UNDERSTANDING METEOROLOGICAL CONTROLS ON WIND SLAB PROPERTIES

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ABSTRACT: Wind-deposited snow has a broad range of possible physical and mechanical properties. The properties of a wind slab layer can vary greatly over short distances, creating difficult avalanche conditions. This variability causes particular challenges for avalanche workers in data-sparse regions where important snowpack information 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 we aim to better understand how changes in meteorological variables relate to changes in wind slab physical properties. During two winters we recorded temperature, humidity, and wind speed at study sites in Montana's Madison Range and collected snowpack data during or immediately following blowing snow events. We 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 relative humidity was not different between the two hardness categories. Although wind speed at 1.5m had a significant positive linear relationship with wind slab density, it was a poor predictor of actual slab density. Our findings help improve understanding of near surface winds and their impact on wind slabs, which will aid avalanche forecasting and mitigation planning particularly in windy climates.

KEYWORDS: Wind slab, Wind transport, Meteorological variables

1. INTRODUCTION

Wind transport of snow can form dangerous avalanche conditions leading to property destruction, injury, and loss of life. Unfortunately, wind slabs can be difficult to manage from a forecasting and mitigation perspective due to their spatial complexity. This is due in part to the wide range of possible values for the physical, and therefore mechanical, properties of wind deposited snow, and the associated spatial variability. Physical properties such as hardness and density play an important role in avalanche formation, where stronger and harder slabs are more difficult to trigger but may result in larger avalanches (van Herwijnen & Jamieson, 2007). The physical properties of snow layers, including wind slabs, are controlled in a large part by local meteorological variables (Sturm & Benson, 2004). Therefore, if we can learn more about how meteorological variables influence wind slab properties during and immediately following formation, we can better predict wind slab avalanches. Understanding the link between meteorological variables and snowpack properties is particularly useful in data-sparse regions where important data on snowpack physical properties may be limited and so meteorological variables play a larger role in avalanche forecasting. Information from this study could help avalanche forecasters in determining avalanche problem type, avalanche hazard, and appropriate mitigation strategies, particularly in areas prone to wind slab formation.

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2. BACKGROUND

2.1 Definitions

Wind has long been recognized as a contributing factor to avalanche formation (Atwater, 1954; Mellor, 1965; Perla, 1970; Seligman, 1936), and the term wind slab has been used since at least the 1920s (Seligman, 1936). Despite common use of the term, exact definitions vary. Some definitions focus on composition and physical properties (eg. Fierz, 2009), while others highlight formation processes (eg. Statham et al., 2018). Most references state that wind slabs form in lee areas, (eg. Fierz, 2009; McClung & Schaerer, 2006) while recent experiments have also shown wind slab formation upwind of an obstacle (Sommer et al., 2018). Using concepts from previously established definitions, our definition of a wind slab for this study will be:

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

Another term we will use is "wind skin," which we 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.

This differs from a wind crust, which is defined by the International Classification of Seasonal Snow on the Ground (ICSSG) as a thinner and irregular version of a wind slab, with no specified thickness or hardness (Fierz, 2009). A wind skin is distinct from a wind crust in that it necessarily soft and breakable, as well as less that one centimeter in thickness, and may or may not be irregularly distributed. Wind skin layers, as defined in this study, were too thin to obtain accurate hardness and density measurements, and so the term wind skin in itself was used as physical description of these snow layers.

An additional source of inconsistency in wind slab definition is the close association of wind slabs with storm slabs (de Leeuw et. al., 2023, this issue). Some references describe a wind slab as formed from redeposition only, which is when snow from the ground is entrained, transported, and subsequently deposited (eg. European Avalanche Warning Services, 2023). Others additionally include preferentially deposited snow in their definition of a wind slab (eg. Statham et al., 2018). Preferential deposition occurs when snow is deposited from the air column in a spatially variable manner due to wind action, and has not previously touched the ground or undergone saltation (Lehning et al., 2008). In this study we included wind slabs formed from both processes and did not separate between the two, as they often happen concurrently.

2.1 Transport processes

The redistribution of snow, which can lead to wind slab formation, is a three-step process (McClung & Schaerer, 2006). The first step is entrainment of snow by wind. Once entrained, snow is transported by rolling, saltation (whereby snow particles bounce along the ground), and turbulent suspension (McClung & Schaerer, 2006). Then snow is deposited as wind speed slows due to eddying or other flow changes to a point where transport can no longer be maintained.

