SNOW BEDFORM GROWTH AS A FUNCTION OF WIND SPEED AND SNOW AGE

By Clea Bertholet

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Department of Geological Sciences

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Defense Committee:

Robert Anderson – Geological Sciences – Advisor

Charles Stern - Geological Sciences - Honors Council Representative

Carol Wessman - Ecology & Evolutionary Biology

ABSTRACT

Snow bedforms, which are 3-dimensional features that form in the snow as a result of wind patterns, cover up to 11% of the Earth's surface annually (Filhol et al., 2015). These features are widespread but have not yet been studied in great depth. Snow bedforms are concentrated at the poles of the Earth, and they therefore cover critical areas that are widely influential for many global processes, including Arctic energy balances, atmospheric and heat exchanges, and sea ice melt rates. These zones are changing rapidly as global temperatures increase, and further study on snow bedforms is essential to improve our understanding of the changing Arctic. Niwot Ridge on the Colorado Front Range proved to be an excellent site to investigate the conditions in which snow bedforms form, because the site is easily accessible and has strong, reliable winter winds. This paper examines the types of snow bedforms that occur on Niwot Ridge and the relative wind speeds and snow ages that lead to the specific formations. The main goal of the study was to quantify the weather conditions under which each type of bedform grows, which is imperative for future modeling of snow bedforms. We correlated the average and gusting wind speeds with the age and the type of bedform, and generated several comprehensive diagrams to illustrate the relationship between these variables. We found that stationary erosional features such as sastrugi formed in snow anywhere from 0-20 days old and under wind speeds of 10-20 m/s, moved only in snow younger than about 2 days with wind speeds from about 6-15 m/s. Depositional features such as dunes and ripples were almost always seen moving, and formed with snow less than two days old and with average wind speeds around 15 m/s. This information was then used to speculate and generate a figure on the conditions under which these bedforms fall. Snow bedforms affect surface roughness and land morphology and thus play a huge role in energy balances across the globe.

Correlating weather patterns to snow formations will improve our understanding of how the planet will respond to a warming climate and allow us to infer what changes may come to our larger snow-covered land masses.

CONTENT

BACKGROUND

Snow bedforms include various shapes that are formed when wind blows across snow surfaces. These bedforms are classified into seven different forms that can be further separated as erosional or depositional bedforms: snow waves, barchan dunes, whaleback dunes, ripples, crag and tails, pits, and sastrugi (Filhol et al., 2015).

Figure 1. Sastrugi, an erosional bedform, with author for scale, photo looking downwind. (Photo by Kelly Kochanski)

Snow particles move in three ways - creep, saltation, and suspension. In creep, snow grains roll or slide along the surface of the snow, and in saltation, the particles bounce off the snow surface and are swept downwind in the air. In addition to this, snow particles can also move in suspension, in which case the particles are held in the air once wind speeds are high enough that the turbulent velocity fluctuations of the wind are sufficient to counter the weight of the grain. Wind inevitably plays a critical role in snow bedform formation, with factors like velocity, gustiness, and direction all coming together to form a specific snow bedform. Transportation of snow by wind occurs mostly within about 2-3 m of the snow surface (Kobayashi, 1980). As the snow blows around on this level, turbulent and gravitational forces sort out coarser, heavier grains closer to the surface while the finer ones travel higher suspended paths in the air stream. Grains on the ground surface begin to form distinct depositional features that depend on the wind speed and snow flux. While scientists have discovered that certain snow features are indicative of wind direction and even wind speed, there is still limited knowledge about the structure of wind and wind turbulence over snow and ice surfaces while snow is drifting (Kobayashi, 1980). There is still valuable information to be discovered about the physical processes that control how the wind and snow interact with each other.

The actual shape the bedforms take on are a direct result of the deposition of these snow particles from wind activity, and also from erosion once the snow has aged and hardened enough. Out of the seven main types of bedforms outlined above, snow waves, barchan dunes, whaleback dunes, ripple marks, crag and tails, and pits are depositional features; sastrugi are erosional. While snow dunes can generally be broken into three categories - snow waves, barchan dunes, and whaleback dunes, I will divide this category into groups of snow waves, and the other two dunes, for the sake of clarity with the data.

A dune is any pile of snow that has been deposited in an elongated shape by the wind. The position of the dune is independent to wind patterns; dunes can form parallel to, oblique, or across wind directions. Dunes are large - typically at least a meter in height, with some "megadunes" in Antarctica reaching up to several kilometers in length (Filhol et al., 2015).

Figure 2. Snow dunes on Brainard Lake, CO. Trekking pole for scale. Wind is from right to left.

Snow waves are considered a subset of snow dunes and form as a tongue of new snow that propagates downwind over a flat surface, or between other bedforms (Kobayashi, 1980).

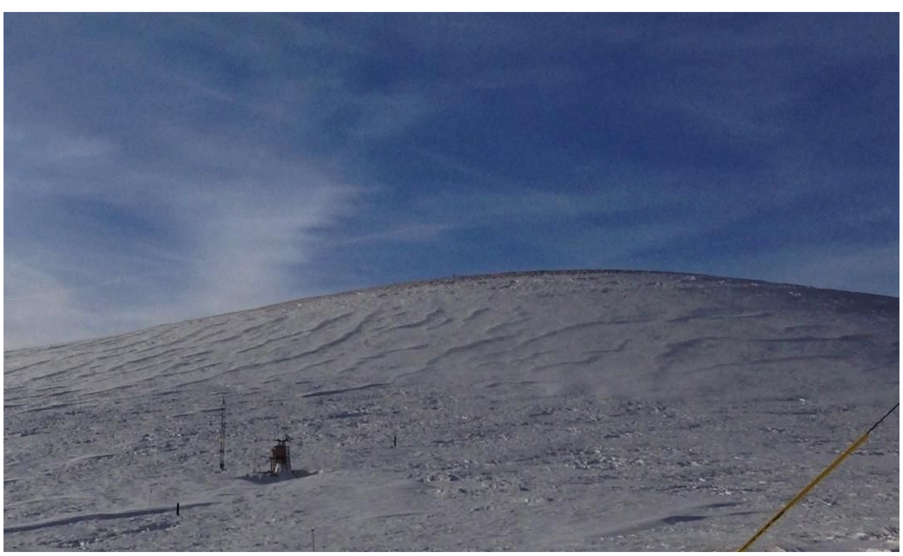

Figure 3. Snow waves several meters in length on Niwot Ridge, seen as the wavy lines running up the slope.

Ripple marks form transverse to the wind pattern and show up as elongated wave patterns, with wavelengths of 5 to 20 cm and amplitudes of 0.2 to 2 cm (Filhol et al., 2015). They require a specific amount of creep and saltation to form, typically only between wind speeds of 5-7m/s. When the wind speed is too high the snow particles will only saltate and form a flat surface, and when the wind speed is too low there is not enough momentum transfer between the particles to initiate creeping (Filhol et al., 2015). Snow ripples form in a nearly identical manner to that of sand ripples, however snow ripples are unique in that they often form into a y-shaped pattern, the cause of which is still unknown. Crag and tails form as the result of small, elongated drifts occurring on the lee side of an unmoving object, typically an ice pellet, ball of snow, or small rock. A small erosion scour forms on the upwind side of the unmoving object, and often continues around the sides of the drift. Pits are small, rounded impressions in the snow that form as a result of an overlying layer of thin, hard snow that forms depressions due to variations in snow hardness. All of these features propagate downwind at varying speeds (Filhol et al., 2015).

Sastrugi is a term to describe a wide array of erosional features that have been lumped into one general category. A sastrug, the singular term, manifests as an elongated shape with steep wind-facing slopes, and gentle downwind slopes. Starting out as a mound of snow gradually widening downwind, the underside of the wind-facing point is eventually carved out by wind and particle bombardment. The sastrugi that form must have a hard enough top layer to maintain support, yet still remain soft enough to erode below the hardened wind slabs. If this point is carved out enough and the top layer of the snow hard enough, it will often bend over under its own weight to form a tunnel shape, shown in Figure 4. One of the most advanced forms of sastrugi form as anvil heads, referred to as lanceolate sastrugi, shown in Figure 5 (Kobayashi, 1980).

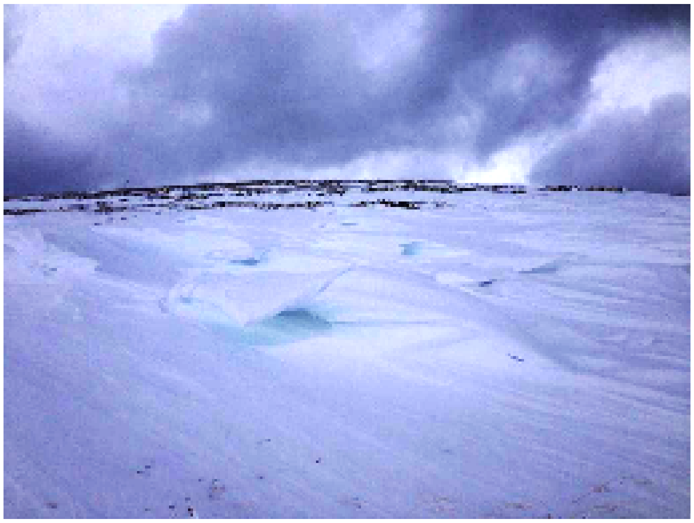

Figure 4. Sastrugi on Niwot Ridge. Here the points have hardened and started to bend under their own weight. View looking downridge and downwind.

Figure 5. A lanceolate sastrugi on Niwot Ridge. View looking upridge and upwind.

Generally, the features are 0.3 to 0.5 m high but can grow up to 2 m in amplitude, and the sastrugi themselves have regularly spaced bedding (Watanabe, 1992). However, other than when wind erosion has exposed layering patterns due to differences in hardness, further efforts to determine bedding patterns of sastrugi have been futile.

