Snow Surface Indicators of Wind Direction

Windy Gully WA

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3/19/2021

Abstract.

Snow surfaces are heavily influenced by wind driven erosion and deposition. Grains of snow are transported and re-organized by wind forming distinct windblown snow bedforms. These unique bedforms not only add variation to snow cover but provide information on weather conditions at their location. Bedforms can be used to indicate wind direction in snow covered locations. In this study windblown snow bedforms are observed and analyzed to improve understanding of wind direction in Windy Gully. A total of 18 features are identified and used to determine wind direction. Snow depth is also examined in Windy Gully as the wind has created large variability in snow depth. Using supplemental weather station data, the reliability of this process is also tested. Observations of windblown snow bedforms, depth, and weather station data combined support that Windy Gully receives a local east wind.

Introduction

Wind and snowfall act to create snow bedforms in mountainous areas. Due to the distinct conditions required to create each feature, the distribution of bedforms provides a summary of the past conditions that have formed them. Interpreting and understanding past weather conditions can be a very important aspect of many fields of research. The importance of water resources in Washington State has driven research in snow and ice. With the discovery of the Windy Gully rock glacier, research efforts have begun in attempt to understand the conditions that influence this unique permafrost. Weather can be very influential in preserving year-round ice driving interest in the weather at Windy Gully. As the name implies this site is often very windy. Could the wind at Windy Gully play an influential role in the survival of the rock glacier? Without long term wind data for this site, I set out to see what could be learned about the wind at

Windy Gully. Using a combination of windblown snow bedforms, snow depths, and short-term weather station data, research was conducted on the wind direction and impact on snow cover at Windy Gully.

Literature Review

Snow is rarely a homogenous surface with variable depths and bedforms. Wind blowing over snow can organize individual grains into various snow bedforms (Kochanski, Anderson, Tucker 2019). This organization of snow is common throughout mountainous regions with consistent wind, such as the Wenatchee Mountains. Windblown snow bedforms are classified into two formation processes, depositional and erosional (Doumani 1967). Depositional features form from the redistribution of snow grains by wind transport. Snow can be transported by wind through three process. Creep occurs with the lowest wind speeds and biggest grain size as wind transported snow rolls along the surface. With higher winds and smaller grain size snow grains can saltate, bouncing along the surface. Lastly, when winds are strong enough and grain size is small, snow can be transported through suspension. Topography creates variability in wind speed with windward areas receiving high wind while leeward zones experience reduced wind speed. As wind speed reduces in leeward zones, the ability to transport snow grains is also reduced causing snow to deposit into various bedforms. Erosional bedforms form due to differences in snow density. Soft snow is more susceptible to wind transport than hardened or dense snow (Doumani 1967). Areas of soft unconsolidated snow is transported or eroded from the surface while harder more dense structures remain. In result, numerous erosional bedforms with distinct patterns can form on the snow surface.

Classifying and naming windblown snow bedforms in this study was achieved using descriptions and classifications as published in *The evolution of snow bedforms in the Colorado Front Range and the processes that shape them.* Published in 2019, this study provides a recent investigation into the processes that form windblown snow bedforms. Individual features are classified and described. Using these descriptions, features were classified in this study. Plane beds are described as flat uniform snow surfaces that form during periods of fresh snowfall with light wind (Kochanski, Anderson, Tucker, 2019). Snow ripples form small lines perpendicular to the mean wind direction (Kochanski, Anderson, Tucker, 2019). Sastrugi is an erosional bedform with distinct steep points elongated into the wind (Kochanski, Anderson, Tucker, 2019). Additional features excluded from the 2019 study including tails, crags, exposed rock, depositional faces, and step dunes were found at Windy Gully and described in this study.

