

METEOROLOGICAL CONTROLS ON
WIND SLAB PROPERTIES

by
Nathalie Marika de Leeuw

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ABSTRACT

Snow avalanches are dangerous phenomena, which can be made increasingly consequential through wind transport of snow. Wind-deposited snow has a broad range of possible physical and mechanical properties which can vary greatly over short distances, creating inconsistent and thus difficult avalanche conditions. This variability causes particular challenges for avalanche workers in data-sparse regions where important snowpack information at desired scales may be unavailable. Instead, snowpack properties are commonly inferred from available meteorological data. Though wind slab properties vary in space and time as meteorological conditions change, previous work has not explicitly studied these relationships at the slope-scale. In this research I aim to better understand how changes in meteorological variables relate to changes in wind slab physical properties. During two winters I recorded temperature, humidity, and wind speed at study sites in Montana's Madison Range (45.237, -111.424) and collected snowpack data during or immediately following blowing snow events. I found that average wind speeds at 0.5m and 1.5m above the snow surface were significantly higher during hard wind slab formation than soft wind slab formation, while unobstructed wind speed, maximum gust, and the length of time of wind transport were not associated with wind slab hardness. Temperature was higher during hard than soft wind slab formation, while humidity was not different between the two hardness categories. Although wind speed at 1.5m had a significant positive linear relationship with both wind slab density and blade hardness gauge force, it was a poor predictor of actual values for both of these parameters. Our findings help improve the understanding of the impact of near surface winds on wind slabs, which will aid avalanche forecasting and mitigation planning particularly in windy climates.

CHAPTER ONE

INTRODUCTION

1.1 Overview

A snow avalanche, hereafter referred to as an avalanche, is a mass of snow and other entrained debris moving under the force of gravity. Avalanches occur in mountainous areas around the world and can have serious consequences for people who live and travel there. This includes property destruction and associated economic loss, isolation due to road closures, and risk of personal injury and death. Between 2013 and 2023 avalanches killed an average of twenty-four people each year in the United States (Colorado Avalanche Information Center, 2023). Most of these people were backcountry recreationists, though avalanches also endanger lives at ski resorts or worksites. Avalanches can also influence the landscape through displacement of material on the underlying bed surface, and through vegetation destruction (Luckman, 1977). Further, they influence hydrology and water availability by transporting snow to lower elevations and slowing melt rates due to the dense nature of avalanche debris. While experts do their best to predict avalanche occurrence, there is often a high degree of uncertainty in avalanche forecasting (LaChapelle, 1980; Statham et al., 2018), which is one of the reasons that avalanches remain so dangerous.

Predicting avalanches often involves identifying the types of avalanches most likely to occur given the combined snowpack, weather, and terrain. Understanding avalanche type helps predict avalanche hazard level and dictates mitigation strategies (Statham et al., 2018).

Avalanche types can be broadly separated into loose snow and slab avalanches. Loose snow

avalanches usually involve only surface snow and start from a single point before spreading out and entraining additional snow (McClung & Schaerer, 2006). Slab avalanches constitute a block of snow moving as one mass, and begin when a failure occurs in a weak layer. Of these two avalanche types, slab avalanches are typically the most dangerous (Atwater, 1954; Harvey et al., 2016; McClung & Schaerer, 2006). A slab avalanche requires a relatively thicker and stronger snow layer, called a slab, to overlie a relatively thinner weak layer (Figure 1). Weak layers are formed on the snow surface or within the snowpack through metamorphism. Slab layers are created by snow accumulation through snowfall or wind transport and subsequent strength increase due to bonding and cohesion. If a trigger, such as a skier, causes stress on the snowpack a crack may initiate and propagate in a weak layer. Provided the slope is steep enough to overcome the force of friction, a slab avalanche will occur (Schweizer et al., 2016). The minimum slope angle threshold for avalanche occurrence is around 30° , with slab avalanches

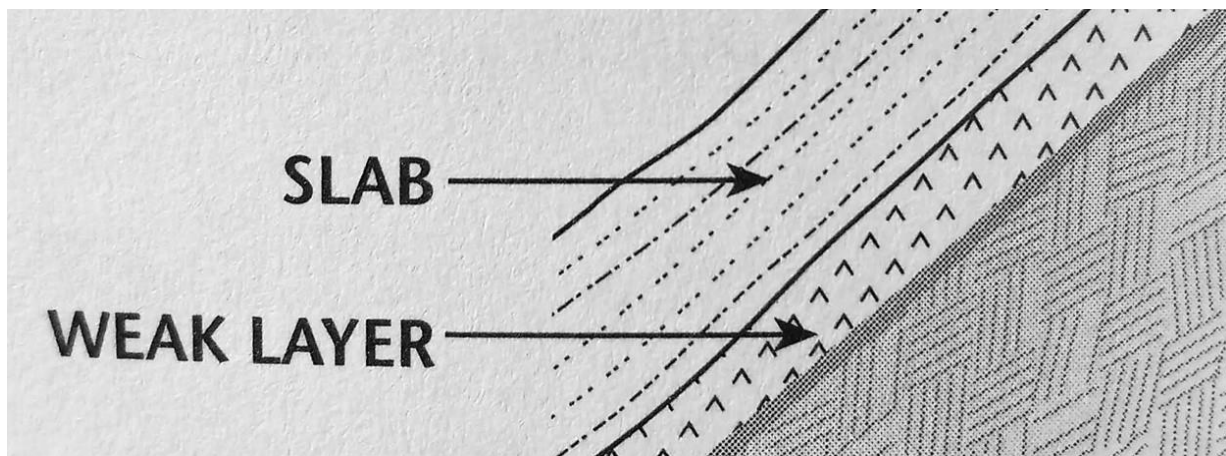


Figure 1: An example of the snowpack structure necessary for a slab avalanche, where a strong and cohesive slab of snow overlies a weaker layer (From Tremper, 2018, p.13).

occurring up to 55°, at which point loose avalanches become more common. Understanding and identifying the requirements for slab avalanches helps avalanche workers locate areas where avalanches may occur, and understand and communicate potential consequences.

Slab formation can vary dramatically across avalanche start zones due to the influence of wind. Wind transports snow into lee areas, where surface slabs can become thicker than in surrounding areas. In addition to creating a thick slab, wind action increases slab strength by manually fragmenting snow grains into smaller particles. These small grains pack closely together during deposition resulting in a high-density slab (Colbeck, 1991; Fierz et al., 2009). High density snow means a greater number of contact points between grains which increases bond formation and slab strength. Bonding begins immediately following deposition (Van Herwijnen & Miller, 2013). Through this process wind transport results in localized thick and strong slab layers, known as wind slabs, which can form dangerous avalanches.

Wind slabs create particularly difficult avalanche conditions due in part to their strength and spatial variability. Strength is important because a stronger and stiffer slab disperses stress over a larger area, reducing the depth to which stress penetrates (van Herwijnen & Jamieson, 2007). Thus, a stiffer slab reduces the chance that a given load (i.e. a trigger), will affect a buried weak layer, as well as increases the critical crack length necessary for crack propagation (Birkeland et al., 2019; Thumlert & Jamieson, 2014). This increases uncertainty regarding necessary trigger size and complicates avalanche prediction. Increased strength can also increase the distance of propagation, leading to larger avalanches (van Herwijnen & Jamieson, 2007). Further, wind deposition of snow is spatially variable due to the interaction of topography and wind. Thus, wind slab location can be variable and difficult to predict as wind speed and

direction change. This variation in physical properties and physical location contribute to making wind slabs a challenging avalanche type to manage.

Another important aspect of avalanche forecasting is knowledge of meteorological conditions such as temperature, wind, and snowfall, as these meteorological variables influence weak layer and slab formation at a variety of scales. Temperature can control snowpack metamorphism at the scale of a snowpack layer, wind can influence snow loading on the slope-scale, and snowfall patterns can influence snow distribution at the regional scale. In wind slab formation, snowfall provides snow for transport and wind creates a slab layer through mechanical fragmentation of snow crystals and subsequent deposition. Temperature influences wind slab formation as higher temperatures increase threshold wind speeds required for snow entrainment (Li & Pomeroy, 1997a). Relative humidity, which is closely tied to temperature, influences wind transport as lower humidity leads to increased sublimation of snow from the air column (Pomeroy et al., 1993). Though we know that these meteorological variables influence wind redeposition during entrainment and transport, less is known about how they influence slope-scale wind slab formation during deposition. By understanding the role of meteorological variables during all parts of wind transport we can better understand wind slab properties and better predict wind slab avalanches.

The goal of this project is to improve our understanding of the relationships between meteorological variables and slope-scale wind slab properties during and immediately following deposition. I focus on meteorological variables from ski resort weather stations supplemented by near-surface wind speed observations. These are combined with detailed field measurements of the snowpack properties commonly measured by avalanche operations. The rationale is that by

using these common inputs this research will be more applicable to avalanche workers.

Measured variables include wind speed (at multiple heights above the snow), wind direction, temperature, humidity, and the snowpack variables hardness and density. In addition, I used measurements from a blade hardness gauge (BHG) (Figure 2) to support my analyses (Borstad & McClung, 2011). Results from this work will improve our understanding of wind slabs and could lead to improvements in avalanche forecasting and the safety of those working and recreating in avalanche terrain.



Figure 2: The Fraser Instruments blade hardness gauge (BHG) as used in this study. Blade dimensions are 10cm x 5cm x 1mm. The blade is inserted horizontally into the snow profile wall to measure penetration resistance of a snow layer.

1.2 Research Question

This work explores the relationship between meteorological variables and wind slab properties. I identified and characterized wind slabs in the field and compared them to meteorological data collected by proximal weather stations. This project investigates the following questions:

- 1) Given snow available for transport, which meteorological variable or combination of variables best explains whether or not a wind slab will form?
- 2) Given wind slab formation, which meteorological variable or combination of variables best explains the physical properties of that wind slab?

I hypothesize that all of the measured meteorological variables will play a role in explaining both wind slab formation and the physical properties of a wind slab. I further hypothesize that wind speed will have the strongest relationship to both wind slab formation and physical properties, with a positive correlation between wind speed and all measured wind slab properties.

CHAPTER TWO

BACKGROUND

2.1 Slab Avalanche Formation

Slab avalanches require a cohesive slab of snow overlying a weak layer. Increasing stress on the snowpack through application of a load, such as new snow, a person, vehicle, or explosive, may lead to avalanche release through a complicated multi-step process. If stress exerted on the snowpack overcomes weak layer strength, grain-to-grain bonds in the weak layer will break (Schweizer et al., 2016). If the length of damage along the weak layer is greater than the critical crack length for that particular slab/weak layer combination the crack will become self-propagating. Critical crack length is reached when stress concentrations at the edge of the crack overcome the strength, or toughness, of the weak layer (Schweizer et al., 2016). At this point the failure become self-propagating through a combination of slab deformation and reduction in weak layer volume (Gaume et al., 2018). If this occurs on a sufficiently steep slope, slab sliding may occur so that shear stress and normal stress exist simultaneously at the crack tip. At some super-critical crack length, the crack becomes driven predominantly by shear (Trottet et al., 2022). The transition to this super-shear failure mode is controlled largely by slab strength, where weak slabs may undergo tensile failure before reaching super-critical crack length. Stronger slabs are more likely to reach super-critical crack length, leading to faster and further propagation, and therefore larger avalanches (Simenhois et al., 2023). In this case, tensile failure is often dictated by terrain features such as ridgelines or rocks. Once tensile failure occurs, the

slab becomes fully detached from surrounding snow and moves downhill as dictated by terrain features and snow properties.

Slab physical properties are a critical component of the size and likelihood of triggering a slab avalanche. A slab is any cohesive snowpack layer or group of snow layers (American Avalanche Association, 2022), and is usually thicker, denser, stronger, and stiffer than the surrounding snow. Sometimes slabs bond well with the interface below them, and sometimes they overlie a weak layer. These weak layers can be classified as either persistent or non-persistent. Persistent weak layers form at the snow surface or within the snowpack, and can cause avalanche problems long after their initial burial or formation (Statham et al., 2018). In contrast, a slab overlying a non-persistent weak layer often creates a surface problem that does not persist beyond the end of the storm. Slab layers can be formed through snowfall or wind transport, called a storm slab and a wind slab respectively.

2.2 Definitions and Common Applications of Terms

Wind has long been recognized as a contributing factor to avalanche formation (e.g. Atwater, 1954; Mellor, 1965; Perla, 1970; Seligman, 1947), and wind slabs have been acknowledged in literature since at least the 1920s (Seligman, 1936). The term wind slab is now near ubiquitous in the avalanche industry, as is the term wind slab avalanche to describe an avalanche resulting from a wind slab (e.g. American Avalanche Association, 2010; Fierz et al., 2009; Statham et al., 2018). These terms are also used to communicate avalanche hazard to the public (e.g. European Avalanche Warning Services, 2017; Haegeli et al., 2010). Wind slabs are additionally important in snow hydrology where they influence snow density and albedo, thereby

controlling snow-melt patterns (Brown et al., 2021). Wind can redistribute snow within and between watersheds, so an understanding of wind transport is important in predicting water availability (Pomeroy et al., 1993). In polar research the term wind slab is used when describing snow stratification (e.g. Benson, 1967; Massom et al., 2001; Thompson & Kelly, 2021), which can have implications for energy balance and wildlife movements (Berteaux et al., 2017). Wind has an important influence on snow in alpine environments in ways that concern a variety of researchers, industries, and recreationists, and common terminology aids communication.

Despite its common use, the definition of “wind slab” varies throughout literature and reference articles (Table 1). Early works on avalanche hazard recognized the role of wind in loading slopes and creating slabs, but acknowledged that the process was poorly understood. (Atwater, 1954). Seligman (1936) used the term wind-packing to describe the process of wind slab formation, and defined a wind slab as being hard and composed of rounded grains. It is now generally recognized that wind slabs are relatively denser, harder, and thicker than surrounding snow (American Avalanche Association, 2016; Colbeck, 1991; Sommer, 2018; Statham et al., 2018), and found on slopes leeward to the wind (Clifton et al., 2006; Fierz et al., 2009; McClung & Schaerer, 2006), though studies also show deposition on windwards aspects (Sommer et al., 2018). The International Classification for Seasonal Snow on the Ground (ICSSG) additionally defines a wind slab as being composed of small, abraded, well-sintered particles, which it terms wind-packed rounds (Fierz et al., 2009). Though each of these sources define the term slightly differently (Table 1), combining them gives a comprehensive picture of a wind slab that I will use for the remainder of this study. Considering already existing definitions, I define a wind slab as:

A snow layer of locally deep, dense, and hard snow, composed of small rounded grains, and formed by the transport and deposition of snow by wind.

Wind can entrain, transport, and deposit snow already on the ground, a process called redeposition, or deposit snow directly from the air column, a process called preferential deposition (Lehning et al., 2008). An important distinguishing feature is whether or not erosion occurs, and whether or not snow undergoes saltation, both of which are absent from preferential deposition. The distinction between these transport processes leads to terminology confusion where some consider the result of both processes to be a wind slab, while others refer to preferential deposition as a storm slab (de Leeuw & Birkeland, 2023). Additionally, it can be difficult to differentiate avalanche problems in the field, and redeposition and preferential deposition often happen simultaneously. The Conceptual Model of Avalanche Hazard (CMAH), widely used in North America, includes both transport processes in wind slab formation (Statham et al., 2018). The European Avalanche Warning Services (EAWS) considers only redeposition in wind slab formation, and groups preferential deposition with the “new snow” avalanche problem (European Avalanche Warning Services, 2023). Reference articles such as the Operational Guidelines and Recording Standards (OGRS) (Canadian Avalanche Association, 2016), and the Snow Weather and Avalanche Guidelines (SWAG) (American Avalanche Association, 2022), do not address the subject. Due to the extensive overlap and difficulties in distinction, I consider wind slabs resulting from both redistribution and preferential deposition for this study.

Another term I will use is “wind skin,” which I define as:

A thin (< 1cm) layer of soft and breakable snow, composed of small and rounded grains, and formed by the deposition of snow by wind.

Table 1: Definitions and proposed processes of wind slab formation from a selection of literature, sorted by date of publication.

Publication	Wind Slab Definition	Proposed Process of Formation
Seligman, G., (1936). <i>Snow structure and ski fields</i> . Macmillan	“A snow deposit which has been packed tough... by wind agency [with a] high proportion of regularly rounded ice grains,” (Seligman, 1936, p. 164).	Through the process of wind packing, which is “a special form of firnification accelerated by a wet wind ” (Seligman, 1936, p. 200).
Seligman, G. (1947). Wind slab avalanches. <i>Journal of Glaciology</i> , 1(2), 70-73.	Does not define wind slab explicitly.	Through wind packing (as above), as well as “riddling” which occurs when smaller grains “shake themselves into spaces between [larger] grains” (Seligman, 1947, p. 124-125).
Atwater, M. M. (1954). Snow avalanches. <i>Scientific American</i> , 190(1), 26-31.	A “slab is a type of wind packed snow which commonly forms on lee slopes” (Atwater, 1954, p.26).	Wind is “essential to the formation of a slab in ways which we do not yet completely understand” (Atwater, 1954, p.31).
Benson, C. S. (1967). Polar regions snow cover. <i>Physics of Snow and Ice: proceedings</i> , 1(2), 1039-1063.	Hard and fine-grained, and one of “the extreme end products of diagenetic processes” (Benson, 1967, p. 1040)	Due to the movement of saturated air in snow which creates necks between grains. Wind accelerates this process by depositing snow grains with low vapour pressure between them.
Martinelli, M. (1971). <i>Physical properties of alpine snow as related to weather and avalanche conditions</i> (Vol. 64). Rocky Mountain Forest and Range Experiment Station.	“Wind action... toughens the snow and often leads to slab formation” (Martinelli, 1971, p. 1) “Initial hard slab” describes snow with a density and strength increase soon after deposition.	“Initial hard slab appears to require high winds, low temperatures, and a high drift ratio,” drift ratio being the comparison of snow in start zones to measured precipitation. Occurs “either during snowfall or during the transport and redeposition of old snow” (Martinelli, 1971, p. 26)
Colbeck, S. C. (1991). The layered character of snow covers. <i>Reviews of Geophysics</i> , 29(1), 81-96.	“...thicker layer of wind hardened snow” (Colbeck, 1991, p. 83).	“Wind breaks the ice particles into smaller shards.... Because of their small size and movement of air by the wind, they round off and sinter quickly” (Colbeck, 1991, p. 83).

Zhang, T., Osterkamp, T. E., & Stamnes, K. (1996). Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime. <i>Water Resources Research</i> , 32(7), 2075-2086.	“Hard, wind-packed layer” (Zhang et al., 1996, p. 2076).	Did not propose method of formation.
Massom, R. A., Eicken, H., Hass, C., Jeffries, M. O., Drinkwater, M. R., Sturm, M., ... & Allison, I. (2001). Snow on Antarctic sea ice. <i>Reviews of Geophysics</i> , 39(3), 413-445.	“A medium to high density surface layer” (Massom et al., 2001, p. 422) which can be soft to very hard.	“Wind... mechanically fragments and compacts the snow” (Massom et al., 2001, p. 417).
McClung, D., & Schaerer, P. A. (2006). <i>The avalanche handbook</i> . The Mountaineers Books.	“Most slabs consist of cohesive wind-deposited or well-bonded old snow” (McClung & Schaerer, 2006, p. 95).	“... as snow is redistributed, the particles become broken and abraded as they impact the snow surface, ...these small fragments, upon deposition, become tightly packed and rapidly produce a slab-like texture...” (McClung & Schaerer, 2006, p. 35).
Clifton, A., Rüedi, J. D., & Lehning, M. (2006). Snow saltation threshold measurements in a drifting-snow wind tunnel. <i>Journal of Glaciology</i> , 52(179), 585-596.	“Increased deposition of snow on lee slopes” (Clifton et al., 2006, p. 592).	Particles are moved “both from the surface and the snow which has not yet reached the ground” (Clifton et al., 2006, p. 592).
DeWalle, D. R., & Rango, A. (2008). <i>Principles of snow hydrology</i> . Cambridge University Press.	“A densified, dry-snow layer at the snowpack surface” (DeWalle & Rango, 2008, p. 54) formed by wind.	“Formed due to ... deposition and packing of broken crystals of blowing snow” (DeWalle & Rango, 2008, p. 54)
Fierz, C. R. L. A., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., ... & Sokratov, S. A. (2009). The international classification for seasonal snow on the ground.	“Thicker, often dense layers, usually found on lee slopes” composed of “small, broken or abraded, closely packed and well-sintered particles” (Fierz et al., 2009, p. 15).	“Packing and fragmentation of wind transported snow particles that round off by interaction with each other in the saltation layer” (Fierz et al., 2009, p. 15).

Haegeli, P., Klassen, K., & Atkins, R. (2010). <i>Decision-making in Avalanche Terrain: A Field Book for Winter Backcountry Users</i> . Canadian Avalanche Centre.	“Consist of snow crystals broken into small particles and packed together by the wind... created on lee slopes” (Haegeli et al., 2010, p. 1). Vary from medium to very hard, and often have a “pillowed” shape.	“Form when there is sufficient wind to transport falling snow or surface snow” (Haegeli et al., 2010, p. 1). Depends on wind speed, duration of wind event, and snow available for transport.
Canadian Avalanche Association. (2016). <i>Observations guidelines and recording standards for weather snowpack and avalanches</i> . Revelstoke, British Columbia.	Does not define wind slab specifically, but includes material from ICSSG (Fierz et al., 2009).	Does not propose process of formation separate from ICSSG (Fierz et al., 2009).
Sommer, C. G., Lehning, M., & Fierz, C. (2017). Wind tunnel experiments: saltation is necessary for wind-packing. <i>Journal of Glaciology</i> , 63(242), 950-958.	The result of wind packing.	Through wind packing, which is “the process of snow hardening under the influence of wind” (Sommer et al., 2017, p. 950)
Sommer, C. G. (2018). <i>Wind-packing of snow: How do wind crusts form?</i> (Publication No. 8628). [Doctoral Dissertation EPFL]	“Hard layers of well-sintered snow” (Sommer, 2018, p. v).	“Wind-packing of snow.” (Sommer, 2018, p. v).
Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israelson, C., Tremper, B., ... & Kelly, J. (2018). A conceptual model of avalanche hazard. <i>Natural hazards</i> , 90, 663-691.	“Cohesive slab of locally deep, wind deposited snow” (Statham et al., 2018, p. 675).	“Wind transport of falling snow or soft surface snow. Wind action breaks snow crystals into smaller particles and packs them into a cohesive slab” (Statham et al., 2018, p. 675).
Thompson, A., & Kelly, R. (2021). Estimating wind slab thickness in a Tundra snowpack using Ku-band scatterometer observations. <i>Remote Sensing Letters</i> , 12(11), 1123-1135.	“Small, wind-fractured fragments in a hard-packed, high-density layer” (Thompson & Kelly, 2021, p. 1123).	As a result of “aeolian and thermodynamic snowpack processes” (Thompson & Kelly, 2021, p. 1123).

American Avalanche Association, 2022; <i>Snow, weather, and avalanches: Observation guidelines for avalanche programs in the United States</i> , 4 th edition, American Avalanche Association, Denver, Colorado	“A dense layer(s) of snow formed by wind deposition” (American Avalanche Association, 2022, p. 62).	Through the process of wind deposition.
European Avalanche Warning Services. (2023). <i>Typical avalanche problems</i> . https://www.avalanches.org/standards/avalanche-problems/	Defined by formation process.	“Wind slabs are formed when loose snow in near-surface layers (new snow or old snow) is transported and deposited by wind” (European Avalanche Warning Services, 2023, "Wind Slab" section)

This differs from a wind crust, which is defined by the ICSSG as a thinner and irregular wind slab, with no specified thickness or hardness (Fierz et al., 2009). A wind skin is distinct from a wind crust in that it is necessarily soft and breakable, as well as less than one centimeter in thickness, and may or may not be irregularly distributed. Wind skin layers were too thin to obtain accurate hardness and density measurements, and so I use the term wind skin in itself as description of snow hardness.

2.3 Spatial Scale in Avalanche Research

Environmental phenomena, including patterns of snow distribution, occur at a multitude of spatial scales, from point-scale (e.g., a single tree intercepting snowfall) to continental scale (e.g., the movement of cold fronts). Matching sampling scale to process scale is a major challenge in environmental research, and altering the sampling scale may substantially change a study's results and interpretations (Blöschl, 1999). Variation in snowpack properties important for avalanches are usually best represented at the slope-scale (1 to 100s of meters) and the individual mountain-scale (100s to 1000s of meters) (Mott et al., 2018). This is because snow distribution measurements at the larger regional scale (>1000s of meters, includes entire mountain ranges) are likely to reflect the influence of elevation over other factors. While snow distribution processes happen at all scales, avalanche studies often occur at the slope and individual mountain scale, as this is the scale at which individual avalanches occur.