I discuss one other snow feature in this paper: edges. An edge often appears as multiple flat layers of a few millimeters to half a centimeter of snow in terraced forms that I hypothesize to be eroded by wind.

Figure 6. Edges at Brainerd Lake in Colorado. Author for scale. (Photo by Kelly Kochanski)

Including the ice sheets of Antarctica and Greenland, these various snow features cover up to 11% of the Earth's surface (Filhol et al., 2015). Their wide geographic range in addition to their ability to increase surface roughness in the critical regions of the Arctic and Antarctic makes these features a crucial influence on regional and global processes. Snow bedforms heavily impact energy balances, water balances, atmospheric air exchanges, sea ice melt rate, transfer of momentum between the atmosphere and sea ice, and influence the interpretation of deep ice cores (Colbeck, 1997).

One of the first persons to study this phenomenon was Vaughan Cornish in 1902. This British geographer traveled around Canada and observed the relationship between precipitation, temperature and the features that formed in the snow; he was the first person to pose the scientific question of what factors were responsible for the bedform shapes (Filhol et al., 2015). Most of his questions have remained unanswered. Extensive research has focused on sand bedforms, yet little attention has been paid to their snowy cousins. Historically, snow bedforms have been studied to map wind patterns across the Antarctic plateau, as sastrugi are elongated in the direction of the wind. Other than this, research on snow bedforms has been rarely applied, and is rarely cited. Despite the extreme climate and inaccessibility of study sites, further research on this subject has enormous potential for new and fascinating information, as well as critical material concerning climate change and energy balance. Studying snow bedforms is crucial for understanding many surficial processes of the planet, especially at the poles, which have a tremendous effect on the climate and energy balance of the planet (Filhol et al., 2015).

Previous work on snow bedforms includes a study by Simon Filhol et al. (2015), which classifies the various bedforms, movement of grains by wind, and sintering. While many snow bedforms are in many ways similar to sand bedforms, sintering is a key difference. As a vapor gradient builds up between snow grains, a bond will form, leading to rounding of grains, bonding of several snow grains together, and eventual sintering of the snowpack (Blackford, 2007). Considerable strength can develop in these bonds, and this appears to play an important role in the formation of many erosional features. For sintering to occur, a grain of snow must remain in position for a long enough period (usually less than 24 hr.) until bonding occurs and the snow undergoes temperature gradient metamorphism – at this point, the conditions for bedform formation shift from depositional to erosional. Due to the increase in strength of snow that comes with sintering, erosional features like sastrugi are much more common than depositional forms like ripples and dunes. Sintering limits the size of snow dunes as well, causing them to be much smaller than similar features in sand (Colbeck, 1997).

The aim of my research was to explore how the wind speed and snow age affect the types of snow bedforms that occur. Many variables support the formation of certain types of snow bedforms, but wind is a crucial factor in transport and deposition of the snow particles, as well as in facilitating movement of snow bedforms. In addition, the age of the snow is important to consider, as sintering occurs after a short amount of time and will affect whether the snow surface remains depositional or turns erosional. Can we predict which types of snow bedforms will occur given wind speed and snow age? By measuring the wind speeds, estimating snow ages, and observing snow bedform evolution during many repeat trips to the field, I aim to answer this question.

FIELD SITE

Although snow bedforms cover a large fraction of the Earth's land surface during the winter months, they have not been extensively studied because the majority occur in remote Arctic, Antarctic and alpine regions. However, Niwot Ridge on the northern Colorado Front Range is a prime location to study these features. While Niwot Ridge is only covered in snow during the winter season (typically November through May), it is an excellent place to study snow structures during these months due to strong, persistent wind and cold weather. An additional advantage of this site is that the Niwot LTER records the wind speed and temperature.

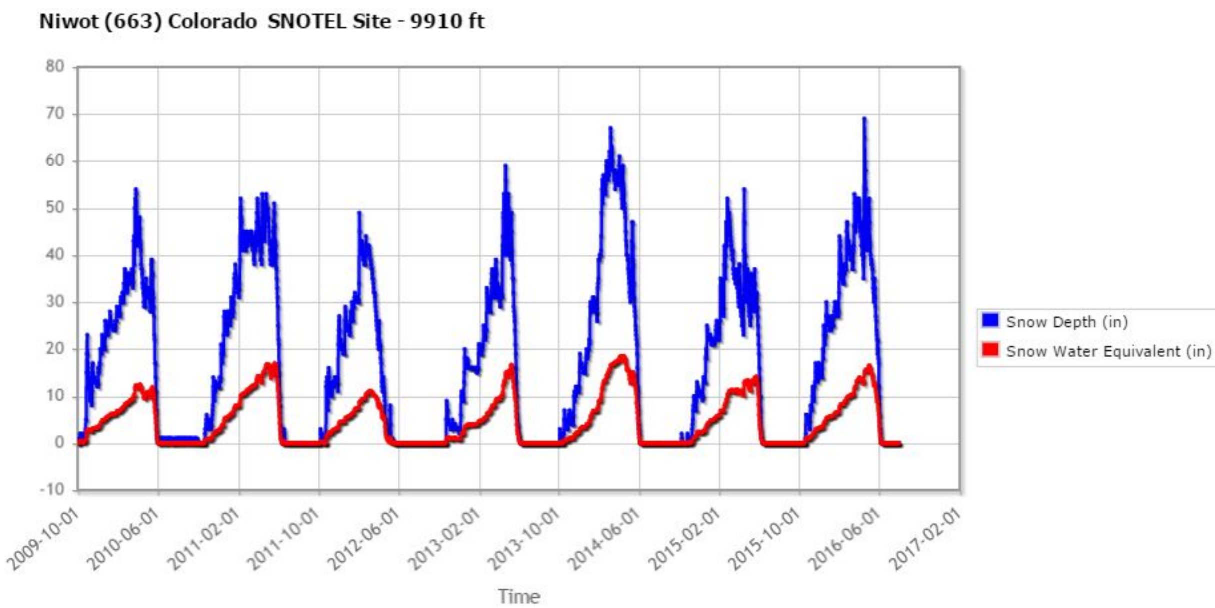

Figure 7. SNOTEL measurements of snowpack and snow water equivalent for the Niwot Ridge LTER from 2009-2016 show ample snow accumulation, with depths ranging up to 70 inches, making it an ideal study site.
(https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=663_)

Field site location

Located in Roosevelt National Forest on the northern slopes of the Colorado Front Range, the Niwot Ridge Long Term Ecological Research (Niwot LTER) program became a part of the network of over 2,000 scientists supported by the National Science Foundation in 1980. It has also been designated as a United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserve, an Experimental Ecology Reserve (USDA Forest Service), is used by National Oceanic and Atmospheric Administration (NOAA), and is run from the Mountain Research Station of the University of Colorado. As the entire study site is above 3000m, Niwot Ridge focuses on building research in high-elevation and alpine environments (http://niwot.colorado.edu/). Alpine ecosystems are extremely sensitive and snowpack is one of the aspects that is most affected by fluctuations in climate. Long-term observations conducted at Niwot Ridge can therefore lead to a deeper insight into the impacts of environmental change. While the Niwot Ridge LTER consists of subalpine coniferous forests, a glacier and various glacial landforms, and alpine tundra, the research done on snow bedforms was conducted in the alpine tundra in the saddle of Niwot Ridge.

The study site is about 100 m uphill and to the west of the Tundra Lab in the saddle of Niwot Ridge (Figure 8). The trailhead up to the saddle can be accessed at the Mountain Research Station, a few miles up the Rainbow Lakes road off Highway 72, roughly 7 miles south of Nederland, Colorado. From here, it is about a 4 mile snowshoe up to the Niwot Ridge Biosphere Reserve and the 1200 hectare area preserved for the study of tundra and alpine ecosystems.

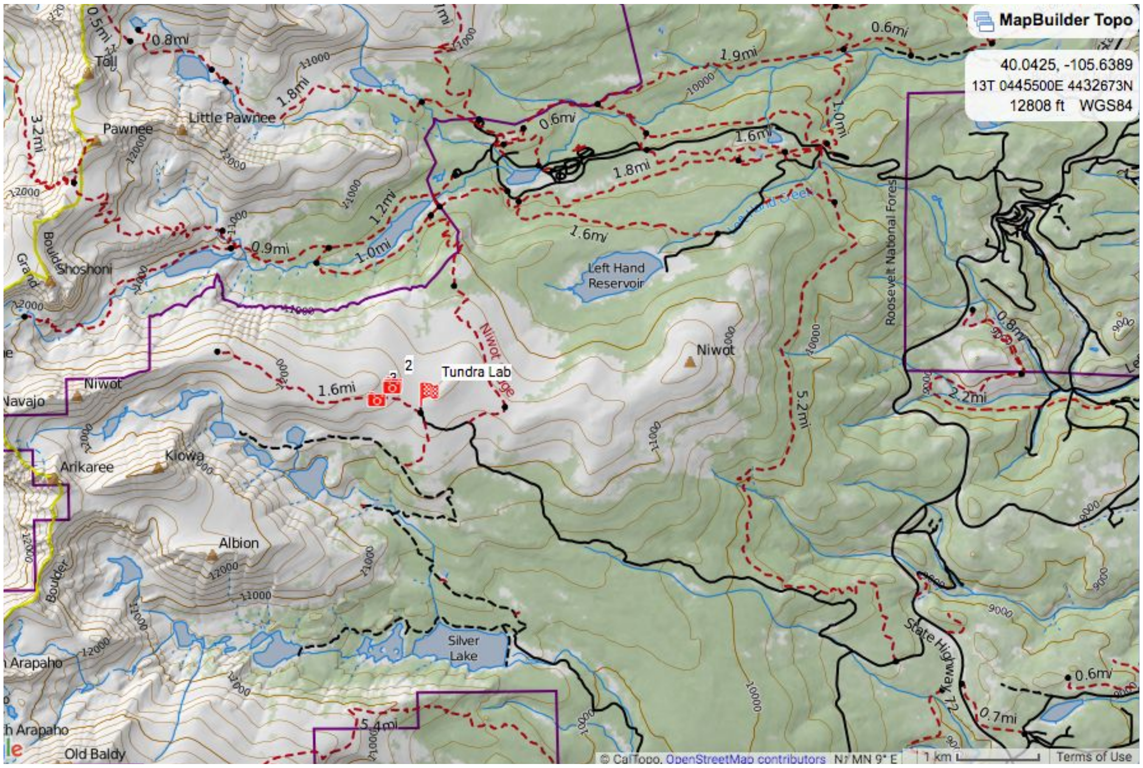

Figure 8. Niwot Ridge shown on the upper half of the topographical map, north up. The trail follows the bold black line northwest up to the ridge, where it connects to the dotted red line at the saddle. The Tundra Lab is marked with a red flag, and the study sites with red cameras. (https://caltopo.com/map.html#ll=40.0558,-105.58924&z=16&b=mbt)