Study Area Description

Setting out to study windblown snow, Windy Gully was selected as the study site. Windy Gully is located in Central Washington within the Wenatchee Mountains. This remote site is 14 miles from the nearest city of Wenatchee but largely separated by undeveloped mountainous forest. Located in the Okanogan Wenatchee National Forest, this is a common site for winter recreationalists including snowshoers and skiers. Elevation of the study area ranges from 5100-5400ft above sea level. During the winter months this site experiences cold weather and significant snowfall creating continuous snow coverage for the entirety of the winter season. Located in a low-lying gully, this site is surrounded by two prominent mountains. Diamondhead to west sits at an elevation of 5915' with its steep slopes blocking the afternoon sun creating shade in Windy Gully. To the east is Windy Knob, another prominent mountain with steep slopes at 5919'. The topographic relief of these higher mountains act to shade Windy Gully and created cooler temperatures. Topography is also favorable to create cold air drainage through Windy Gully.

Windy Gully is significant as there is mounting evidence of a rock glacier with year-round permafrost buried below the surface. Previous research conducted by CWU students and faculty has resulted in multiple findings that suggest year-round ice beneath the rock surface. Pressure ridges, steep lateral moraines, and a steep toe indicate that this site could be a rock glacier. Additional research using ground penetrating radar has mapped out underlying ice. This previous research has brought scientific attention to the weather conditions at Windy Gully.

Methods

Windy Gully was frequently visited and observed from January 16 to March 13. Visits were typically done every other week during this period, with some variability due to scheduling. Reaching the site involved over snow travel using snowshoes and skis. Observations and data collected on each visit provided insight into what conditions were like at Windy Gully throughout the winter of 2021. Windblown snow bedforms were observed and photographed on each visit. Additionally, weather conditions including cloud cover, wind speed, wind direction, air temperature and precipitation were recorded. While this data did not play a major role in the final data of this study, it provided baseline information about Windy Gully and improved understanding of how conditions evolved throughout the winter of 2021.

A survey of windblown snow bedforms was conducted at Windy Gully. To include a variety of features, the survey covered a large area including the bottom of Windy Gully below the rock glacier snout and mid gully on the surface of the rock glacier. Bedforms were visually identified and photographed for future reference. A series of data was collected for each bedform. In total 18 bedforms were identified. These bedforms were classified by the type. The formation process of the bedform, either depositional or erosional was also recorded. Bedforms often have features that indicate wind direction. Using a compass and these indicators, the wind direction indicated by each feature was recorded. For example, tails form on the leeward side of an obstructing object. The direction a tail forms can indicate the direction wind is blowing towards. Additionally, snow depth was measured on each bedform using a probe. Most windblown snow bedforms do not have a uniform depth. To account for this variability, depth was measured as a range yielding a minimum snow depth, maximum snow depth and an average snow depth. Lastly, GPS was used to gather coordinates at each bedform. This data was recorded in an excel spread sheet for further analysis.

This study also included two snow depth transects to better understand the variability of snow depth spatially. Separate transects were completed at the snout of the rock glacier and the surface of the rock glacier. To start, a bearing for the transect to follow was chosen. The bearing for each transect was chosen based on the wind direction indicated by the nearest windblown snow bedform to the starting point. At the snout of the rock glacier, the transect was completed on a bearing of 280°, as indicated by a nearby tail. Using a 3-meter probe, depths were measured every 3 meters along the transect. The resulting depths were recorded in a standard field notebook. This short 3-meter increment was chosen to provide detailed spatial resolution and make use of a standard avalanche probe that all snow scientists likely carry with them in the backcountry. The distance of the transect varied between the two locations. The rock glacier snout transect was 51 meters long, ending where trees began to shelter the snowpack from wind. At the surface of the rock glacier, the transect was completed on a bearing of 260° as indicated by tails formed off extruding rocks. This transect was a length of 90 meters, with depth measured every 3 meters in a similar process to the first transect. Data was entered into Excel for further analysis and graphing.

Lastly, air temperature, wind speed, and wind direction data were collected using an on-site weather station. This weather station was hiked into Windy Gully in pieces and assembled on site. Included on the station is a thermometer for gathering air temperature, anemometer for wind speed, and a wind vane for wind direction. Data from each instrument was recorded using a hobo computer. Data from the weather station was downloaded near the end of the study period to provide comparison with data collected from snow bedforms.