Wind distribution can highly complicate slope-scale avalanche prediction (Schweizer et al., 2008). Wind erodes snow from windward areas and deposits snow in leeward areas, and these patterns can change rapidly with slight changes in wind speed and direction. Erosion and

deposition also occur at the individual mountain-scale, where depositional patterns can be compounded by feeder clouds and preferential deposition (Mott et al., 2018). While a wind slab forming event can happen across an entire individual mountain or regional-scale mountain range, individual wind slabs most commonly form at the slope scale, as the terrain breaks which define specific slopes also influence depositional patterns (Clark et al., 2011). Thus, the slope-scale is appropriate for studying wind slab properties.

Although wind loading and erosion occur at the slope-scale, sub-slope-scale spatial variability exists in deposition patterns (Schweizer et al., 2008). Slight variations in wind direction can cause flow patterns to interact differently with terrain and concentrate deposition on varying parts of a slope. Trees can influence snow depth patterns by enhancing point-scale deposition in their lees. Constantly fluctuating wind transport rates are responsible for the formation of snow bedforms such as ripples and dunes, which cause snow depth and physical property variability at the sub-slope scale (Filhol & Sturm, 2015). Ripples usually occur at a scale of 5-20 centimeters, while dunes are commonly measured between 5-15 meters. These bedforms occur in depositional zones and result in spatial variability within an individual wind slab. Thus, slope-scale studies must acknowledge the effects of sub-slope scale variability.

2.4 Early Wind Slab Research

Seligman (1936) had a particular fascination with wind slabs and wind slab avalanches, which he described as “the most insidious of all avalanches” (p. 160). In his 1936 book he traced discussions of wind influence back to 1902 and noted that little had been done to investigate wind slab formation. He also acknowledged the difficulties in studying wind slabs due to their

inherently dangerous nature, their formation in dangerous locations, and the vast array of meteorological data needed to quantify their formation (Seligman, 1936). The problem of many variables with complex interactions continues to challenge researchers today. Despite difficulties with direct observation, Seligman (1936) provided a thorough summary of wind slab properties and formation as understood at that time. His research and ideas provided the language and platform to build the study of wind slabs and wind slab avalanches.

Early research distinguished between a wind slab and a wind crust (Seligman, 1936). A wind crust, unlike a wind slab, was said to be anchored to the ground and safe to travel over. Seligman (1936) observed that wind crusts were very hard and formed on wind exposed slopes, as opposed to wind slabs which varied from very soft to very hard and formed on lee slopes. The evidence for this was mostly observational, and it was acknowledged that a wind crust often formed in conjunction with a sun crust, and distinguishing between the two was difficult (Seligman, 1936). Additionally, a wind slab was said to require snow transport, while a wind crust was formed by a humid wind without snow transport. It has since been demonstrated that any wind hardening does require snow transport (Sommer et al., 2017), and that both wind slabs and wind crusts are found in lee areas (McClung & Schaerer, 2006). It is possible that Seligman observed what is now called a wind-glaze, or a wind-polished surface, thought to form from long-term exposure to down-slope winds (Scambos et al., 2012). Both a wind crust and a wind slab are now considered depositional features, where a wind crust is a thin and irregular version of a wind slab (Fierz et al., 2009).

Early theories of wind slab formation suggested that a high humidity wind would thaw snow and grains would cement together by subsequent freezing (Seligman, 1936). Heat

generated from friction during wind action was thought responsible for the round form of wind transported grains, due to enhanced melting at sharp corners. Later it was proposed that wind hardening was supplemented by “riddling”, defined as smaller grains filling the gaps between larger grains (Seligman, 1947), and by upward migration of water vapour which would condense on newly drifted snow (Benson, 1967). The definition of riddling is similar to the modern understanding that smaller grains pack closely together, and it is now understood that the process of hardening is due to bond formation rather than humidity and melt-freeze (Van Herwijnen & Miller, 2013). Rounding is now attributed to mechanical fragmentation during saltation, rather than melting (Colbeck, 1982; Comola et al., 2017; McClung & Schaerer, 2006).

2.5 Wind Transport Processes

Wind transport plays an important role in snow depth and distribution (Mott et al., 2018). The first step in wind transport is entrainment, which occurs when wind shear stress exceeds snow cohesion, bonding, and frictional resistance (Li & Pomeroy, 1997b). The minimum threshold wind speed for the entrainment of low-density unbonded snow is around 5 m/s (Filhol & Sturm, 2015; McClung & Schaerer, 2006) (Table 2). This value is based on “unobstructed” wind speed, where wind speed measurements are taken at a height sufficient to minimize the influence of surface roughness on wind speed and direction. In the avalanche industry this metric is usually measured at a ridgetop, or 10m above the snow surface in areas not at ridgetop. In many situations threshold wind speed is greater than 5 m/s due to snowpack properties such as grain size and bond strength. (Clifton et al., 2006). As snow temperature decreases the rate of bond formation decreases, as does cohesion due to a decrease in thickness of the quasi-liquid layer between grains (Li & Pomeroy, 1997b). As a result, the threshold wind speed for transport

decreases with decreasing temperature. However, below approximately -25°C this relationship reverses as frictional resistance, which increases with decreasing temperature, dominates over bonding and cohesion. Old or previously transported snow generally has a higher bond density and therefore requires higher threshold wind speeds than new snow. Snow at 0°C or snow that has refrozen also has a much higher threshold wind speed (Li & Pomeroy, 1997a). Finally, snow already in transport can collide with particles on the ground and dislodge them in a process known as splash entrainment (Paterna et al., 2016), and so if particles are already in motion, threshold wind speed is reduced.

Table 2: The minimum threshold wind speed for entrainment of snow, as stated by a selection of studies and reference articles. These studies most commonly measured “unobstructed wind speed,” at approximately 10m above the snow surface, where wind flow is generally unobstructed by the influence of topography, vegetation, or human structures.

Reference	Threshold Wind Speed
Mellor (1965)	<ul style="list-style-type: none"> • 3-8 m/s surface for loose unbonded snow
Berg, (1986)	<ul style="list-style-type: none"> • 4-6 m/s
Li & Pomeroy (1997a)	<ul style="list-style-type: none"> • 4-11 m/s (average 7.7 m/s) for dry snow
Filhol & Sturm (2015)	<ul style="list-style-type: none"> • 5 m/s for small grains
McClung & Schaerer (2006)	<ul style="list-style-type: none"> • 5 m/s for low density snow
American Avalanche Association (2022)	<ul style="list-style-type: none"> • 7 m/s, stated as 25 km/h for the onset of snow-drift
Canadian Avalanche Association (2016)	<ul style="list-style-type: none"> • 7 m/s, stated as 25 km/h for the onset of snow-drift

Once entrained, snow can be transported by rolling, saltation, and turbulent suspension (Figure 3). Rolling occurs at the lowest wind speeds when snow grains creep along the surface at a height of 1mm or less (McClung & Schaerer, 2006). Saltation begins as wind speeds increase and snow grains begin to follow curved trajectories between 5-10cm above the ground periodically contacting the snow surface (Pomeroy & Gray, 1990). Saltation causes manual fragmentation, which breaks dendritic snow crystals into smaller fragments and rounded grains

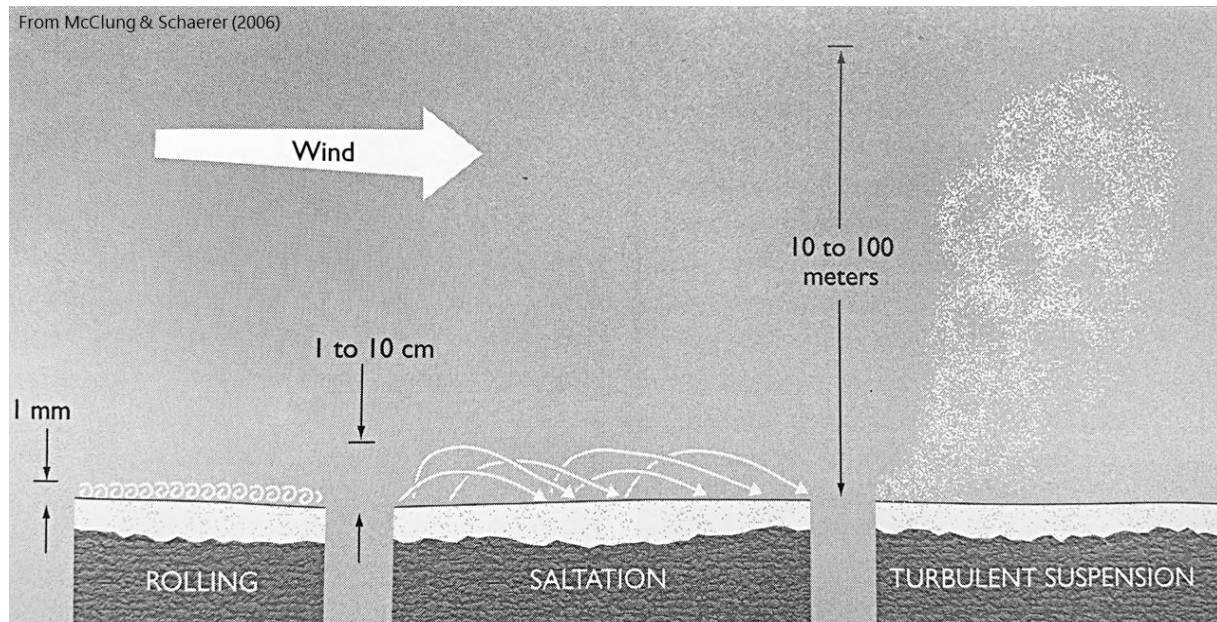


Figure 3: A schematic showing the three methods of snow transport by wind, where height of transported snow increases as wind speed increases (From McClung and Schaerer, 2006, p. 33).

(Comola et al., 2017). Turbulent suspension occurs when wind speeds increase enough to lift particles above the saltation layer where they can be transported up to hundreds of meters without touching the ground (Mott et al., 2018). If relative humidity levels are low, snow in suspension may sublime and be removed from the local snowpack mass balance (Pomeroy et al., 1993). Transported snow that does not sublime is eventually deposited when wind speed decreases or flow patterns change. This usually happens in lee features and eddy zones behind obstacles (Mellor, 1965) (Figure 4). Deposited snow forms wind slabs composed of closely packed rounded grains.

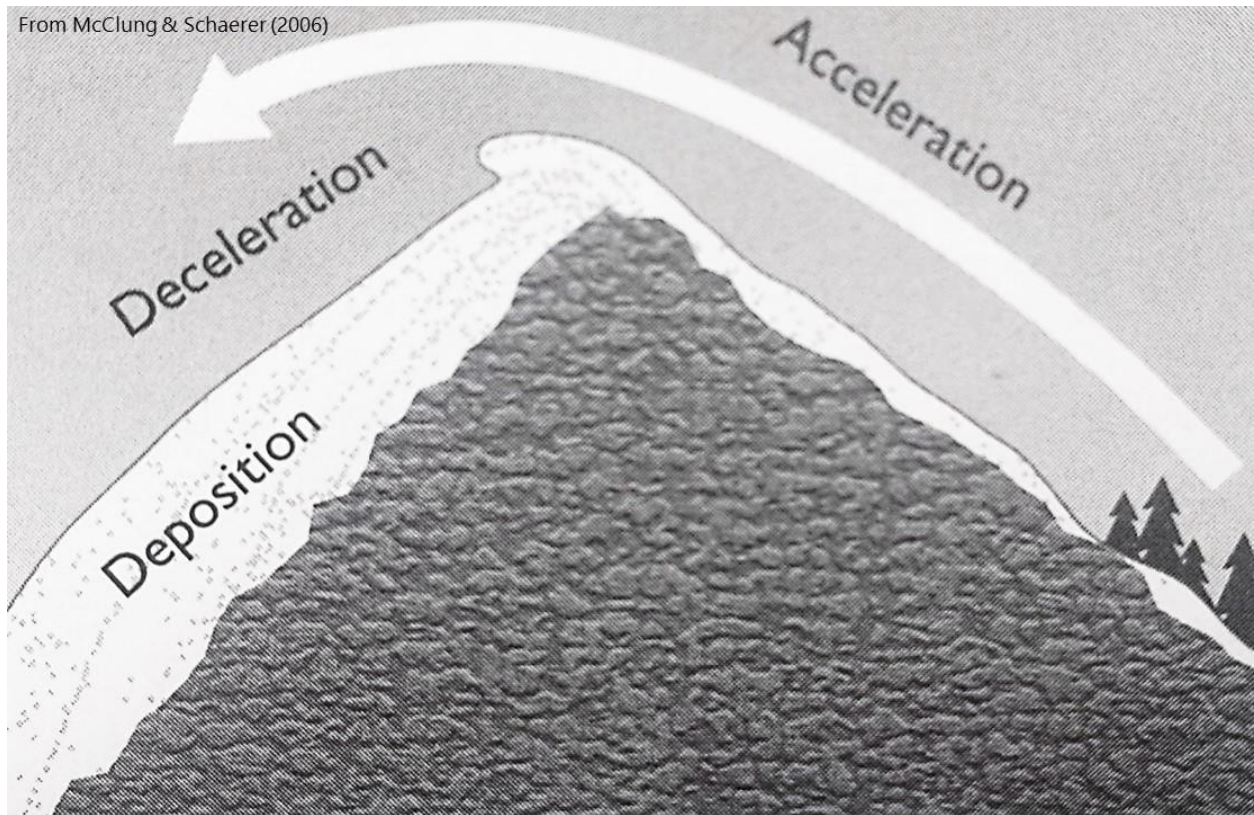


Figure 4: Wind deposits snow in areas where wind speed deceleration occurs. This is often in lee areas to the terrain (From McClung and Schaerer, 2006, p. 34).

2.6 Wind Slab Physical Properties

Wind slabs are usually stronger, stiffer, and thicker than surrounding snow layers, though the exact physical properties of individual wind slabs differ. Strength is the amount of stress a material can handle before failure, while stiffness describes elasticity and deformation (Leckie & Bello, 2009). These physical properties and their variation have important implications for avalanche formation. Stiffer layers do not readily deform and are more likely to transfer stress laterally, thereby decreasing the concentration of stress applied to a buried weak layer (Figure 5) (McClung & Schweizer, 1999; van Herwijnen & Jamieson, 2007). Thick wind slabs can also

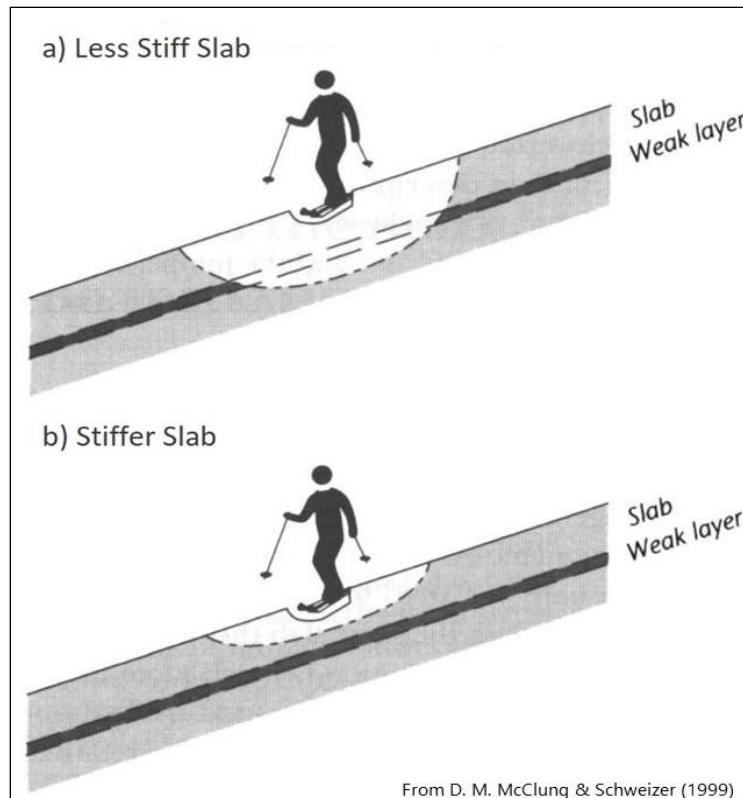


Figure 5: As compared to a less stiff slab, a stiffer slab spreads force laterally which decreases the ability of external stress, such as a skier, to affect a buried weak layer (From McClung and Schweizer, 1999, p. 192).

reduce stress transferred to a weak layer. Increasing slab strength, stiffness, and thickness increases critical crack length necessary for self-propagation (Gaume et al., 2017), as slab bending is required for weak layer collapse (Bergfeld et al., 2022). As the likelihood of affecting a weak layer decreases and the critical-crack length increases, uncertainty in the size of trigger required to initiate failure increases, making it difficult to predict if an avalanche could be triggered by a skier. Further, cracks associated with stiffer and stronger slabs often have faster propagation speeds, as they are able to reach a super-critical crack length for super-shear, leading to larger avalanches (Simenhois et al., 2023). These physical properties of wind slabs mean that stiff wind slabs are more difficult to predict, and can result in larger avalanches.

Stiffness and strength are difficult to measure in the field, and so are usually implied by measuring snow hardness. Hardness is defined as resistance to penetration, and in snow the resisting force comes from a combination of bending, grain bond rupture, compaction, and friction (Borstad & Mcclung, 2011). Bending and bond rupture are described by stiffness and strength respectively. Hardness can be measured quantitatively using tools such as a Snow Micro-penetrometer (SMP), or blade hardness gauge (BHG) (Figure 2). The SMP provides the most reliable hardness measure as it is inserted at a constant rate, while rate is difficult to control with a BHG (Borstad & Mcclung, 2011). Most avalanche workers do not have access to these tools, so field hardness is usually estimated qualitatively using the hand hardness test. This involves inserting objects of decreasing surface area into the snow with consistent force, where values range from fist (F) to ice (I) (Fierz et al., 2009). Wind slabs are often hard, however the actual hardness of wind deposited snow can vary from soft (four finger or even fist) to very hard (pencil or knife). Hardness is related to density, as density is a measure of grain packing and therefore influences grain bonding and slab strength. So, as density increases hardness usually increases (Geldsetzer & Jamieson 2000). Exceptions include some depth hoar layers, defined as basal layers formed under strong temperature gradients, which can be simultaneously dense and soft due to close packing but low bond density (Pfeffer & Mrugala, 2002). However, the positive relationship between hardness and density generally exists for rounded forms which compose wind slabs. While it is difficult to accurately measure strength and stiffness in a field setting, these important physical properties can be implied based on other properties such as hardness and density.

2.7 Wind Slab Spatial Properties

The spatial distribution of wind slabs at the slope-scale can also lead to challenging avalanche conditions (Guy & Birkeland, 2013). Wind deposition is spatially variable across a landscape due to terrain variability and the interaction of wind with terrain. As a result, wind slab avalanche problems are spatially variable (Statham et al., 2018). Changing wind patterns can change deposition patterns, and uncharacteristic wind patterns can lead to unexpected avalanche conditions. Wind slab properties such as hardness and thickness can vary at the sub-slope-scale, and one continuous slab may be thinner and softer in certain areas of the slope. This has implications for triggering location, as triggering becomes more likely in thin areas (van Herwijnen & Jamieson, 2007). This makes it challenging to predict the exact location in which a wind slab may be triggered. Uncertainty in the exact variation and values of wind slab thickness and hardness, as well as the location of wind slabs in terrain, can cause difficulty in predicting wind slab avalanches. Spatial variability in location and physical properties leads to difficult avalanche conditions when wind slabs are present.

2.8 Field Studies on the Influence of Wind on Snow

Field studies have found that increased wind speed is associated with increased snow hardness (e.g. Kozak et al., 2003; Martinelli, 1971). Martinelli (1971) tracked snow layers as they developed, and found that average wind speeds were 1.5 times higher when a new snow layer was “hard,” than when “typical” deposition occurred. Kozak et al. (2003) tracked layers over time, and found that wind speed was positively correlated with new snow layer hardness on north aspects where the influence of radiation was minimized. These studies found important

correlations between wind speed and snow hardness, however neither of them studied wind slabs specifically. Thus, caution may be needed in applying these findings to wind slabs. McCollister (2004) showed that increasing wind speed led to more avalanches at the slope to mountain-scale, although these findings varied by path, and the avalanche frequency of some paths was independent of wind speed. He proposed that this spatial variability was due in part to the interaction of wind and terrain, where the region's predominant wind direction caused wind slab formation in some paths but not others. While none of the above-mentioned studies focused specifically on wind slabs, they provide important information on the relationship between winds and snowpack properties.

2.9 Wind Tunnel Studies

Due to the difficulty in controlling external variables in the field, wind tunnels are often used for examining wind and snow processes. The first snow-related wind tunnel work was conducted in the 1930s to analyze snow drifting around obstacles and test wind fences (Mellor, 1965). Because these wind tunnels were not housed in cold laboratories, researchers used snow substitutes such as sawdust, flaked mica, and magnesium carbonate. This helped to build theoretical models of real-life phenomena and define important mathematical parameters. Wind tunnel research using snow began in the late 1970s and early 1980s, and focused largely on saltation processes (Maeno et al., 1979, 1985). These studies contributed important knowledge about the relationship between temperature and entrainment, and air pressure gradients in saltating snow. Though these experiments were not motivated by avalanche research, they provided a basis for continued wind tunnel studies in the field of snow and avalanche sciences.

More recently wind tunnels have been used for avalanche-specific research. (e.g. Sommer et al., 2017, 2018; Yu et al., 2022). Sommer et al. (2017) constructed a round wind tunnel useful for studying wind slabs as it allows for increasingly realistic manual fragmentation by simulating longer transport distance. One important finding from this wind tunnel is that in the absence of other changes in meteorological parameters, snow transport is necessary for snow to become harder in the presence of wind (Sommer et al., 2017). Trials where saltating snow was observed resulted in significant hardness increase of the surface snow, while trials with wind applied but no transport showed negligible hardness increase. This second group of trials was conducted at lower wind speeds, or with snow with a higher threshold wind speed. These findings are in contrast to early work which suggested that snow hardening could happen with wind action but no transport (e.g. Benson, 1967; Seligman, 1936). While the transport of snow was a requirement for wind slab formation, not every trial with snow transport resulted in snow surface hardening (Sommer et al., 2017). This implies that other causes must be involved, which requires further investigation.

Further experimentation with this round wind tunnel found that comparing areas of erosion and deposition could partly explain discrepancies in wind crust formation (Sommer et al., 2018). Hardness increased only where snow was deposited and never in areas where snow was eroded. Deposition was observed on both windward and leeward sides of obstacles (Sommer et al., 2018), contrary to most definitions which state that wind slabs form in leeward areas (e.g. Fierz et al., 2009; McClung, 2002). While many of the ideas tested in recent wind tunnel studies had been previously described (e.g. Benson, 1967; Mellor, 1965; Schmidt, 1982; Seligman, 1947), these trials added important and previously lacking experimental evidence.

2.10 Other Meteorological Variables that Influence Wind Slabs

Wind is only one of many meteorological variables that influence snowpack physical properties. Air temperature influences the snowpack through its control on snow surface energy balance, which in turn influences snowpack temperature gradient. Temperature gradient controls the vapour pressure gradient and therefore the movement of water vapour through the snowpack. The rate of water vapour movement determines snow grain growth rate, where low growth rates lead to stronger rounded forms, and high growth rates lead to weaker faceted forms (Colbeck, 1982). Warmer temperatures increase growth rate as well as bond formation rate, which increases strength and hardness. Conversely, in the short-term, low temperature can result in high hardness as snow stiffens, though this is a secondary process which occurs predominantly at lower temperatures ($< -25^{\circ}\text{C}$) (Li & Pomeroy, 1997a; McClung & Schweizer, 1999). So due to temperature-induced metamorphic processes, above approximately -25°C a wind slab formed at higher temperature would likely be harder than a wind slab formed at lower temperatures, all other variables being equal.

The influence of relative humidity on snowpack properties and wind slab development is less clear. Early observations suggested that the bonding necessary for wind slab formation could only occur at relative humidities close to 100% (Hosler et al., 1957; Seligman, 1947). However, these observations were made almost exclusively during storms, where relative humidities are inherently high. Sommer et al. (2017) used a wind tunnel to show that relative humidity does not influence wind slab hardness, however, this study was conducted only at high relative humidities ($>85\%$), which do not represent the entire range of possible relative humidities in an alpine

environment. Therefore, the role of humidity in snow hardness and wind slab formation over a wide range of humidities remains unclear.

Wind slabs can only form if snow is available for transport, whether that is falling snow or surface snow. For surface snow redeposition, wind speeds must additionally exceed the threshold wind speed. As time since snowfall increases, bond formation increases, which increases threshold wind speed and decreases the availability of snow for transport (Li & Pomeroy, 1997b). However, if temperatures remain low, inhibiting bonding, snow may remain available for transport longer. Further, snow that has already been transported by wind has a higher threshold wind speed, and so a second wind event may not result in new wind slab development unless it includes significantly higher wind speeds than the first wind event. In the spring, snow is usually less available for transport due to melt-freeze crusts formed by rain, insolation, and above-freezing temperatures (Haegeli et al., 2010). Climate plays a role in snow availability for transport and therefore wind slab formation, as coastal climates are more prone to above-freezing temperatures and rain year-round. Snow availability for transport is a key factor in wind slab formation, as without snow, winds cannot form a wind slab.