Niwot Ridge weather and climate

Located 5.6 km from the Continental divide, Niwot ridge encompasses a wide area of alpine and subalpine. The Mountain Research Station maintains a weather station at the Tundra lab in the ridge saddle, at D1 sites, and at C1, another site below treeline. The ridge stretches for about 5km west-northwest with wind running parallel to the ridge, with wind speeds varying from 3-20 m/s and gusting up to 4-25 m/s. Temperatures at the T-Van can reach as low as -20° C, and during windy days after snowfall fresh powder can make visibility very poor (Kochanski, 2016).

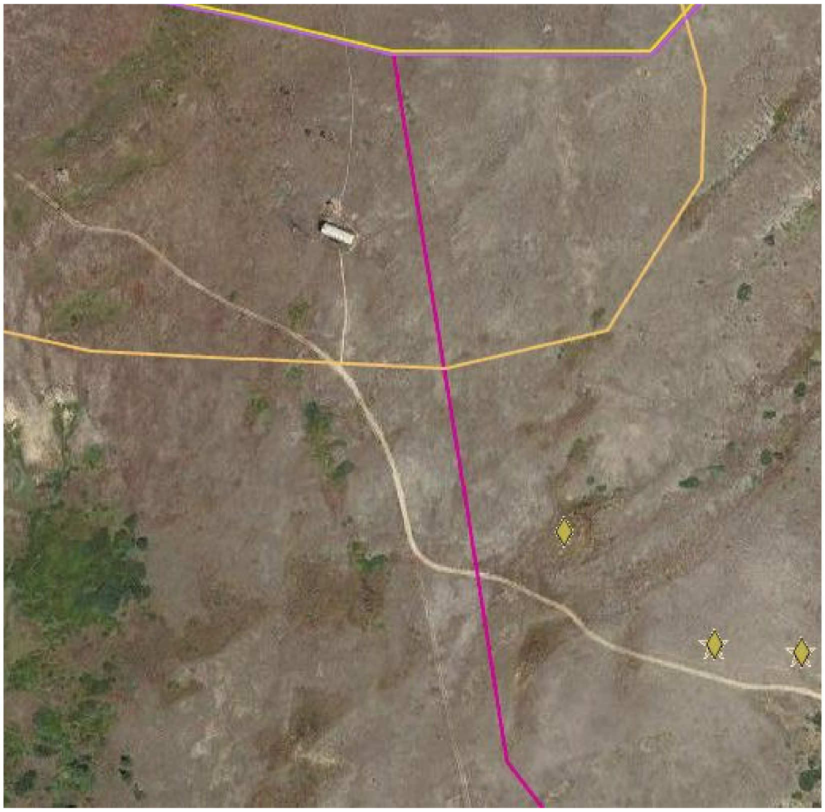

Figure 9 - A satellite image shows the Niwot Ridge saddle. The Tundra Lab is the white rectangle to the left of the bold pink line. Tvan weather stations are marked with yellow diamonds on the lower right corner.
(https://www.google.com/maps/d/viewer?mid=1r4TchmIxp8edDSOBOWqzoLIHtjI&hl=en&ll=40.05296975370468%2C-105.58815018982693&z=17)

METHODS

While some of the best methods for observation include field trips to see the bedforms in person, it was impossible to visit Niwot Ridge every day for the full winter. Even in many visits, it was still difficult to grasp how the bedforms formed when observed in real time on minute-to-hourly timescales. Therefore, we used time-lapse photography to monitor the bedform evolution; camera footage taken over an entire day at the field site can be sped up to be viewed in a matter of minutes. We established three cameras at the saddle on Niwot Ridge, two surveying one patch of snow about 100 m directly west of the Tundra Lab, and the third about 50 m south of those in a less wind-sheltered area.

Figure 10. An expanded version of Figure x with the location of all 3 camera marked as red camera icons to the left, and the Tundra Lab as the red flag in the lower right corner. (http://caltopo.com/map.html#ll=40.05585,-105.59166&z=17&b=mbt)

The cameras used at these sites were extremely useful in monitoring how bedforms initiate and evolve. The cameras I used were Day6 Plotwatcher Pro trail cameras, powered by lithium batteries, and take photos every 10s during daylight hours. They were mounted on tripods and secured with webbing with the camera angled down to achieve a proper view of a snowfield. Lithium batteries and memory cards (up to 32 Gb) were replaced on a regular basis - at least once a month - so that the batteries did not discharge from cold and the memory cards did not overwrite their data once full.

Data processing

In order to go through the data we reviewed the time lapse footage and divided it up into several categories which would later become "events", or data points in the figures. The camera footage recorded from sunrise to sunset, and the events were divided into several categories, generally either whiteout, lens obscured, or visible snow events. Within the snow events category existed more divisions of the specific bedforms seen, with specific moving or unmoving bedforms observed and marked with a distinct number. Unfortunately no visible snow bedforms could be witnessed during whiteouts or when the lens was covered. All footage was recorded onto a mix of 8, 16, and 32 Gb memory cards which were uploaded onto a google drive folder using the computer in the Tundra Lab, so that the memory card could be wiped clean and used again without hiking back down from the ridge.

Events with high wind speed were disproportionately likely to be obscured. Blizzard events are important to consider as they are often deposit new snow and are accompanied by high winds. However, the visible events were of the most importance to the project and were considered most carefully in the data processing, as they provided a look at the deposition, erosion, and movement of the bedforms considered in this project.

An excel spreadsheet was created to organize and process the data. An event was distinguished as any point where something in the field changed – typically where a bedform stopped or started moving, or when visibility improved or declined a significant amount. Once the specific events were noted they could be further analyzed in the later columns. For example, if I saw several sastrugi moving I would note when I observed this event start and end, and write this down in the the “time start” and “time end” columns, and mark whichever bedforms I saw with a number in the “event” column (6 for moving sastrugi). Length of event was then found by subtracting the time start from time end. I would also note movement and presence of new snow during the event. The time for old snow would remain constant as the last time seeing any old snow before a new snow event, and the time for first time seeing new snow would be the time when a new snowpack was observed, which remained constant until another new snowpack covered this one. From this, I could derive an estimated minimum and maximum age of the snow. Minimum age was inferred to be the difference between the time of the event starting and when the new snow was seen; maximum age was the difference between the end of the event and the last time the old snow was seen. The best guess at the age of the snow was then found by averaging the values of maximum and minimum age for an event.

Historic wind speed data for Niwot Ridge is available on the LTER data site under “climate data”. The data is collected from the saddle climate station (3523 m in elevation), using a Campbell Instruments CR1000 data logger, which records data every 10 minutes (Losleben, 2017). Wind speed data from 2017 was received in private communication. Wind speeds were given in ten minute intervals so data was collected by taking wind speeds from between the bounds of the start and end of an event, rounding to the nearest ten minute interval in order to include the most accurate wind speeds. The values collected for each event were for the average and maximum wind speeds; these were averaged, and put into the spreadsheet to go with the event.

After this data was collected, a series of scatter plots were created, with wind speed in the Y axis and snow age on the X axis, and each bedform type as discussed above entered as its own series and set of data points. In terms of error bars, the positive vertical error corresponded to the difference between the average wind speed and the 25th percentile wind speed, and the negative error corresponded the difference between the average wind speed and the 75th percentile. Positive and negative horizontal error bars supplied the difference between the average, and the maximum and minimum age of snow, respectively.

Errors

There were significant errors in this project, mostly due to unpredictable discrepancies in weather and technology. In the 2015-2016 field season we found that many of these cameras lacked sufficient battery life or did not stand up to the cold well enough to use in the field. The alkali batteries these cameras used were only good to about -2 °C, so once temperatures plummeted the cameras were rendered useless. This caused excessive trips up to Niwot Ridge to replace the cameras, or to check on them only to find that they had died after a few days or hours of being exposed to the elements. This problem was eventually solved when new Day6 Plotwatcher Pro cameras were bought for research. The Plotwatcher Pros use very little power and we used lithium batteries that are good down to -40 °C, and thus were more reliable in cold weather conditions on Niwot Ridge. The only issue with the Plotwatcher Pros was that the memory card would overwrite once it filled. In the 2016-2017 field season we therefore used three Plotwatchers with lithium batteries and large memory cards that were frequently replaced to combat all these problems. We still found that the cameras sometimes failed to record data; this was the case in the last few weeks of February 2017.