Results

Prevailing down gully wind out of the east was identified using 18 windblown snow bedforms. Table 1 shown below includes surveyed features classified with corresponding formation process, wind direction, snow depth, and additional notes listed. Wind directions indicated by windblown snow bedforms ranged from 72-128°. Bedforms showed that the prevailing wind has blown out of the east, as many of these features have been building over long periods of time. Large scale depositional features such as dunes and tails that have grown throughout the season indicate an easterly wind. Depositional features form over long periods of time through multiple storms. New snow fall provides loose grains that can be transported to depositional zones where they accumulate over time. Large depositional bedforms with indication of east winds show that this wind direction has been the primary direction over time. Smaller erosional features such as crags and sastrugi also indicated an east wind. These smaller erosional features can form on a shorter time frame, typically between periods of snowfall. An east wind indication from these small features shows that wind has primarily blown from the east since the last significant snowfall. The average wind direction of all 18 features is 95°, blowing out of the east and down Windy Gully. Based on the windblown snow bedforms, Windy Gully experienced a prevailing east wind during the winter of 2021.

Number	Classification	Formation	Wind Direction	Min Snow Depth (cm)	Max Snow Depth (cm)	Average Snow Depth (cm)	Additional Notes
1	tail	D	115	255	300	277.5	Leeward of Large tree
2	sastrugi	E	88	15	20	17.5	Windward side of ridge
3	tail	D	96	153	210	181.5	
4	sastrugi	E	92	14	20	17	crest of ridge
5	snow ripples	D	124	175	190	182.5	outlet of glacier
6	crag	E	96	0	23	11.5	ice near tree, soft snow on outside
7	tail/step dune	D	128	160	187	173.5	cornis like
8	sastrugi	E	118	28	40	34	very soft and light
9	depostional face	D	110	not measured	not measured	not measured	face below crest of #8
10	dune	D	96	30	310	170	steep edge of rock glacier
11	exposed rock	E	90	0	15	7.5	
12	plain bed/ripple	D	80	90	100	95	low spot
13	exposed rock	E	80	0	10	5	pressure ridge, tails on leeward side
14	plane bed	D	80	130	140	135	leeward
15	exposed rock	E	78	0	15	7.5	pressure ridge with tail
16	plain bed	D	none	135	135	135	
17	exposed rock	E	72	0	10	5	deposited on leeward side of pressure ridge
18	snow ripples	D	80	56	56	56	

Table 1. Observed windblown snow bedforms and descriptive data collected at Windy Gully.