2.11 Terrain Variables that Influence Wind Slabs

Terrain plays an important role in wind slab formation and location in alpine environments. Terrain dictates where wind can decelerate enough to deposit snow, and deposition locations may change as wind direction changes. Terrain also controls fetch, which is the aerial extent of terrain from which snow can be entrained, and therefore how much snow is transported (Pomeroy & Gray, 1990). Studies in the prairies show that an uninterrupted fetch of

up to 500m may be needed for transport rates to reach equilibrium between entrainment and deposition (Pomeroy & Gray, 1990). As wind direction changes even slightly, the fetch area can change, resulting in more or less snow in the air column for eventual deposition. Ground roughness in the fetch area also controls snow availability, where higher stubble decreases the transport rate of snow (Pomeroy et al., 1993). Terrain plays an important role in wind slab development by dictating the amount of snow available, and where it is deposited.

2.12 Snow Distribution Models

Wind transport models are another way that the interaction of snow and wind is studied, with both hydrological and avalanche hazard motivations. Early models, such as the Prairie Blowing Snow Model (Pomeroy et al., 1993), were based on meteorological variables and were created to predict snowpack for water availability. The first models to predict wind loading in alpine were terrain based models that assigned each cell in a digital elevation model (DEM) a wind shelter index based on aspect and slope (Purves et al., 1998). Subsequent models included distance from upwind obstruction to further refine the wind shelter potential of each cell (Winstral et al., 2002), and threshold wind speed to estimate erosion (Lehning & Fierz, 2008). This method of quantifying wind transport has been incorporated into other models, such as those predicting potential avalanche start zones (Veitinger et al., 2016a). Wind transport is an important element in snow cover models such as Alpine 3D which employs a module called SnowDrift to model wind influence on snow depth and distribution (Lehning et al., 2006). The snowpack layering model Crocus uses wind speed in its model chain to predict snow layer density as well as sphericity of new snow (Vionnet et al., 2012). Although Crocus on its own does not predict spatial variability, it has been combined with the atmospheric model Meso-NH

to produce snow transport models (Vionnet et al., 2014). Newer iterations of both Crocus and SNOWPACK include preferential deposition in snowpack distribution (Lehning et al., 2008; Vionnet et al., 2014) and can even model the influence of preferential deposition separately from redeposition (Mott et al., 2010). While the study of wind transport through modelling has important implications for snow distribution, the ability of models to give details on the specific physical properties of wind transported snow is still limited.

2.13 Implications and Importance of this Study

While meteorological variables such as wind speed and temperature do influence the properties of wind deposited snow (e.g. Seligman, 1947; Sommer et al., 2017; van Herwijnen & Jamieson, 2007) many previous studies are theoretical or conducted in a wind tunnel, and field-based evidence is lacking. Some reference articles state that increasing wind speed is associated with increased wind slab hardness (e.g. Fierz et al., 2009; Haegeli et al., 2010), but specific field studies are lacking. Meteorological variables play a role in snow entrainment (e.g. Clifton et al., 2006; Li & Pomeroy, 1997a), but considerably less is known about how meteorological variables influence snowpack properties during deposition. Understanding the properties of wind slabs during and immediately after deposition is important because direct-action avalanches happen as wind slabs are built and then triggered by continued loading. A link between meteorological properties and snowpack properties is particularly important for avalanche workers in areas with limited ability to observe snowpack properties, as they often must predict snowpack properties from meteorological variables. This increases forecast uncertainty (LaChapelle, 1980). The susceptibility of a wind slab to forming an avalanche can be determined in part by its physical properties, and physical properties are determined in part by meteorological variables. A field-

tested link between slope-scale meteorological variables and wind slab properties would help predict avalanches, particularly when resources or safety concerns do not allow for travel in or near start zones.

CHAPTER THREE

METHODS

3.1 Study Area

I collected data from two study sites at the Yellowstone Club ski area, located on Pioneer Mountain and Eglise Rock adjacent to the Big Sky Ski Resort in the Madison Range Mountains of Southwestern Montana (45.237, -111.424) (Figure 6). This is an intermountain snow and avalanche climate, capable of either the mild temperatures and heavy snowfall of a coastal climate, or cold temperatures and lighter snowfall of a continental climate (Mock & Birkeland, 2000). During their study period Mock & Birkeland (2000) found that based on climatic parameters Big Sky actually classified as continental rather than intermountain in three of five seasons. This was attributed to the northerly location and high elevation of Big Sky Resort (summit elevation 3404m). Similar to much of the east slope of the Rocky Mountains, the Big Sky area is known for windy conditions and hard layers of wind-deposited snow, creating an ideal location to study wind slabs.

3.2 Desktop Analysis and Site Selection

In selecting study sites, I began with a series of maps depicting wind loading potential (Figure 7). I created these maps by editing R code from a pre-existing model that predicts potential avalanche start zones and incorporates a wind shelter index (Veitinger et al., 2016b). This wind shelter index uses the distance downwind or upwind from an obstacle to

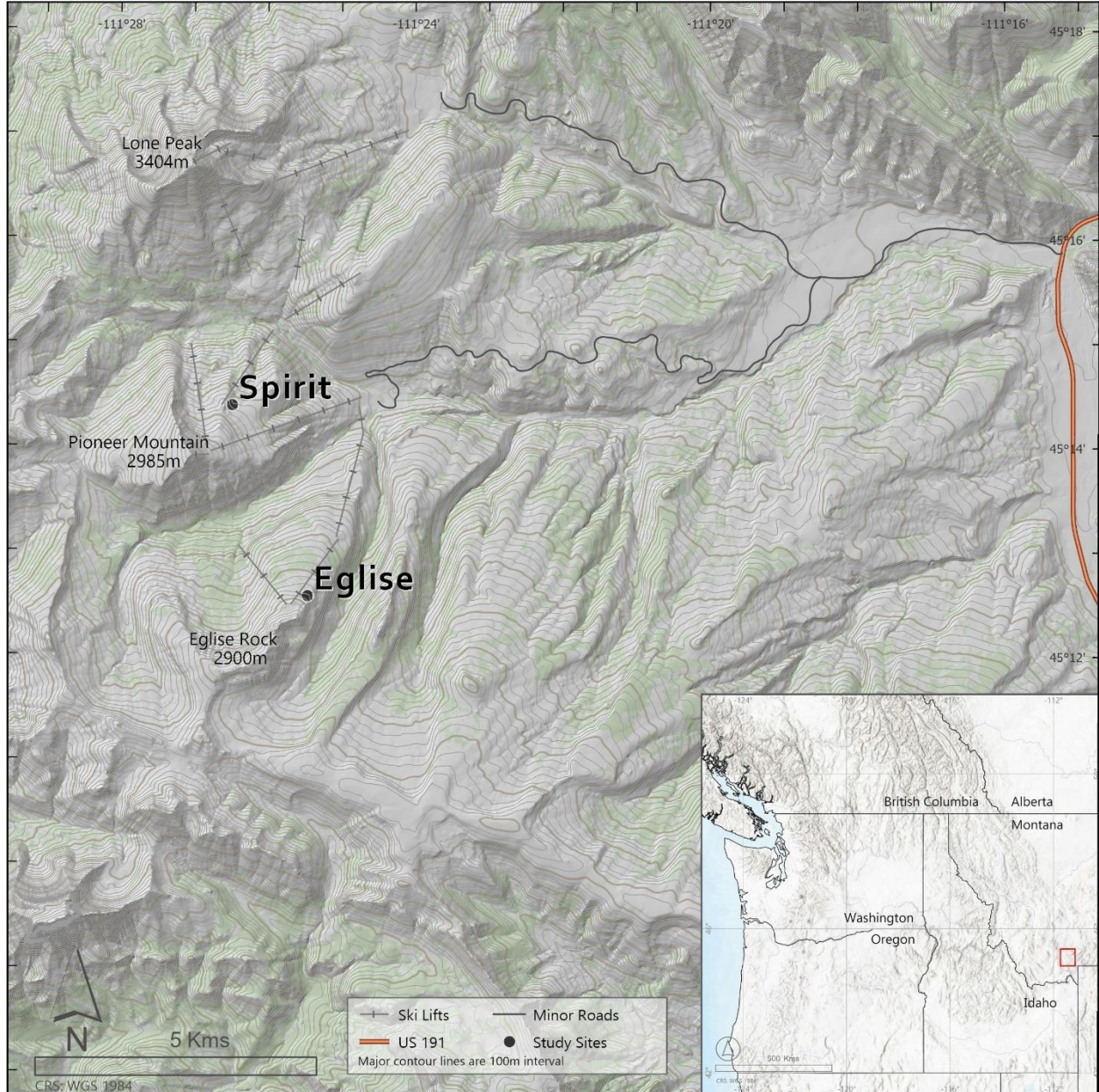


Figure 6: The location of the two study sites. These sites were located at the Yellowstone Club directly south of Big Sky Resort in southwestern Montana.

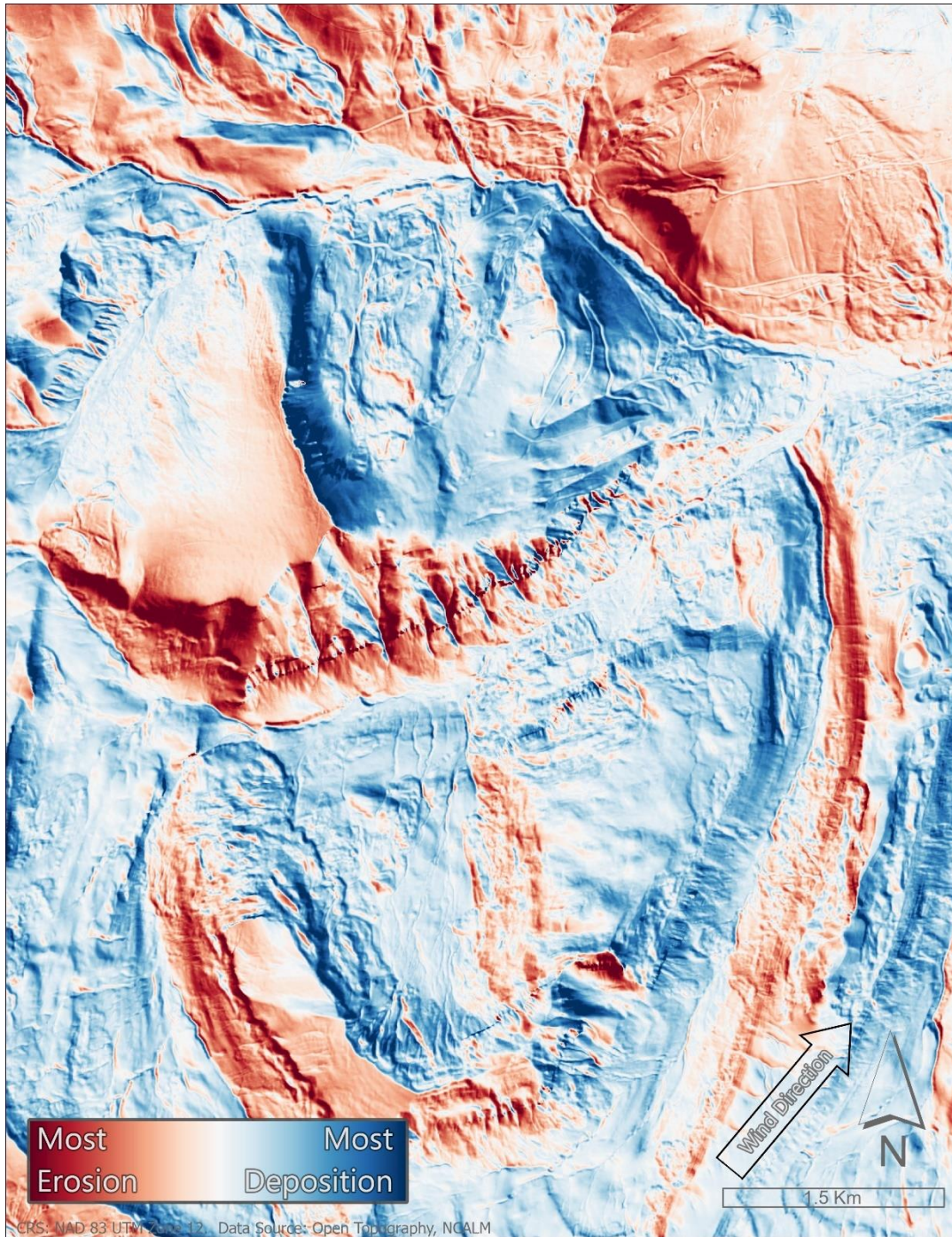


Figure 7: Output map produced from a wind loading model using a southwest wind direction. Red colouring indicates potential for wind erosion of snow, and blue indicates potential for wind deposition of snow, where hue indicates extent. This map was created from a bare ground DEM without vegetation, as most potential study sites were largely unvegetated.

predict the potential for wind loading or erosion in each cell of a digital elevation model (DEM) (Winstral et al., 2002). I applied the updated R script to a one-meter resolution DEM (Gardner, 2005) of Pioneer Mountain and Eglise Rock with a variety of common wind directions. Potential study sites were visually selected from the output maps and corroborated with local knowledge. I visited these locations in December 2021 and selected two study sites (Figure 8) based on wind slab presence, proximity to weather stations, ease of access, and avalanche safety. I chose sites

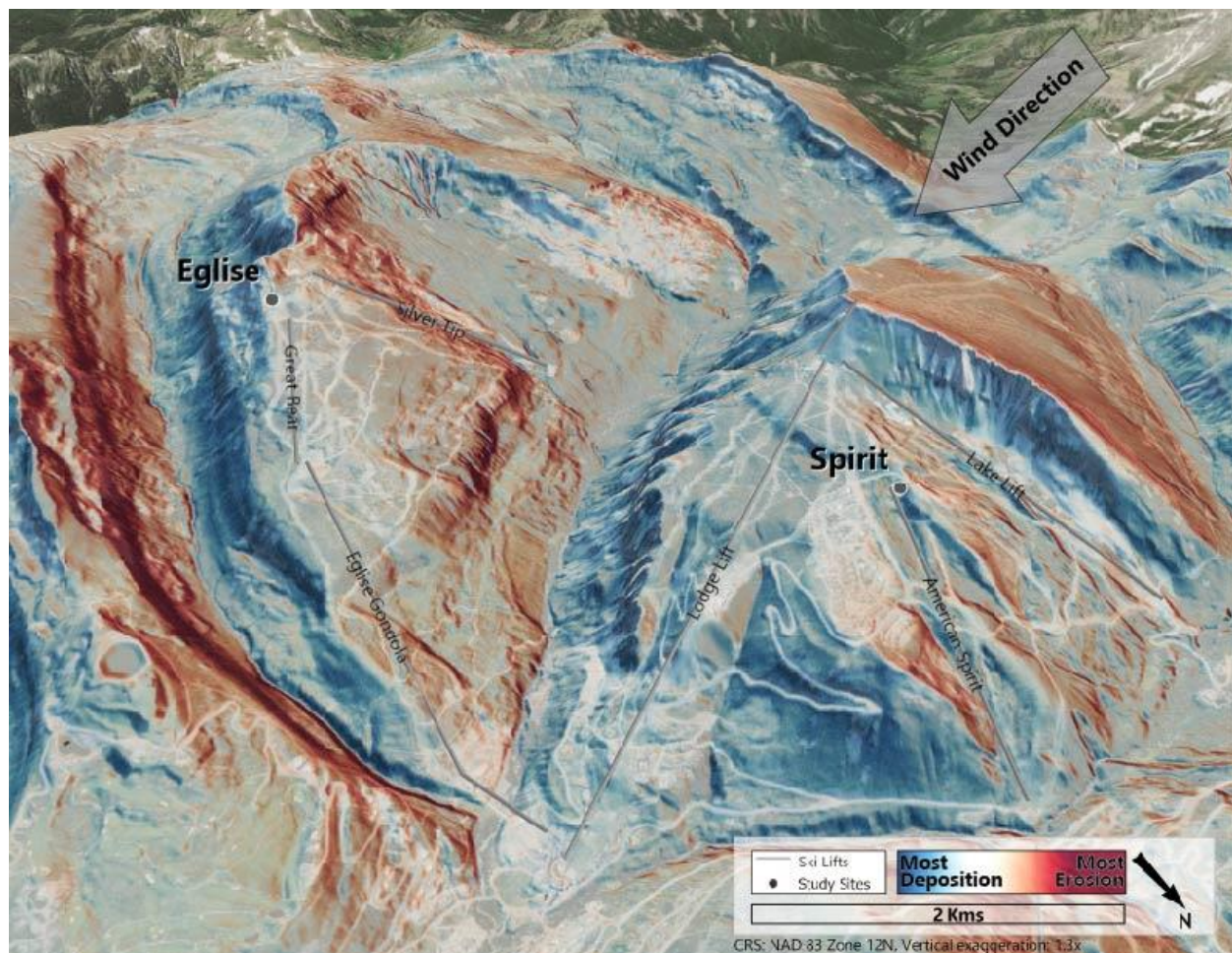


Figure 8: The location of the Spirit and Eglise study sites in relation to the Yellowstone Club terrain and ski lifts, overlaid with a wind loading potential map with southwest wind. Red represents potential wind erosion, and blue represents potential deposition, where hue indicates the extent of either erosion or deposition.

with obvious and uniform terrain features, which I predicted may provide consistent slab development with southwest winds, as this is the area's prevailing wind direction. To ensure avalanche safety these sites had slope angles less than 25 degrees and were within the ski area boundary. The American Spirit study site was located near treeline on the eastern flank of Pioneer Mountain on an east to northeast slope at 2670m (Figure 9). The Eglise study site was located near treeline on Eglise Rock in a north-facing gulley at 2820m (Figure 10).

3.3 Field Methods

3.3.1 Meteorological Data Collection

Each study site had one mobile weather station constructed from wooden dowels and PVC pipe (Figure 11a). These stations contained an Onset Hobo U23 Pro V2 temperature and



Figure 9: The American Spirit study plot looking NE. Aspect: ENE, Elevation: 2760. The red highlighted area is the maximum extent of profile locations.



Figure 10: The Eglise study plot looking SE. Aspect: NNE, Elevation: 2820. The red highlighted area is the maximum extent of profile locations.

relative humidity sensor 1.5 meters above the snow surface, and two Rainwise Inc WindLog anemometers 1.5 meters 0.5 meters above the snow surface. Both study sites were proximal and at similar elevation to a permanent weather station containing a Campbell Scientific 500 temperature and relative humidity probe, a Campbell Scientific SR 50 snow depth sensor, and an R.M Young 05103L anemometer approximately 10m off the snow surface. The wind speeds and directions recorded by the permanent weather station were defined as unobstructed wind measurements. Though these weather stations were not at ridgetop, they were proximal to the study sites in areas free from vegetation and other topographic obstructions. At the Spirit site the permanent weather station was ~20m from the field site, and at the Eglise site it was ~100m

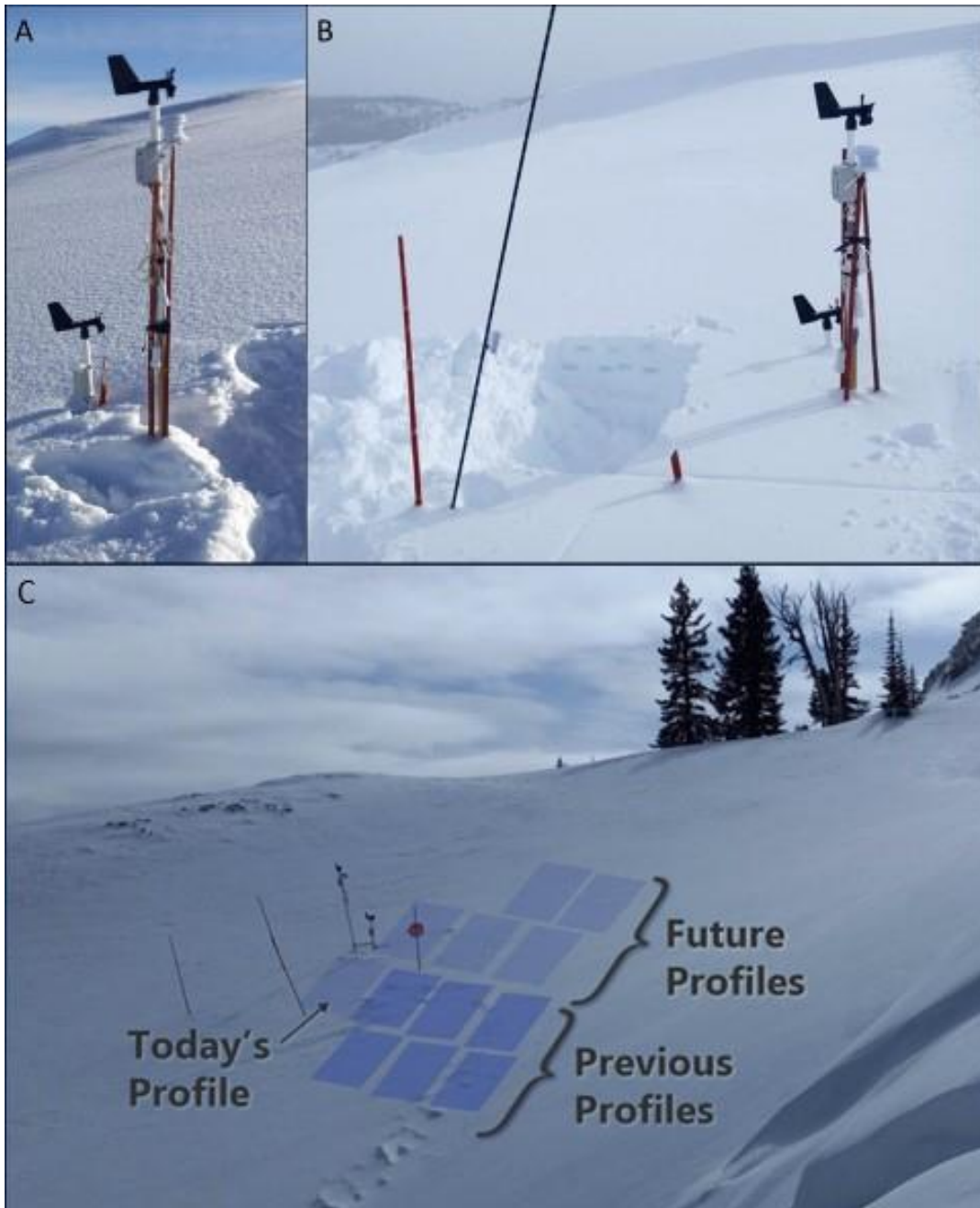


Figure 11: Each mobile weather station contained an anemometer 0.5m off the snow surface, an anemometer 1.5m off the snow surface, and a temperature/humidity sensor 1.5m off the snow surface (a). Profiles were dug directly below the weather station (b), which was moved in a grid pattern across the slope after each site visit (c). This was done to ensure that each subsequent profile was located as close to the sensors as possible and as close to the previous profile location as possible, while also in a previously undisturbed location.

away. These permanent weather stations were maintained by the Yellowstone Club for their weather reporting and snow safety program.

On each visit I dug a profile directly below the weather station (Figure 11b) and then moved the weather station across the slope so that the next profile could be dug in an undisturbed location (Figure 11c). This allowed me to both keep track of previously disturbed snow, and allowed the weather station to remain as close as possible to each profile. To minimize the influence of spatial variability I moved the weather station as little as possible each time. Where possible, I simply excavated further from the previous profile. I investigated sub-slope spatial variability with gridded probe measurements, which were interpolated across the slope (Appendix A) in order to better understand spatial variability at each site. With the creation of these maps, I was able to confirm that my profile locations were concentrated in the most wind-loaded parts of the site, and where snow depths were mostly consistent. Although the profile location had to change slightly each time due to the destructive nature of snowpack tests, keeping the profiles close together reduced spatial variability as much as possible given the survey methods.