Figure 11. Author at the field site in February 2017, checking the third camera to make sure the batteries have enough charge and that the camera is recording properly. Trips up to the ridge were made about once every two weeks to recover the footage off the memory cards so that they would not overwrite. (Photo by Maxwell Fanning)

Alpine weather is often unpredictable and this proved to be frustratingly true in the project. The winter of 2016-2017 field season came late and had relatively small snowfall, which led to less data than we had hoped for. Once the snow did come, in late November 2016, enough snow dumped on the study site to completely bury two of the cameras after they had only recorded a month or two of data; the buried cameras were impossible to find or retrieve until the following summer. A similar problem happened in the previous field season, in which all data after March 2016 was lost after the camera recording the study site was buried in deep snow until the late spring, and all the footage it recorded had overwritten itself. After the first two cameras were buried in December 2016, a third camera was set up in a more wind-scoured area and went on to record decent footage without burial. On several occasions the third camera was almost completely buried, but each time it was found and dug out of the snow.

Figure 12. CU undergraduate Maxwell Fanning digging the third camera out of the snow before it gets buried and lost for the season.

In addition to the burial of cameras, whiteouts often reduced visibility to the point where no bedforms could be seen. A snow event with high wind speeds and falling snow is necessary to form depositional bedforms; this was often not observed because these events usually manifest as a whiteout with very low visibility. Thus, many of the times when the most crucial aspects of bedform evolution occur coincide with low visibility, resulting in a lack of camera record. Every whiteout in the data signifies deposition of new snow and possible evolution of depositional bedforms. Whenever I went into the field to observe bedforms during a blizzard on Niwot ridge I found that visibility was often less than one meter, and the extreme cold and high wind that accompanies blizzards made it challenging to stay out of the shelter of the Tundra Lab for more than 20 minutes.

Another problem with the data collection was that the camera lens was often obscured when snow blew over it. In the time lapse footage this resulted in a foggy white cover that could often be mistaken for a whiteout when going through data. However, once the sun came up and warmed the lens sufficiently the snow almost always melted off completely. During March 2016, our cameras had visibility for 22% of the recording time, which equated to about 44% of the daylight hours (Kochanski, 2016). The days with good visibility occurred disproportionately on clear, sunny days with no snow movement.

Challenges also arose in the interpretation of the data. Specifically the age of the snow was difficult to determine. The snow age was calculated as the average of the maximum and minimum age, discussed above, however this is just a best guess, not an exact age, and is reflected in the results. When there was a long period of low visibility, i.e. a blizzard, the maximum age of snow would increase as there was no solid proof in the data of a new snowfall occurring, even though there likely was fresh snow during these periods of poor visibility. Therefore for many of the depositional bedforms, the best guess at snow age was determined to be much higher than it likely actually was, due to the data points being skewed by a high maximum possible age. While it can be interpolated that the age of these bedforms was much younger than the data suggested, there is no way to alter the data processing to consider only some of these instances while disregarding others. Future long-term studies of this would have to take determining snow age into account, but for the time limit on this project there was not enough information or time to determine a more accurate age of the snow. Thus, we settled on using the mean of the maximum and minimum snow ages, while considering error bars.

RESULTS

The data was used to generate a series of comprehensive scatter plots in which the different bedforms were plotted under corresponding wind speeds and snow age. The goal of these results were to see what trends the bedform formation would reveal, and to create several generalized plots of behavior. The ultimate end goal of the data processing was to interpolate a general figure which would show which bedforms fall under which conditions of wind speed and snow age.

Figures 13 shows a plot of bedform type vs snow age in days on the x axis, and wind speed on the y axis. The observed bedforms - ripples, edges, dunes, sastrugi, and waves – are plotted separately as their own shapes, and movement is denoted by filling in the shape.. It is clear that edges and sastrugi dominate the data, and when included all together generate a large x axis to accommodate the data points for these figures under old snow. In Figure 14 we shorten the axis to more clearly represent trends in the data.

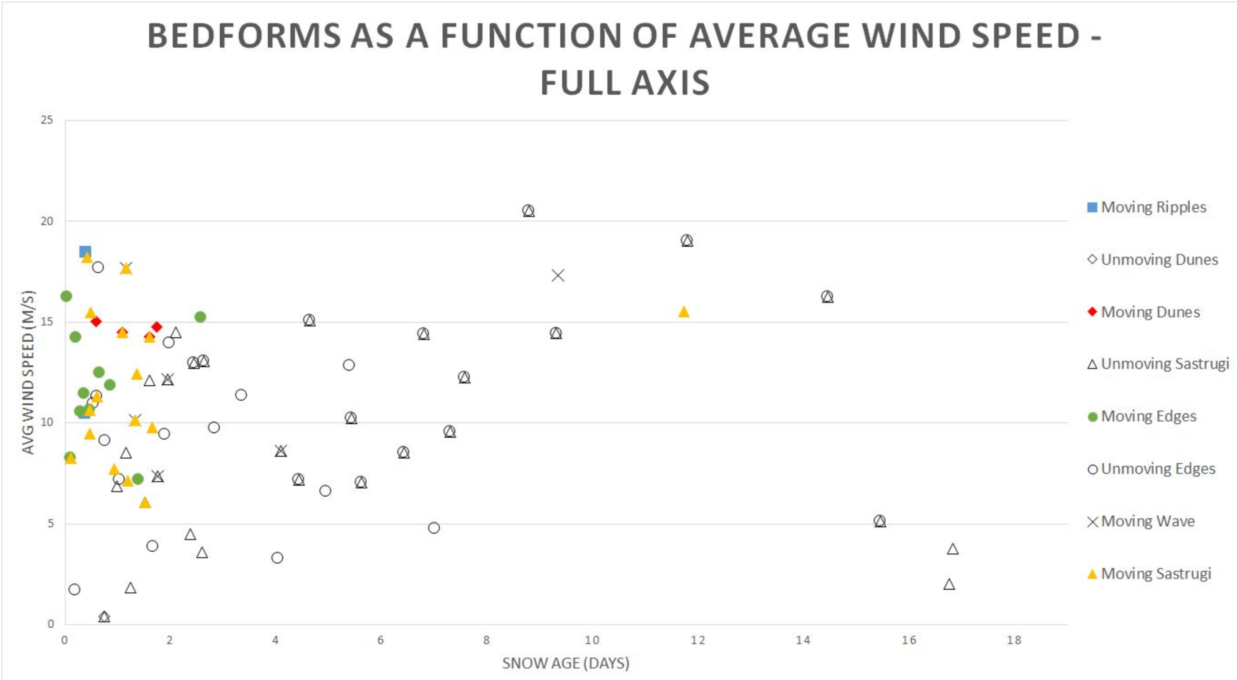

Figure 13. Bedform type as a function of snow age and average wind speed, shown for snow ages up to 2 weeks.

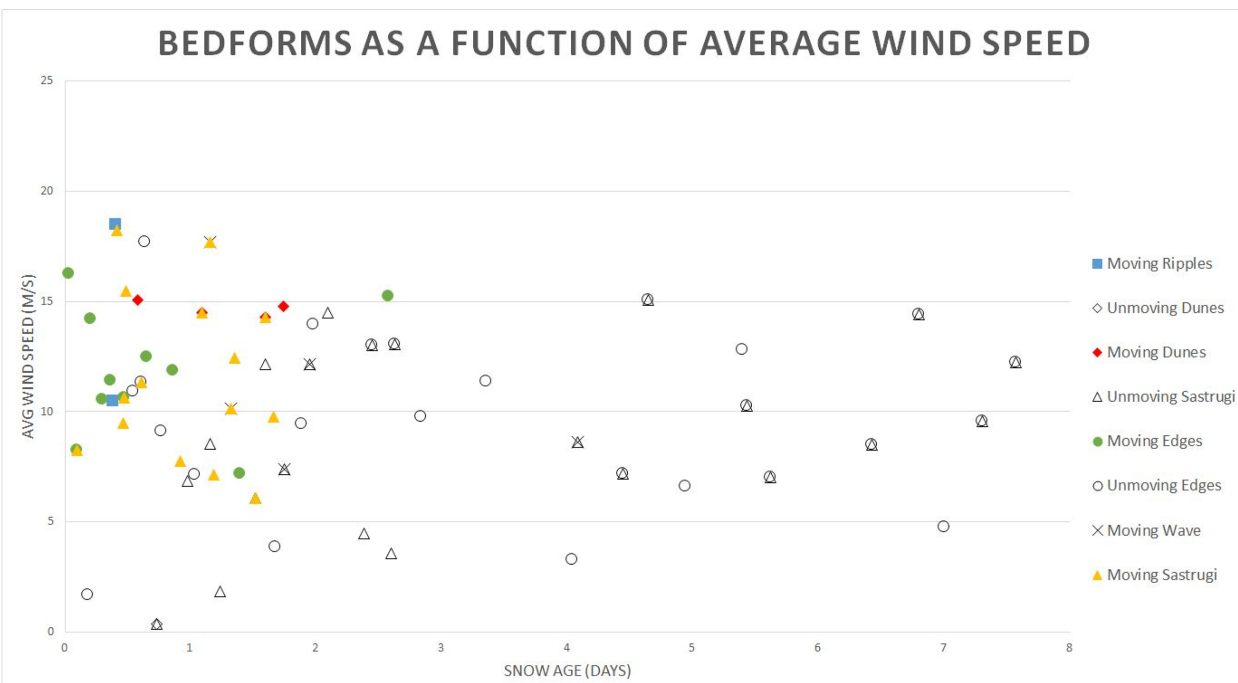

Figure 14. Expansion of phase plot showing bedforms occurring at young snow ages.

The majority of the depositional bedforms - ripples, dunes, and waves - exist under relatively young snow ages and clump together, mostly disappearing after the snow has aged past a day or two. The edges and sastrugi are more widespread over snow age, meaning they exist in much older snow than depositional bedforms do. Error bars have been added to show ranges for possible values of data points, as shown in Figure 15. Examination of the error bars reveals that there is a wide range of possible snow ages for many of the data points, which is taken into consideration further on in the study.