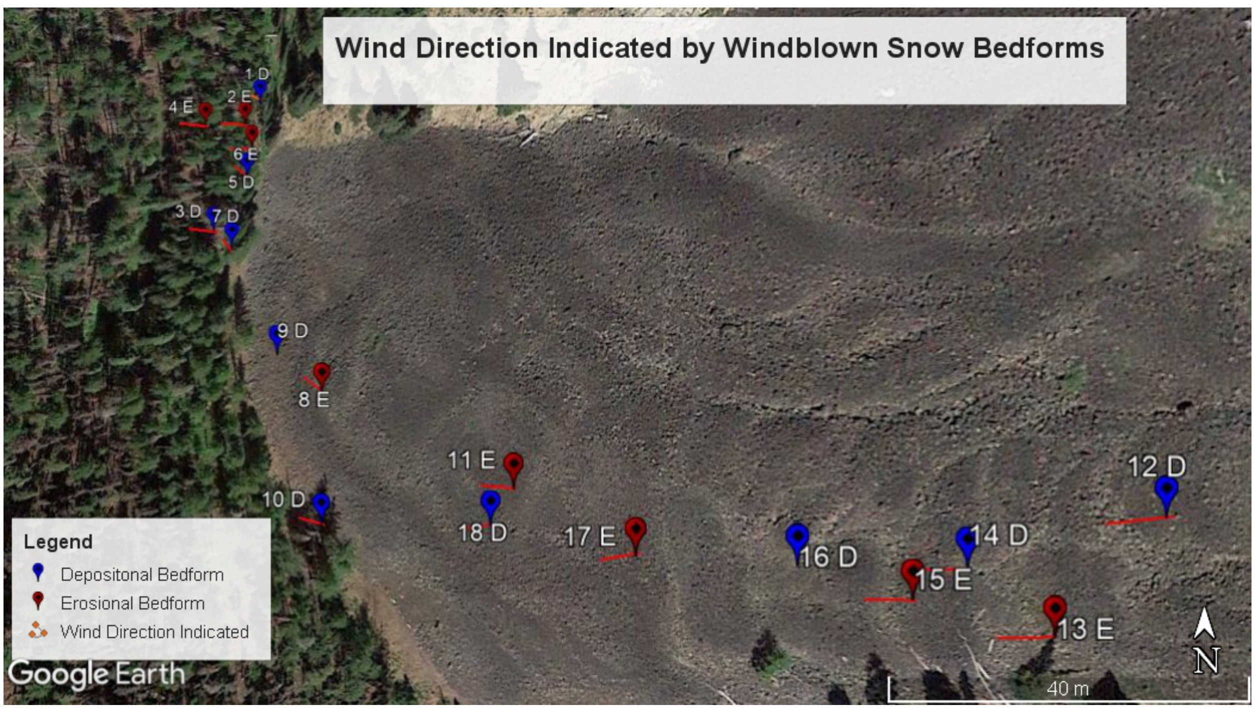
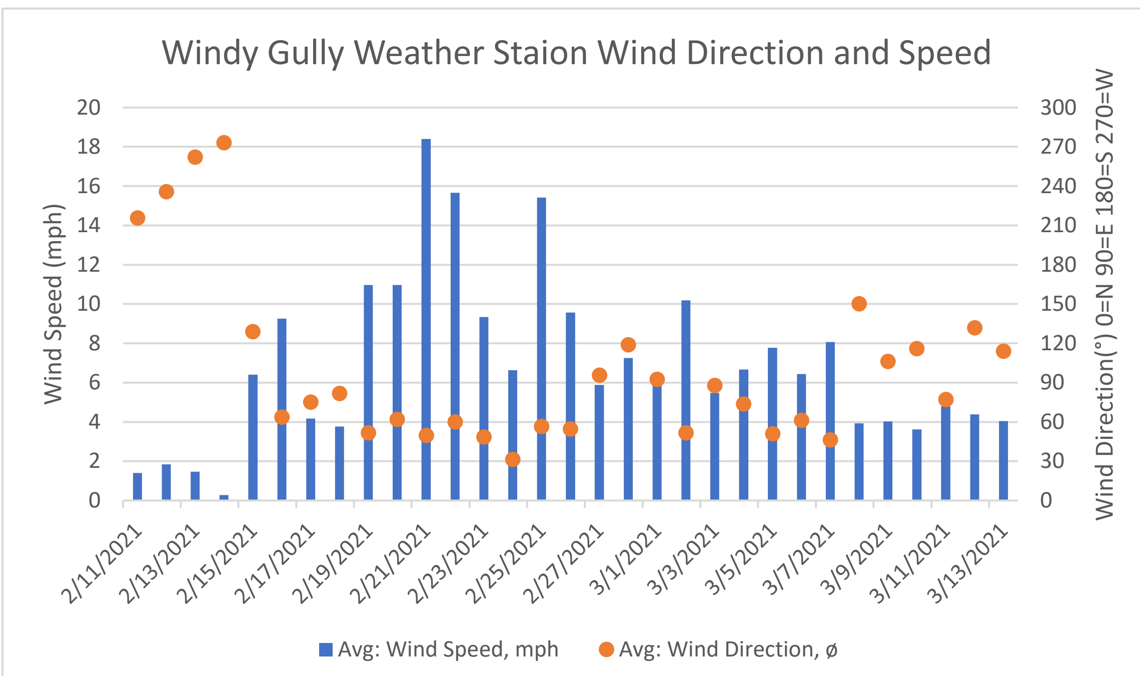


Figure 1. Map of snow bedforms and corresponding wind direction at Windy Gully indicated.

