The geometry and evolution of aeolian snow bedforms

Looking upwind at sastrugi. R. Anderson, Niwot Ridge, CO.

When the wind picks up snow, it whirls through the sky - except in Terre Adélie, Antarctica, where freezing air falls 3200m from the Antarctic Plateau to the Dumont D'Urville Sea. The katabatic winds that result are the strongest and most persistent on Earth, with average windspeeds of 19.5m/s[1]. If you placed a metre-stick on that ground, over 10^6kg of snow would blow across it in one year [2].

Blowing snow moves by the same processes as aeolian, or wind-blown, sand: saltation, suspension, and creep. Like sand, snow deposits form ripples and dart-like barchan dunes. But unlike sand, little attention - from numerical, laboratory or field workers - has been given to snow. Yet snowy landscapes are beautifully self-organized and possess unique physical properties. Given time, snow grains sinter and solidify. They form hard surfaces which the wind scallops and abrades into orderly, elongate sastrugi [3]. These features often form in the course of a single storm, so we can easily watch them evolve.

Places with katabatic winds, like Terre Adélie and certain parts of the North American Rockies, are natural laboratories for aeolian snow transport. Moreover, snow surfaces influence the climate of Antarctica, as I explain below. This landscape is a crucial testing ground for aeolian geomorphology.

1 Simulation of snow bedform evolution

I propose build a model that will characterise the roughness and geometry of snow bedforms.
Research aim — to lead us towards a process-based understanding of snow surfaces, to characterise the geometry of snow bedforms, and to improve the accuracy of polar climate models.
Software — I will build the simulation with LIGGGHTS [4], which is a community-standard computational fluid dynamics (CFD) package. The software is suitable because it can simulate turbulent air; track suspended snow grains; and detach particles from a solid bed. It is open-source, so I can edit it with C++. I will modify one of the program's built in cohesion functions to make snow grains sinter. My second choice software is called OpenFOAM.
Skills — I am proficient in Python, Matlab and C#. In 2014 I worked on a similar project at Shell, where I modified CFD software to model floating bodies in water. My advisor, Robert Anderson, has worked extensively on both aeolian transport and polar landscapes.
Computing — I have access to CU's Community Surface Dynamics Modeling System (CSDMS) 704-core high performance computing cluster 'beach'. If this is insufficient, I can gain access to CU's NSF-supported 16,416-core supercomputer 'Janus'. An NSF GRF would provide access to XSEDE and further expand my computational resources.

2 Validation case studies

Terre Adélie, Antarctica — [2] took extensive measurements of aeolian snow transport in Terre Adélie. They provide good lower-bounds for snow mass flux at various wind speeds, and estimate the shear stress exerted on snow beds by the wind. I will use this data to verify that my model is robust in extreme wind and cold, and therefore useful for polar climate models.
Barker Reservoir, CO — This reservoir, whose frozen surface is host to barchan snow dunes every winter, is only 15 miles from the University of Colorado (CU). With an undergraduate field

assistant, I will monitor weather data and aeolian snow fluxes on the reservoir next winter. At every visit we will measure the positions and sizes of the dunes. My model must produce dunes within the natural variability. This will be the first data set to document the evolution of snow bedforms.

3 Applications of the model : Intellectual merit

Hypothesis 1: Bedforms control the characteristic roughness length of snow surfaces
Surface roughness, which controls near-surface wind speeds and turbulence, is a major source of uncertainty in polar climate models [5]. I will have the first simulation that can resolve boundary-layer turbulence around snow bedforms, which are the dominant roughness feature on many ice shelves and plateaus. Modellers will be able to use my results to estimate the size of bedforms in their region and thereby choose a realistic roughness length and turbulence model. This will improve the accuracy of aeolian snow flux and climate models of the polar regions.

Hypothesis 2: Wind speed and direction can predict the reflectance of snow surfaces
The shadows of linear sastrugi cause the reflectance of snow fields to vary by 10% as a function of the azimuthal angle between the sastrugi and the sun [6]. Using the best current observations, this bias still skews radiation-balance calculations by -5 to $7\mathrm{Wm}^{-2}$ [7]. This is approximately 2% of Antarctica's net summer radiation. I will combine my field measurements with simulation results to create a database of sastrugi orientations and geometries. This will allow me to model the of sunlight scattered from the bedforms and to provide climate modellers with a full picture of the reflectance of snowy surfaces.

Hypothesis 3: Snow dunes increase the fraction of sea ice covered by spring melt ponds
Snow insulates sea ice from warm air and delays melting. In spring, melt ponds form on sea ice in the bare spaces between snow dunes [8]. Ponds have a lower albedo than the ice and accelerate melting. I predict that high wind speeds will consolidate snow, expose more underlying ice, and increase the area of the ponds. The variability of snow cover may be as important to sea ice preservation as the snow depth. My results will quantify that variability.

4 Broader impact strategy

This research plan targets three major sources of uncertainty in polar climate models. Improving the accuracy of these models will help us to **anticipate the effects of our changing climate**. Moreover, predicting sea ice melt rates is important for Arctic transport, shipping and drilling.

To **communicate my results**, I will publish in journals and at conferences, and will give regular talks to local polar researchers at INSTAAR and the National Snow and Ice Data Center.

The Colorado Front Range experiences katabatic winds when cold air flows down from the Rockies. I will **engage local teachers** by explaining this local weather on CU's Portal to the Public, and **make my work publicly accessible** by showcasing Barker Reservoir on my blog [tinyurl.com/blog-geo] and uploading photos and animations to [tinyurl.com/csdms-edu].

Finally, as detailed in my personal statement, I am offering a new hands-on course through CU's Science Discovery Program. The course is modelled after a 6-week program I organized and taught last summer, and is designed to **teach research skills to high-school students**.

[**1**] Parish, T. & Bromwich, D. *Nature*, **328**, 1987. [**2**] Trouvilliez et al. *Cold Regions Sci. and Tech.*, **108**, 125-138, 2014. [**3**] Filhol, S. & Sturm, M. *J. Geo. Res. Earth Surf.*, **120**, 2015. [**4**] Christoph, K., et al. *Progress in CFD, An Int. J.*, **12**(2/3), 140-152, 2012. [**5**] Amory, C. et al. *The Cryosphere*, **9**, 1373-1383, 2015. [**6**] Warren, S. & Brandt, R. *J. Geo. Res.*, **103**(E11), 25789-25807, 1998. [**7**] Corbett, J. & Su, W. *Atm. Meas. Tech.*, **8**(8), 3163-3175, 2015. [**8**] Petrich, C. et al. *J. Geo. Res.*, **107**(C09029), 2012.