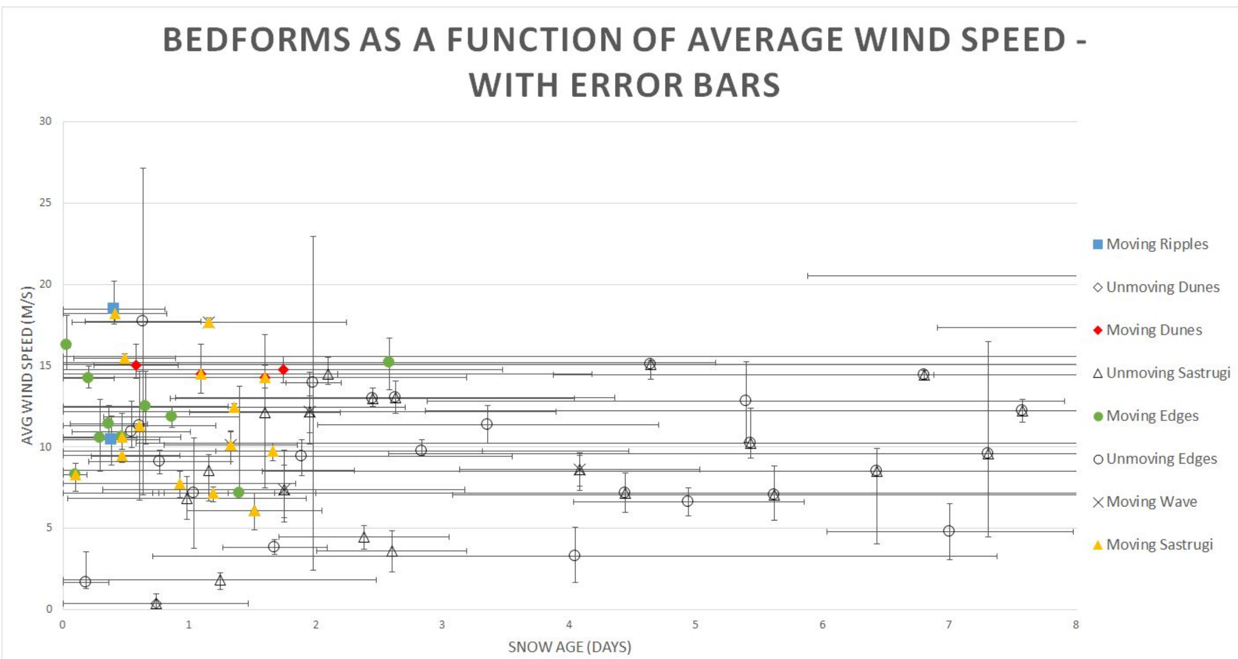

Figure 15. The phase plot of bedforms, with error bars to show where the data points could possibly fall.

Gusting wind speeds are also important to consider, as often times it takes a burst of high winds to move or erode a bedform. Thus a series of similar scatter plots were generated, where bedforms were plotted against the gusting wind speed. The trends in the data are very similar to those shown in the plots of average wind speed.

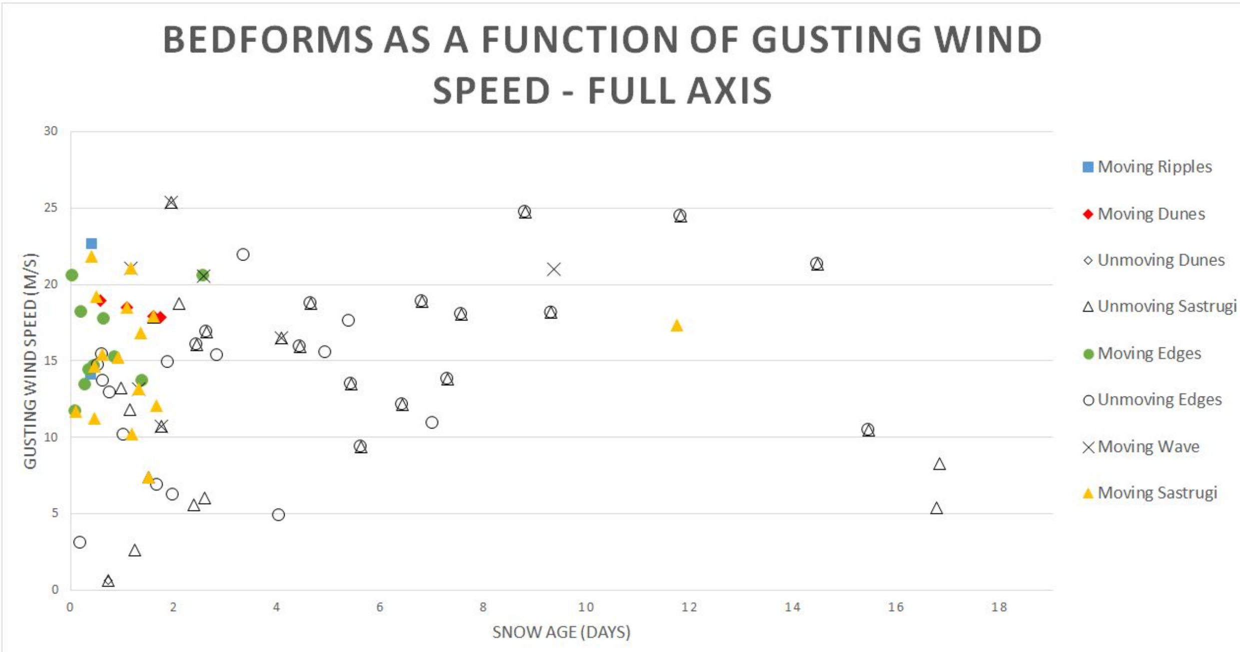

Figure 16. Bedform type as a function of snow age and average wind speed, shown for snow ages up to 2 weeks.

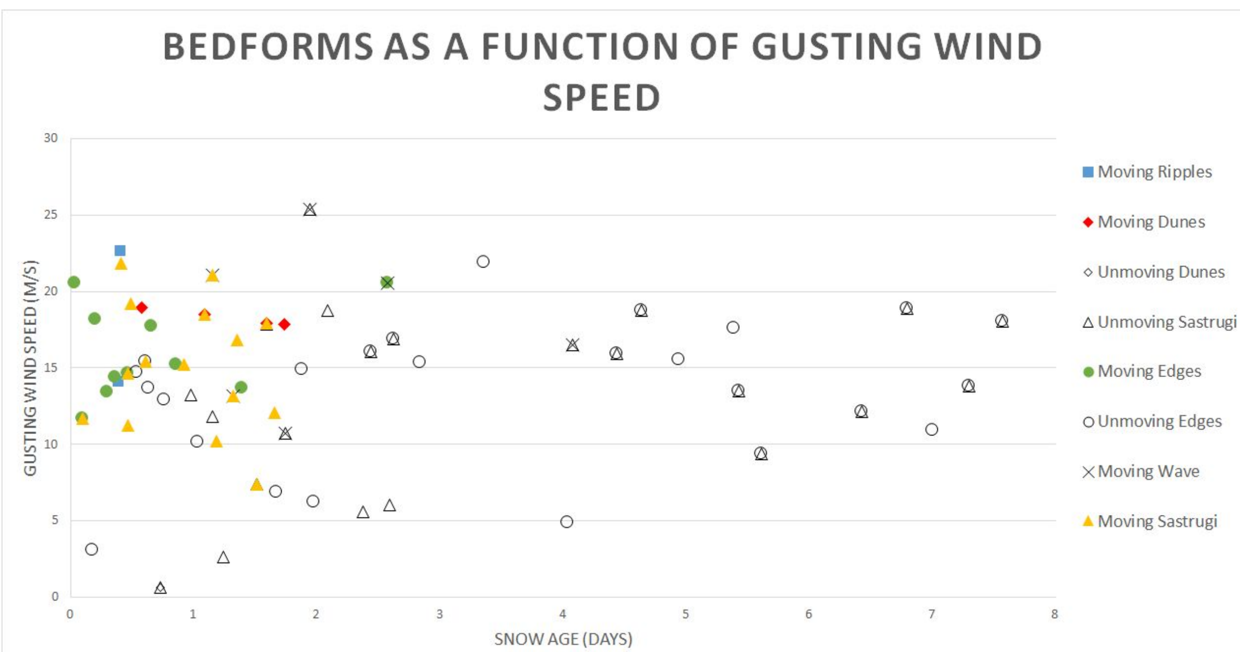

Figure 17. Expansion of phase plot showing bedforms occurring at young snow ages.