The Windy Gully weather station data also supports an easterly down gully wind direction from 2/11/2021 to 3/13/2021. Weather station data shows more variation in wind direction than snow bedforms. Average daily wind direction ranged from 31.3-273.1°, a significantly larger range than indicated by snow bedforms. Despite this higher variability, the average wind direction for the entire study period was an east wind at 101° which is really close to the 95o result from the bedforms. It is important to note a period of unusual wind measured by the station. From 2/11 to 2/14 average daily wind direction ranged from 215.7-273.1° showing southwest and west wind. This period does not fit with the trend in wind direction for the rest of the period. Even with this unusual wind direction, the average wind direction for the study period was an east wind. Data gathered by the Windy Gully weather station shows a local prevailing

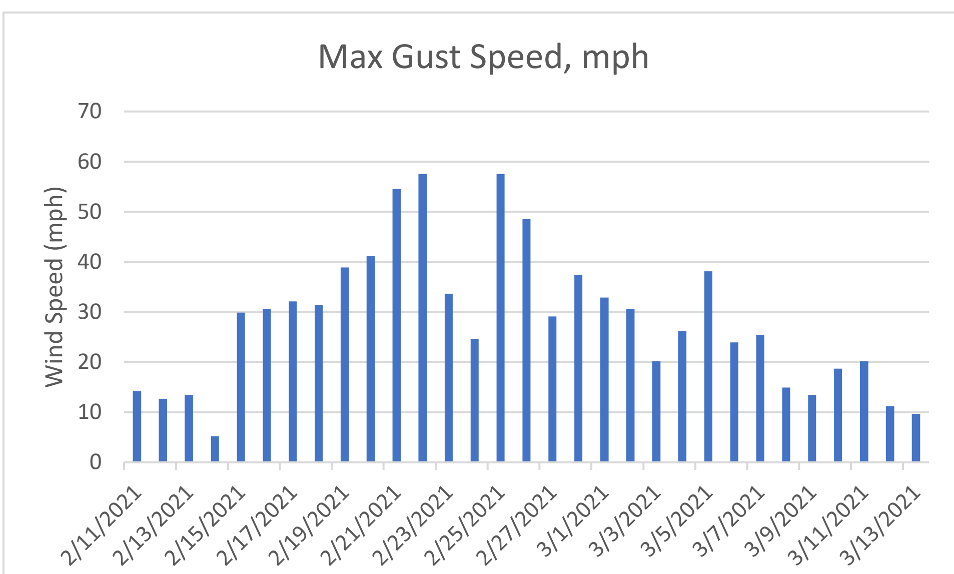


down gully wind blowing out of the east.

Figure 2. Average wind speed and direction data gathered from the Windy Gully weather station. A period of west/southwest wind can be seen from 2/11 to 2/14 that does not fit the general trend of east wind the rest of the period.

From February 11th to March 13th, the Windy Gully weather station recorded consistent wind. A short period of low wind occurred from 2/11 to 2/14 with average wind speed below 2mph. During this period wind was blowing out of the west, as compared to the east direction observed much of this time frame. Beyond this period, average wind speeds stayed above 3.5 mph. Average wind speeds ranged from 0.28 mph on 2/14 to 18.4 mph on 2/21. For all 31 days the average wind speed was 6.91 mph.

The Windy Gully weather station also provided data on maximum wind gust speed. From 2/11 to 3/13, maximum wind gust speed ranged from 5.23 mph to 57.53 mph. The average maximum gust speed during the 31 day period was 28.3 mph. On average, wind gust speed got high enough to achieve transport of snow grains. While suspension only occurs with wind speeds greater than 30 mph, saltation and creep can occur at speeds as low as 11ph. While these gust speeds do not represent continuous wind, they do show that on 29 out the 31 days, wind gusted at



a high enough speed to transport snow grains. High gusts do not show consistent transport of snow but do indicate potential to transport snow during periods of high gusts.