All meteorological values were collected from weather stations except for absolute humidity. While absolute humidity is not commonly measured by forecasting operations, it is a useful scientific tool. This is because dew point and relative humidity are associated with air temperature, and so it can be difficult to determine whether changes in these variables are due to changes in humidity or changes in temperature. Absolute humidity provides a measure that is independent from air temperature. Absolute humidity was calculated using the following series

of formulas (Dingman 2002). First, I calculated saturation vapour pressure (e^*) in kilopascals (kPa) where T is temperature in degrees Celsius:

$$e^* = 0.611 * \exp\left(\frac{17.3 * T}{(T + 237.3)}\right) \quad (1)$$

From this, I calculated actual vapour pressure (e), where W_a is relative humidity expressed as a decimal number, and e^* is the saturation vapour pressure in kPa from equation 1.

$$W_a = \frac{e}{e^*} \quad (2)$$

Finally, I used actual vapour pressure (e) to calculate absolute humidity (ρ_v) in Kpa, where T is temperature in degrees Kelvin.

$$\rho_v = \frac{e}{T * 0.622} \quad (3)$$

3.3.2 Snowpack Data Collection

Data collection took place throughout the northern hemisphere winters of 2021/22 (December 2021 - April 2022) and 2022/23 (December 2022 - April 2023). Throughout both winters I closely monitored remote weather data, and selected field days where wind speeds had recently been above 5 m/s (the commonly accepted threshold wind speed for transport) and occurred in conjunction with snowfall, or were preceded by a snowfall event, and no melt-freeze event had occurred. I then travelled to the site during or as soon as possible following the wind event. I was able to confirm presence or absence of snow for transport through communication with local ski patrollers which increased the likelihood of finding a recent wind slab on field days. On each field day I dug a test profile at each site which included recording depth, grain

form, grain size, hardness, and density for each layer (Table 3), per SWAG guidelines (American Avalanche Association, 2022). I measured hardness using both the hand hardness test and a Fraser Instruments BHG (Figure 2). Though I initially recorded

Table 3: Snowpack observations collected for each layer in each profile, as well as the units and methods for each parameter.

Parameter	Unit	Methods
Thickness	Centimeters (cm)	Measured vertically with a foldable ruler.
Hand Hardness	Categorical hand hardnesses of fist (F), four finger (4F), one finger (1F), pencil (P), knife (K), ice (I).	Object pushed into snow at a rate of 10-15 N (Fierz et al., 2009).
Grain form	Categorical classification as per ICSSG guidelines (Fierz et al., 2009) with limited use of subclasses	Observed on a gridded crystal card with a 10x loupe.
Grain size	Millimetres (mm)	Observed on a gridded crystal card with a 10x loupe.
Temperature	Degrees Celsius (°C)	Measured vertically every 10cm on the profile wall with a shaded digital thermometer.
Liquid Water Content*	Categories of dry, moist, wet, very wet, slush	Squeezing snow with a gloved fist to observe its behavior, as per SWAG guidelines (American Avalanche Association 2022).
BHG Force Hardness	Newtons (N)	Blade inserted parallel at a rate of approximately 10 cm/s as per Borstad & Mcclung (2011).
Density	Kilograms per meter cubed (kg/m ³)	Removed snow with a 200 cm ² triangular cutter and weighed on an electronic scale.

*Only conducted for layers at 0°C, as snow below this temperature is inherently dry since melting does not begin until 0°C.

+ and – values with hand hardness, these qualifiers were eventually dropped as their use resulted in many categories with a low number of observations. Additionally, hand hardness interpretation can vary between practitioners, so eliminating + and – categories eliminated some of the nuances in personal interpretation. I took three each of density and BHG measurements per layer to

obtain a mean value, with outliers or unrealistic measurements disregarded. Any measurement that was more than ten percent different from the other measurements was considered an outlier. In some situations, a snowpack layer was so inconsistent that even with many repeated measurements it was impossible to get all measurements within ten percent of each other. In this case five measurements were taken and the largest and smallest were discarded. Study design did not allow for reliable measurement of snow available for transport, or physical properties of snow before transport.

3.4 Data Processing

3.4.1 Layer Classification

I classified all surface and recently buried layers as either a wind slab layer or a null layer, based largely on field observations of active transport, or evidence of recent transport (Figure 12). I then individually investigated formation-history of all wind slab layers and discarded those where I could not be certain the layer was a wind slab. These layers were fully



Figure 12: Surface evidence of wind transport including ripple marks (A), drifting (B), and localized erosion (C).

removed from the analysis, and not re-classified as null layers. Layers were discarded if I was not highly certain that snow was available for transport during the wind event, or if I suspected the site had been subject to wind erosion in addition to deposition. Availability of snow for transport was confirmed with weather station records and ski patroller observation. I suspected erosion if I noticed erosional features such as sastrugi within the study site, or if meteorological records indicated a major change in wind direction during the wind period. Through these means I discarded three layers, which were all associated with wind events occurring more than 72-hours before data collection, as determined from weather station data, while all remaining wind slab layers were associated with more recent wind events. The 72-hour timeframe became a useful guide in determining that wind slabs retained in the study could be considered “recent.” The importance of ensuring that wind slabs were recent minimized chances that physical properties were due to conditions occurring after the wind event. With these methods, I did my best to ensure that each layer I classified as a wind slab was indeed a wind slab, and that physical properties were the result of meteorological variables during transport.

The importance of null layers was to provide a benchmark of “recent” snow which had not been subject to wind transport, but could have been with increased wind speed. For consistency I used a 72-hour time period to define “recent” null layers, and discarded any layers where snowfall had occurred outside of this timeframe. Since null layers were chosen to represent recent storm snow which theoretically could have been transported, I discarded any null layers that had been subject to melt-freeze processes. This was determined with field observations and temperature records. I also discarded any null layers which were not on the surface, as they were less likely to have been transported in a wind event, since the overlying

snow would have had to be removed first. In some situations, I was unsure if a layer was a true null layer or had been subject to some wind transport. These layers were removed completely from the analysis. Without constant observation of blowing snow presence and absence from the field sites I could not ever be completely confident in layer classification, however these additional checks increased my confidence that I had classified both null and wind slab layers as accurately as possible.

3.4.2 Determining Wind Periods

After classifying all layers and discarding those which did not fit either criterion, I designated a wind slab formation period for each wind slab layer in order to define an exact time frame from which I would assess meteorological variables. For each layer (both wind slab and null layers) I used weather station data to determine the time at which snowfall contributing to that layer had occurred. For each wind slab layer, I then highlighted every one-hour period from the start of snowfall until data collection where the average unobstructed (~10m) wind speed was greater than 5 m/s. This threshold was chosen to maintain consistency with previous studies (Table 2). Although the dataloggers from the mobile weather station recorded at ten-minute intervals, the permanent weather stations only recorded hourly averages. I defined each wind slab layer's period of formation as the combination of all of these one-hour periods, whether continuous or not. The value of all meteorological variables for a wind slab layer were determined from its period of formation. Null data by definition did not have an associated formation period, so to obtain meteorological values for null layers I included all one-hour units from the time snowfall began until the time of data collection. Due to equipment issues some

wind speed data were missing, and these were filled by linear regression using data from other wind speed heights (Appendix B).

3.5 Statistical Analysis

I chose to analyze data from both sites as one dataset, since I would expect similar processes controlling wind slabs to occur at both sites, and the two sites fell into visually similar areas of wind loading potential (Figure 8). Also, a Mann-Whitney U test (Kanji, 1999) provided strong evidence that the two sites had statistically similar temperature ($p = 0.473$) and relative humidity ($p = 0.753$) during wind periods. Wind speed at all heights was statistically different between sites (unobstructed $p=0.007$, low $p<0.001$, ground $p<0.001$) during wind periods, and this allowed for observations of a wider range of wind speeds. Finally combining the data from both sites allowed for a larger dataset and therefore a more robust analysis.

I conducted all analyses in R statistical software (R Core Team, 2021). The first step in the analysis was to determine meteorological differences when wind slabs formed when they did not (null situations). After this, I conducted a series of analyses to compare each explanatory meteorological variable to each snowpack physical property response variable (Table 4) in situations when wind slabs did form. I initially applied a variety of other explanatory values such as the difference between wind speeds at different heights, a drift index (wind speed multiplied by approximate depth of snow available for transport) (Hendrikx et al., 2014), and time since wind period, however none of these variables provided significant or insightful information (Appendix C). I also did not assess layer thickness as a response variable, as layer thickness is controlled by initial snowfall amount, which I did not have a means to accurately capture.

Table 4: All variables measured in this study, their type (explanatory or response), units of measurement, and weather station source if applicable.

Variable	Type	Units	Weather Station
Average Unobstructed Wind Speed (~10m)	Explanatory	Km/h	Permanent
Average Low Wind Speed (1.5m)	Explanatory	Km/h	Mobile
Average Ground Wind Speed (0.5m)	Explanatory	Km/h	Mobile
Maximum Unobstructed Gust	Explanatory	Km/h	Permanent
Wind Period Time	Explanatory	Hours	Permanent
Average Temperature	Explanatory	°C	Permanent
Average Dew Point	Explanatory	°C	Mobile
Average Relative Humidity	Explanatory	%	Mobile
Average Absolute Humidity	Explanatory	g/m ³	Calculated
Hand Hardness	Response	Categorical	N/A
Blade Hardness Gauge Force (Hardness)	Response	Newtons	N/A
Density	Response	Kg/m ³	N/A

3.5.1 Wind Slab Formation

I used an unpaired Mann-Whitney U test to determine which meteorological properties best explained wind slab formation at these sites, by comparing each explanatory meteorological variable between the wind slab group and the null group. The Mann-Whitney U test is a non-parametric test to determine the likelihood of two different samples coming from the same population. I chose this non-parametric test as not all datasets met the assumptions of normality, as tested with a Lilliefors test (Kanji, 1999). All data sets did meet the assumption of independence required by the Mann-Whitney U test, as each wind slab formed during a separate wind period or at a separate site, and each null layer was the result of a separate snowfall event. Further, no single data point existed in both groups, implying independence between groups. Using the same test between all datasets was important as the goal was to compare datasets to each other to determine which meteorological variables could predict wind slab formation. This comparison would have been less valid if different tests had been used for different datasets.

3.5.2 Individual Hand Hardness Comparisons

After determining which meteorological variables were associated with wind slab occurrence, I sought to explain relationships between meteorological variables and hand hardness. I first applied a Kruskal-Wallis test (Kanji, 1999) to each meteorological dataset to determine if any hand hardness category in that dataset had a statistically different distribution than any other category in that dataset. The Kruskal-Wallis test is a non-parametric ANOVA that can be used when data is not normally distributed (Kanji, 1999). Again, I checked normality with a series of Lilliefors tests. Any meteorological dataset with a significant statistical result from the Kruskal-Wallis test was analyzed further to determine which hand hardness categories were different from each other. This was done with a Mann-Whitney U test on all possible pairings of the hardness values for wind skin, four finger, one finger, and pencil. I did not measure any knife hardness layers, likely because I only looked at recent wind slabs, nor did I observe any fist hardness layers, as wind slabs are almost always harder than fist.

3.5.3 Grouped Hand Hardness Comparisons

Next, I grouped hand hardness into binary soft and hard categories. Soft layers included wind skin or four finger hardness, and hard layers included one finger or pencil hardness. These are divisions proposed by the American Avalanche Association for hard and soft (American Avalanche Association, 2022), and so this classification is consistent with how practitioners define hard and soft. Reclassification resulted in a series of datasets where each meteorological variable was individually compared to hardness as a binary value. The meteorological values of each binary variable were compared in each dataset using a Mann-Whitney U test as they did not all meet the assumption of normality required for a parametric test.

3.5.4 Simple Linear Regression

I used simple linear regression (SLR) (Ryan, 1997) to compare each meteorological variable independently to both density and BHG force. This resulted in nine SLR models associated with density, and nine SLR models associated with BHG force. Not all datasets perfectly met the assumptions of linear regression (Appendix D), likely due to the low number of observations. Linear regression techniques are fairly robust with respect to small deviations from these assumptions but these SLR results should be viewed with appropriate caution. I applied a log transformation to BHG force values in order to meet the assumption of linearity and for consistency with previous analyses (e.g. Borstad & McClung, 2011; Pogue & McClung, 2016). Outliers were assessed both visually in scatterplots, and with residuals vs. leverage plots where an outlier was defined as any data point with Cook's distance of 0.5 or greater. Outliers were then investigated on a case-by-case basis and removed if deemed appropriate.

3.3.5 Multiple Linear Regression

After each series of SLRs, I conducted a backwards step-wise multiple linear regression (MLR) (Ryan, 1997) for each continuous explanatory variable, density and BHG force. I chose backwards MLR over forwards MLR because it allows each variable to be explored and is more robust when variables are jointly significant but not individually significant (Ryan, 1997). For both density and BHG force, an initial regression model was built using all nine meteorological explanatory variables. I checked for multicollinearity using a variable inflation factor (VIF) for each variable in each dataset, where a higher VIF indicates correlation to other explanatory variables (Ryan, 1997). Explanatory variables with high VIF values were removed one at a time, until all VIF values were below five, indicating no variables were strongly correlated. In

situations where two variables were similar and had very close VIF values, I repeated the stepwise process with each to see if there were any differences in the resulting model. I then created a model each for density and BHG force from only explanatory variables with low VIF values. For the backwards step-wise regression I removed the variable with the highest p-value one at a time, and continued until all individual variables were significant.

3.6 Supporting Studies

During the course of this extended field campaign, I conducted two other studies with complementary goals. The first was an outdoor wind tunnel experiment which sought to control some of the explanatory meteorological variables and their complex interactions. For example, the wind tunnel allowed me to control wind speed as temperature varied. These experiments were to be conducted with actively falling snow to mimic realistic field snowfall and hold relative humidity constant near 100%. However, due to limitations in the physical specification of the wind tunnel and the limited snowfall during the winter of 2021/22, the wind tunnel experiment was mostly unsuccessful. I collected very few datapoints, but an incidental finding of preliminary results showed that the density of initial snow before transport did not relate to wind slab density (Appendix E).

Another side-project was inspired by a desire for a consistent definition for the term wind slab. This study sought to determine how avalanche workers use the terms wind slab and storm slab in professional communication. I investigated a sample of professional communications in the Canadian avalanche industry and searched for instances where the term storm slab was used when wind had clearly played a role in the spatial distribution of the avalanche problem. While

my results were preliminary, they did demonstrate inconsistency in the use of term wind slab in the Canadian avalanche industry (de Leeuw and Birkeland 2023).

CHAPTER FOUR

RESULTS

4.1 Data Summary4.1.1 Snowpack Data

Over two winters I collected information on fifty-two layers useful for analysis, forty-one of which were wind slabs (Table 5). Twenty-nine total layers came from the Spirit site and twenty-three came from the Eglise site (Table 6). For many of wind slab layers I was able to collect density, hand hardness, and BHG force data, however sometimes wind slabs were too thin for one, two, or all of these metrics (Table 7). This was partially solved by using “wind skin” as a hardness classification. The relatively low number of layers with BHG values can be attributed to unavailability of the tool during early parts of the study. The relatively low number of density values can be attributed to the inability to reliably collect this data for layers thinner than four centimeters given the available tools.

Table 5: The number of each type of layer (wind slab or null) recorded in each winter season from both study sites combined.

Year	Wind Slab	Null	Total
2021/22	23	3	26
2022/23	18	8	26
Total	41	11	52

Table 6: The number of each type of layer (wind slab or null) recorded at each site over the course of both data collection winters.

Site	Wind Slab	Null	Total
Spirit	23	6	29
Eglise	18	5	23
Total	41	11	52

Table 7: The number of wind slab layers where each physical property was recorded. While all wind slab layers in this study ($n = 41$) were assigned a hand hardness value, some layers were too thin for accurate BHG and density values. Additionally, the BHG instrument was unavailable during the beginning of the study.

	Wind Slab Layers
BHG	26
Density	29
Hand Hardness	41

4.1.2 Meteorological Data

Most meteorological variables were collected for all wind periods. Exceptions occurred when data loggers or sensors malfunctioned. Missing data were filled by regression from another weather station at the same site (Appendix B). Most often a low height to ground height wind speed linear regression was required. One dew point measurement was not recorded, and I did not fill this data point as regressions resulted in unrealistic values. Additionally, two relative humidity values were removed because they were anomalously low.

Some explanatory meteorological variables were highly correlated during wind slab forming periods (Table 8). The highest correlation value (0.936) was between low and ground wind speed. While unobstructed wind speed and low wind speed were significantly correlated throughout the entirety of two winters (Appendix B) this relationship differed during wind slab forming periods, likely due to the interaction of wind with terrain with varying wind directions. Temperature, dew point, and absolute humidity were also highly correlated to each other. The level of correlation between different explanatory variables is important to keep in mind when interpreting the results. Correlation is particularly important to consider for MLRs, however I compensated for multicollinearity by removing variables with high VIF values.

	Unobstructed Wind Speed	Low Wind Speed	Ground Wind Speed	Temperature	Dew Point	Gust	Absolute Humidity	Relative Humidity	Wind Time
Unobstructed Wind Speed	1	0.164 (<0.001)	0.190 (<0.001)	0.165 (0.132)	0.251 (0.071)	0.528 (<0.001)	0.0338 (0.352)	0.192 (0.957)	0.453 (<0.001)
Low Wind Speed	0.164 (<0.001)	1	0.936 (<0.001)	0.136 (0.173)	0.175 (0.175)	-0.048 (0.253)	0.102 (0.352)	-0.054 (0.402)	0.051 (0.725)
Ground Wind Speed	0.190 (<0.001)	0.936 (<0.001)	1	0.308 (0.023)	0.323 (0.175)	0.089 (0.253)	0.215 (0.352)	-0.119 (0.402)	0.014 (0.725)
Temperature	0.165 (0.132)	0.136 (0.173)	0.308 (0.023)	1	0.923 (<0.001)	0.210 (0.450)	0.874 (<0.001)	-0.116 (0.134)	0.370 (0.204)
Dew Point	0.251 (0.071)	0.175 (0.175)	0.323 (0.175)	0.923 (<0.001)	1	0.180 (0.222)	0.889 (<0.001)	0.223 (0.501)	0.336 (0.075)
Gust	0.528 (<0.001)	-0.048 (0.253)	0.089 (0.253)	0.210 (0.450)	0.180 (0.222)	1	0.061 (0.642)	-0.078 (0.797)	0.341 (0.104)
Absolute Humidity	0.034 (0.352)	0.102 (0.352)	0.215 (0.352)	0.874 (<0.001)	0.889 (<0.001)	0.061 (0.642)	1	0.156 (0.797)	0.307 (0.104)
Relative Humidity	0.192 (0.957)	-0.054 (0.402)	-0.119 (0.402)	-0.116 (0.134)	0.223 (0.501)	-0.078 (0.797)	0.156 (0.797)	1	0.155 (0.406)
Wind Time	0.453 (<0.001)	0.051 (0.725)	0.014 (0.725)	0.370 (0.204)	0.336 (0.075)	0.341 (0.104)	0.307 (0.104)	0.155 (0.406)	1

Table 8: Pearson correlation coefficient (r) values between all explanatory meteorological variables during data collection (i.e. wind slab formation) periods (top number), with the p-value of the correlation underneath (in brackets).

One difficulty in environmental-style studies is the unpredictability of seasonal weather. Due to time constraints, it was not always possible to sample during or immediately following all wind events. During the winter of 2021/22 (Figures 13a and 13b) snowfall amounts were below average in the Big Sky area, so while it was regularly windy, there was often no snow available for transport. The winter of 2022/2023 (Figures 13c and 13d) had more snowfall events than the previous winter, particularly in the latter half of the season, however sustained wind events were less common. So, while I hoped for both abundant snow and wind, neither winter produced optimal sampling conditions. Despite these challenges, I still collected sufficient data over the course of two winters to conduct statistical analyses.

4.2 Statistical Analysis of Wind Slab Formation

Results of unpaired Mann-Whitney U tests provided strong evidence that average unobstructed wind speed ($p < 0.001$), average low wind speed ($p < 0.001$), average ground wind speed ($p < 0.001$), and maximum wind gust ($p = 0.013$) were significantly higher when wind slabs formed than when they did not (Figure 14). Given that unobstructed wind speed was used to define wind slab layers it was a given that this variable would be highly significant, and unsurprising that other wind speed variables were as well. Temperature ($p = 0.246$), dew point ($p = 0.416$), absolute humidity ($p = 0.653$), and relative humidity ($p = 0.092$) were not significantly different when wind slabs formed than when they did not (Figure 15).

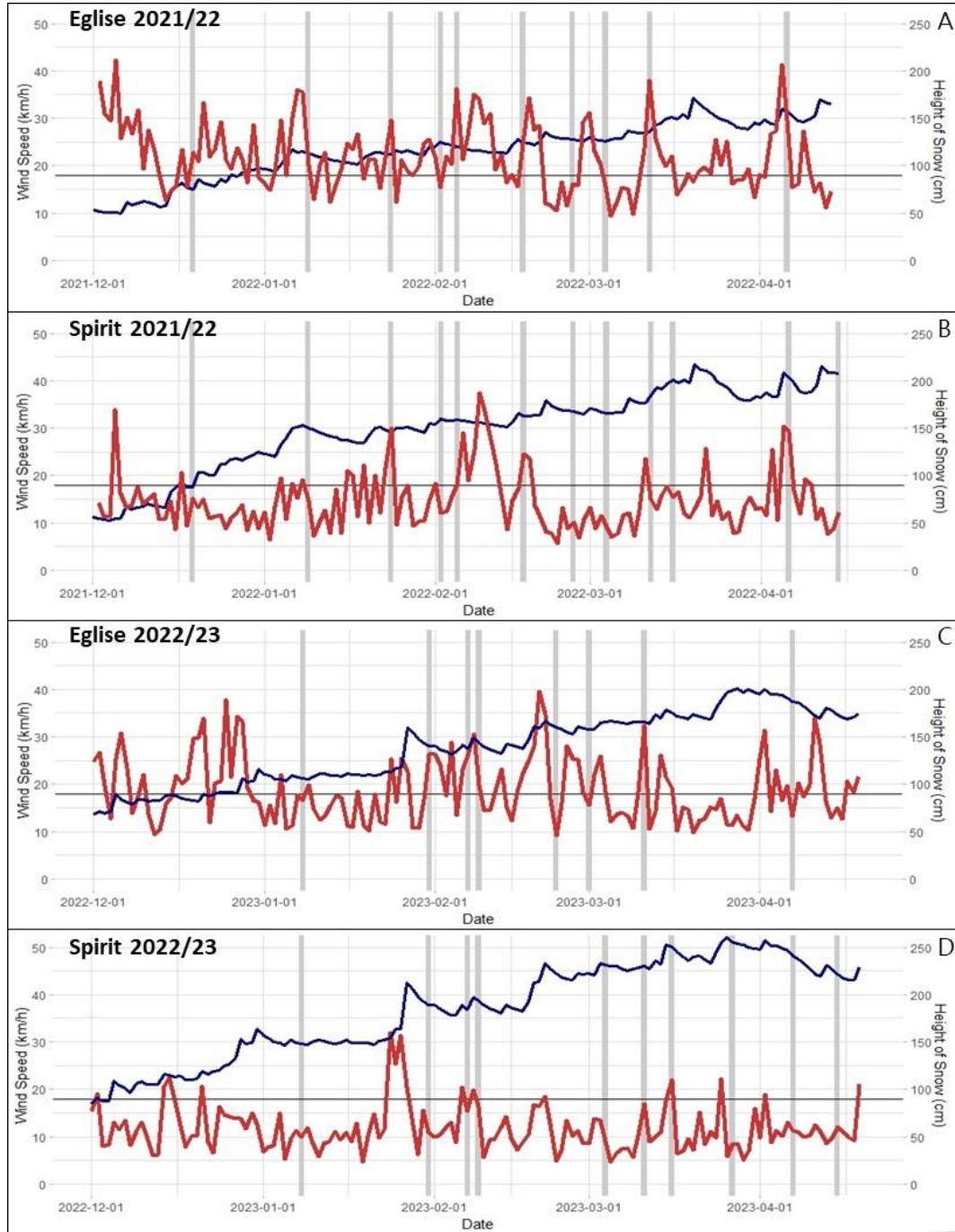


Figure 13: Timeseries of each site for each season showing total height of snow (cm) (blue line) at the end of each ski hill operational day (4pm), and average wind speed for each day (km/h) (red line). Vertical grey lines are days I sampled a wind slab. The horizontal line at 18 km/h (5 m/s) represents the threshold wind speed for classification as a wind slab. Note: some wind slab sampling occurred when daily average wind speed was not above 18 km/h. However, there were periods during each of these days when wind speed was above 18 km/h.

