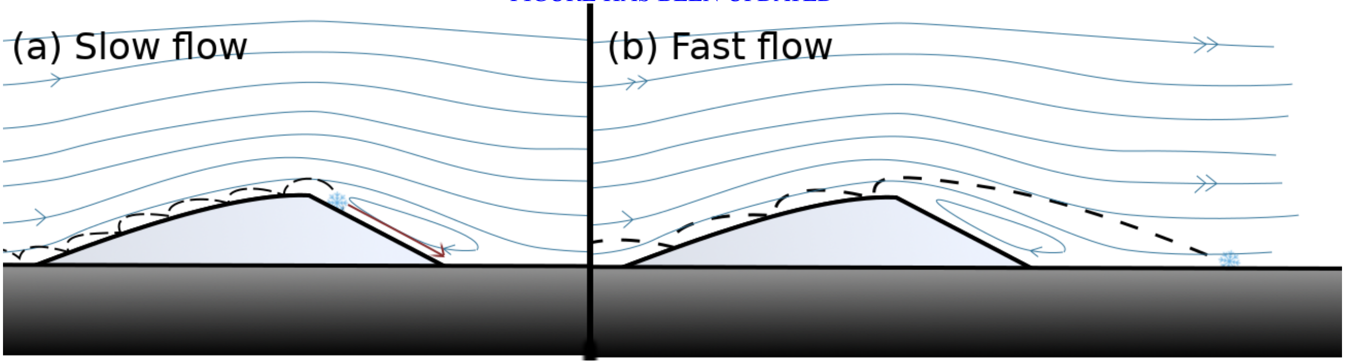

Figure 14. Conceptual model of grain transport over a dune in (a) slow-moving air and (b) fast-moving air. Solid blue lines are time-averaged streamlines, with boundary-layer fluctuations omitted for clarity. Dashed black line shows a grain trajectory. The arrow in (a) shows an avalanche path.

FIGURE UPDATED

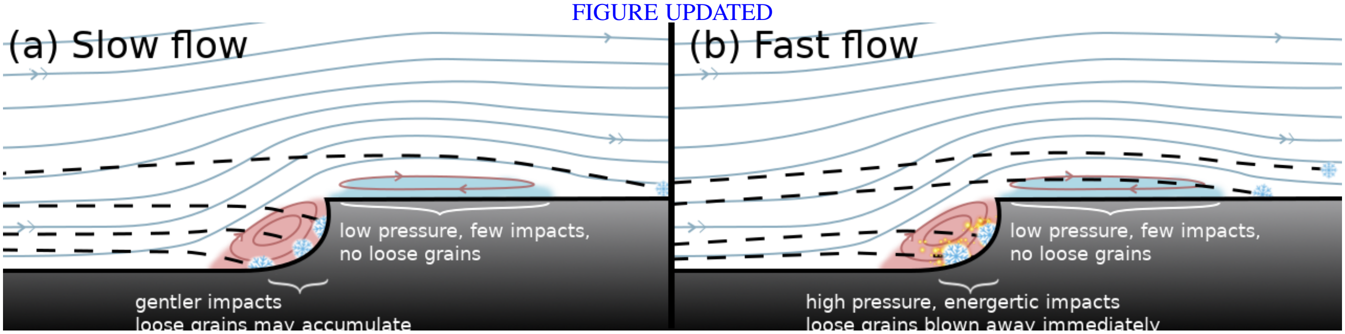

Figure 15. Conceptual model for air and particle flow over a snow-step in (a) slow-moving and (b) fast-moving air. Solid lines show idealized streamlines over the step, including two regions of detached flow (shaded in a). Dashed black lines show snowflake trajectories.

steps and sastrugi ~~retreat~~ migrate downwind, which indicates that erosion is concentrated on the vertical steps. In Fig. 15, we present a conceptual model that demonstrates how this erosional pattern could be generated around a snow-step.