Figure 3. Maximum wind gust speeds as recorded by the Windy Gully weather station.

Wind has heavily influenced snow coverage at Windy Gully with highly variable snow depths throughout the area. Over time many depositional zones gained snow depth. Large features such as tails and dunes had a maximum depth of up to 310cm. Erosional zones had shallow snow depths with as low as 0cm, or exposed rock. Snow erosion and deposition have both created variable coverage on the surface of the Windy Gully rock glacier. The distribution of erosional and depositional bedforms also support a prevailing east wind. On the upper portion of the rock glacier, a series of pressure ridges run perpendicular to the slope. On the windward or east side of the ridges, snow depths were shallow with exposed rock ranging from 0-60cm deep. The leeward or west side of the ridges had significantly deeper snow, ranging from 50-135cm deep. To achieve this pattern of snow depth the east side of the ridge must be windward, and the west side must be leeward, further supporting prevailing east wind.

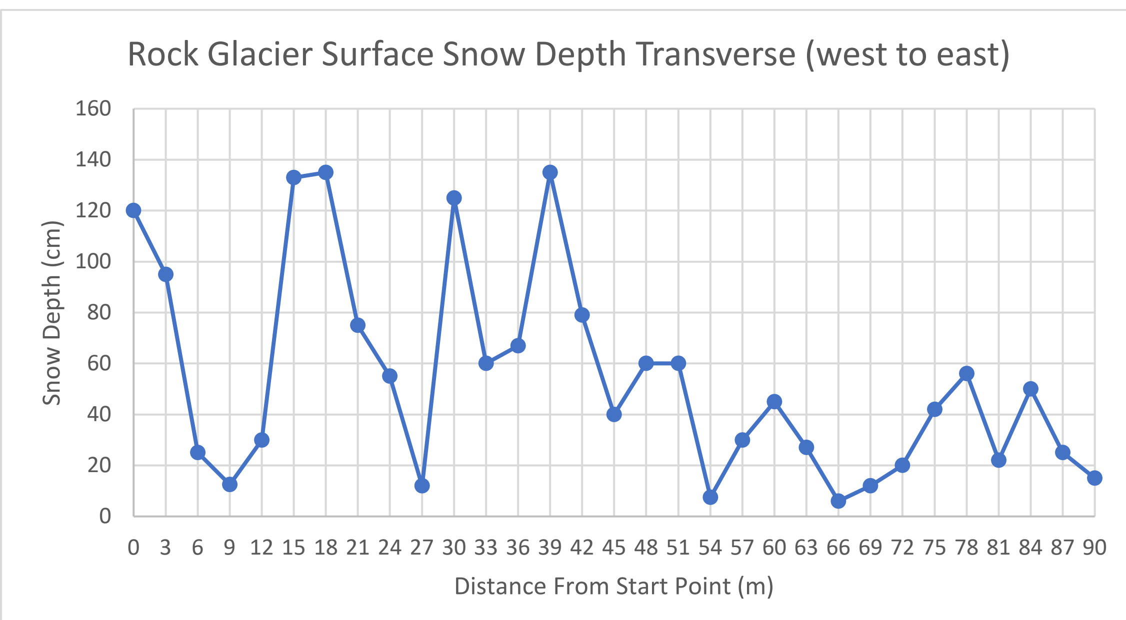


Figure 4. Snow depth at Windy Gully measured along the Rock Glacier Surface transect. Areas of low snow depth indicate windward locations while areas of deeper snow indicate leeward deposition.

Figure 5. Variable snow depths seen along the pressure ridges of the Windy Gully rock glacier. Looking to the west, the exposed rock can be seen on the windward east side of the ridges, while deeper snow is seen on the leeward west facing side of the ridges.

The snow depth transect at the outlet of the glacier also supports an east wind. Set on a bearing of 280°, topography varies from east to west along the lower transect. The transect starts partly up the toe of the rock glacier and then drops into the low drainage of the glacier outlet.

