When does snow self-organize?

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Background: Wind-blown snow self-organizes

Wind-blown snow forms depositional (Fig. 1b-f) and erosional (Fig. 1g-j) bedforms. The most widespread bedform, sastrugi (Fig. 1h,g), textures much of Antarctica and Greenland.

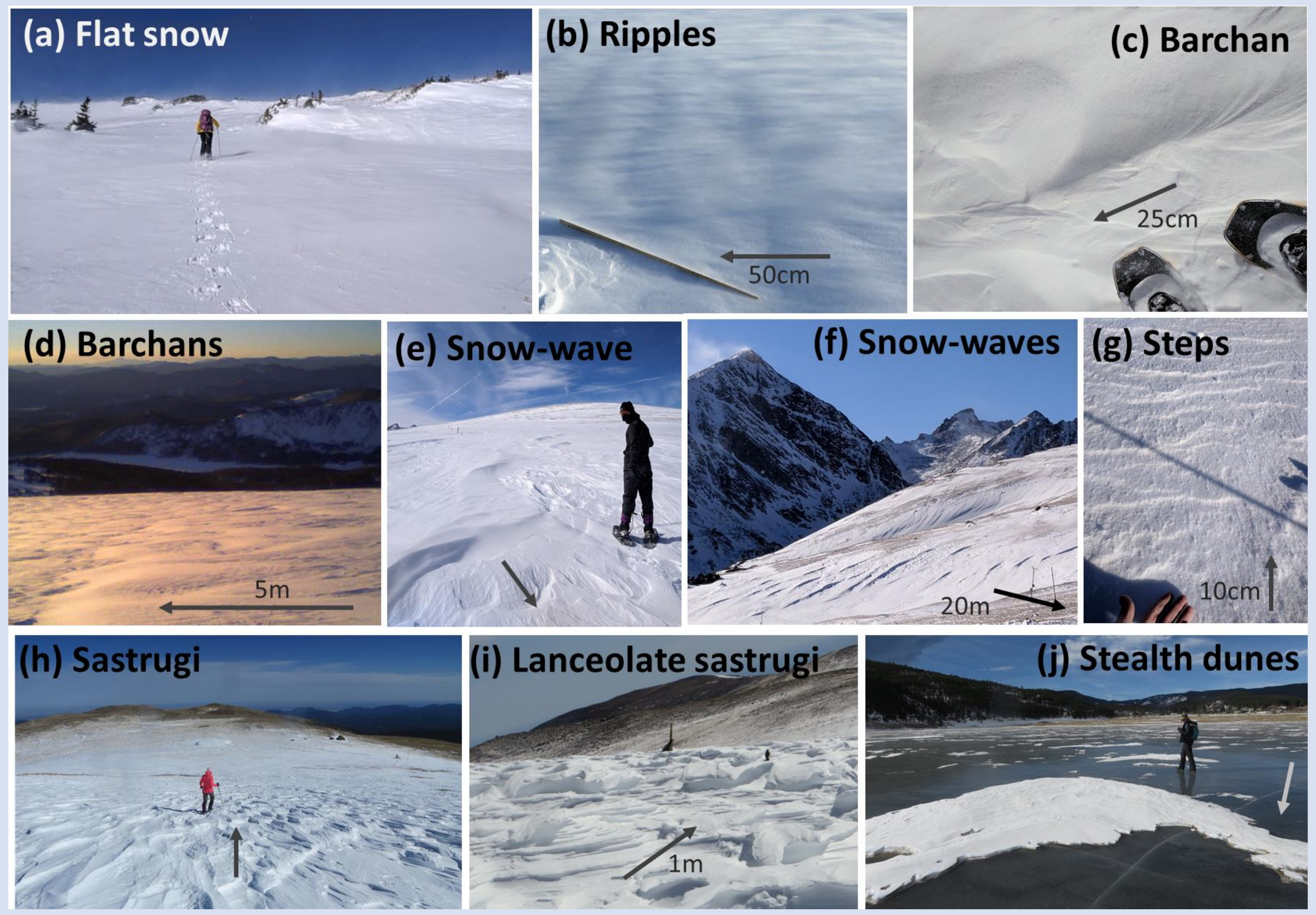

Fig 1

These bedforms have well-documented effects on the properties of snow surfaces. They increase the aerodynamic roughness of the snow [1], and lower its albedo [2] and thermal conductivity [3]. Despite these effects, no model has previously predicted where and when snow bedforms appear.