The flow pattern around our conceptual step is modelled after the flow around an upwind-facing step in steady laminar flow. Steps create two ~~flow detachments~~ recirculation zones : one on the upwind side of the step, where flow stagnates, and one on the top of the step (shaded in Fig. 15) . ~~Each flow detachment is associated with a recirculation zone (shaded in Fig. 15a) with slow, overturning flow. We have ommitted boundary-layer eddies and turbulence for clarity, and have neglected the loss of flow momentum to saltating particles and the porous snow.~~

This flow pattern offers several opportunities for particles to detach from the flow and strike the area around the step. When the flow encounters the step, it reaches an equilibrium state in which the pressure in the ~~stagnation~~ upwind recirculation zone is just high enough to deflect the flow past the step. Snow grains, however, are 200–1000 times denser than air, and thus will be accelerated 200-1000 times more slowly by a given force; the pressure gradient that lifts the air flow will barely deflect the grains. Thus, if the incoming angle of a particle is sufficiently low, that particle strikes the step. This process has been modelled in detail for flow around cylinders, spheres, and disks (Langmuir and Blodgett, 1946; May and Clifford, 1967). Around the forward-facing step, we expect that the highest impact rates will occur before the step and on its vertical face, where gravity assists inertia in detaching particles from the flow. We expect that the lowest impact rates will occur on the top of the step, as particles that successfully cross the step must have upward momentum that will delay their fall.

Only the most energetic of the detached particles will strike the vertical face of the step. Particles that detach from the flow lose energy to air resistance. Any particle that loses too much energy will fall out of the flow without striking the step. These particles are unlikely to carry enough energy to cause erosion. ~~The length of the stagnation zone, and therefore the energy it removes from detached particles, increases with the height of the step and decreases with wind speed~~ . We therefore expect particles to reach the step at ~~more-than-linearly~~ greater rates in high winds, when the particles have high initial energies ~~and the stagnation zone is compressed~~ , than during periods of low wind (compare Figs 15a and b). We also expect fewer particles to strike taller steps, which create longer stagnation zones, than shorter steps. This could place an upper limit on the heights of snow-steps.

Finally, as described above, the erosion rate of solid materials is proportional to the energy of the impacting particles minus a threshold energy (Anderson, 1986). ~~Therefore, steps can only be eroded if two conditions are met: the steps must be struck by saltating particles, and those particles must have more than the threshold energy upon impact.~~ In Fig. 7b, we showed an example of differential erosion on two layers of snow-steps. As these steps were subject to the same fluxes of wind and snow, we assume that the older, non-eroding layer had a higher erosion threshold. ~~The threshold energy for the erosion of snow, unlike the erosion of bedrock, depends on time and weather. Dry, undisturbed snow sinters, or hardens, with time (Colbeck, 1998). Sintering can be accelerated by wind action (Colbeck, 1991), and is accelerated by several orders of magnitude by the presence of any liquid water (Blackford, 2007). Previous work at our field site found that snow-steps stop moving days after snowfall, or immediately after the temperature rises above o C (Kochanski et al., 2018).~~ Based on our current observations, however, we do not expect snow-step erosion rates to be determined by the average properties of the snow pack. Fig. 9c shows five snow-steps moving at different velocities, despite being mere meters apart. Those snow-steps decelerated over time. We infer from this that snow-step erosion rates are a function of the age of the step, but that this age differs from step to step across the shifting landscapes of bedform-covered snow.

4.4 Stealth dunes

We presented one previously undocumented erosional bedform: the stealth dune. Like other erosional bedforms, they have vertical windward edges, and like sastrugi they present points to the wind. Unlike sastrugi, however, they have distinct crescent shapes and are not arranged in a regular pattern. We saw stealth dunes only on the surface of Barker Reservoir, and have only found one record of them in the prior literature: Cornish (1902) sketched an "erosion form analogous to a barchan" on land in British Columbia. Cornish hypothesized that these dunes are the eroded remnants of transverse waves. We concur. We occasionally see complete waves downwind of the stealth dunes on Barker Reservoir. Our observations allow three reasons why these dunes are rarely reported: (1) they are formed from snow waves, and little previous literature has documented snow-waves, (2) Barker Reservoir, with its narrow valley and upwind town, provides a rare combination of high, unidirectional winds and low snow supply, or (3) stealth dunes are visible only in contrast to a dark surface, like lake ice.

4.5 Sastrugi formation

Sastrugi are the most widespread snow bedform (Filhol and Sturm, 2015), and can be the largest (Mather, 1962). They are therefore more interesting, from a broad view of the polar sciences, than other bedforms. We fear, however, that they are also more complex.