Continuing to the west, the transect crosses over a small ridge before descending into the next drainage. The start of the transect (0-9m) is deep with a depth of 145-295cm as it crosses the low drainage. This deeper portion indicates a leeward depositional zone. From 9-27m the snow depth drops to a minimum of 11cm, indicating an erosional zone on the windward side of the ridge. Once over the crest of the ridge, depth begins to increase again as snow has deposited on the leeward side. This series of deposition and erosion along the east to west transect further supports an east wind and the highly variable snow depth in the area.

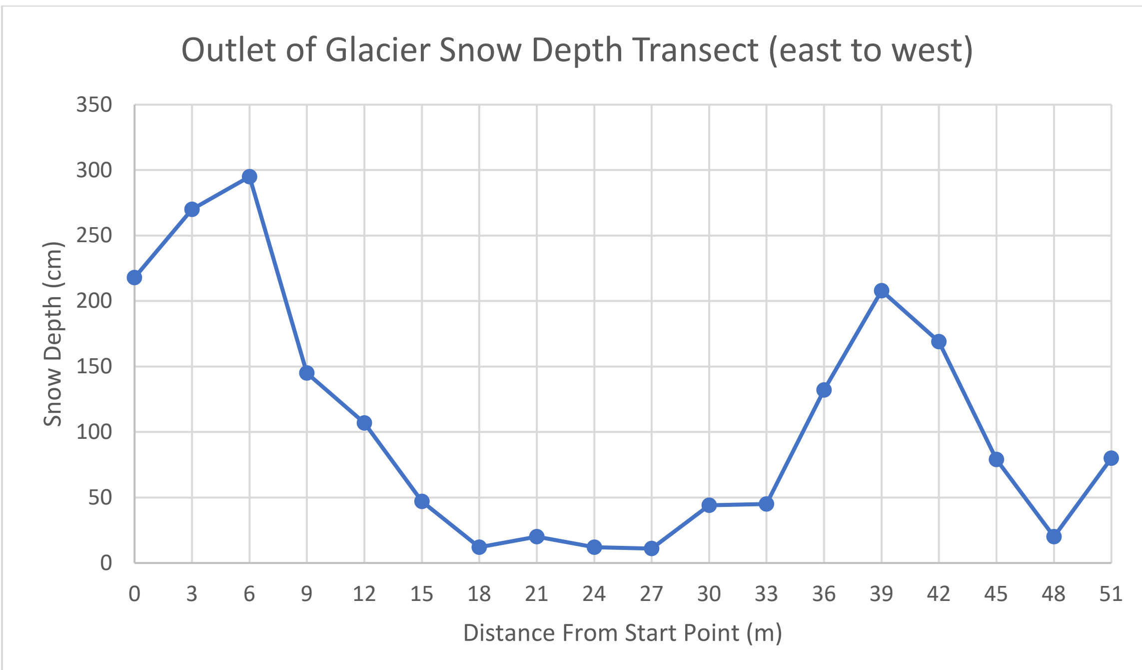


Figure 6. Snow depth along the transect completed near the outlet of the Windy Gully rock glacier. Again, deep areas represent leeward deposition while shallow snow represents areas of windward erosion.

Discussion

The use of windblown snow bedforms has proved to be a reliable method of determining local wind. In total, 18 unique bedforms were found within Windy Gully. While the location, snow depth, and formation type of these bedforms all varied, all features indicated an east wind down Windy Gully. No two features were the same, but the wind direction indicated by them was very similar. Ranging from 72-128°, all windblown snow bedforms indicated an east wind, down windy gully. Furthermore, the wind directions shown by windblown snow bedforms matched up with the average wind direction measured by the Windy Gully weather station. The average wind direction indicated by bedforms was 96.43° and an average of 100.7° was found with the weather station data. While these directions are not exactly the same, they both indicate an east wind down Windy Gully. This close comparison between wind direction from bedforms and weather station data show that using snow bedforms as an approximation for wind speed is a reliable method.