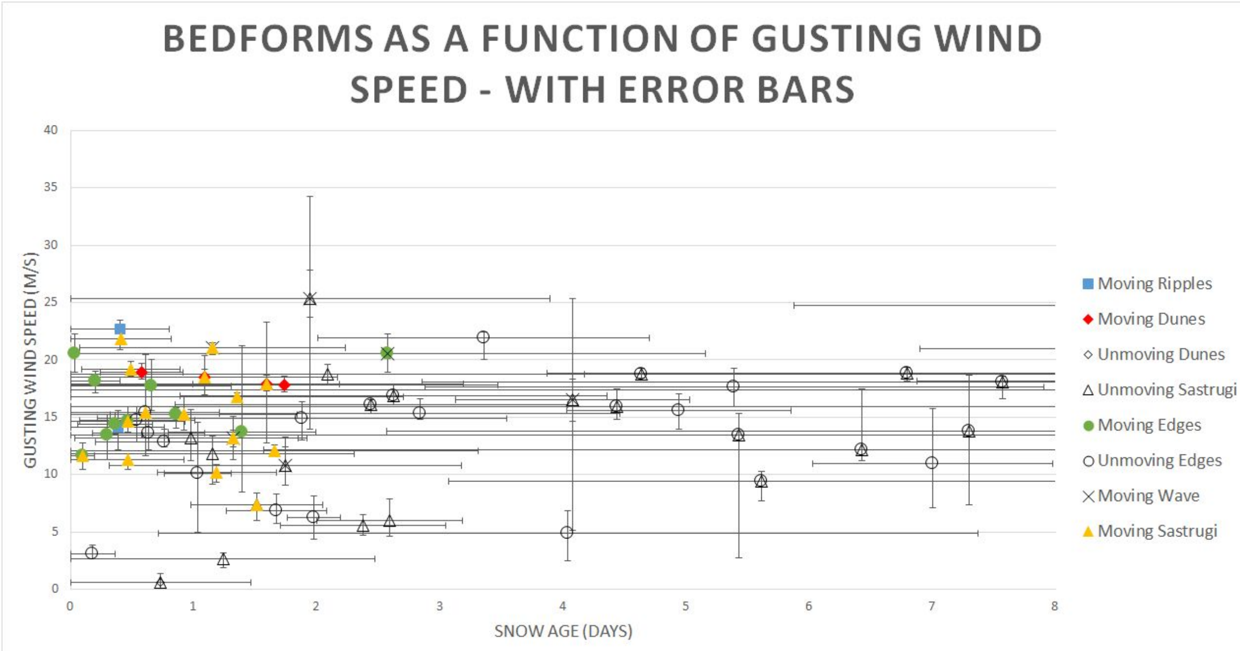

Figure 18. The phase plot of bedforms, with error bars to show where the data points could possibly fall.

Here I discuss trends in the data. There were few events in which snow dunes were visible. However, the points that do exist that they occur when snow is between 0.5 and 1.75 days old, and when wind speeds exceeds 14-15 m/s. There is one event in which a stationary snow dune was spotted; snow then is about 0.75 days old, and wind speed is 0-1 m/s. We expected the ripples to be younger than the 1.75 to 2 days they were plotted under. In the field ripples were only ever seen when the snow was less than a day old with the only exception being when they formed on top of snow waves, which is a special case. Ripples too are rare, and in all the events in which they were seen the ripples were moving. While the plot implied ripples to be older than expected, the wide range in error bars leaves room for interpretation of the data. Age aside, ripples evolved at wind speeds of 10-13 m/s. Snow waves were often plotted in conjunction with ripples and were commonly found together in events; the moving waves occur at 1-2.5 day old snow and wind speeds of 7-17 m/s. Existing at a more widespread wind speed range, waves made of new snow were often observed to move while older bedforms remained stationary.

Edges and sastrugi existed at a wider range of wind speed and snow age than these depositional bedforms. The edges move at about 0-2 days old, under 3-12 m/s wind, and remained stationary when the snow was young (0-15.5 day old) and under 1-20 m/s wind. Sastrugi moved in snow about 0-2 days old with 7-18 m/s wind, and remained stationary in snow 0-17 days old with wind speeds 0-21 m/s.

As sastrugi and edges dominate the plots, these were investigated further in Figures 19 and 20. It appears that the edges will cease to move once the age of the snow exceeds two days. The sastrugi also remain stationary after about 2 days, except for one outlier case (see Figure 15). While there appear to be constraints on movement, the stationary sastrugi and edges are more widespread across the snow ages and wind speeds.

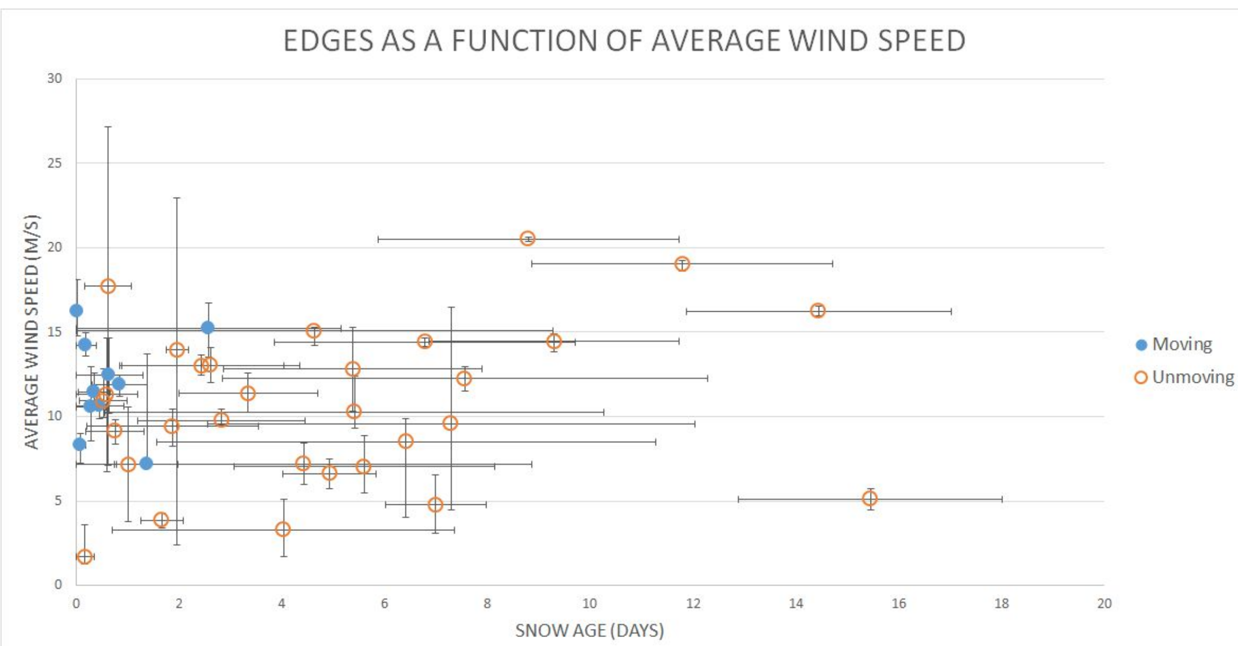

Figure 19. Edges as a function of wind speed and snow age.

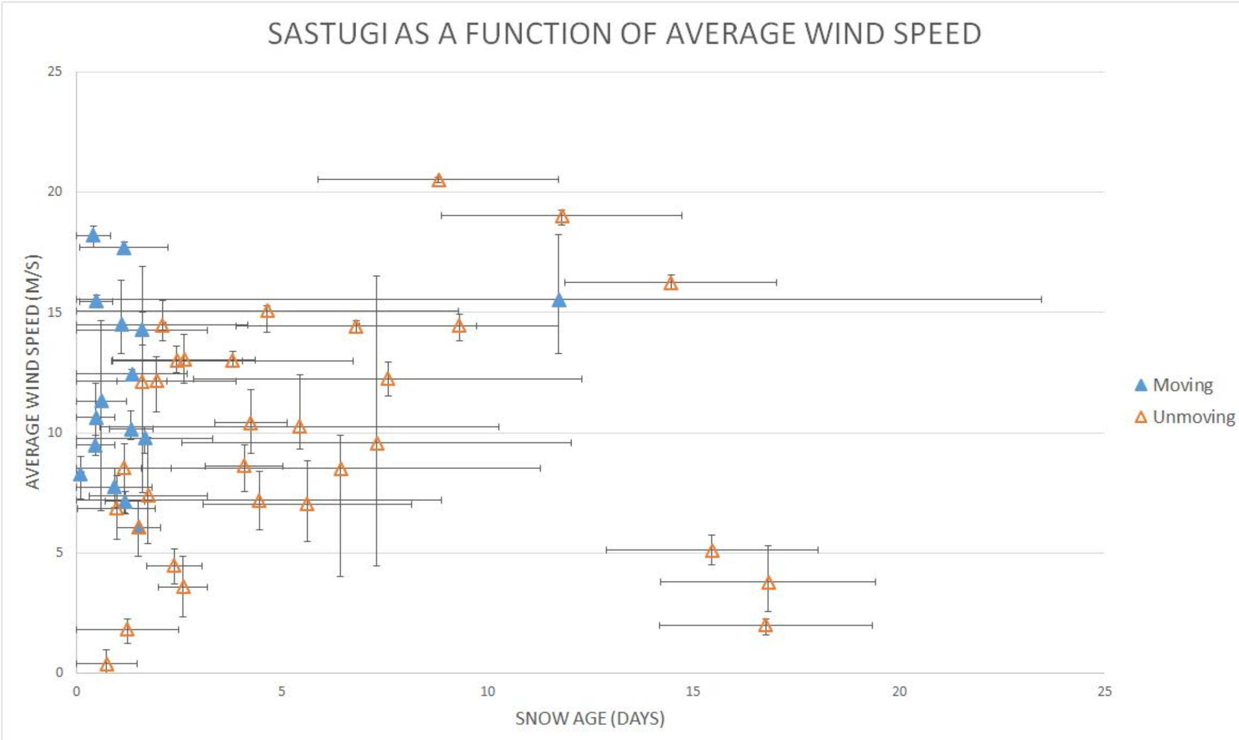

Figure 20. Sastrugi as a function of wind speed and snow age

We can generalize this data and combine both types of erosional bedforms into a plot to show movement thresholds more clearly.