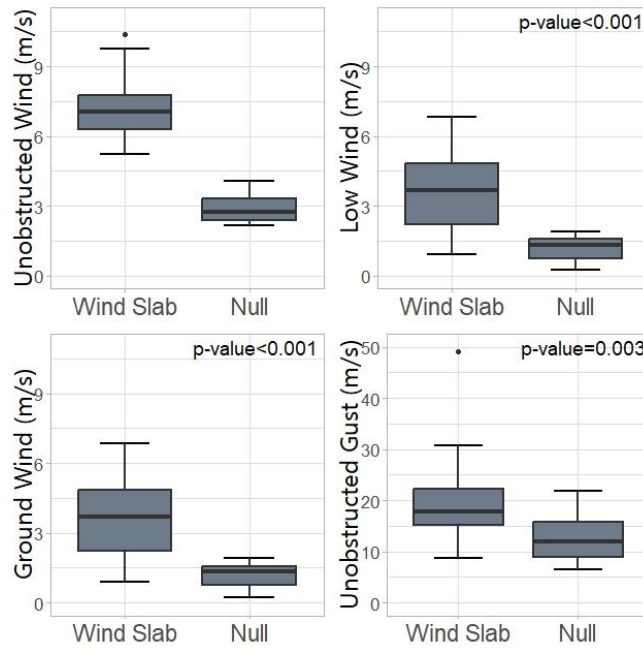


Figure 14: Box plots comparing all wind speed variables between situations when wind slabs formed and when they did not (windslab $n = 41$, null $n = 11$). Note that the Unobstructed Gust graph has a different y-axis scale than the other three.

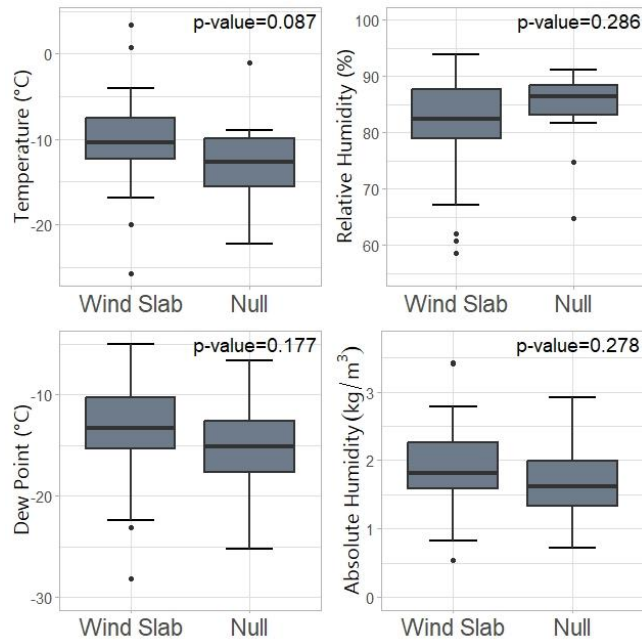


Figure 15: Box plots comparing all non-significant variables (temperature and three humidity metrics) between situations when wind slabs formed and when they did not (windslab $n = 41$, null $n = 11$).

4.3 Statistical Analysis of Wind Slab Properties

4.3.1 Individual Hand Hardness Comparisons

Kruskal-Wallis tests provided evidence that average low wind speed ($p = 0.001$), average ground wind speed ($p = 0.010$), and wind period time ($p = 0.040$) each had at least one hand hardness category that was statistically different from at least one other category in wind slabs at these field sites (Figure 16) (Table 9). No other meteorological variables had any one hand hardness category that differed (Table 9). For each of the significant datasets, I conducted further Mann-Whitney U tests to determine which categories of hand hardness were statistically different from each other (Table 10). Each of the low wind, ground wind, and wind period time had at least two significant pairings.

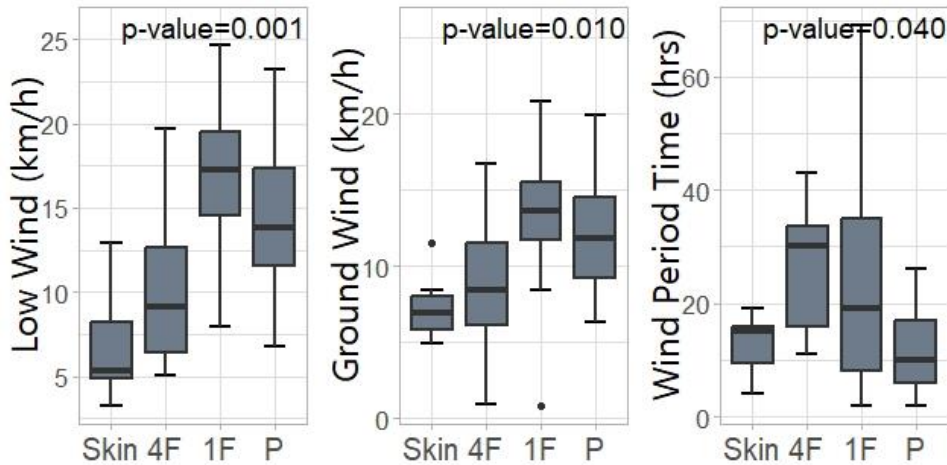


Figure 16: Box plots comparing values of each hand hardness category (wind skin (Skin), four-finger (4F), one-finger (1F), pencil (P)) for all three variables with a significant p-value from a Kruskal-Wallis test (skin $n = 7$, 4F = 11, 1F = 13, P = 10). Each of these meteorological variables had at least one hand hardness category with a significantly different median from at least one other hand hardness category.

Table 9: Each meteorological variable and its p-value from Kruskal-Wallis tests conducted to determine if any one hand hardness category had a median value that was different than others for that meteorological variable.

Variable	P-value
Average Unobstructed Wind Speed (~10m)	0.127
Average Low Wind Speed (1.5m)	0.001*
Average Ground Wind Speed (0.5m)	0.010*
Maximum Unobstructed Gust	0.277
Wind Period Time	0.040*
Average Temperature	0.157
Average Dew Point	0.354
Average Relative Humidity	0.070
Average Absolute Humidity	0.629

*indicates statistically significant ($p < 0.05$) variables

Table 10: All significant ($p < 0.05$) pairings from unpaired Mann-Whitney U tests conducted on each possible hardness pairing for meteorological variables which were significant in the previous Kruskal-Wallis test. Non-significant pairings are not shown.

Pairing	P-Value
Average Low Level Wind Speed	
Wind skin – One finger	0.001
Wind skin - Pencil	0.002
Four finger – One finger	0.012
Four finger - Pencil	0.043
Average Ground Level Wind Speed	
Wind skin – One finger	0.003
Wind skin – Pencil	0.007
Four finger – One finger	0.041
Wind Period Time	
Wind skin – Four finger	0.033
Four finger – Pencil	0.007

4.3.2 Combined Hand Hardness Categories

With hardness categories reclassified as soft and hard, Mann-Whitney U tests provided strong evidence of a difference between hardnesses for average low wind speed ($p < 0.001$), average ground wind speed ($p < 0.001$), and temperature ($p = 0.047$) (Figure 17) (Table 11). Even though the median temperatures were different, there was extensive overlap between the range of the

two categories. All temperature values for soft wind slab formation, except for one datapoint near -25°C , fell within the range of temperature values for hard wind slab formation. The distinction between soft and hard occurred around 3 m/s (10.8 km/h) for the low anemometer, and around 2.5 m/s (9.0 km/h) for the ground anemometer. The remaining meteorological variables were not significantly different between situations of soft wind slab and hard wind slab formation (Figure 18) (Table 11).

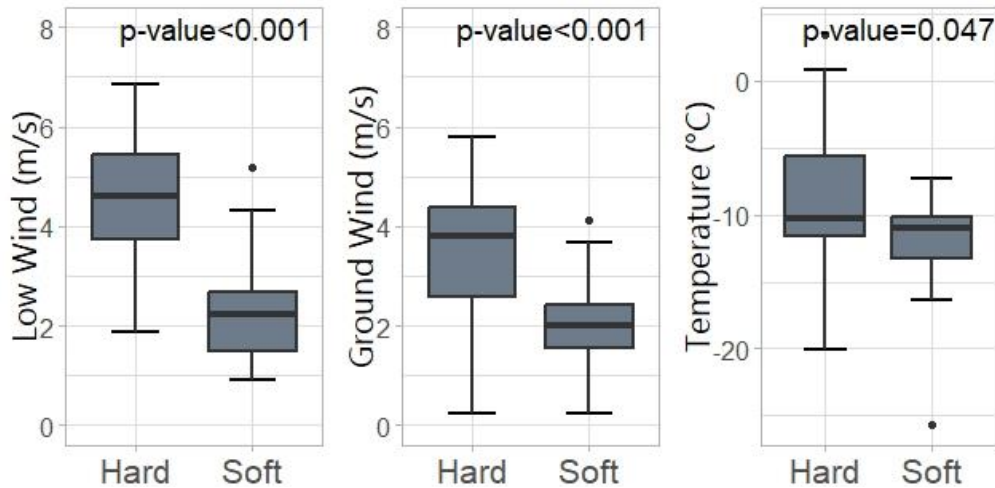


Figure 17: Box plots showing meteorological variables that were significantly different between hard wind slab and soft wind slab formation (hard $n = 24$, soft $n = 17$).

Table 11: Each meteorological variable and its p-value from the unpaired Mann-Whitney U tests conducted to determine if that variable differentiated between hard and soft wind slabs.

Variable	P-value
Average Unobstructed Wind Speed	0.906
Average Low Wind Speed	< 0.001*
Average Ground Wind Speed	< 0.001*
Maximum Unobstructed Gust	0.308
Wind Period Time	0.228
Average Temperature	0.047*
Average Dew Point	0.131
Average Relative Humidity	0.190
Average Absolute Humidity	0.380

*indicates statistically significant ($p < 0.05$) variables

4.3.3 Density

A SLR model provided strong evidence that average low wind speed had a significant positive relationship to wind slab density ($p=0.033$, $r^2=0.157$) (Figure 19). Initially average relative humidity had a significant negative linear relationship with wind slab density at these sites ($p=0.028$, $r^2=0.14$), however there were three obvious outliers with much lower relative humidity values ($<70\%$) (Figure 20a). Though these relative humidity values are not abnormal for the area, they exerted a disproportionate leverage on the resulting model. With these values removed, relative humidity was no longer significant ($p=0.211$) (Figure 20b). Aside from average low wind speed, no meteorological variables had a significant linear relationship with wind slab density (Table 12).

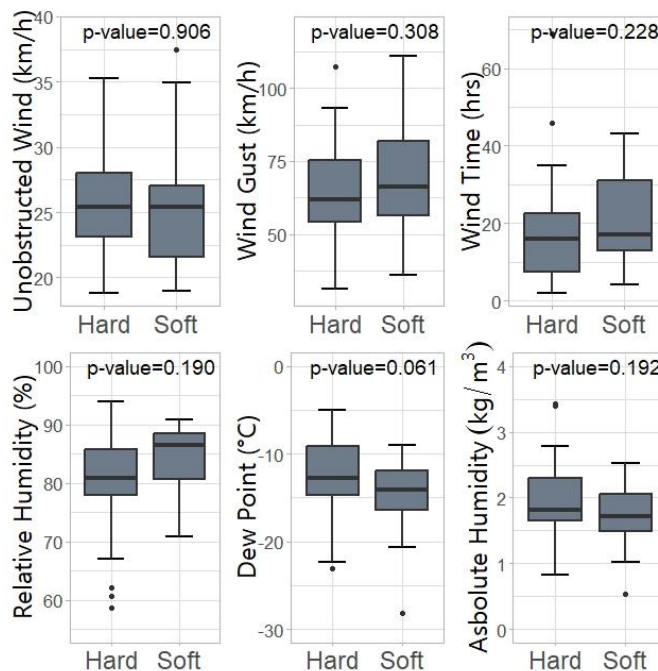


Figure 18: Box plots showing all variables that were not significantly different between hard wind slab and soft wind slab formation (hard $n = 24$, soft $n = 17$).

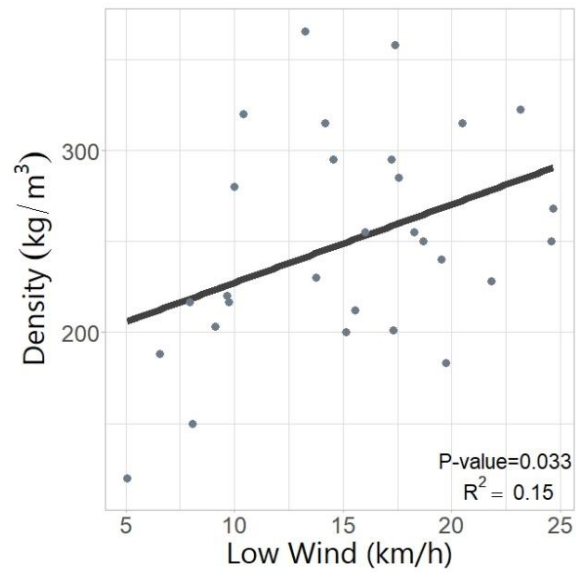


Figure 19: There was a positive linear relationship between average low wind speed and the density of resulting wind slabs as seen in this SLR model

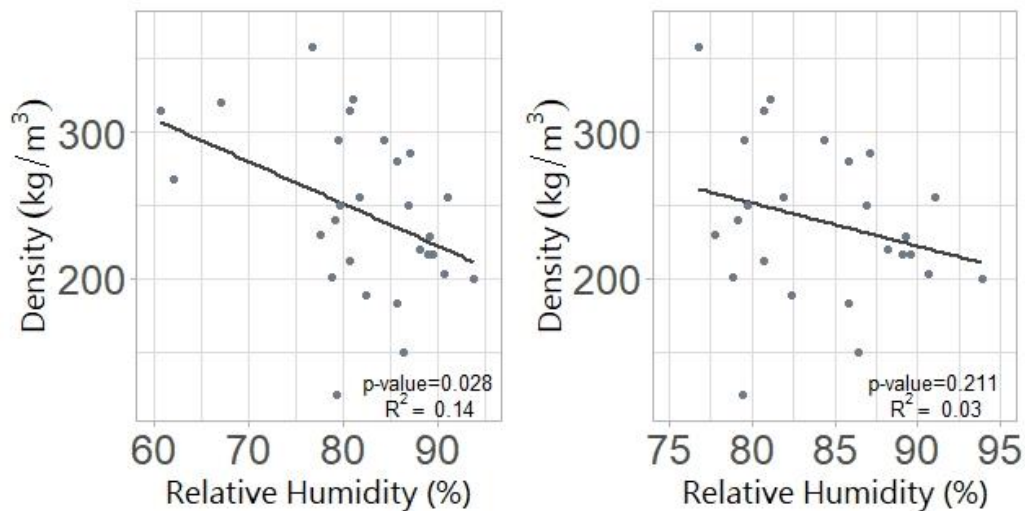


Figure 20: The SLR model between relative humidity and density before (a) and after (b) three outliers below 75% relative humidity were removed. The outliers likely exerted significant leverage on the first model (a), and so once they were removed the SLR model was no longer significant (b).

Table 12: Each meteorological variable and its p-value from the SLR conducted to determine if that variable was correlated with wind slab density.

Variable	P-value
Average Unobstructed Wind Speed	0.612
Average Low Wind Speed	0.033*
Average Ground Wind Speed	0.071
Maximum Unobstructed Gust	0.680
Wind Period Time	0.483
Average Temperature	0.265
Average Dew Point	0.990
Average Relative Humidity	0.210
Average Absolute Humidity	0.837

*indicates statistically significant ($p < 0.05$) variables

After removing explanatory variables with high VIF values one at a time (Table 13), only two of the six explanatory variables were individually significant in the first significant MLR model ($p=0.033$, $r^2=0.559$) (Table 14). Although the overall model was significant, the lack of individually significant explanatory variables, the relatively high r^2 value (compared to subsequent models (Figure 19)), and the low number of datapoints led me to suspect that this model was overfit. Overfit defines a situation where a statistical model becomes more complex than is needed and begins to describe the random error (Babyak, 2004). This implied that using highest r^2 as the definition of the best model would have been a poor choice. Instead, I continued the stepwise MLR by removing the least significant variable in each model until all individual explanatory variables were significant (Table 15). This resulted in the final MRL model matching the SLR model for average low wind speed (Figure 19).

Table 13: Initial and final VIFs for each explanatory variable. Values over five indicate a high level of correlation to other variables. Variables with the highest value were removed one at a time until all values were below five, indicating no significant correlation between variables.

Variable	Initial VIF	Final VIF
Average Unobstructed Wind Speed	2.69	2.42
Average Low Wind Speed	11.51	1.71
Average Ground Wind Speed	14.14	-
Maximum Unobstructed Gust	2.70	1.94
Wind Period Time	3.01	2.74
Average Temperature	37.30	-
Average Dew Point	16.13	1.60
Average Relative Humidity	18.77	2.22
Average Absolute Humidity	4.73	-

Table 14: Individual p-values of each explanatory variable in the first significant model produced by the backwards step-wise MLR for wind slab density.

Variable	P-Value
Average Unobstructed Wind Speed	0.295
Average Low Wind Speed	0.066
Maximum Unobstructed Gust	0.036*
Wind Period Time	0.001*
Average Dew Point	0.342
Average Relative Humidity	0.306

*indicates individual significant ($p < 0.05$) variable

Table 15: Each subsequent model in the backwards step-wise MLR process comparing meteorological variables to wind slab density, as well as its p-value, r^2 value, and variables used in the model. In each step the least significant variable was removed.

Step	P-value	R ²	Explanatory Variables Included	Least Significant Variable
1	0.003*	0.559	Unobstructed wind speed, Low wind speed, Unobstructed gust*, Wind time*, Dew point, Relative humidity	Dew point
2	0.002*	0.359	Unobstructed wind speed, Low wind speed*, Unobstructed gust, Wind time*, Relative humidity	Unobstructed wind speed
3	0.007*	0.389	Low wind speed*, Unobstructed gust, Wind time*, Relative humidity	Relative humidity
4	0.192	0.070	Low wind speed*, Unobstructed gust, Wind time	Wind period time
5	0.093	0.103	Low wind speed*, Unobstructed gust	Unobstructed gust
6	0.033*	0.157	Low wind speed	-

*indicates statistically significant ($p < 0.05$) variables and models

4.3.4 Blade Hardness Gauge Force

The initial series of SLR models comparing the log of BHG force to each meteorological variable had no significant correlations (Table 16). However, a series of residuals vs. leverage plots showed that average low wind speed and average dew point each had outliers with a Cook's distance greater than 0.5 (Appendix D). Upon further examination I found no reason to remove the outlier from the dew point dataset, as it was consistent with other dew point values measured nearby on that day. Additionally, running the model without this value made no difference to the statistical significance of the SLR model. The outlier in the average low wind speed dataset had a BHG force value of 0.95N and a hand hardness of one-finger, while all other one-finger layers had BHG values varying from 1.53N to 4.97N. When a log transformation was applied to these values to match the analysis, the outlier had a value of -0.022, while the rest of the dataset was normally distributed with a mean of 0.370. Using the qnorm function in R (R Core Team, 2021), I determined that the outlier value was well outside the lower 0.05 percentile of the distribution. With this information, I felt confident removing this outlier from the dataset. Additionally, this measurement was collected early in the first season before proper training with the BHG, and so user error was likely to blame for the erroneously low value. After removing this outlier, the SLR model provided strong evidence of a positive linear relationship between average low wind speed and the log of BHG force measurement at these sites($p\text{-value}=0.009$, $r^2=0.231$) (Figure 21).

Table 16: Each meteorological variable and its p-value from the SLR model with the log of resulting wind slab BHG force value. These are initial models before the outlier was removed from the average low wind speed dataset, and no models were significant.

Variable	P-value
Average Unobstructed Wind Speed	0.178
Average Low Wind Speed	0.065
Average Ground Wind Speed	0.114
Maximum Unobstructed Gust	0.986
Wind Period Time	0.140
Average Temperature	0.145
Average Dew Point	0.524
Average Relative Humidity	0.363
Average Absolute Humidity	0.658

*indicates statistically significant ($p < 0.05$) variables

After using VIF values to control for multicollinearity (Table 17), the first significant model in the step-wise MLR for log BHG force contained no individually significant variables ($p = 0.033$, $r^2 = 0.347$) (Table 18). Once again, I suspected the significant of the overall model was due to overfit and so continued the backwards step-wise process until only significant variables were included in the model (Table 19). With this requirement the final model matched the SLR with average low wind speed (Figure 21).

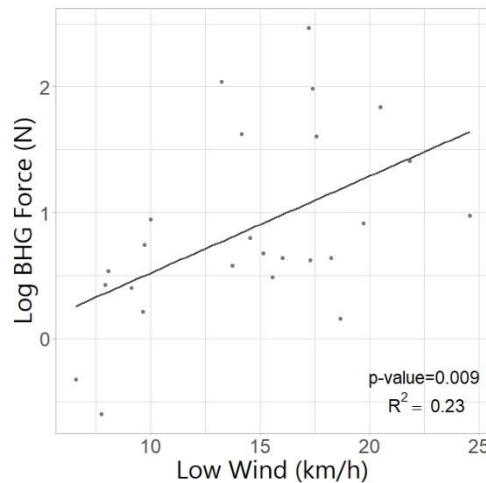


Figure 21: There was a positive linear relationship between average low wind speed and the BHG force value of resulting wind slabs as seen in this SLR model.

Table 17: Initial and final VIFs for each explanatory variable. Values over five indicate a high level of correlation to other variables. Variables with the highest value were removed one at a time until all values were below five, indicating no significant correlation between variables.

Variable	Initial VIF	Final VIF
Average Unobstructed Wind Speed	10.97	-
Average Low Wind Speed	9.21	1.60
Average Ground Wind Speed	14.29	-
Maximum Unobstructed Gust	2.37	1.73
Wind Period Time	7.80	1.58
Average Temperature	35.25	3.36
Average Dew Point	44.08	-
Average Relative Humidity	4.14	1.14
Average Absolute Humidity	6.39	2.62

Table 18: Individual p-values of each explanatory variable in the first significant model produced by the backwards step-wise MLR for wind slab log BHG force. No variables were independently significant, but the overall model was significant ($p = 0.033$)

Variable	P-value
Average Low Wind Speed	0.055
Maximum Unobstructed Gust	0.311
Average Temperature	0.329
Wind Period Time	0.355
Average Relative Humidity	0.061
Average Absolute Humidity	0.632

Table 19: Each subsequent model in the backwards step-wise MLR process comparing meteorological variables to wind slab log BHG force, as well as its p-value, r^2 value, and variables used in the model. In each step the least significant variable was removed.

Step	P-value	R ²	Explanatory Variables Included	Least Significant Variable
1	0.033*	0.347	Low wind speed, Unobstructed gust, Temperature, Wind period time, Relative humidity, Absolute humidity	Absolute humidity
2	0.017*	0.375	Low wind speed*, Unobstructed gust, Temperature, Wind period time, Relative humidity	Wind period time
3	0.010*	0.381	Low wind speed*, Unobstructed gust, Temperature, Relative humidity*	Unobstructed gust
4	0.004*	0.401	Low wind speed*, Temperature, Relative humidity*	Temperature
5	0.003*	0.366	Low wind speed*, Relative humidity	Relative humidity
6	0.009*	0.231	Low wind speed*	-

CHAPTER FIVE

DISCUSSION

5.1 Wind slab formation

All wind speed variables in this study (unobstructed, low, ground, and gust) were greater when wind slabs formed than when they did not. This is consistent with previous findings (Fierz et al., 2009; Sommer, 2018) and colloquial guidelines used by avalanche workers. Further, these results are controlled by the methods, as unobstructed wind speed was used to define wind periods. The fact that other wind speed variables also differentiated between wind slab and null events supports the use of 5 m/s at an unobstructed level as a cut-off wind speed. This does not preclude the fact that other values, such as 6 m/s or 7 m/s, may have given similar results. Temperature was the same in situations of wind slab formation and null layer formation, which provides evidence that this study captured wind slabs and not storm slabs. This is because temperature influences bonding and so plays a role in slab development in the absence of wind. These results, combined with steps taken to accurately identify wind slabs, increase my confidence in layer classification.

The stark difference in the number of observations in each category (windslab $n=41$, null $n=11$) was due to study design, where I prioritized field days when a new wind slab was expected at one or both sites. The disparity in n values between categories may have influenced the results. For example, in the relative humidity dataset there were three datapoints in the wind slab category below 65%, and none in the null category (Figure 15), which likely lowered the p -value. However, the wind slab category contained three times as many observations as the null

category, and it is possible that values below 65% existed during null events where I did not collect data. All other non-significant explanatory variables (Figure 15) had much higher p-values (>0.3) than relative humidity. So, although the null category n value is small, high p-values indicate that the variables are significant. However, to be more confident in these results I would want to collect additional data.

5.2 Individual Hand Hardness Comparisons

Average low wind speed ($p=0.001$), average ground wind speed ($p=0.010$), and wind period time ($p=0.040$) all had at least one hand hardness category that differed from at least one other. However, a major limitation of these datasets were the low n values in each category. Reclassifying hand hardness into binary categories increased the n value in each group, creating a more robust analysis. Further, while hand hardness classifications of a specific snow layer may vary between avalanche workers, it is more likely that classifications of hard versus soft slab would remain consistent. Aside from decreasing the number of classifications, the descriptors hard and soft convey information about potential avalanche behavior, which may be more easily and consistently interpreted than hand hardness classifications. For these reasons, reclassifying wind slab layers as soft or hard made the results more robust and applicable for avalanche workers.