To develop a model of sastrugi evolution, we will need to overcome major field and computational challenges. First, stationary sastrugi geometries have not yet been characterized in detail. This problem may be solved by ongoing LiDAR studies. Second, sastrugi evolution is not easy to observe. Kochanski et al. (2018) found that sastrugi are formed during winds of at least 20 m/s (45 mph); in our study, we captured many hours of data without observing an instance of sastrugi formation. Third, sastrugi, unlike snow-steps, are fully three-dimensional features, and wind-blown snow follows winding three-dimensional paths between their points. Moreover, we have shown that even a simpler bedform, the snow-step, is stabilized by complex flow structures and flow detachments. We therefore suspect that a successful model of sastrugi must resolve the three-dimensional flow structures around sastrugi points. We are, however, optimistic that grain sorting and wind-pumping are secondary effects that could be excluded from a useful model. Such a model, especially if it included the motion of blowing snow grains, would still require considerable computational expense.

4.6 Cycles of deposition and erosion

In Fig. 13d, we presented a conceptual model of a bedform in which aeolian transport, snow accretion, and erosion coexist. This is a mixed-surface bedform, in which loose snow and hardened snow alternate on the ground. The preeminent examples of mixed-surface bedforms are snow-waves. In the field, we saw wave crests made of loose, granular snow, with snow-steps forming in cohesive snow on their upwind sides (e.g. Fig. 8c). From these observations, we infer that loose snow is deposited on the downwind lee of the wave, that the snow becomes cohesive in the time it takes for the wave to move past, and that some but not all of the newly-deposited snow is eroded into steps. At least some snow grains are thus accreted onto the surface during passage of the wave, some of which are then eroded back out of it with every passing wave (Fig. 12). If this conceptual model is correct, then the nature of hardened-surface bedforms — and the presence or absence of accreted snow — is determined by the frequency of passing snow dunes and waves.

This pattern invites us to consider cycles of erosion and deposition on longer length and time scales. When a region of snow ~~is deeply eroded~~ erodes , it releases snow particles into the wind. ~~This increases the flux of transported snow into downwind regions, pushing them from erosional to depositional regimes. Snow bedforms, then, are local manifestations of long-distance snow transport.~~ Thus, the erosion of upwind bedforms may provide a snow flux that drives the evolution of downwind bedforms. The effect of this snow flux will depend on the wind speed and the nature of the downwind bedforms. If the wind speed decreases, we expect blowing snow to be deposited in dunes, waves, or smooth drifts. In windswept conditions, we have seen blowing snow grains erode snow-steps, and remove mass from snow dunes.

5 Conclusions

Here we have presented numerous examples of snow bedform movement to illustrate the modes of bedform growth and evolution. These examples are drawn from a library of over 1000 hours of time-lapse footage of snow bedform evolution, available at Kochanski (2018b), and from detailed field observations in the Colorado Front Range. The data include a large number of observations of snow-waves (examples in § 3.1.6) and the first description of an erosive feature we term the 'stealth dune' (Fig. 10).

We have used the observations published here to develop conceptual models of the evolution of snow barchans, snow-steps, and snow waves. We propose that snow bedforms should be characterized in terms of the primary processes that form them: snowfall, aeolian transport, erosion of cohesive substrates, and sintering.

These processes are all well-known to snow scientists and Earth surface scientists, but their interactions have not yet been studied. We hypothesize that future studies of snow bedforms will reveal new regimes of self-organization in nature, and lead us towards a quantitative understanding of the snow features that cover the alpine and polar regions of Earth.

Data availability. Time-lapse observations from March 2016–April 2017 are archived at http://doi.org/10.5281/zenodo.1253725 (Kochanski, 2018b). Weather (Losleben, 2018a) and precipitation (Losleben, 2018b) data for the Niwot Ridge field site are available from the Niwot Ridge Long-term Ecological Research program at niwot.colorado.edu.