2.2 Threshold wind speed

Entrainment occurs when wind stress exceeds snow cohesion, bonding, and friction. (Li & Pomeroy, 1997a). The minimum threshold wind speed for entrainment of low-density unbonded snow is around 5 m/s (18 km/h) (Berg, 1986; Filhol & Sturm, 2015; McClung & Schaerer, 2006). Although some variation exists in measured and estimated threshold wind speeds, most published values are close to or include 5 m/s (Table 1). The standard protocol for measuring wind speeds for snow transport uses an anemometer unobstructed by trees or terrain features, or at approximately 10m above the snow surface.

Table 1: Previously studied threshold wind speeds from select literature and reference sources.

Reference	Threshold Wind Speed
Mellor (1965)	3-8 m/s
Berg (1986)	4-6 m/s
Li & Pomeroy (1997b)	4-11m/s for dry snow
Filhol & Sturm (2015)	5 m/s
McClung & Schaerer (2006)	5 m/s for low density snow
American Avalanche Association (2022)	7 m/s for snow drifting
Canadian Avalanche Association (2016)	7 m/s for snow drifting

In many practical situations the threshold wind speed for snow entrainment is higher than 5 m/s due to physical properties of snow such as grain size and bond strength, where larger grains and those with more bonds require higher wind speeds for entrainment (Clifton et al., 2006). Increasing temperature also increases threshold wind speed. This is due to accelerated bond growth at high temperatures, and increased thickening of the quasi-liquid layer surrounding each grain, leading to greater strength and cohesion (Li & Pomeroy, 1997a). This relationship reverses below approximately -25°C, as elastic frictional forces begin to dominate over bonding and cohesion. Threshold wind speeds may decrease when particles are already in motion, such as during snowfall events, as falling particles can collide with and dislodge particles on the ground, perpetuating the saltation process (Paterna et al., 2016).

2.4 Wind slab physical properties

Wind slabs are usually stronger than surrounding snow layers. This is because during transport snow grains collide with each other and the snow surface resulting in smaller broken grains (Colbeck, 1982). When deposited, these grains pack closely together, leading to increased surface area contact between grains, more bond formation, and subsequently increased strength. Stronger layers disperse stress over a wider lateral area due to their stiffness, thus reducing the chance of affecting a buried weak layer and triggering an avalanche (McClung & Schweizer, 1999). As triggering an avalanche becomes more difficult, the uncertainty regarding necessary trigger size increases. Stronger layers can also result in larger avalanches due to increased crack propagation speed (Simenhois et al., 2023). Thus, wind slabs are prone to creating large avalanches associated with high levels of uncertainty.

Hardness is a commonly measured proxy for snow strength, and provides avalanche workers with important information on avalanche potential. While wind slabs are often hard, the exact hardness of wind transported snow varies within and between individual wind slabs. This variation contributes to the difficulty in predicting wind slab avalanches, often making it nearly impossible to predict triggering locations for a specific wind slab. Thickness has a similar influence to strength, where increasing thickness can increase the force required for triggering (van Herwijnen & Jamieson, 2007). In addition to the difficulty in predicting exact physical properties and associated spatial variability, wind slab locations may be unpredictable due to changing wind directions. This can lead to wind slab formation in uncharacteristic and unexpected places, further complicating the problem of predicting wind slab avalanches.

2.5 Role of meteorological variables

Meteorological variables influence the properties of all snow layers. Temperature plays a role in metamorphism through controlling the vapour pressure gradient (Colbeck, 1982), and wind is an important force in snow distribution across a landscape (Sturm & Benson, 2004). Avalanche workers often use meteorological information to infer snowpack properties and thus infer avalanche hazard. However, forecasting avalanche behavior from meteorological observations alone can lead to difficulty in interpretation, and introduces a large amount of uncertainty (LaChapelle, 1980).

In the case of wind slab development, temperature and wind speed exert control on snow entrainment. (Li & Pomeroy, 1997b). However, we know much less about the role of meteorological variables during transport and deposition, which is when wind slabs form. Humidity may play a role during the transport process, particularly during turbulent suspension, as sublimation increases with low humidity, removing snow from the system (Schmidt, 1982). Some articles state that increasing wind speed leads to increased wind slab hardness (eg. Fierz, 2009; Martinelli, 1971), yet field validation of this statement is limited. The lack of field experiments could be because wind slab avalanche problems tend to be short-lived, and wind slabs inherently form in hazardous locations during periods of elevated avalanche danger (Seligman, 1936). Our study aims to better understand the influence of meteorological variables on wind slab formation and properties at the slope scale. An established field-verified link between meteorological variables and wind slab physical properties may help us more reliably predict avalanches, particularly when resources or safety concerns do not allow for travel in start zones.