The variation between bedform and weather station data could be due to the different temporal resolution of the two data sources. Windblown snow bedforms are created and manipulated starting at the first snowfall and ending when the snow melts. The wind direction indicated by bedforms in Windy Gully represent wind direction from the first snow fall to the time of observation. Bedforms can change drastically over time and may be completely altered by individual storms, lacking daily temporal resolution. On the other hand, the weather station data accounts for every single day it is recording. In the case of the Windy Gully weather station, it did not start recording wind direction until 2/11/2021. The data reported from the weather station does not account for wind that occurred earlier in the snow season that manipulated the snow surface into some of the larger bedforms. Differences in temporal resolution between these two methods could account for the discrepancy in the calculated average wind directions.

Windy Gully experiences an east wind direction, but based on additional evidence in the surrounding area this is likely not a widespread wind direction. To the north of upper Windy

Gully, Windy Knob has evidence supporting a west wind. A large cornice has formed along the leeward east edge of this high point. For snow to deposit on this east facing aspect, wind must be blowing from the west. Additionally, dead trees that have fallen in the wind are oriented from west to east. Multiple trees can be seen laying in this orientation, indicating a prevailing west wind. Branches on live trees are more numerous on the leeward east side of the tree than the windward west side, further supporting a west wind direction. To the west of Windy Gully, Diamondhead also has shown signs of a west wind direction with large drifts and depositional features located on the leeward east side of the mountain. Wind direction indicators in the surrounding area show signs of a prevailing west wind, unlike Windy Gully that has mounting evidence of an east wind direction. Comparison between evidence in Windy Gully and the surrounding areas leads me to believe that the east wind observed in Windy Gully may be a highly localized wind direction.

Figure 7. Photograph of fallen trees laying in a west to east orientation. In the top right corner of the image branches are more numerous on the east facing leeward side than the west facing windward side, an indicator of a west wind.

With numerous windblown snow bedforms, Windy Gully has an uneven snow depth. Moving in the wind direction indicated by bedforms, transects showed that the snow depth was highly variable over the uneven topography. Windward areas had been eroded with shallow

depths. Leeward areas had significantly deep snow. The rise and fall of snow depth over the pressure ridges on the surface of the rock glacier and the ridge near the outlet support an east wind. With the arrival of a spring melt, variation in snow depth will result in uneven melting.

Windward areas will melt down to soil and rock sooner than leeward areas due to the shallower snow depth. The amount of exposed rock along the pressure ridges became a lot larger later in the season during a period of warm sunny weather before my visit on 3/13/2021. This uneven coverage on the rock glacier may have an impact on the thermal processes of cooling the permafrost. Deep snow can act to insulate and trap cold air while melted out exposed rock may allow the flow of air into the glacier.

Conclusion and Further Research

Overall, evidence supports a prevailing east wind down windy gully. All 18 windblown snow bedforms observed indicate an east wind direction. Additional weather station data supports an east wind direction with and average wind direction of 100.7°. Oriented east to west, snow depth transects show shallow windward depths on east facing features and deeper leeward snow depths on west facing slopes. Data collected and observations throughout the winter of 2021 have proved that wind blows out of the east down Windy Gully.

Moving forward, proof of an east wind down Windy Gully has the potential to lead to future research. While an east wind has been observed during this study, continued monitoring of Windy Gully is important to find if this is a year-round occurrence. Additional monitoring in the surrounding areas could be used to figure out why Windy Gully experiences this localized east wind. Adding temperature and air pressure monitoring in nearby areas such as Diamondhead and Windy Knob could provide further insight into the conditions that drive this east wind. Cold air drainage may be causing this local wind and should be further investigated. The continued study of wind and snow in Windy Gully could prove very valuable in understanding the Windy Gully rock glacier. This rock glacier is significant as it lies further east and at lower elevation than many known rock glaciers in the Cascade Mountains. Wind direction, snow cover, and air temperature could all be important factors in maintaining year-round ice in the rock glacier. Improving understanding of these factors and their influence on the rock glacier are important in a world faced with rapid climate change, prompting further research in Windy Gully.

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