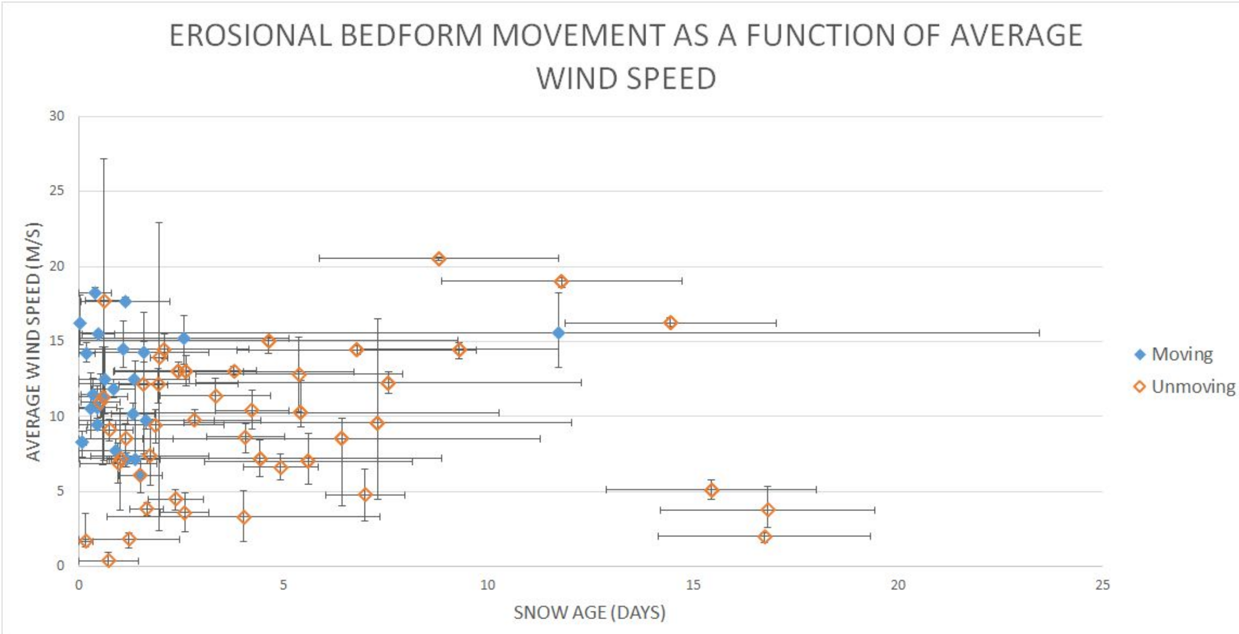

Figure 21. Erosional bedforms combined to show movement thresholds

DISCUSSION

My observations in the winters of 2016 and 2017 suggest that certain bedforms will form under specific wind speed and snow age and that there exists a threshold wind speed for movement of some bedforms. We found that once wind speed was high enough the bedform would move, as long as the snow was young enough, but once the snow reached a certain age all bedforms would cease movement. In addition, we found that depositional features such as ripples and dunes evolve with young snow, while erosional features such as sastrugi and edges evolve in snow of any age but are more common in older snow.

Wind speed and snow age implications for bedform type

The aim of the study was to quantify what type of bedforms were present, what types were moving, and under what conditions were required for each. The only time we failed to see snow bedforms during good visibility was when there was a sheet of fresh snow covering everything. Otherwise, at least one type of bedform existed. Bedform-free snow on Niwot ridge is very rare and only exists when there is a period of low wind immediately after snowfall; these events were not considered in great depth for the project. However this in itself is interesting in that it demonstrates that un-ornamented snow surfaces are unstable, and inevitably self-organize into bedforms of one or another type.

The two most common bedforms on Niwot Ridge were sastrugi and edges. This is likely due to the fact that these two bedforms are erosional; while they can form when the snow is young or older, they will persist as the snow continues to age. The footage from late December 2016 to early January 2017 showed several sastrugi that did not move or change shape noticeably during this almost two-week period. The structure and durability of erosional bedforms can ultimately be traced back to sintering in the grains, as discussed in the introduction.

While edges are not commonly discussed, they were included in this project due to their wide range and similarity to sastrugi. Edges behave in very similar way to sastrugi, forming and moving under very close wind speeds and snow ages. The main difference is that that edges are not as elongated or eroded as sastrugi. However, they could possibly be considered a form of non-pointed sastrugi, or might even lead to sastrugi if the snow was given a point to start building off of. Perhaps even if the edges are scalloped enough, they can form as an evolutionary predecessor to sastrugi.

Figure 22. Edges, scalloped enough to possibly begin to form into sastrugi. Wind left to right.

Figure 23. The start of sastrugi forming, seen as elevated sections of snow in a "v" shape, with no erosion yet forming underneath the nose. Wind left to right.

As seen in the Figures 22 and 23 the shapes of the scalloped edges and of young sastrugi are similar. With further erosion, the edges could possibly evolve into sastrugi. This could be an interesting question to examine for future studies.

The depositional features, ripples and dunes, were far less common and rarely seen in either the field or the time lapse footage. Depositional features require a very young snowpack, as once the snow has time to sinter and metamorphose it will begin to erode. These features were most frequently seen immediately after a blizzard, when the snow was very young. Ripples were most commonly found on a moving snow wave, in which a tongue of young snow would creep across the older bedforms. Many times the wave continued without ripples, but on a few occasions its surface would be rippled. As the data suggested that waves and ripples formed under very similar snow ages and wind speeds, it is likely that they occur together frequently.

As reviewed in the results section, the data from this project can ultimately be used to interpolate where certain bedforms for which we do not have data points may fall. Examining movement thresholds in Figures 15, and 19-21, we can start to get a better idea of where the data generally falls. Figure 24 is a representation of this elucidation, where hard lines separate moving and unmoving bedforms and dashed lines speculate where the other data points fall.

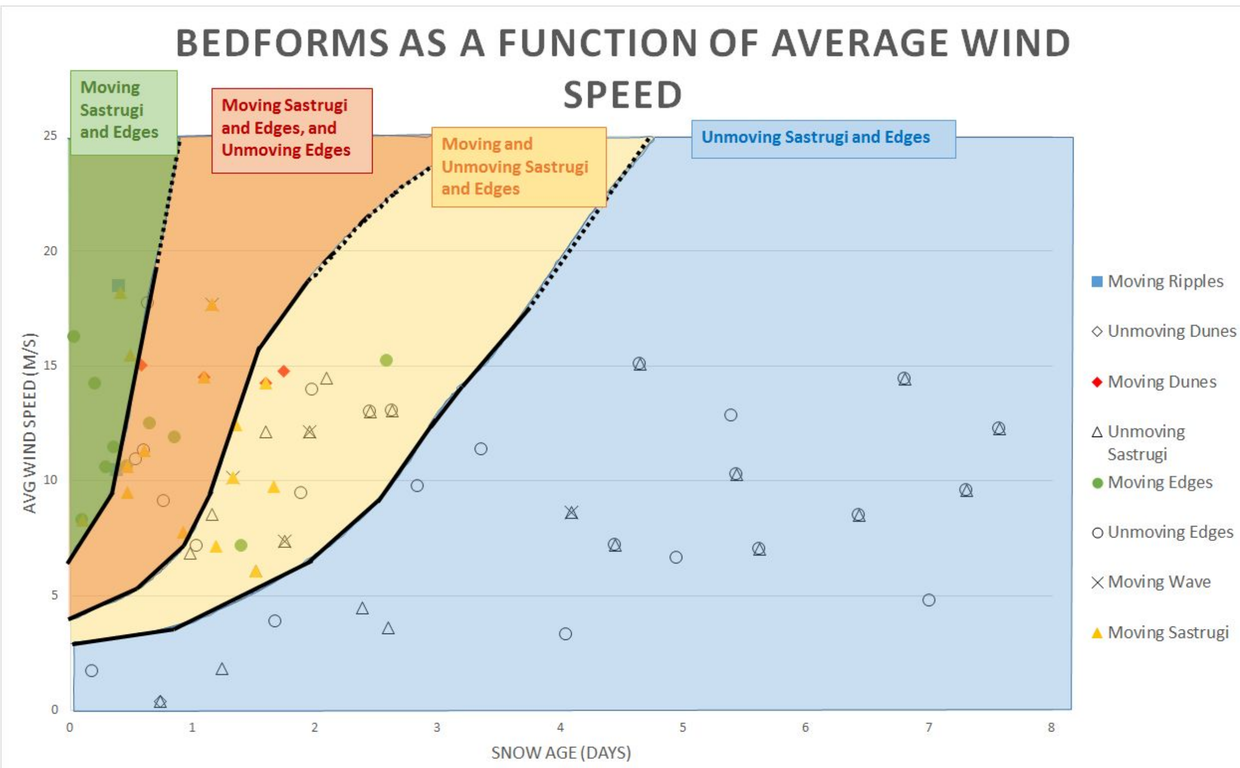

Figure 24. Movement of erosional bedforms. Thick lines represent separation between moving and non moving bedforms and dotted lines represent speculation on where data could fall.

The data as plotted in Figure 24 shows that in young snow sastrugi and edges show movement, then edges are the first bedform to remain stationary as the snow ages and sastrugi and other edges continue to move. Eventually, sastrugi and edges are seen as both moving and nonmoving bedforms as the snow ages further, and finally after about 2 days, all movement or erosional bedforms ceases regardless of bedform type. Outlier data points were not included in this interpretation after consulting camera footage and error bars.

Further speculations of the data resulted in Figure 25, in which the depositional bedforms are plotted over Figure 24.