3. METHODS

3.1 Field Methods

We collected data over the winters of 2021/22 and 2022/23 from two study sites at the Yellowstone Club ski area, located near Big Sky in the Madison Range Mountains of southwestern Montana (Figure 1). Weather stations at each site collected hourly wind speed at three different heights above the snow surface (0.5m, 1.5m, ~10m), relative humidity, temperature, and snowfall amount. The two lower-height anemometers were moved after each site visit to ensure these metrics were collected as close as possible to the next profile location (Figure 2).

Figure 1: General location of the research area in southwestern Montana.

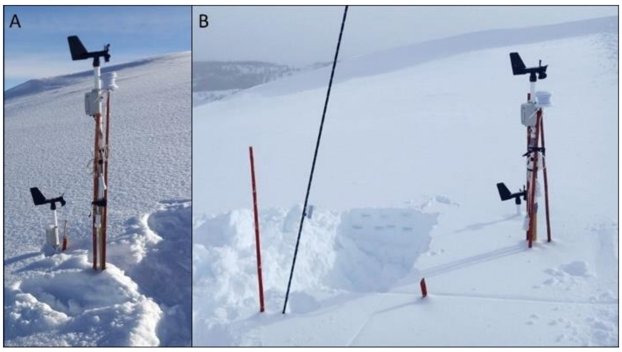

Figure 2: One of the two mobile weather stations which measured 0.5m height wind speed, 1.5m height wind speed, temperature, and relative humidity, (a) as well as the weather station's spatial relationship to each snow profile (b). These weather stations were moved after each site visit so that the next profile could be dug in an undisturbed location while maintaining close proximity to the weather station.

Site visits for data collection occurred during or immediately following wind transport events. Potential wind transport events were identified in advance by closely monitoring weather forecasts and telemetry, and ensuring that snow would be available for transport during the wind event. On each field day we dug test profiles at both sites where we prioritized collection of hand hardness and density information for the top meter of the snowpack. We used a 200 cm^3 triangular cutter and electric scale to measure density. To ensure consistency, all snowpack measurements were conducted by the same researcher each time.

3.2 Data Processing

For all snow pits we first categorized each surface and recently buried layer as either a wind slab layer or a null layer. Classification was based on the presence or absence of active wind transport during data collection, surface features indicating previous wind transport, and/or recently recorded weather station data. To identify which wind slab layers were considered "recent," and thus appropriate for our dataset, we required wind slabs to have been formed within the previous 72-hours, not subject to other metamorphic processes such as melt-freeze or faceting, and located at the surface or very recently buried by new storm snow. Any wind slab layer that did not meet these criteria was discarded from the dataset. We also used a previous 72-hour timeframe to define "recent" null layers, and discarded any null layers that were older than this, or had been subject to major metamorphic processes. After discarding all wind slab and null layers that did not meet the requirements for their respective category, we were left with forty-one wind slab layers, and fourteen null layers.

We then determined an exact wind period for each wind slab layer in order to constrain the timeframe when formation occurred. Individual wind periods included all one-hour units from the start of relevant snowfall to the time of data collection where average unobstructed wind speed was over 5 m/s (18 km/h) and snow could reasonably be transported. The 5 m/s cut-off was applied to unobstructed wind speed at ~10m above the snow surface, as this is the height most consistent with previous studies (Table 1). The values of all other meteorological variables were taken from these same one-hour units. Null data did not have an associated wind period, so meteorological variables for these layers were taken from the time of snowfall onset to the time of snowpack data collection.

3.3 Statistical Analysis

We used Mann-Whitney U tests to statistically compare the values of each explanatory meteorological variable (listed in Table 2) during periods when wind slabs formed and when they did not. We also used Mann-Whitney U tests to compare values of each meteorological explanatory variable to hand hardness of the resulting wind slab. Hand hardness was divided into the binary categories of "soft" and "hard", where soft included wind skin and four finger layers, and hard included one finger and pencil layers. We did not measure any knife hardness layers, likely because we only looked at recent wind slabs, nor did we observe any fist hardness layers, as wind slabs are almost always harder than fist. We chose the Man-Whitney U test because our datasets did not meet the assumption of normality required by the t-test, but did meet the assumption of independence of observations required by the Mann-Whitney U test.

Table 2: All meteorological explanatory variables used in this study and their associated units.