Author contributions. K. Kochanski acquired funding for field equipment, carried out the field campaign, analysed the data and wrote the manuscript. G. Tucker and R. Anderson supervised the project. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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References

Amory, C., Naaim-Bouvet, F., Gallée, H., and Vignon, E.: Brief communication: Two well-marked cases of aerodynamic adjustment of sastrugi, The Cryosphere, 10, 743–750, https://doi.org/10.5194/tc-10-743-2016, 2016.

Amory, C., Gallée, H., Vincent, F. N.-B., Vignon, E., Picard, G., Trouvilliez, A., Piard, L., Genthon, C., and Bellot, H.: Seasonal variations in drag coefficient over a sastrugi-covered Snowfield in coastal East Antarctica, Boundary-Layer Meteorology, 164, 107–133, https://doi.org/10.1007/s10546-017-0242-5, 2017.

Anderson, R. S.: Erosion profiles due to particles entrained by wind: application of an eolian sediment-transport model, Geological Society of America Bulletin, 97, 1270–1278, 1986.

Bagnold, R. A.: The transport of sand by wind, The Geographical Journal, 89, 409–438, 1937.

Bagnold, R. A.: The Physics of Blown Sand and Desert Dunes, Methuen, London, 1941.

Blackford, J. R.: Sintering and microstructure of ice: a review, Journal of Physics D: Applied Physics, 40, R355–R385, https://doi.org/10.1088/0022-3727/40/21/R02, 2007.

Brown, D.: Tracker : Video analysis and modeling tool, https://physlets.org/tracker/, 2018.

Clifton, A., R uedi, J.-D., and Lehning, M.: Snow saltation threshold measurements in a drifting-snow wind tunnel, Journal of Glaciology, 52, 585–596, https://doi.org/10.3189/172756506781828430.

Colbeck, S. C.: The layered character of snow, Reviews of Geophysics, 29, 81–96, 1991.

Colbeck, S. C.: Sintering in a dry snow cover, Journal of Applied Physics, 84, https://doi.org/10.1063/1.368684, 1998.

Corbett, J. and Su, W.: Accounting for the effects of sastrugi in the CERES clear-sky Antarctic shortwave angular distribution models, Atmospheric Measurement Techniques, 8, 3163–3175, https://doi.org/10.5194/amt-8-3163-2015, 2015.

Cornish, V.: On snow-waves and snow-drifts in Canada, with notes on the "snow-mushrooms" of the Selkirk Mountains, The Geographical Journal, 85, 342–365, https://doi.org/10.2307/1774538, 1902.

Doumani, G. A.: Surface structures in snow, in: International Conference on Low Temperature Science: Physics of Snow and Ice, pp. 1119–1136, Hokkaido University, Hokkaido, Japan, 1967.

Elbelrhiti, H., Claudin, P., and Andreotti, B.: Field evidence for surface-wave-induced instability of sand dunes, Nature, 437, 720–723, https://doi.org/10.1038/nature04058, 2005.

Filhol, S. and Sturm, M.: Snow bedforms: A review, new data, and a formation model, Journal of Geophysical Research: Earth Surface, 120, 1645–1669, https://doi.org/10.1002/2015JF003529, 2015.

Filhol, S., Pirk, N., Schuler, T., and Burkhart, J. F.: The evolution of a snow dune field, in: American Geophysical Union, Fall Meeting, pp. C51E–01, New Orleans, LA, USA, 2017.

Goodwin, I. D.: Snow accumulation and surface topography in the katabatic zone of Eastern Wilkes Land, Antarctica, Antarctic Science, 2, 235–242, https://doi.org/10.1017/S0954102090000323, 1986.

Harder, S., Warren, G., and Charlson, R. J.: Sulfate in air and snow at the South Pole: Implications for transport and deposition at sites with low snow accumulation, Journal of Geophysical Research, 105, 22,825–22,832, https://doi.org/10.1029/2000JD900351, 2000.

Hunter, J. D.: Matplotlib: A 2D graphics environment, Computing in Science & Engineering, 9, 90–95, 2007.

Inoue, J.: Surface drag over the snow surface of the Antarctic Plateau 1. Factors controlling surface drag over the katabatic wind region, Journal of Geophysical Research, 94, 2207–2217, https://doi.org/10.1017/CBO9781107415324.004, 1989a.