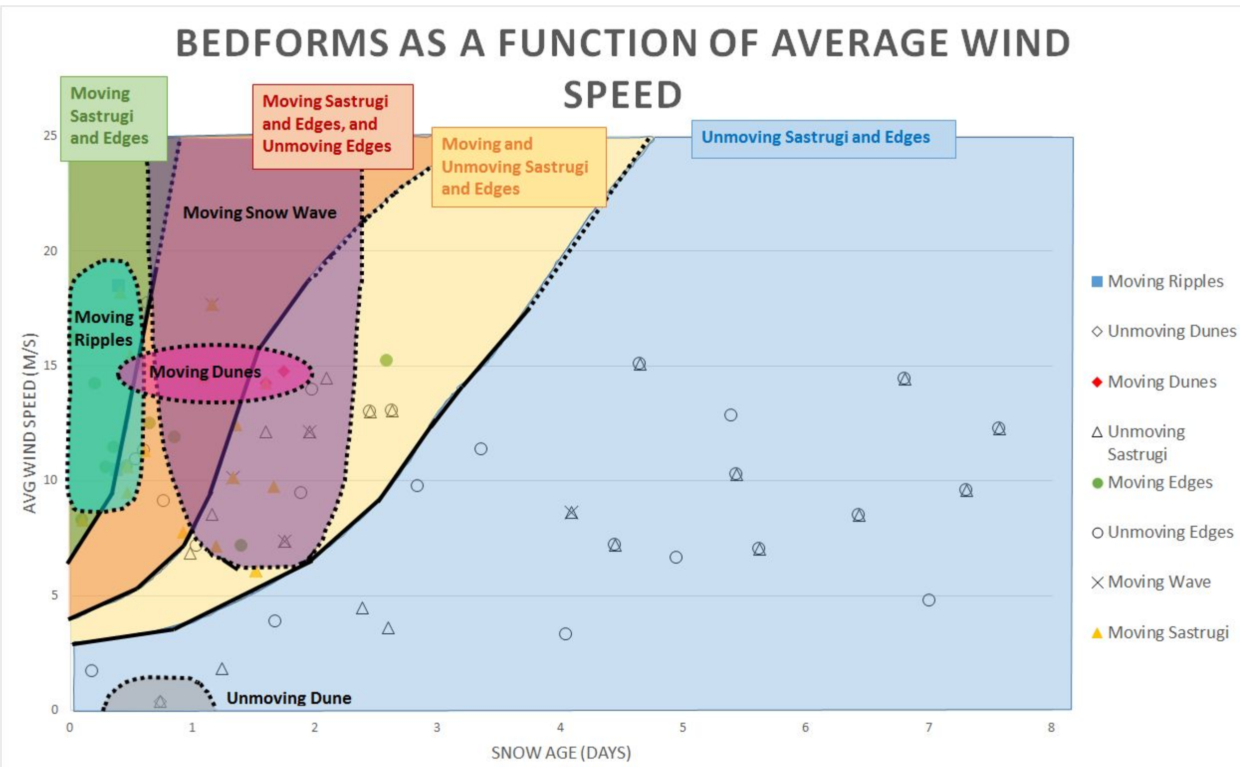

Figure 25. A generalized interpolation of the data, in which all bedforms seen in the data are plotted, with shading to show where the points could fall. Thick lines represent separation between movement of bedforms, and dotted lines represent speculation as to where the data could fall.

This data is a valuable starting point for predicting under which conditions certain snow bedforms will form. Despite this, Figure 25 is merely an estimation of these trends given the patterns in the data, and further investigation is necessary to build a more accurate image.

Field observations of bedforms

While the timelapse footage proved to be extremely helpful in collecting data around the clock, observations of the study site during field trips provided additional valuable insights. Visits to the study site a handful of times revealed that the sastrugi varied greatly in size and shape across the study site. The sastrugi on the north of the site were heavily eroded and many were carved out in an anvil shape, while the ones south of the site were massive in size, stretching up to 2 meters long and were large enough to walk across their tops. In contrast, the sastrugi in the middle of the ridge were very small in size and had not been sculpted as much; on one occasion several huge snow waves were spotted here (Figure 3). The middle of the ridge is more protected from the wind, and thus sees higher snowfall deposition, whereas the edges have been scoured from the wind. As wind is one of the main factors in eroding sastrugi, the anvils clearly existed in a more windy part of the ridge whereas the smaller sastrugi occur under more sheltered conditions. One remaining question is why the sastrugi on the south side of the study site were so large. A hypothesis is that it is a site where both deposition and erosion are large, so the sastrugi are allowed to grow to huge sizes with the ample snow and wind. This could be examined in later studies as well. Figure 26 shows a LiDAR image of Niwot Ridge representing snow depth; the image is of the study sites considered in this project, with the summit of the ridge running left-right through the middle of the image. Image was received in private communication.

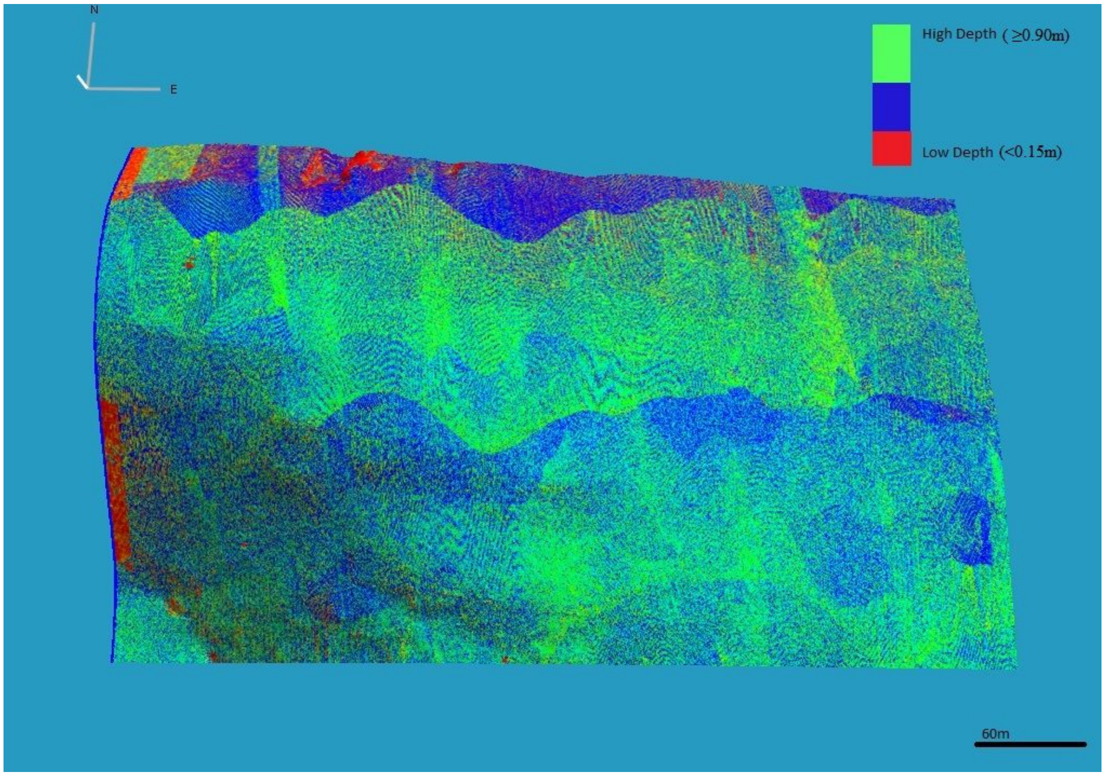

Figure 26. LiDAR data collected on Niwot Ridge after substantial snow accumulation on May 20/21, 2010. Image shows snow depth, with green points as deep snow and red as shallow snow. The data was collected in collaboration between the National Center for Airborne Laser Mapping (NCALM) project and the Boulder Creek Critical Zone Observatory (CZO), both funded by the National Science Foundation (NSF). The dataset contains 1 m Digital Surface Models (first-stop), Digital Terrain Models (bare-earth), with a LiDAR point density of 8.94 pts/m2.

Platform: Airborne Lidar
Point Density: 8.94 pts/m2
Survey Date: 05/20/2010 - 05/21/2010
Horizontal Coordinates: UTM z13N NAD83 (CORS96) [EPSG: 26913]
Vertical Coordinates: NAVD88 (GEOID03) [EPSG: 5703]

LiDAR data provided by OpenTopography. Image courtesy of Maxwell Fanning.

Statistical analysis has shown that high, persistent winds will eventually scour a surface free of snow (Das, 2013), so with some surmise Figure 26 can be used to consider wind patterns as well. As Figure 26 shows, snow accumulates along the middle of the ridge while the sides are more barren, and there is some significant accumulation along the south side of the ridge. When considered in conjunction with wind scour, it can be theorized that the massive sastrugi on the south slope were formed as a result of high winds and high deposition, where the deeper snow in the middle of the ridge is more wind sheltered. In addition, the sastrugi characteristic of high winds were located on the northern slope, which has relatively shallow snow in FIgure 26. It must be considered that the image is taken from preceeding the study by 5 years, however Figure 7 shows that snow depths were similar for 2010 and 2016. Relating wind speed and snow depth in future studies could provide more insight on this phenomenon, and is another fascinating application of studies on snow bedforms.

While this study provided some interesting correlations between snow age, wind speed, and bedform type, many unanswered questions remain. For one, it would be interesting to know how fast the bedforms were moving. The relationships between their rate of movement, wind speed and snow age should be investigated. Erosion rate could be considered as well. In addition, exploring whether and under what conditions edges evolve into sastrugi could provide insight into the likely evolution of a snow surface through time. The initiation of sastrugi also remains a mystery: whether they need a point in the snow to build from, or if the erosion of a fresh sheet of snow or snow edge is required, or another unforeseen method.

Future research would undoubtedly improve our data set, as we have learned much from our mistakes. The original plan was to collect the majority of the data in the winter season of 2016-2017; this winter resulted in relatively late snowfall and fewer than expected snowfall events. Multiple field seasons are clearly required to obtain sufficient data. Finally, more cameras to view the bedforms in more locations would provide the data necessary to expand the project, and would in addition provide backup if some of the cameras were buried in heavy snowfall.

This study revealed some interesting patterns with the evolution of snow bedforms and further investigation would undoubtedly reveal new and compelling information on the way snow interacts in its environment. Understanding snow bedforms is crucial to understanding energy balances of the entire planet, as their occurrence in the critical zones of the Arctic, alpine and Antarctic regions influences many processes around the world. With increasing concern about climate change and energy balances on the globe, new research on the evolution of snowy surfaces has great potential to increase understanding of mass balance and accumulation of precipitation on ice caps, relationships between bedform-related melt on sea ice, and the use of microwave remote sensing in estimating precipitation, to name a few (Picard et al., 2014).

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