5.3 Grouped Hand Hardness Comparisons

After reclassifying wind slabs, the variables average low wind speed ($p<0.001$) average ground wind speed ($p<0.001$), and average temperature ($p=0.047$) significantly differentiated between categories. Although temperature was not significant with a Kruskal-Wallis test which

considered all hardness categories, switching to a binary classification changed the results. Wind period time, though significant with four hardness categories, was no longer a significant differentiator of hardness with binary categories. Due to the higher n values the binary classification is likely a more reliable comparison of meteorological variables and wind slab hardness, and so I considered these results more meaningful.

5.3.1 The Role of Wind

While average low and ground wind speeds differentiated wind slab hardness categories at these study sites, average unobstructed wind speed and maximum unobstructed gust did not. This is consistent with the observation that wind speed measured at height (i.e. ridgetop or unobstructed) is not always associated with avalanche occurrence in some avalanche paths (McCollister, 2004). It highlights the importance of collecting localized and lower-height measurements of wind speed rather than inferring this information from ridgetop or otherwise unobstructed wind speeds. At the Eglise site the unobstructed anemometer was approximately 100m away, and at the Spirit site it was directly adjacent to the study site, within 25m, and both anemometers were at the same elevation as their respective study sites. Despite close proximity, wind speeds measured at the two unobstructed anemometers did not differentiate wind slab hardness, implying that ridgetop anemometers, as used by most operations, may not always provide accurate information on wind slab properties in all start zones.

The lack of association between unobstructed wind speed and wind slab hardness in this study could be due to terrain features and their influence on wind patterns. As wind direction changes, terrain dictates deposition location as well as fetch area (Pomeroy & Gray, 1990), which are both important parameters in wind slab development. Terrain also controls localized

wind speed and direction by changing surface flow patterns as regional wind direction and speed change. This implies that the extent of correlation between unobstructed and lower-height wind speeds may depend on wind direction and the resulting interaction of wind and terrain. It is likely that unobstructed or ridgetop wind speed predicts wind slab properties in some locations, and that association between wind speed and wind slab properties could be different with different wind directions. Due to proximity, localized and low-height wind speeds are more likely than unobstructed wind speeds to be similar to start zone wind speeds. While my findings show that wind speed is in some situations associated with wind slab hardness and density, they emphasize the importance of collecting localized wind speed measurements from start zones at the slope-scale, rather than relying solely on information from unobstructed wind speeds when forecasting avalanches.

One way to improve understanding of local terrain and wind speed correlations at different heights could be to install a few temporary anemometers on representative slopes until a reliable relationship between low height and unobstructed wind speed at different wind directions is developed. This would help improve local knowledge and could bridge the gap between wind speeds at different heights in specific areas. Ideally, operations would install permanent anemometers in all windy start zones, however this is impractical and cost prohibitive for most operations. Low-height anemometers in areas prone to wind loading would get buried, and maintenance of these sensors could be dangerous. Operations with a few important paths prone to wind slab formation could benefit from local anemometers at lower heights proximal to start zones, while operations that cover large areas should keep in mind that unobstructed wind speeds may not be adequate for predicting local variations in wind slab hardness, and take

observations to better understand relationships specific to their terrain. While wind speed can in some cases be extrapolated from one location to another, a close understanding of specific terrain is necessary to do this confidently.

The distinction between soft and hard slabs occurred around 3 m/s (10.8 km/h) for low wind speed, and around 2.5 m/s (9.0 km/h) for ground wind speed (Figure 17). This is inconsistent with literature stating that a wind speed of 5 m/s (8 km/h), is required for transport of soft low-density snow (Table 2). One possible explanation is that while wind speed was averaged hourly, wind transport may have occurred only when wind speeds were above the average value. Another possible explanation is that previous studies measured unobstructed wind speed (e.g. Filhol & Sturm, 2015; Mellor, 1965) as is common in the avalanche industry. As height above the snow surface decreases wind speed decreases (Schmidt, 1982), and so it is likely that during times when unobstructed wind speed was greater than 5 m/s wind speeds at 1.5m and 0.5m above the snow surface were lower. Thus, these results do not necessarily contradict the importance of the 5 m/s threshold, since unobstructed wind speed is most commonly measured for snow and avalanche studies.

The initial goal of the ground level anemometer at 0.5m above the snow surface was to measure depositional wind speed. However, saltation occurs from the snow surface up to approximately 0.1m, at which point suspension begins (Schmidt, 1982), and so 0.5m above the snow surface proved to be well into the transport zone. Datalogger electronics prevented installing the sensor much lower to the ground than 0.5m. To truly be in a depositional zone, an anemometer would have to be installed directly on the snow surface, which would result in difficulties keeping it snow-free and operating reliably. It would be near impossible to keep an

anemometer exactly on the snow surface in an area of wind slab formation, as these are depositional areas and so any anemometer would be continually buried. An alternative to a propeller-style anemometer could be an ultrasonic anemometer, however this would still be prone to burial as snow depth increased. So, although the ground level anemometer was in the depositional zone of wind slab formation, it did not record the wind speed at which snow actually left the air column and was deposited on the ground.

5.3.2 The Role of Temperature

In this dataset the average temperature during wind periods was significantly higher when hard wind slabs formed than when soft wind slabs formed (Figure 17). However, there was considerable overlap in the range of these two categories. Because of this, it may not be practical to use temperature to predict wind slab hardness. However, relative temperature could be a useful guide in predicting relative hardness. For example, with wind speeds remaining mostly constant, harder slabs may form as temperatures rise. The increase in wind slab hardness with increasing temperature agrees with literature that bond formation is greater at higher temperatures (Colbeck, 1982). However, an opposite relationship can dominate at low temperatures due to material stiffness (McClung & Schweizer, 1999). Only two datapoints in this study were recorded below -20°C , and so it is possible that a different relationship between wind slab hardness and temperature exists at this temperature range, but was not captured. Further, the considerable overlap in values between the two hardness categories indicates that while the medians were different, the range of possible temperatures for hard wind slabs and soft wind slabs may not be substantially different. My results indicate the need for further investigation,

specifically at a wider range of temperatures, in order to determine the full extent of the usefulness of temperature for predicting relative wind slab hardness.

This study examined the role of temperature only during wind slab forming events, however the influence of temperature continues after deposition. While wind slabs exposed to relatively high temperatures following a storm may form harder slabs, they also may bond to underlying layers more quickly, reducing or eliminating the weak layer, and thus reducing the likelihood that the slope in question will avalanche (McClung & Schaerer, 2006). In this study the influence of temperature following the wind slab forming event did not relate to wind slab physical properties (Appendix C). Further research could provide a more holistic picture of temperature's influence. Temperature plays an important role in snowpack metamorphism and snowpack properties, but as evidenced by this study, distilling the role of temperature into a simple relationship is difficult.

5.3.3 The Role of Humidity

None of the humidity variables varied significantly between hard wind slab formation and soft wind slab formation in this study. This is consistent with previous findings from wind tunnel trials (Sommer et al., 2017). However, in both my study and the wind tunnel study (Sommer et al. 2017) only high relative humidities (>85%) were recorded. High humidities occur during snowfall events, while snow transport without concurrent snowfall could happen at low humidities. This suggests a possible connection between humidity and transport type (preferential deposition vs. redeposition) and further investigation is needed to decouple the role of humidity from transport type. Relative humidity in the snowpack matrix is always at or close to 100%, and so it seems likely that relative humidity of the air would only influence the very

surface of the snow, if at all. However, further investigation at a wider range of humidities, and with more context of wind transport type, is needed to understand the relationship between humidity and wind slab hardness.

Humidity influences can be difficult to interpret due to humidity's close link with temperature. Avalanche operations usually measure relative humidity, which is partly controlled by air temperature. The humidity measure most independent from temperature is absolute humidity, which evaluates the concentration of water vapour in the air. However, this is a difficult metric to measure, and most avalanche operations do not have absolute humidity sensors. Information on absolute humidity, while interesting from a scientific perspective, has less use to avalanche workers. Interestingly, in this study relative humidity was less correlated to average temperature than dew point or absolute humidity during wind transport events (Table 8). This is interesting as relative humidity is directly linked to temperature, and these metrics were measured from the same sensor. One potential explanation could be that the presence of blowing snow during wind transport events changed the relative humidity within 1.5 meters of the ground, which is the height at which these measurements were taken. The fact that relative humidity was not highly correlated with temperature in this case does not necessarily mean that relative humidity is independent of temperature during wind slab forming events. The low correlation could be due to a non-linear relationship between the two, rather than a lack of association. Without further investigation it is difficult to know the extent to which humidity influences snow properties, rather than just reflects the influence of temperature.

5.4 Density

Although density is less commonly measured than hand hardness by avalanche workers, it is a useful metric because unlike hand hardness it is a continuous variable, and when done properly should be independent of variation between observers. Density is positively associated with strength for most grain types, including rounds which form wind slabs (Van Herwijnen & Miller, 2013). The relationship between density and hand hardness was apparent in this study, where the layers of each measured hand hardness category had significantly different densities (Appendix F). As hand hardness increased density also increased. By measuring the density of a snow layer, we can infer important information about the snow layer's mechanical properties.

5.4.1 Simple Linear Regression

The only meteorological variable that had a significant linear relationship with density was average low wind speed ($p=0.033$) (Figure 19). Ground wind speed did not significantly predict wind slab hardness ($p=0.071$), and it is possible that wind speed 0.5m above the ground is not as directly related to actual snow transport as wind speed 1.5m off the ground. This is supported by low wind speed having a greater relative difference between hand hardness categories than ground wind speed (Figure 17). Similar to the hand hardness analysis, average unobstructed wind speed and maximum unobstructed gust were not correlated with wind slab density. This provides additional evidence that average low wind speed measured at approximately 1.5m above the snow surface may be the most reliable metric for some start zones when forecasting wind slab properties.

Although average low wind speed was related to wind slab density, the relatively low r^2 value of 0.15 indicates that low wind speed poorly predicts actual wind slab density at these

study sites. This study did not include a validation dataset, and so I could not test the appropriateness of the SLR model. Wind and snow processes are incredibly complex, and so explaining more than 15% of the variance may be unrealistic. Wind deposition is not just influenced by meteorological variables, but also by the interactions of terrain with wind direction, and the fetch area. Given the complexity of these relationships it is encouraging that this SLR model explained 15% of the variance.

5.4.2 Multiple Linear Regression

With 15% of the variation in wind slab density explained by average low wind speed, a MLR model would be able to show if any other variable, or combination of variables, explained the remaining 85%. Interestingly, in the MLR stepwise process, the first model to become significant contained only two significant explanatory variables (Table 14). This model also had the highest predictive power of all models ($r^2=0.56$) (Table 15) which, coupled with a low n value, is a sign of overfit (Babyak, 2004). With no validation data from these sites, I assumed this model was inappropriate despite its significant p -value, and continued the stepwise process until all variables were individually significant. Finally, all variables except for average low wind speed were removed, resulting in a return to the SLR model. This means that for this dataset, no other meteorological variable improved upon the ability of average low wind speed to predict wind slab density. There may be other, unmeasured variables that would have improved this prediction, such as fetch area, wind direction, or wind transport type. These results show that none of the variables tested in this study improved upon the predictions of low wind speed at these particular study sites.

5.5 Blade Hardness Gauge

A BHG provides another measure of wind slab hardness and another means of collecting data on a continuous scale. Previous studies found that the log of BHG force correlates with both density and hardness (Borstad & McClung, 2011; Pogue & McClung, 2016). This was also the case in my study (Appendix F). Density and hardness are both indicators of snow strength, and so their correlation with BHG values implies that BHG force also provides useful information on snow strength.

Although a measurement provided by an instrument could be considered highly reliable compared to the hand hardness test, BHG measurements are prone to operator error and inconsistency. Insertion rate affects BHG measurement, as too slow an insertion rate may not accurately capture brittle failure (Borstad & McClung, 2011). It can be difficult to ensure similar insertion rate between different practitioners, or even by one practitioner inexperienced with the tool. This is a likely explanation for the low-value outlier collected early in this dataset. A BHG tool, like hand hardness, can return very different measurements within one layer if the strength of the layer is inhomogeneous. In these cases, a hand hardness measurement may prove more reliable due to the larger sampling area (i.e. support). Further, the BHG tool itself is still relatively rare in the avalanche industry, and most avalanche workers do not have access to one. However, this tool was useful because it allowed me to conduct another set of linear analyses, and it provided additional evidence to support my conclusions.

5.5.1 Simple Linear Regression

Similar to the series of SLRs for density, only average low wind speed was a significant predictor of the log of BHG force ($p=0.009$) (Figure 21). Even though there was strong evidence

of a positive linear relationship, average low wind speed was a poor predictor of the actual log of BHG force value, with an r^2 value of 0.23. However, similar to the density SLR, due to the complicated interaction of explanatory variables, it may be unrealistic to expect a higher value. Given the complexity, explaining 23% of variation in BHG hardness with low wind speed is encouraging.

5.5.2 Multiple Linear Regression

The first significant MLR model ($p=0.040$, $r^2=0.33$) for log BHG force contained five variables, none of which were individually significant (Table 18). The lack of significant individual variables and the low n value indicates that this is also likely an instance of overfit. The pattern of significant p -values for the model, but limited significant p -values for individual variables continued through the MLR steps as variables were removed (Table 19). This shows that, similar to the density MLR, the addition of variables does not improve on the ability of average low wind speed to predict wind slab density.

CHAPTER SIX

CONCLUSION

6.1 Key Findings

These findings support the important role of wind speed in forecasting slope-scale wind slab formation and wind slab physical properties. In this study wind speed variables were the only significant variables in wind slab formation, and at least one wind speed variable was significant in determining all three measured wind slab physical properties (hand hardness, density, and BHG force). Wind period time, on the other hand, was not significant in any of these situations. Interestingly, unobstructed wind speed did not significantly differentiate between wind slab hardness or correlate with wind slab density at these sites, while wind speed closer to the ground (1.5m and 0.5m) did. This is important, as unobstructed wind speed is commonly measured by avalanche operations, and may not, in some cases, relate to actual wind speed in all start zones. At lower heights wind is more likely to interact with terrain, which could explain these observations. It is likely that unobstructed wind speed correlates with wind slab properties in some situations, but these results shows that this relationship is not a given. Operations with the ability to install more anemometers, or with specific important paths prone to wind loading, may benefit from installing lower height anemometers proximal to start zones. In situations where this is cost or logistically prohibitive, similar goals could be accomplished by temporarily installing these anemometers to get a better idea of their location-specific wind effects, or by studying surface to understand how wind direction differs in different locations with the terrain.

Though temperature did not differentiate whether or not a wind slab formed, it may be worth considering temperature when predicting wind slab hardness. Increasing temperature increases the strength of a snow layer, which was captured in this study. Although there was a difference in median temperature between slab hardness categories, the ranges had such overlap that the role of temperature warrants further study. Similarly, relative humidity did not correlate with any measured wind slab physical properties, however it is difficult to separate the role of humidity from that of temperature and storm occurrence, and further investigation is necessary to disentangle these relationships.

Although the interaction of meteorological variables with each other, the snowpack, and terrain is complex, this work provides promising approaches towards better predicting wind slab properties at the slope-scale. Being able to better forecast snowpack properties from meteorological variables could help improve avalanche forecasts in data-sparse regions. An improved understanding of the influence of meteorological variables on wind slab properties may help increase forecast confidence and accuracy in windy climates. While this study did not address all important factors in wind slab formation and was location specific, it could provide a useful basis for further research.

6.2 Research Limitations

A primary limitation of this study is its location specificity, and therefore scope of inference. These findings indicate that unobstructed wind speed does not predict slope-scale wind slab density or hardness at these specific sites, however due to the limited extent of the study sites I cannot directly apply these conclusions to other locations. Similar phenomena may

exist elsewhere, however this study does not provide evidence of that, since wind slab formation is terrain-dependent. Because low wind speed in mountainous terrain is influenced by terrain features, the terrain at these study sites could be the controlling factor in my results. Though it may not be possible to translate these results directly other areas, this research provides guidelines for future site-specific studies on the influence of wind speed and other meteorological variables on wind slab physical properties.

Further, the sub-slope-scale spatial variability within each site may have biased the results. While I tried to keep successive profiles as close together as possible, and chose field sites with uniform terrain where wind loading was likely to occur from a consistent direction, the many nuances in wind deposition and snowpack spatial variability meant I could not control for sub-slope-scale spatial variability. I chose not to assess wind slab thickness, as this can vary across the extent of an individual wind slab due to terrain, however other physical properties can vary just as much. The snowpack depth maps (Appendix A) combined with the assumption that variation was due to wind loading, allowed me to focus data collection on areas where depth was greatest and most consistent, however I did not incorporate metrics from these maps into the study design. Further, it is not a given that variation in total height of snow correlates with variation in physical properties. While I attempted to account for sub-slope variation to an extent, this was a major limitation of the study design.

Another limitation is the low number of observations. This was the reality due to study design which required digging a profile for each data point, where a maximum of only two data points were usually collected per field day. This was an inherent problem with the study design, and less time-consuming methods, where more data points could have been collected in a day,

could have improved the study. Although the Big Sky area is known for wind and wind slab formation, the first winter of data collection had limited snowfall, and the second winter had limited wind. This, in addition, to the study design, did not support the collection of very many data points.

Finally, I was unable to account for and control all variables that could influence wind slab formation, such as terrain, which plays a major role in depositional patterns. Terrain controls where wind slabs form, and the fetch area. As wind direction changes the influence of terrain can change, and this study did not account for wind direction. Study design also did not include a reliable way to assess snow physical properties before transport, so provided no indication of their influence on wind slab properties. So, while my study assessed common meteorological variables, it did not capture the important impact of terrain and pre-entrainment snow, which can play a role in wind slab formation and properties.

6.3 Future Work

A different study design could have accounted for many of the short-comings in this study. For example, season-long daily measurements of snow properties in a specifically defined depositional area would provide a more continuous picture of wind influence, and decrease spatial variability. The location could be held constant using a high-accuracy GPS unit, terrain markers, or building a platform with an obstruction. This platform could be cleared and reset after each measurement. If the platform could rotate on its own so that the obstruction was always 90° to the wind, relative wind direction could be controlled. This data could be supplemented with hourly or sub-hourly measurements of physical properties during specific

wind slab formation periods. Associated blowing snow and sky cover observations could help determine if wind slab formation was the result of predominantly redeposition or preferential deposition. Presence and absence of blowing snow, as well as saturation level of blowing snow particles could be measured using a snow particle (SPC), as used in some wind tunnel studies (e.g. Clifton et al., 2006). This would allow for quantification of snow transport extent which combined with the height of new snow measured in a nearby sheltered area could describe the proportion of new snow entrained and deposited. Additionally, terrain modelling could help quantify fetch area for each wind direction. These methods to hold location constant, conduct more regularly monitoring, integrate terrain metrics, determine transport type, and quantify blowing snow extent, in combination with meteorological variable measurements could provide a more accurate picture of wind slab formation and produce a more reliable predictive model for wind slab physical properties.

Another way to limit the variability common in field studies would be to expand on wind tunnel research (Appendix E). By holding wind speed constant, it would be possible to better understand the influence of temperature and humidity on wind slab physical properties. Also, using natural snow in the wind tunnel could allow for comparisons between initial snow properties (e.g. density, hardness, grain form, and grain size) and those same physical properties after deposition with a controlled transport distance and controlled wind speed. An SPC could be used to relate the saturation level of blowing snow to physical properties. The current wind tunnel collects snow on the upwind side of an obstacle, and building an obstacle where snow could be collected both upwind and downwind would allow for data collection on the different ways that terrain interacts with wind. Finally, it would be interesting to compare redeposition and

preferential deposition by running trials where snow is already in the tunnel, compared to trials where snow is added to the tunnel during the wind period. This may require a wind tunnel with a longer transport distance, such as the circular wind tunnel used by Sommer et al., 2018.

It would also be interesting to compare depth of newly formed wind slabs to depth of new snow unaffected by wind, in order to quantify the extent to which preferential deposition can increase snow loading. This could be accomplished using a drone-mounted lidar unit or camera for photogrammetry, or with a permanently mounted terrestrial laser scanner (TLS). Depending on the desired spatial resolution, this study could be conducted at the slope-scale or individual mountain-scale. Both SNOWPACK and Crocus have been combined with atmospheric models to predict the depth and distribution of snow by wind (Lehning & Fierz, 2008; Mott et al., 2010, 2018; Vionnet et al., 2014), however these models do not predict the physical properties of wind slabs. While Crocus uses wind speed to predict density and grain sphericity (Vionnet et al., 2012), it is not tuned specifically to wind slab formation and does not on its own predict spatial variability in snow depth due to wind transport. Physical property observations made at regularly spaced intervals across the study area immediately following post-storm drone or TLS data acquisition could help integrate these predictive capabilities into a model. Anemometers in targeted locations could help relate localized wind speeds to wind slab thickness and physical properties, as well as unobstructed wind speeds, and test the accuracy of the atmospheric component of a model. A relationship between snow properties and thickness in different locations and at different wind speeds could help avalanche workers familiar with their local terrain to extrapolate snowpack properties from one location to others across a slope. This study

would be best conducted in an area with consistent flow patterns where wind direction is relatively consistent.

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APPENDICES

APPENDIX A

INTERPOLATED SNOW DEPTHS

We determined rough measurement grids at each site based on desired coverage. At each location ninety to one hundred probe snow depth measurements were taken. An Emlid RS2 Reach GPS (20cm accuracy) recorded the location of each depth measurement. Field assistant Maddy Grubb used ArcPro to interpolate depth data at each site using Empirical Bayesian Kriging (EBK). EBK uses an estimation process for a large number of semi-variograms and then combines them into one interpolation surface (Figure A1)

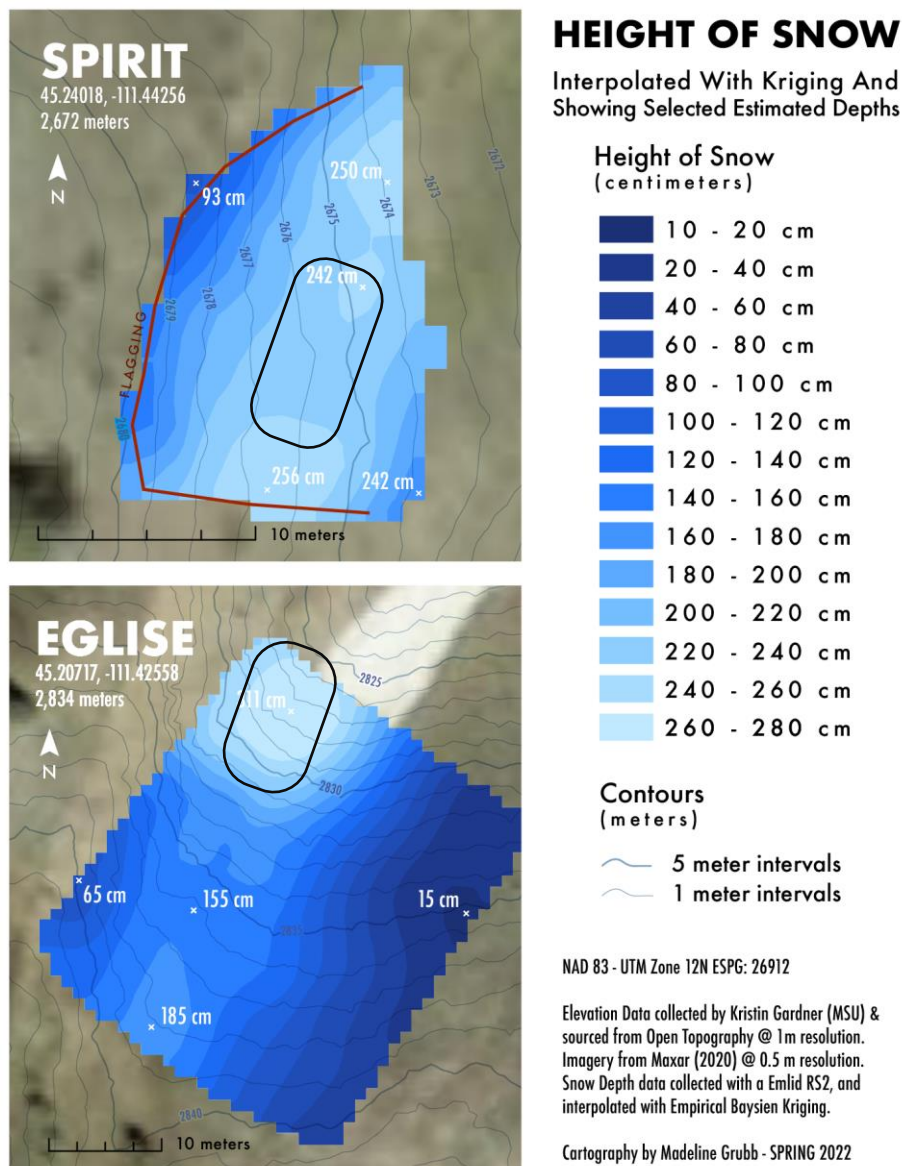


Figure A1: Snow depths at each site, as predicted by EBK based on gridded depth measurement. Black ovals represent the areas where I conducted snow profile analysis. Mapping project by Maddy Grubb.