Inoue, J.: Surface drag over the snow surface of the Antarctic Plateau 2. Seasonal change of surface drag in the katabatic wind region, Journal of Geophysical Research, 94, 2219–2224, https://doi.org/10.1017/CBO9781107415324.004, 1989b.

Jackson, B. S. and Carroll, J. J.: Aerodynamic roughness as a function of wind direction over asymmetric surface elements, Boundary-Layer Meteorology1, 14, 323–330, 1978.

Kobayashi, S.: Studies on interaction between wind and dry snow surface, Contributions from the Institute of Low Temperature Science, A29, 1–64, 1980.

Kochanski, K.: The movement of snow bedforms in the Colorado Front Range, https://doi.org/10.5446/38612, https://av.tib.eu/media/38612, 2018a.

Kochanski, K.: Time-lapse observations of snow bedforms in the Colorado Front Range, 2016-2017 [Data set], https://doi.org/10.5281/zenodo.1253725, 2018b.

Kochanski, K.: Time-lapses of snow bedforms in the Colorado Front Range, http://www.kochanski.org/kelly/snow-bedforms-in-the-colorado-front-range/, 2018c.

Kochanski, K., Tucker, G., and Anderson, R. S.: Statistical classification of self-organized snow surfaces, Geophysical Research Letters, 45, 6532–6541, https://doi.org/10.1029/2018GL077616, 2018.

Kosugi, K., Nishimura, K., and Maeno, N.: Snow ripples and their contribution to the mass transport in drifting snow, Boundary-Layer Meteorology, 59, 59–66, https://doi.org/10.1007/BF00120686, 1992.

Langmuir, I. and Blodgett, K.: A mathematical investigation of water droplet trajectories, U.S. Army Air Force Technical Report 5418, 1946.

Leonard, K. C.: Antarctic Snow Drift Processes, Ph.D. thesis, Columbia University, 2009.

Leroux, C. and Fily, M.: Modeling the effect of sastrugi on snow reflectance, J. Geophys. Res., 103, 1998.

Li, L. and Pomeroy, J. W.: Estimates of threshold wind speeds for snow transport using meteorological data, Journal of Applied Meteorology, 36, 205–213, https://doi.org/10.1175/1520-0450(1997)036<0205:EOTWSF>2.0.CO;2, 1997.

Liston, G. E., Polashenski, C. M., Rosel, A., Itkin, P., King, J., Merkouriadi, I., and Haapala, J.: A Distributed Snow-Evolution Model for Sea-Ice Applications (SnowModel), Journal of Geophysical Research: Oceans, pp. 3786–3810, https://doi.org/10.1002/2017JC013706, 2018.

Losleben, M.: Precipitation data for Saddle chart recorder from 1981-7-31 to ongoing, daily, 2018a.

Losleben, M.: Climate data for Saddle data loggers (CR23X and CR1000) from 2000-6-24 to ongoing, daily., http://niwot.colorado.edu, 2018b.

Mather, K. B.: Further observations on sastrugi, snow dunes and the pattern of surface winds in Antarctica, Polar Record, 11, 158–171, https://doi.org/10.1017/S0032247400052888, 1962.

May, K. and Clifford, R.: The impaction of aerosol particles on cylinders, spheres, ribbons and discs, The Annals of Occupational Hygiene, 10, 83–95, https://doi.org/10.1093/annhyg/10.2.83, 1967.

Oliphant, T. E.: Guide to NumPy, CreateSpace Independent Publishing Platform, USA, 2007.

Petrich, C., Eicken, H., Polashenski, C. M., Sturm, M., Harbeck, J. P., Perovich, D. K., and Finnegan, D. C.: Snow dunes: a controlling factor of melt pond distribution on Arctic sea ice, Journal of Geophysical Research: Oceans, 117, https://doi.org/10.1029/2012JC008192, 2012.

Vermeesch, P. and Drake, N.: Remotely sensed dune celerity and sand flux measurements of the world's fastest barchans, Geophysical Research Letters, 35, https://doi.org/C0.1029/2008GL035921, 2017.

Warren, S. G., Brandt, R. E., and O'Rawe Hinton, P.: Effect of surface roughness on bidirectional reflectance of Antarctic snow, Journal of Geophysical Research, 103, 25 789, https://doi.org/10.1029/98JE01898, 1998.