Data: Snow bedforms in the Colorado Front Range

Snow bedforms cover alpine peaks and ridges throughout the Colorado Front Range. We documented bedform growth on Niwot Ridge, Colorado. Over two winter field seasons, we collected over 800 hours of time-lapse footage showing their evolution.
Three representative evolution trajectories are shown below.

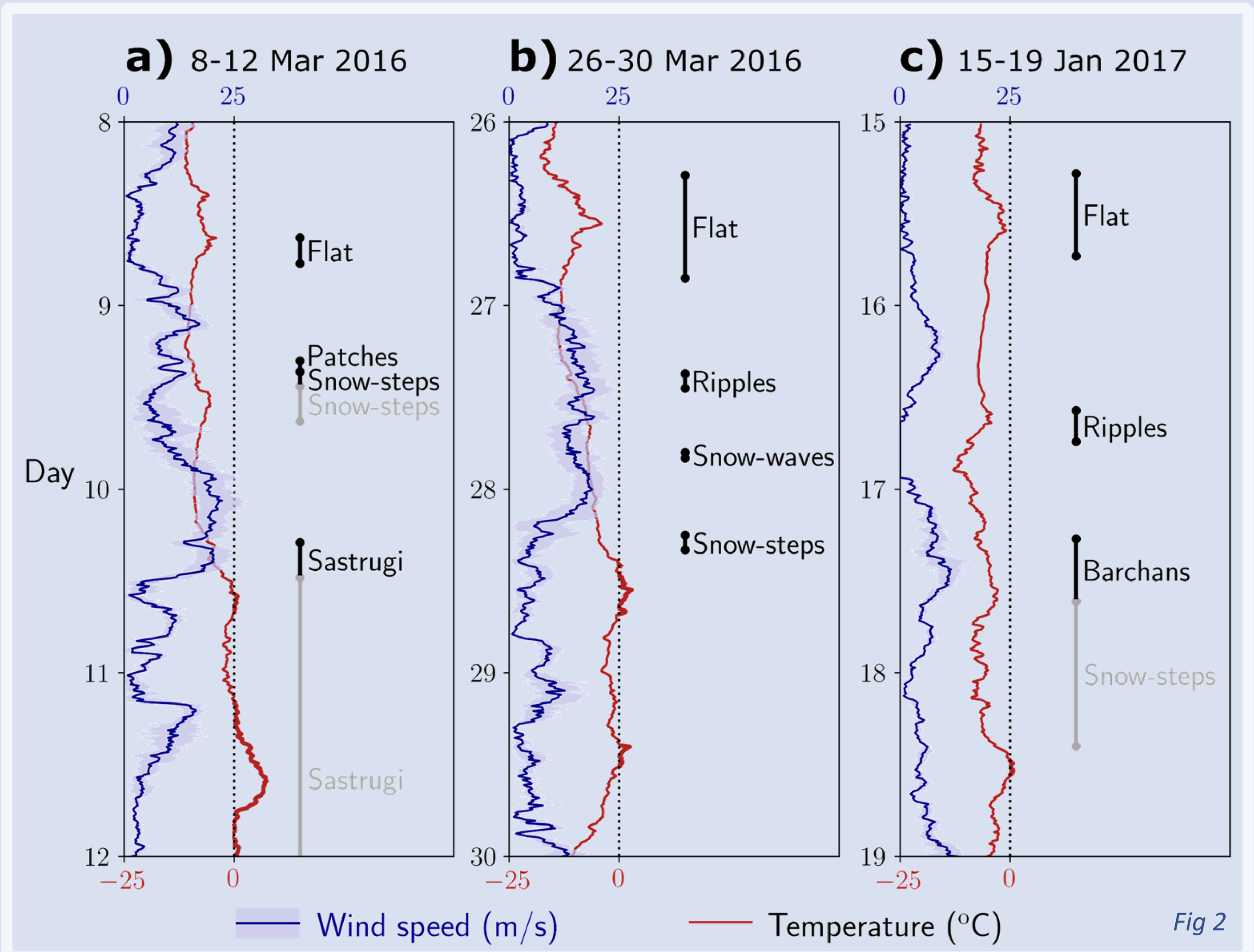

Fig 2

Snow falls flat (Figs 2a,b,c) during periods of low wind. Once the wind rises, it forms depositional features such as ripples and barchan dunes (Figs. 2b,c). These move until the snow begins to harden. Cohesive snow forms erosional bedforms, such as small snow-steps (Figs. 2a,b) or larger sastrugi (2a).