APPENDIX B

REGRESSION FORMULAS

Formulas for wind speeds from an entire season (Figure B1-B6) were used to fill missing data for the 1.5m and 0.5m anemometers. Different regressions were created for each site and season. Data was preferentially filled from one lower anemometer to the other, and regressions with unobstructed wind speed were only used when absolutely necessary. Only the regressions used are shown below. All wind speeds are in km/h.

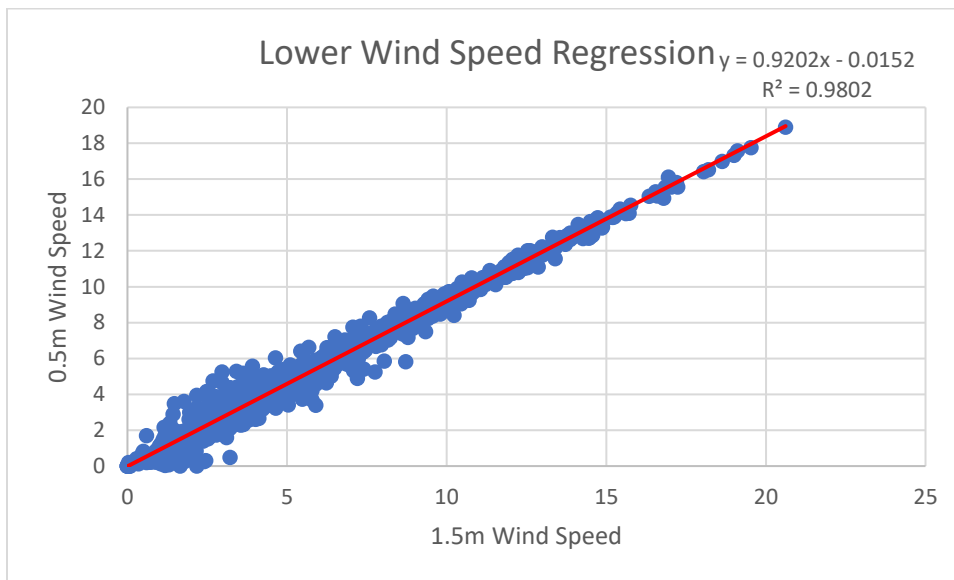


Figure B1: Scatterplot and regression line between 1.5m and 0.5m wind speed (km/h) at the Eglise plot for the winter of 2021/22

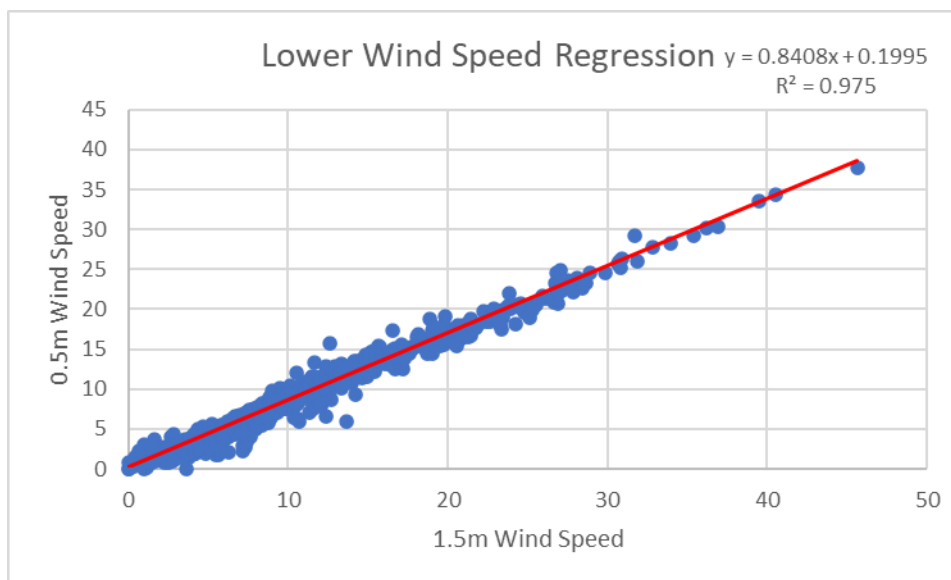


Figure B2: Scatterplot and regression line between 1.5m and 0.5m wind speed (km/h) at the Spirit plot for the winter of 2021/22

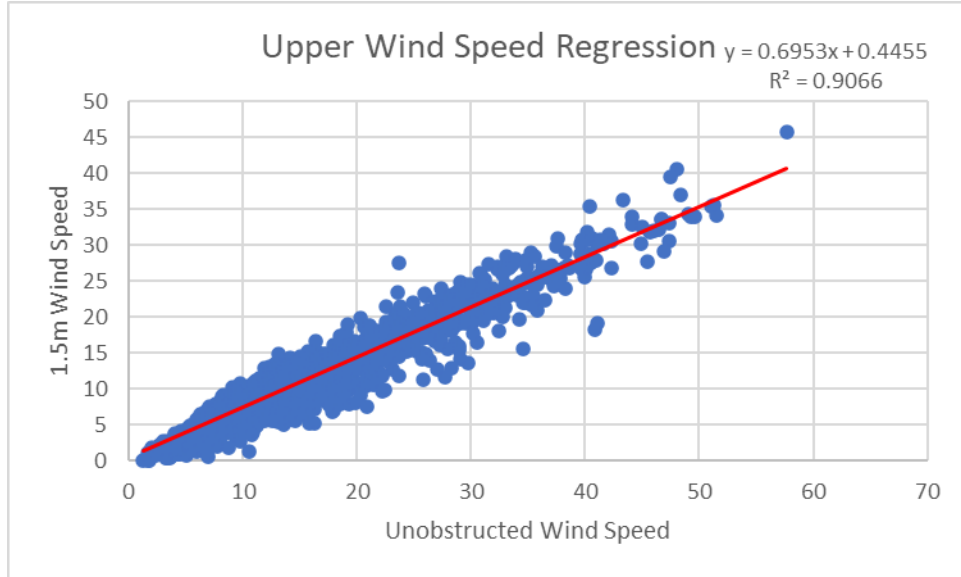


Figure B3: Scatterplot and regression line between unobstructed and 1.5m wind speed (km/h) at the Spirit plot for the winter of 2021/22

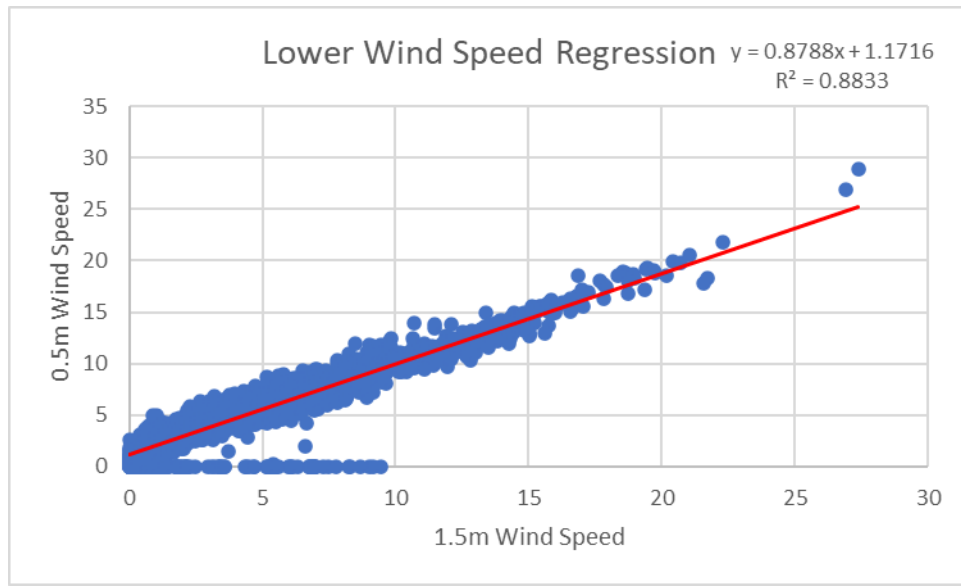


Figure B4: Scatterplot and regression line between 1.5m and 0.5m wind speed (km/h) at the Eglise plot for the winter of 2022/23

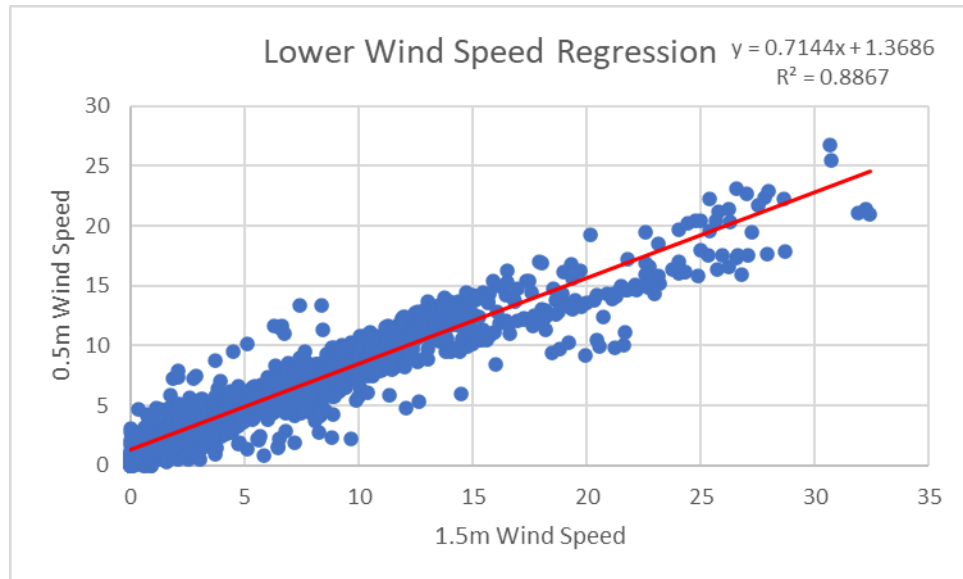


Figure B5: Scatterplot and regression line between 1.5m and 0.5m wind speed (km/h) at the Spirit plot for the winter of 2022/23

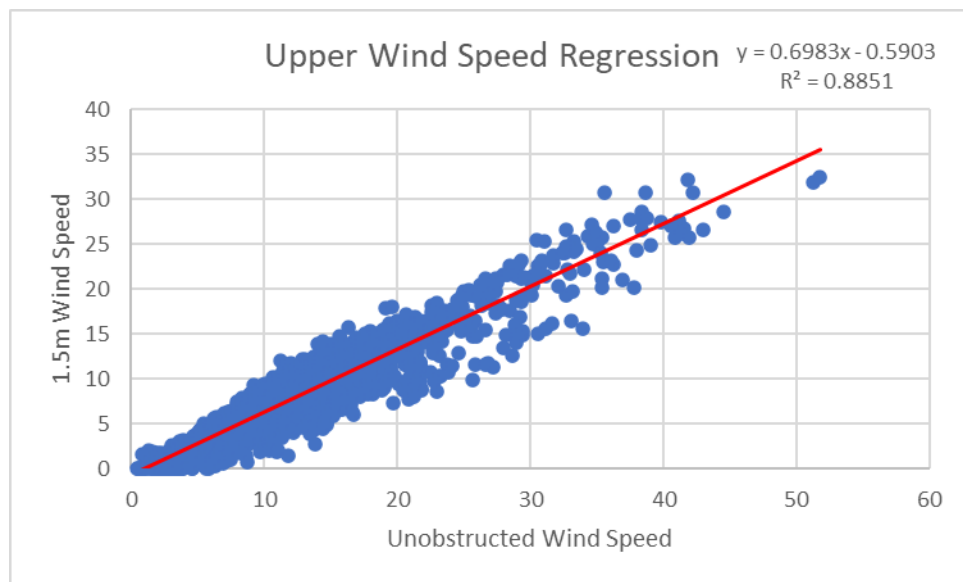


Figure B6: Scatterplot and regression line between unobstructed and 1.5m wind speed (km/h) at the Spirit plot for the winter of 2022/23

APPENDIX C

OTHER EXPLANATORY VARIABLES

The following models were all tested early on in the analysis, but were not pursued further for a variety of reasons stated below.

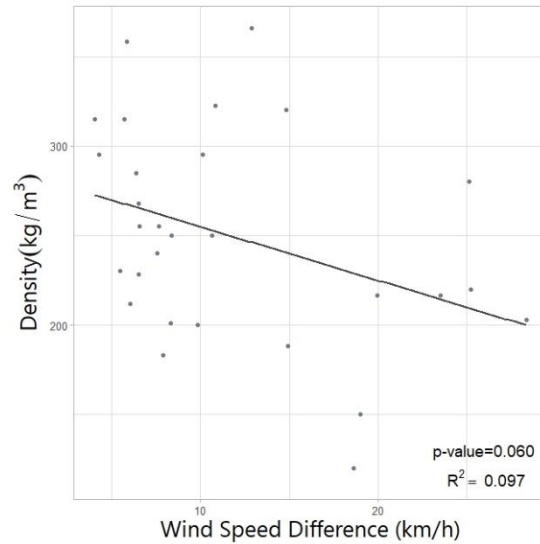


Figure C1: The SLR model between wind slab density and the difference between average unobstructed wind speed and average 1.5m wind speed, for each wind slab forming event. Although the model is close to the alpha value of 0.05, the obvious clustering of data at low wind speed differences decreased my confidence in the predictive abilities of this dataset.

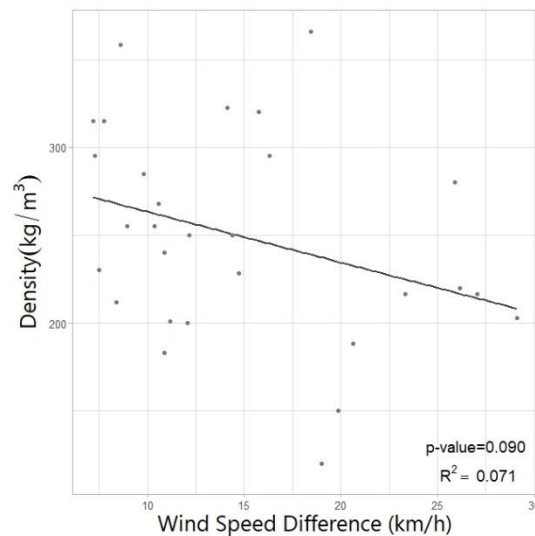


Figure C2: The SLR model between wind slab density and the difference between average unobstructed wind speed and average 0.5m wind speed, for each wind slab forming event. Although the model is close to the alpha value of 0.05, the low density values at relatively greater wind speed differences decreased my confidence in the predictive abilities of this dataset.

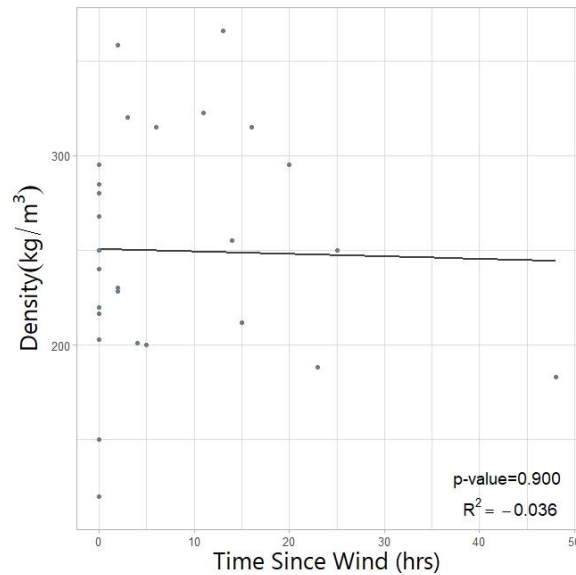


Figure C3: The SLR model between wind slab density and the amount of time between the end of the wind slab forming event and the time of data collection. The high number of events with zero time since wind were collected when wind transport was ongoing. Removing these points or analyzing them separately showed no noticeable trends.

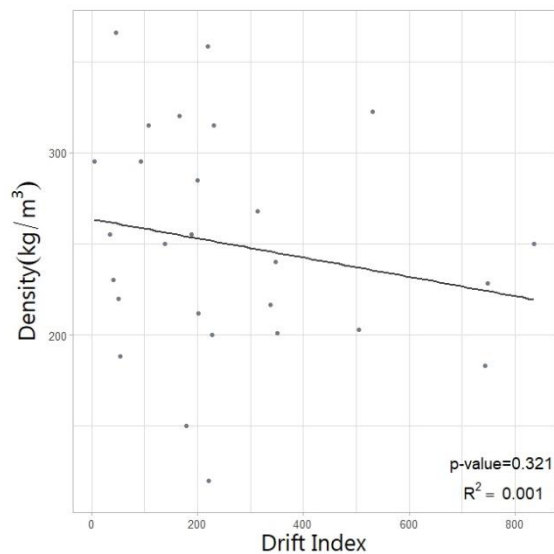


Figure C4: The SLR model between wind slab density and the drift index of the wind slab forming event. The drift index is the average wind speed in km/h multiplied by the amount of snow available for transport in cm (Hendrikx et. al., 2005). This graph showed limited trends and so the drift index metric was not pursued. Further, measurements of snow available for transport were obtained from specific weather stations not necessarily close to the field sites, and where depths were only measured in one-inch (2.5cm) increments, which was considered too coarse.

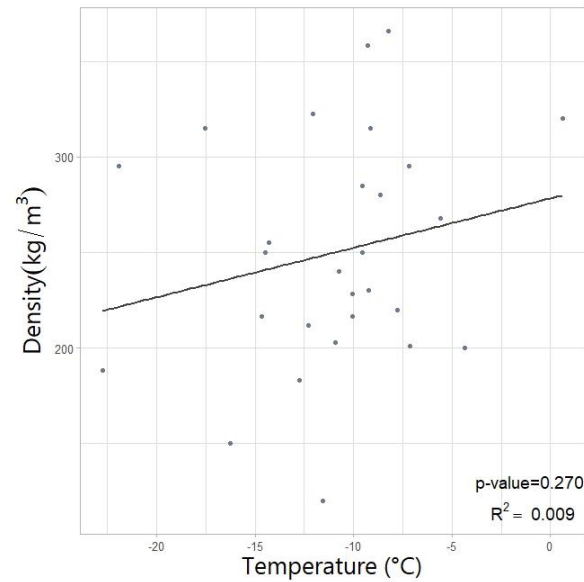


Figure C5: The SLR model between wind slab density and the average temperature from the onset of snowfall until the time of data collection. With the high p-value and the visually random scatter of datapoints I decided not to pursue this metric further. However, more investigation of temperature at different times or grouped into different temperature regimes could provide more information on the complex interactions between temperature and snowpack properties in windy climates.

Reference

Hendrikx, J., Owens, I., Carran, W., & Carran, A. (2005). Avalanche activity in an extreme maritime climate: The application of classification trees for forecasting. *Cold Regions Science and Technology*, 43(1-2), 104-116.

APPENDIX D

ASSUMPTIONS FOR LINEAR REGRESSION

The assumptions for simple linear regression are as follows:

1. A linear relationship exists between the x and y variables. This can be checked with a Residuals vs. Fitted plot, where data points dispersed evenly on each side of the plot (top and bottom) indicates linearity. Unevenly dispersed datapoints demonstrate that the dataset does not meet this assumption.
2. There is constant variance of residuals, also called homoscedasticity. This can also be checked with a Residuals vs. Fitted plot. If the datapoints show a “megaphone” shape or some other obvious pattern the dataset is heteroscedastic, and the assumption is not met.
3. Observations and errors must be independent. This can be assumed based on study design, or checked with a Durbin-Watson test.
4. The distribution of residuals must be normal. This can be checked with a Normal Q-Q plot, where datapoints distributed close to the line of normality indicate the residuals are normal. This can also be checked with a Lilliefors test conducted on the residuals.

In addition to checking assumptions, the Residuals vs. Leverage plot can be used to identify outliers, where any data point with a Cook’s Distance greater than 0.5 likely warrants further investigation to determine whether or not it is an actual outlier.

Assumption Checks for Average Unobstructed Wind Speed

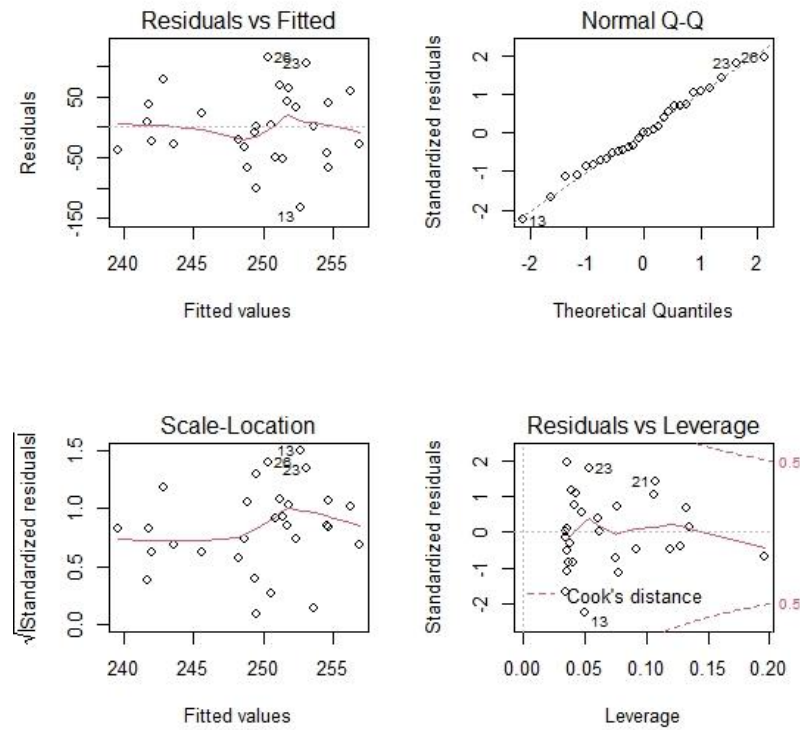


Figure D1: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average unobstructed wind speed.

Durbin-Watson Test: P-value 0.786

Lilliefors test on residuals: 0.901

Assumption Checks for Average Low Wind Speed

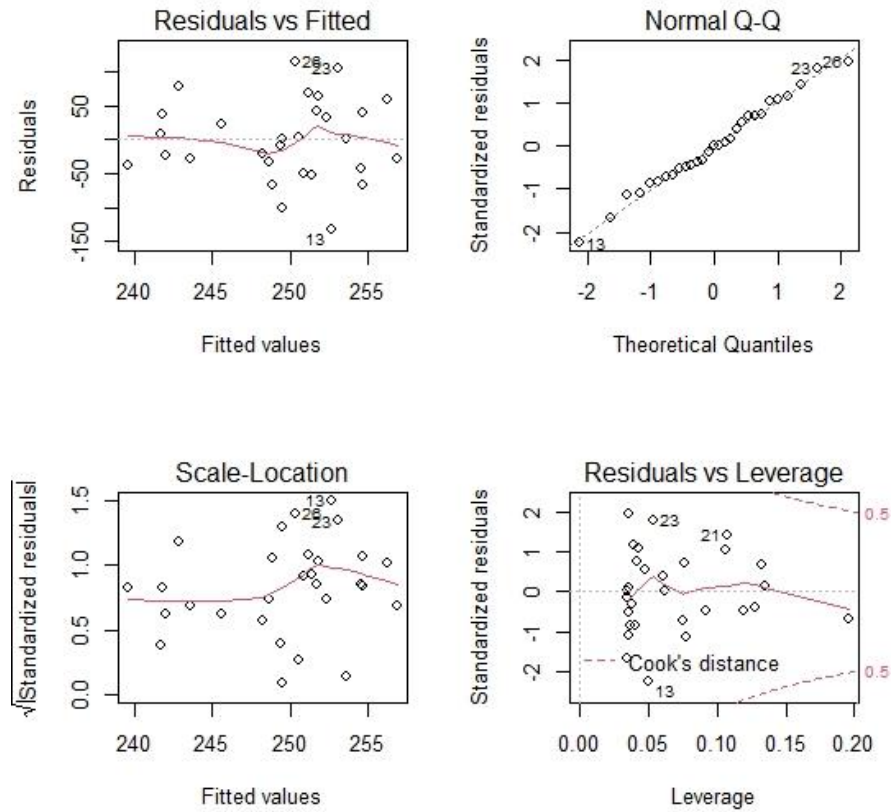


Figure D2: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average low wind speed.

