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

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S1 Contents of video S1

Video S1 (Kochanski (2018), available at https://av.tib.eu/media/38612, doi:10.5446/38612) shows time-lapse imagery of the movement of bedforms on Niwot Ridge. Many figures in the text were derived from this imagery:

Start time in video S1	Title	Related Figure
0:07	Close-packed snow dunes	Fig. 3b
0:38	Barchan snow dunes	Fig. 3d
0:56	Tiny barchan dune, close-up	Fig. 3c
1:06	Barchan snow dunes	Fig. 4a
1:33	Snow ripples	Fig. 5a
2:06	Sand-on-snow ripples	Fig. 5b
2:24	Ripples emerge from flat snow	Fig. 5c
2:51	Sastrugi retreat (play video at high speed)	Fig. 6a
3:06	Sastrugi retreat between snow-waves	Fig. 6b
3:32	Snow-steps behind wave	Fig. 7a
3:57	Snow-steps, two layers	Fig. 7b
4:17	Snow-wave	Fig. 8b
4:44	Snow-wave with ripples and snow-steps	Fig. 9a

S2 Observations of snow bedforms throughout the Front Range

During our initial survey of snow bedforms, we observed diverse snow features on numerous fields, ridges, and frozen lakes throughout the Front Range. These observations are summarized in Table S1. Our observations on Niwot Ridge are listed in Table S2.

Name	Lat.	Long.	Alt.	Site notes	Trip date(s)	Trip notes
Barker Res.	39.963	-105.501	2483m	See 'Methods'	Various	Stealth dunes, wingspans 5cm–2m.
					26/Dec/2016	Stealth dunes, wingspans up to 5m.
Baseline Res.	40.002	-105.204	1621m	900m reservoir on plains	13/Jan/2016	Smooth snow, heavy with melt.
Boulder Res.	40.074	-105.229	1579m	1850m reservoir marred by skiiers	25/Jan/2016	Warm day. Semi-melted snow w/suncups.
Brainerd Lake	40.078	-105.575	3158m	430m lake in forested valley	18/Nov/2016	Windswept ice, ground blizzard. On-shore snowdrifts have ripples and tiny sastrugi.
					4/Feb/2017	Lumpy drifts, tiny sastrugi.
Gold Camp Rd	38.745	-105.123	3030m	Mountain pass strung w/snow fences	28/Dec/2016	Elaborate ripples behind snow fence.
Kite Lake	39.330	-106.130	3667m	195m-long lake in alpine meadow.	18/Feb/2018	Windy Day. Flat snow, shallow sastrugi.
Lake Peterson	40.557	-105.790	2899m	860m lake in forested valley	14/Jan/2016	Shallow sastrugi, indistinct drifts.
Lefthand Res.	40.069	-105.557	2520m	1050m reservoir in forested valley	07/Jan/2016	Good weather. Snow-waves on sastrugi.
					04/Feb/2016	Windy, cold. Fresh drifts on old sastrugi.
					22/Feb/2017	Falling powder. Flat snow everywhere.
Lily Lake	40.307	-105.540	2725m	470m lake in sparse alpine forest	30/Jan/2018	Clear day. Possible dune remnants.
Mt Democrat	39.341	-106.134	4156m	High ridge between two summits	18/Feb2/2018	Clear day, windy. Shallow sastrugi.
Niwot Ridge D1	40.050	-105.616	3741m	Upwind end of Niwot Ridge	28/Mar/2016	Clear, fresh snow. Lanceolate sastrugi.
					20/Jan/2018	Clear, warm. Shallow sastrugi + bare rock.
Quandary Ridge	39.393	, -106.078	3693m	Alpine ridge	09/Mar/2018	Clear day, low wind. Flat snow below treeline, higher elevations windswept.

Table S1. Bedforms observed throughout the Colorado Front Range.

Date	Weather	Bedforms observed
21/Feb/2016	Clear day	Well-developed sastrugi
17/Mar2016	Clear day	Well-developed sastrugi
Date	Weather notes	Bedforms
26/Mar/2016	Falling snow	Flat surface
27/Mar/2016	Ground blizzard	Ripples at 9am, soft sastrugi by 6pm
28/Mar/2016	Clear day	Well-developed sastrugi, angular, some lanceolate
17/Apr/2016	Clear day	Well-developed sastrugi marked by suncups
11/May/2016	Clear day	Shallow sastrugi.
03/Dec/2016	Blowing snow	Shallow sastrugi, much exposed bare ground.
02/Jan/2017	Clear day.	Very large sastrugi/.
03/Jan/2017	Freshly-fallen snow	Flat surface
27/Jan/2017	Ground blizzard, cold.	Well-formed sastrugi.
28/Jan/2017	Ground blizzard.	Loose snow on soft sastrugi, occasional ripples
18/Feb/2017	Day-old snow, windy, some blowing snow	Very big sastrugi, some over a meter deep
25/Mar/2017	Snow beginning to fall in late evening.	Flat surface.
26/Mar/2017	Day after light snowfall.	Smooth, flat snow filling toughs of suncup-coverd sastrugi.
09/Nov/2017	Ground blizzard	Many snow-waves, tiny barchan dunes
12/Nov/2017	Ground blizzard	Patchy snow cover, tall snow-waves on shallow sastrugi
20/Jan/2018	Warm and sunny, gentle winds	Patchy snow, irregular sastrugi
03/Mar/2018	Clear, sunny day	20–50cm tall barchan dunes on shallow sastrugi
14/Apr/2018	Clear, sunny day	Low-lying dunes, snow-steps

Table S2. Field observations on Niwot Ridge, CO

S3 Review: the processes that shape snow surfaces

Bedforms grow from the movement of many individual grains of snow. The movements of those grains are driven by snow processes and by aeolian transport. Here, we provide a brief overview of these processes, as well as the principles of self-organization that allow these granular processes to add up to bedforms. This overview is intended to orient Earth surface process scientists unfamiliar with snow, or snow scientists new to aeolian transport. Full details and rates of each process are provided in references.