Analysis: Statistical classification of self-organized snow surfaces

We aimed to identify weather conditions that produce

1. Snow bedforms as opposed to flat surfaces, and
2. Sastrugi, the largest bedforms, as opposed to anything else

Input variables

First, we identified a set of weather variables likely to influence the growth of snow bedforms. These include wind processes likely to roughen a granular surface, and time and temperature processes associated with snow hardening. The full list is in Table 1. All data is from a weather station 200m downwind of the site.

Input data

We classified each snow surface we observed as 'flat', 'sastrugi', or other. We used a monte-carlo simulation to represent the range of weather conditions which occurred during each observation.

Building classifiers

Next, we build ~460 softmax classifiers which classified the snow surface as a function of different sets of weather variables.

Classifier evaluation

We identified classifiers with the highest likelihoods (a metric of classifier goodness-of-fit), using log-likelihood ratios to penalize classifiers which used larger numbers of input variables. We validated the classifiers by bootstrapping.

Results: Best classifiers

The best classifier for bedform presence predicted that snow surfaces are only flat when the snow is fresh and the wind is gentle. This classifier (Fig. 3) is a function of wind speed *u* and time since snowfall *A:*

$$\frac{u}{u_f} \leq \left(1 - \frac{A}{A_f}\right) \implies P(\text{flat}) \geq P(\text{bedforms})$$

where $u_f = 6.4 \pm 2.2$ m/s and $A_f = 1.42 \pm 0.33$ days. This is the equation of the line in Fig. 3c. This classifier had a total accuracy of 99%, with a 10% false positive and 0.6% false negative rate.

The best classifier for sastrugi presence (Fig. 4) is a function of time since snowfall *A* and the high, or 90th-percentile, wind speed u90:

$$\frac{u_{90}}{u_s} \geq \left(1 - \frac{A}{A_s}\right) \implies P(\text{sastrugi}) \geq P(\text{not sastrugi})$$

where $u_s = 29.70 \pm 0.13$ m/s and $A_s = 10.32 \pm 0.24$ days. This equation is presented visually in Fig. 3d. This classifier had a total accuracy of 84%, with a 16% false positive rate and 21% false negative rate.

Both classifiers are shown graphically below.