Durbin-Watson Test: P-value 0.566

Lilliefors test on residuals: 0.135

Assumption Checks for Average Ground Wind Speed

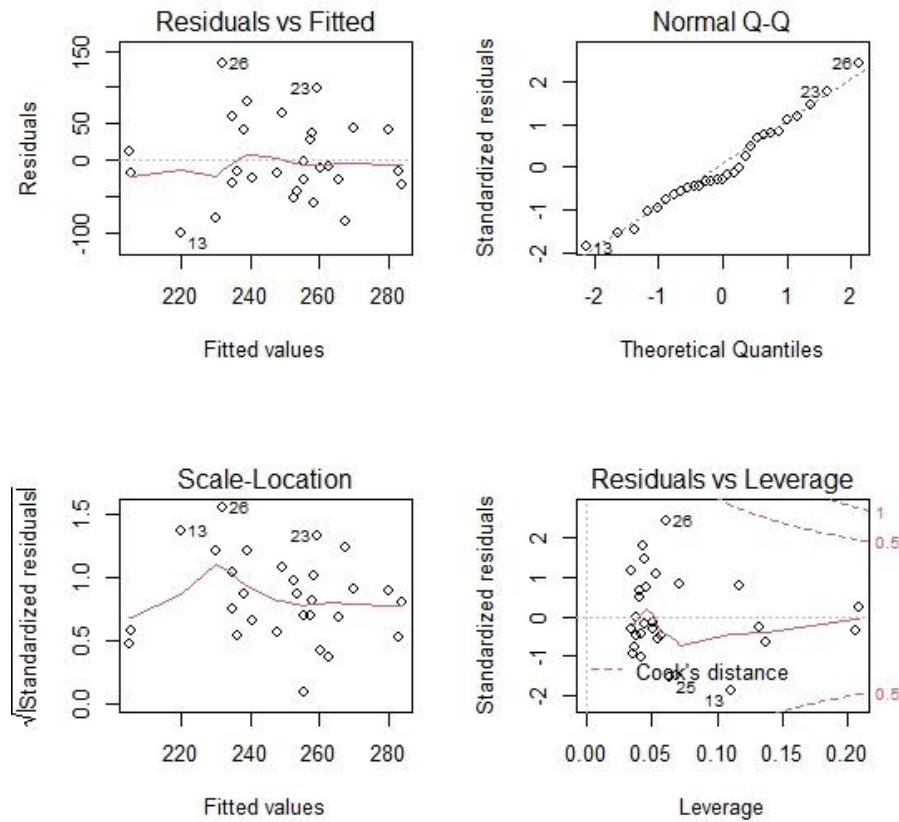


Figure D3: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average ground wind speed.

Durbin-Watson Test: P-value 0.570

Lilliefors test on residuals: 0.135

Assumption Checks for Average Temperature

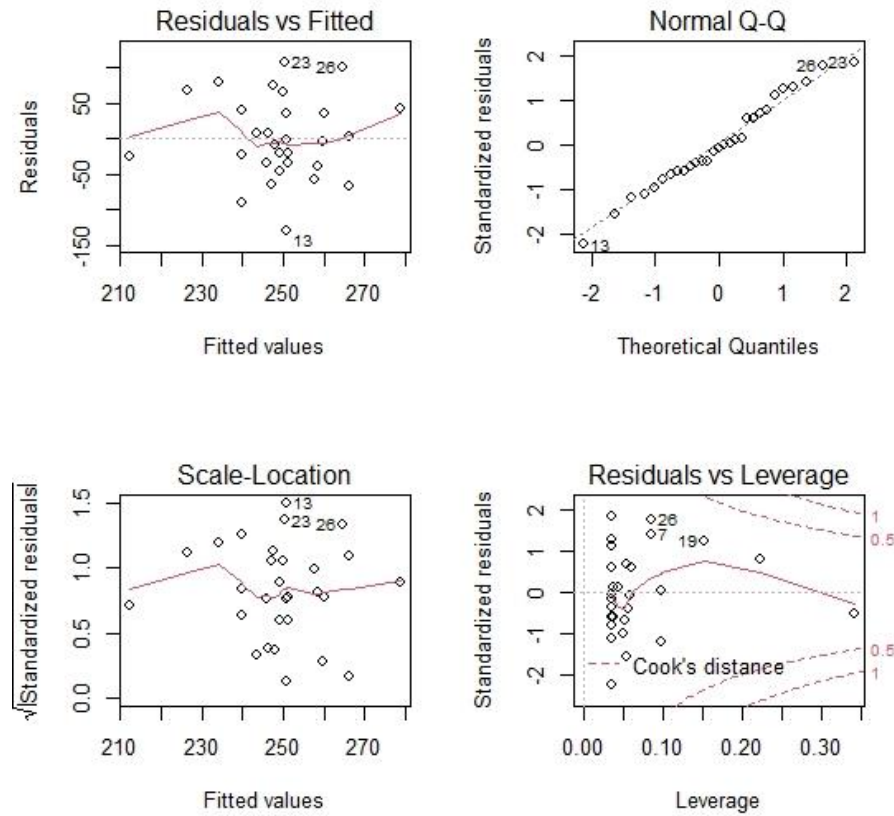


Figure D4: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average temperature.

Durbin-Watson Test: P-value 0.552

Lilliefors test on residuals: 0.694

Assumption Checks for Average Dew Point

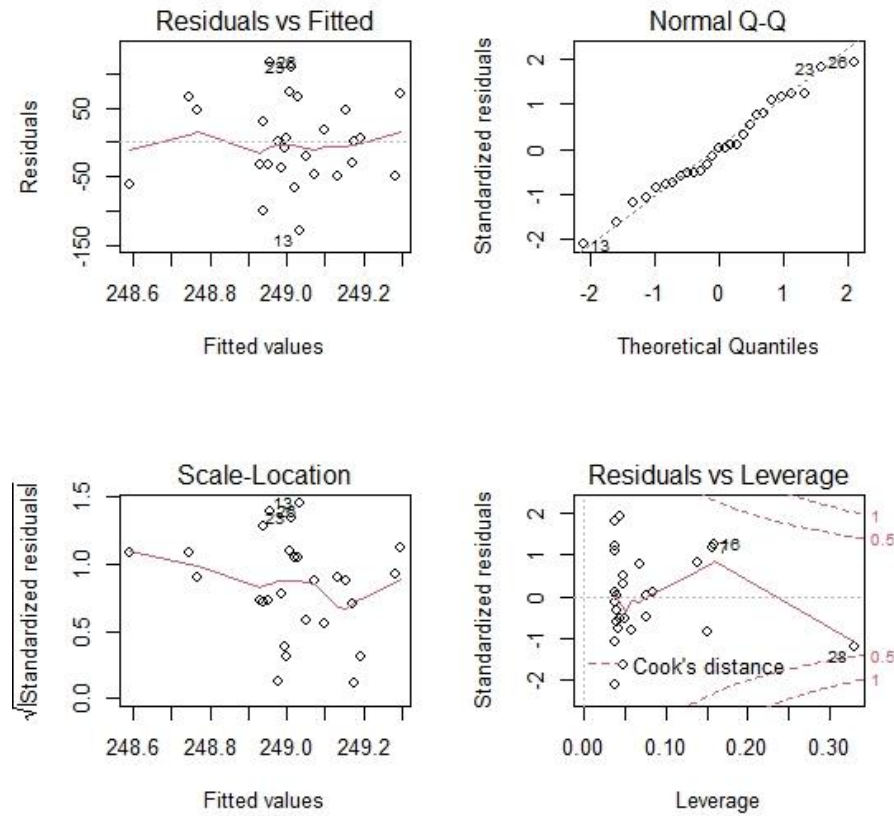


Figure D5: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average dew point.

Durbin-Watson Test: P-value 0.682

Lilliefors test on residuals: 0.814

Assumption Checks for Wind Period Time

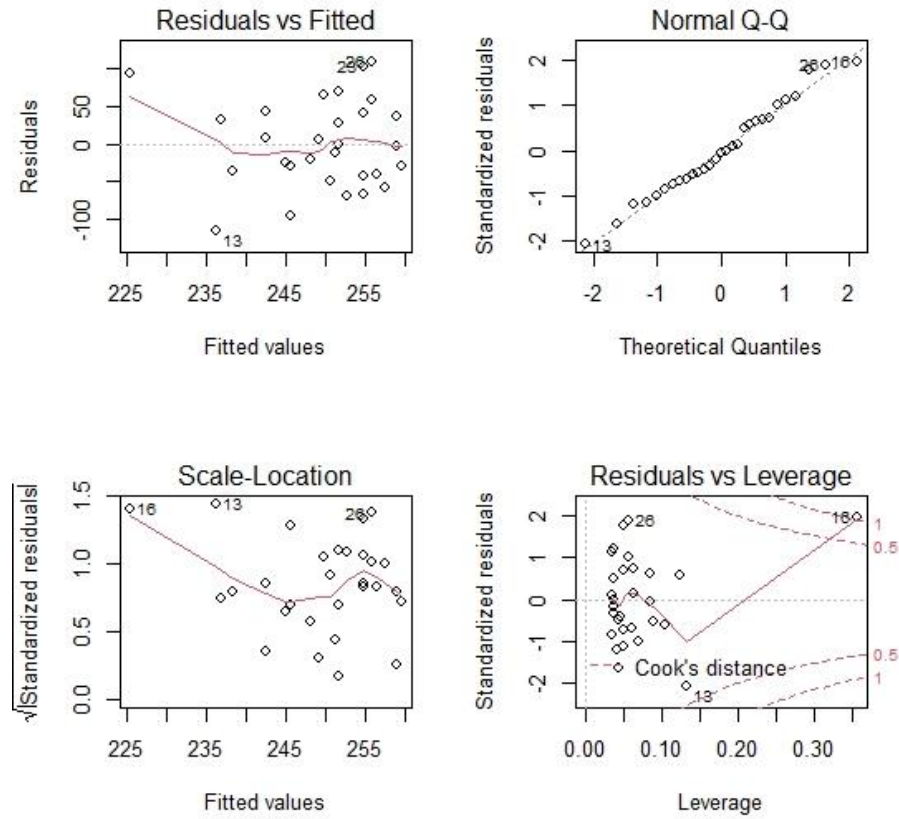


Figure D6: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for wind period time.

Durbin-Watson Test: P-value 0.736

Lilliefors test on residuals: 0.897

Assumption Checks for Maximum Unobstructed Gust

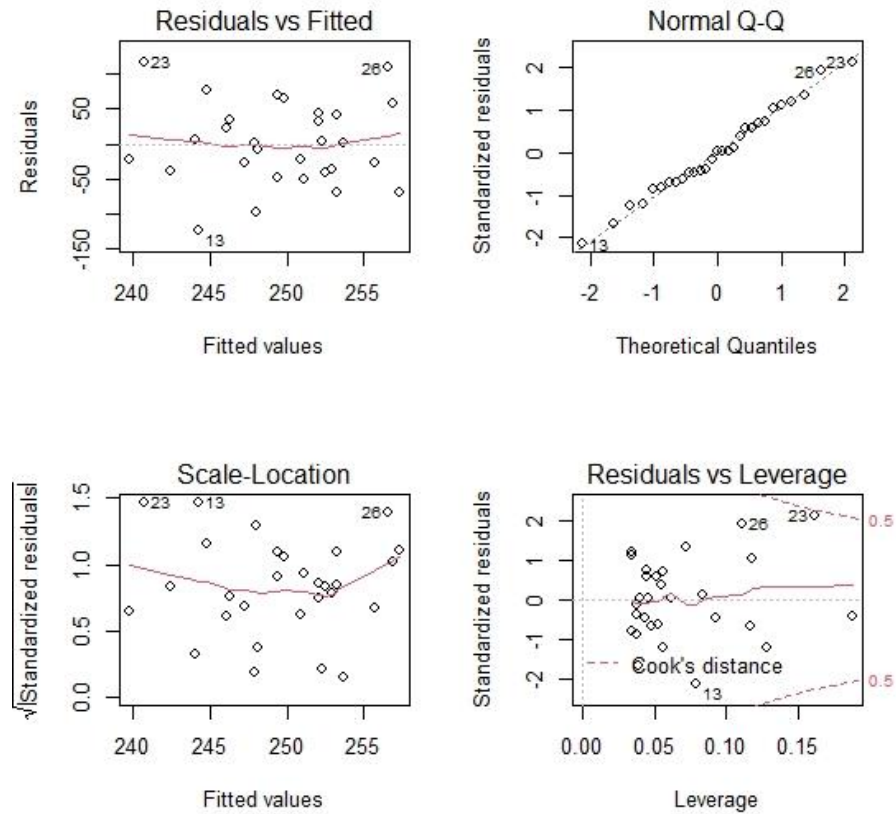


Figure D7: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for maximum unobstructed gust.

Durbin-Watson Test: P-value 0.788

Lilliefors test on residuals: 0.690

Assumption Checks for Average Absolute Humidity

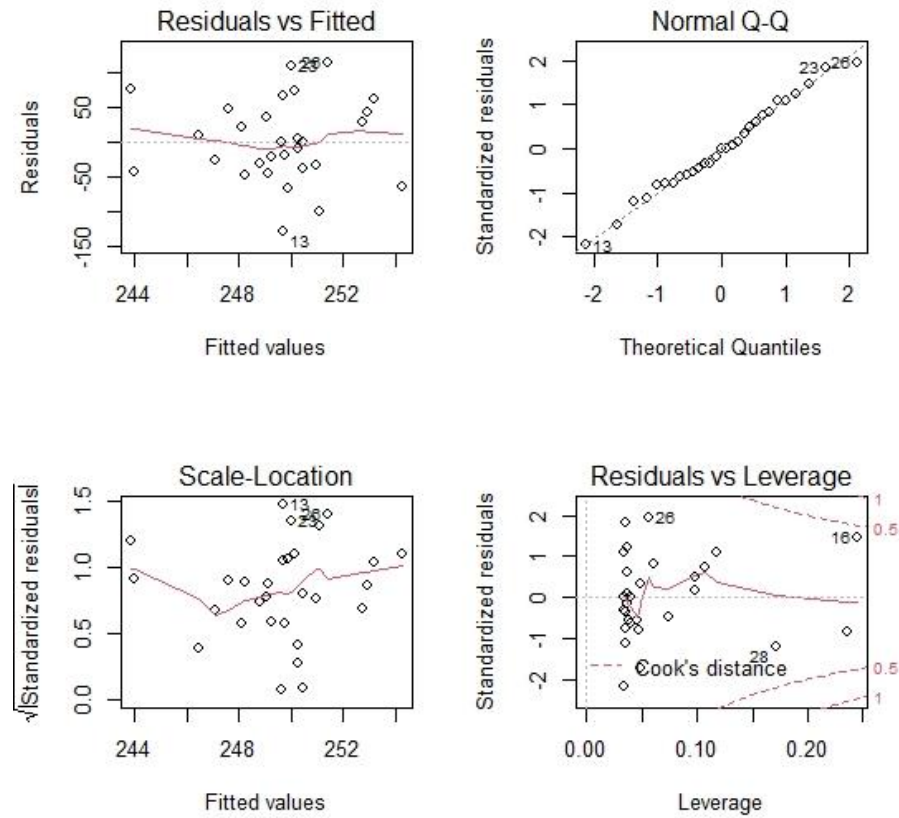


Figure D8: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average absolute humidity.

Durbin-Watson Test: P-value 0.834

Lilliefors test on residuals: 0.914

Assumption Checks for Average Relative Humidity

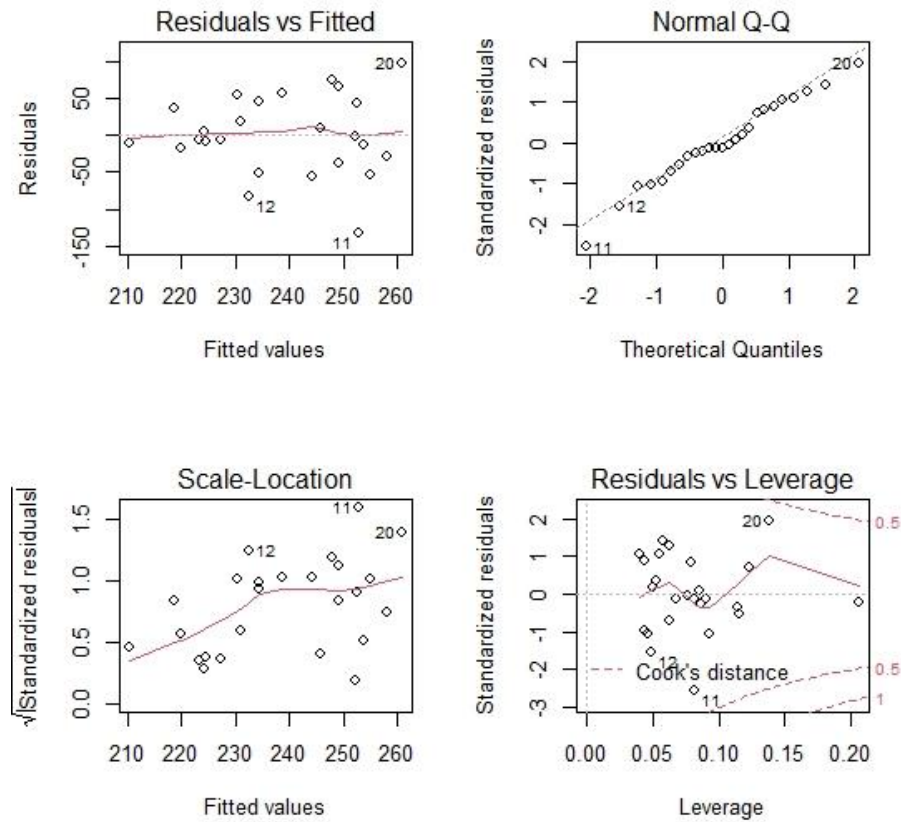


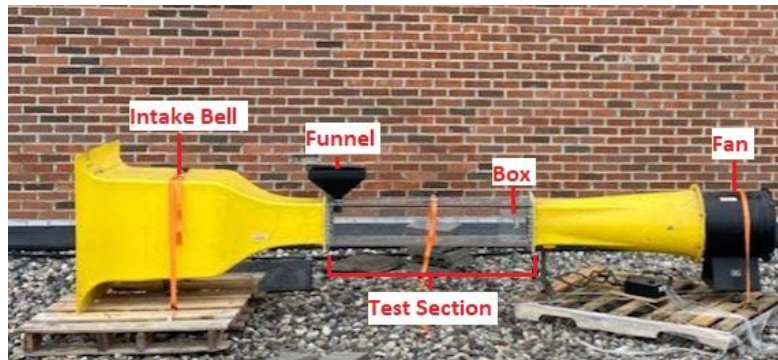
Figure D9: Tests of Residuals vs. Fitted, Normal Q-Q, Scale-Location, and Residuals vs. Leverage for average relative humidity.

Durbin-Watson Test: P-value 0.760

Lilliefors test on residuals: 0.812

APPENDIX E

WIND TUNNEL STUDY



E1: The wind tunnel used for this portion of the research. Snow was added through the funnel, underwent saltation the test section before accumulating in the box to form a wind slab.

Table E1 – Snow densities on the ground prior to wind tunnel treatment, compared to snow densities in the box after wind tunnel treatment.

Trial Number	Ground Density (Kg/m ³)	Box Density (Kg/m ³)	Percentage Increase
1	102.0	213.0	209%
2	41.3	137.6	333%
3	41.3	180.0	436%
4	78.3	105.8	135%
5	61.2	185.2	185%

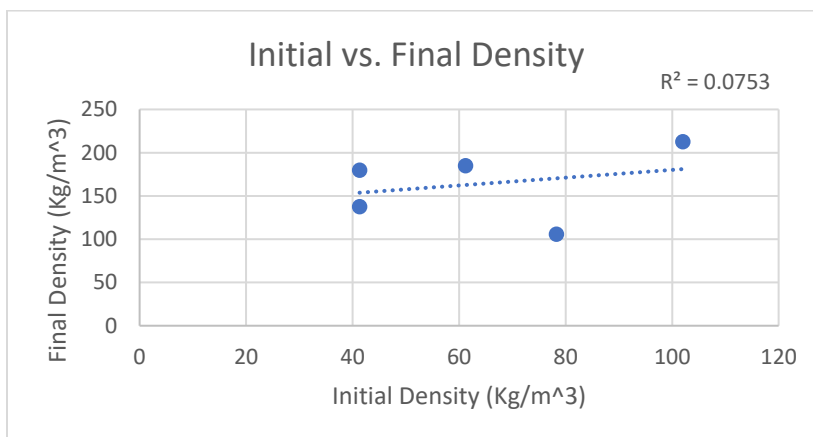


Figure E2 – Initial versus final densities for snow before and after wind tunnel treatment. This plot indicates that the density of snow before treatment was not related to the density of snow after wind tunnel treatment. Unfortunately, meteorological conditions limited trials, and with $n=6$ it is difficult to draw conclusions.

APPENDIX F

COMPARISONS OF SNOWPACK PHYSICAL PROPERTIES

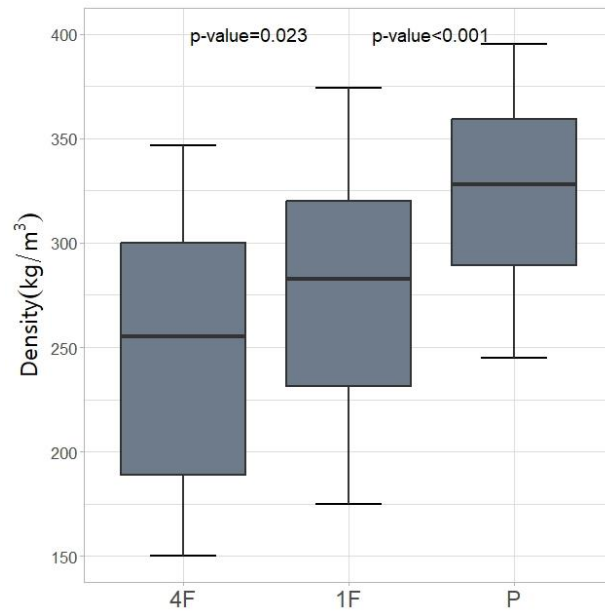


Figure F1: The relationship between layer density and layer hardness for all snow profile layers in this study. This shows that there is a significant difference between median layer density for each hand hardness category in this study.

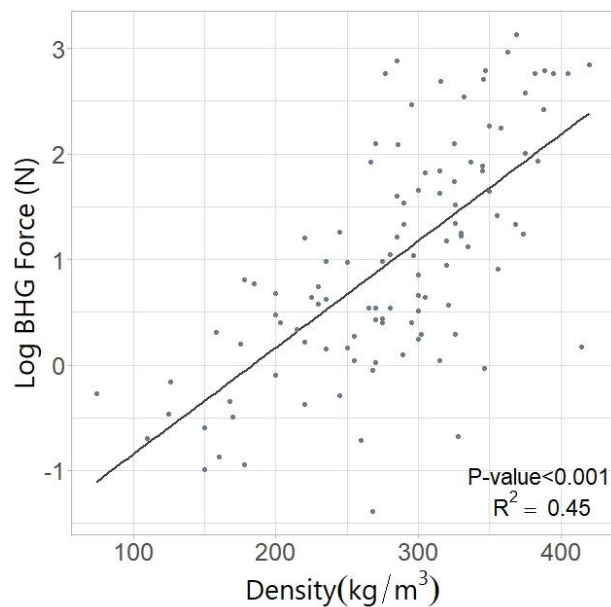


Figure F2: The positive linear relationship between layer density and the log of BHG force for all snow profile layers in this study. This shows that there is a significant relationship between snow layer density and BHG force in this study.

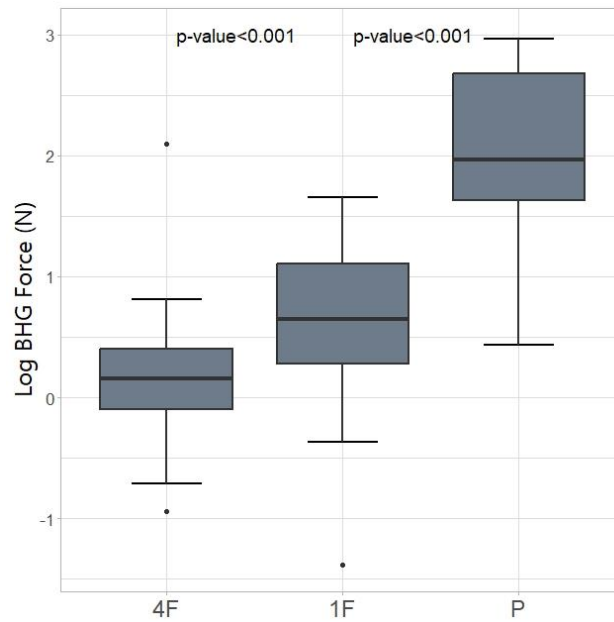


Figure F3: The relationship between layer density and the log of BHG force value for all layers in this study. This shows that there is a significant difference between mean layer log BHG force for each hand hardness category in this study.