S3.1 The appearance and disappearance of snow

Snow surfaces exchange mass with the open air. Snow is usually added to a surface by snowfall. Freshly-fallen snow particles are usually larger and more dendritic than particles that have been exposed to air, warmth, or wind (Fierz et al., 2009). Snow may also be carried into an area from upwind (§).

When snow is in contact with dry air, it turns into water vapor by sublimation. This vapor moves through the pores of the snowpack. If the vapor exits into open air, the snowpack loses mass (Marks and Davis, 1992) without becoming wet. The rate of sublimation depends on the relative humidity and on the surface area of the snow, which is highest for dendritic or airborne snow.

S3.2 The solidification of snow

Water vapor forms wherever ice crystals touch air. This vapor moves through the pores between snow grains, and re-crystallizes in response to local temperature and vapor pressure gradients. This microscopic sublimation and deposition leads to the *dry metamorphism* of snow. Absent a strong temperature gradient, the water vapor tends to diffuse from the convex edges of snow particles to their concave contact points (Colbeck, 1983, 1998). This bonds the particles together and increases the hardness and cohesion of the snowpack. This process, known as *sintering*, is reviewed by Blackford (2007). Sintering depends strongly on temperature, humidity, and grain size. Small, wind-broken snow particles have high surface area and sinter extremely quickly. This process, known as *wind hardening*, forms hard, dense surface layers known as *wind slab* (Colbeck, 1991; Fierz et al., 2009).

If saturated snow is subject to repeated melting and freezing temperatures, it may form internal ice layers (Fierz et al., 2009), or a surface *sun crust* (also called a ‘rain crust’ or ‘spring crust’). Smaller quantities of liquid water, that do not fully saturate the snow, are subject to surface tension in the pores of the snow, and bond snow grains together through *wet metamorphism* much faster than they could sinter in dry air (Blackford, 2007). Most snow bedforms have been documented in dry climates where these wet processes are rare.

S3.3 The transport of loose snow and the erosion of solid snow

Airborne particles of sand or snow capture momentum from the air. When they strike the Earth, they launch further grains into the air (Anderson and Haff, 1988; Bagnold, 1941; Kobayashi, 1972; Schmidt, 1986). This process, known as saltation, is the primary method of momentum and energy transfer from the wind to a granular bed (Anderson and Haff, 1988; Schmidt, 1986). Saltation is initiated above a certain windspeed at which snow from the surface is entrained (Li and Pomeroy, 1997), and has considerable momentum thereafter.

In a unidirectional flow, saltation impacts are concentrated against the upwind sides of any emerging bedforms. This generates a positive feedback that enlarges small variations in the topography and leads to self-organization. Sustained saltation on a bed of loose grains leads to the formation of ripples (Anderson, 1987; Kobayashi, 1980). On hard surfaces, saltation impacts form bedforms such as yardangs, pits, and flutes (Laity, 1994).

The shear stress of the wind or the grain-grain forces associated with saltation impacts are not always sufficient to launch a particle into the air. Loose particles may be dislodged from the bed and rolled forward without being separated from the ground. This is known as surface creep (Bagnold, 1937).

While large wind-borne grains fall quickly back to the bed, small grains are sensitive to turbulent fluctuations in the wind. These fluctuations may buffet the grains indefinitely upward (Anderson, 1986), and create long, stochastic flight trajectories. If the grains do not return, then the wind creates a net removal of mass, known as *deflation* (Laity, 1994).

Finally, the impact forces that drive the motion of wind-blown snow also fragment snow crystals (Nemoto et al., 2014). Continuous fragmentation moves ice mass from large particles that creep and saltate into small particles that become suspended (Comola et al., 2017). This potentially limits the total advecting flux of saltating particles that can be produced from a certain quantity of snowfall, before all particles are broken into small fragments that blow or sublimate away.

S3.4 Self-organization

Self-organization occurs in unstable systems, in which tiny perturbations do not decay, but grow into large features. Ripple growth, described above and in (Anderson, 1987), is one example of self-organization driven by the growth of an instability.

The processes that drive self-organization are generally non-linear, or critical, and occur when small movements create large effects. The archetypical critical process is an avalanche of sand grains (alpine snow avalanches are more complex). When sand is piled to its angle of repose, it can get no steeper. It responds to the addition of more grains with a disproportionately large response: an avalanche. The slope angle is thereby organized, and remains unchanged as further grains are added. Avalanches organize the downwind faces of barchan dunes.

Non-linear processes and self-organization are not easy to reverse. Systems that are driven by forces with non-linear effects often exhibit hysteresis, and do not return to their previous states even if the driving force removed or reversed. Ripples, for example, do not become flat if the wind reverses; they just move in a different direction. Moreover, from a physical perspective, self-organization is generally driven by increases in entropy, and cannot be reversed without the addition of directed work or energy.

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