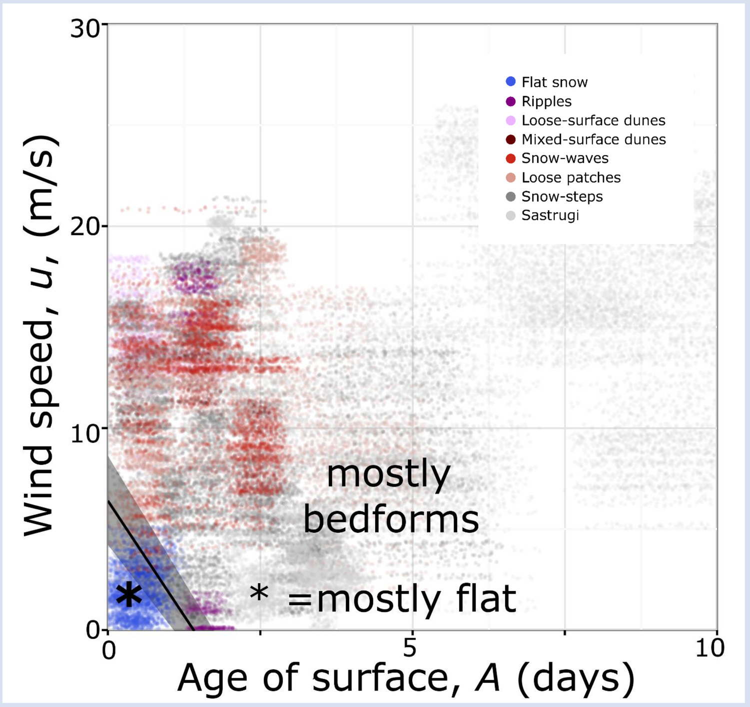

Fig 3

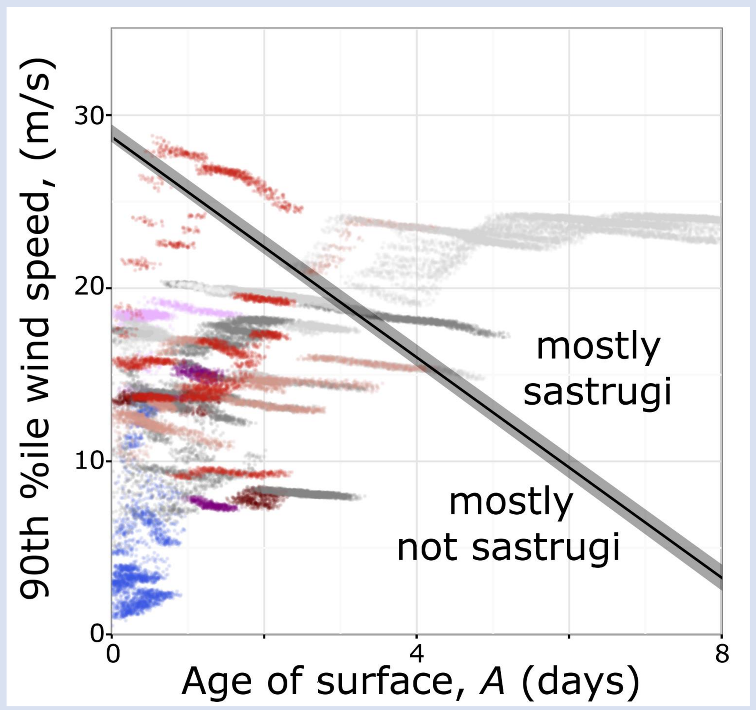

Fig 4

Results: Best predictive variables

Our results are intended to predict where bedforms are and are not likely to be found. They also identify weather variables which have greater and lesser abilities to predict bedform presence, which will allow future researchers to do targeted data collection and analysis.

The table below shows the results of all single-variable, and selected multi-variable, classifiers. Less-negative likelihood values (L) indicate better classifier performance. Averages and percentiles are calculated since snowfall. Excess wind speeds are calculated as values above a 7.3m/s threshold from [4]. Full results and discussion will be available in our upcoming paper [5].

In general,

- Bedforms evolve. Time (A) is an important predictor of their presence and form.
- Sastrugi form over several days. They cannot be understood except in the context of their history; instantaneous weather variables do not predict their presence well.
- Wind direction and temperature have little effect on bedforms.

Weather variable(s) in classifier		Flat/not		Sastrugi/not	
		L	Dir	L	Dir
Single-variable classifiers					
β_0	Constant value (ignores all weather)	−22	–	−55	–
A	Age of snow grains	−14	–	−56	+
$A^{1/2}$	Square root of age	−19	–	−57	+
u	Instantaneous wind speed	−12	–	−57	+
$\overline{u}$	Average wind speed	−13	–	−58	+
$\overline{u^2}$	Average of wind speed squared	−11	–	−58	+
$\overline{u^3}$	Average of wind speed cubed	−12	–	−58	+
$\overline{u_X}$	Average excess wind speed	−13	–	−59	+
$\overline{u_X^2}$	Average of excess wind speed squared	−12	–	−59	+
$\overline{u_X^3}$	Average of excess wind speed cubed	−13	–	−58	+
u_{90}	90th-percentile wind speed	−13	–	−57	+
T	Instantaneous temperature	−32	+	−56	+
T_{max}	Highest temperature	−54	+	−47	+
M	Has surface warmed above -1°?	−36	–	−60	+
θ	Instantaneous wind direction	−94	W	−93	SW
$\overline{\theta}$	Average wind direction	−93	SW	−93	E
Selected multi-variable classifiers					
u, β_0, A	Best classifier for flat surfaces	−3.1		−32	
$u, \beta_0, A^{0.5}$,	Runner-up for flat surfaces	−3.6		−33	
u_{90}, β_0, A	Best classifier for sastrugi	−6		−28	
$u_{90}, \beta_0, A^{0.5}$	Runner-up for sastrugi	−7		−29	

Table 1

Ask me about:

- Ongoing numerical modeling: *how* do bedforms grow?
- Using statistics to ask good questions about geoscience data.
- Snow bedforms.

Affiliations

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