Variable	Units
Mean unobstructed (~10m height) wind speed	km/h
Mean 1.5m height wind speed	km/h
Mean 0.5m height wind speed	km/h
Maximum unobstructed (~10m height) wind gust	km/h
Time period during which snow was transport by wind (wind period time)	hours
Temperature	°C
Relative Humidity	%

We used simple linear regression (SLR) to independently compare each meteorological explanatory variable to wind slab density, and backwards stepwise multiple linear regression (MLR) to compare all explanatory variables together to wind slab density. Multiple linear regression can be a useful addition to simple linear regression because it takes into account the interactions of the independent variables. For the MLR, multicollinearity was determined using variance inflation factor (VIF) values, where explanatory variables with high VIF values were removed until all VIF values were below five, indicating they were not highly correlated (Akinwande et al., 2015). Though our datasets did not fully meet all the assumptions of linear regression, these techniques are fairly robust with respect to small deviations from those assumptions. That said, our SLR and MLR results should be interpreted with an appropriate degree of caution given these deviations and our relatively small sample sizes. We chose an alpha value of 0.05 for all statistical tests, and used R for data management and analyses (R Core Team, 2021).

4. RESULTS

Mann-Whitney U statistical tests provided strong evidence that the average wind speed at all heights above the snow surface (0.5m, 1.5m, and ~10m) was greater during periods when wind slabs formed than when they did not (null cases) (p<0.001), as was maximum unobstructed wind gust (p=0.013) (Figure 3). Using the same analysis methods, average temperature (p=0.246) and average relative humidity (p=0.092) were not significantly different between periods of wind slab formation and null periods (Figure 4).

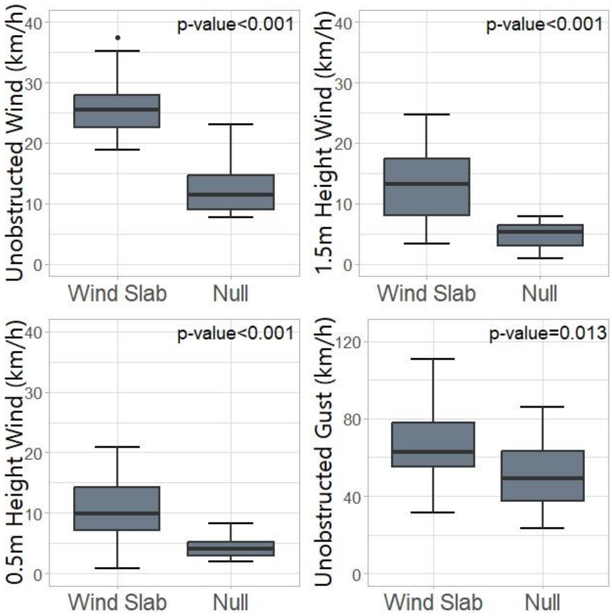

Figure 3: Box plots comparing all wind speed variables between situations when wind slabs formed and when they did not (windslab n = 41, null n = 14). Each box shows the maximum, median, minimum and interquartile range. Note that the Unobstructed Gust graph has a different y-axis scale than the other three graphs.

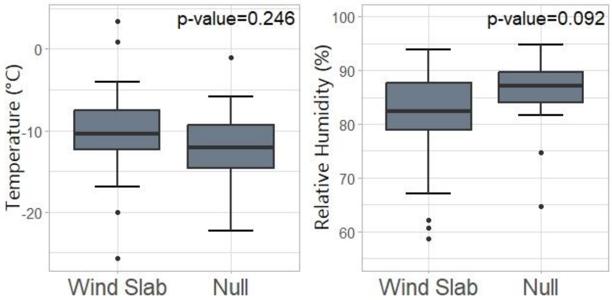

Figure 4: Box plots comparing both non-significant variables (temperature and relative humidity) between situations when wind slabs formed and when they did not (windslab n = 41, null n = 14). Each box shows the maximum, median, minimum and interquartile range.

When we discarded the null layers to consider only wind slabs, and split wind slab layers into "hard" and "soft", the Mann-Whitney U test provided strong evidence that average 1.5m wind speed (p<0.001) and average 0.5m wind speed (p<0.001) were significantly higher during formation of hard wind slabs than during formation of soft wind slabs (Figure 5). Likewise, temperature (p=0.046) was higher when hard wind slabs formed (Figure 5), though aside from one datapoint at -25 °C the full range of temperature for soft wind slab formation fell within the range of temperatures for hard wind slab formation. Average unobstructed wind speed (p=0.906), maximum unobstructed wind gust (p=0.308), wind period time (p=0.228), and average relative humidity (p=0.190) were not significantly different between situations of soft wind slab and hard wind slab formation (Figure 6).

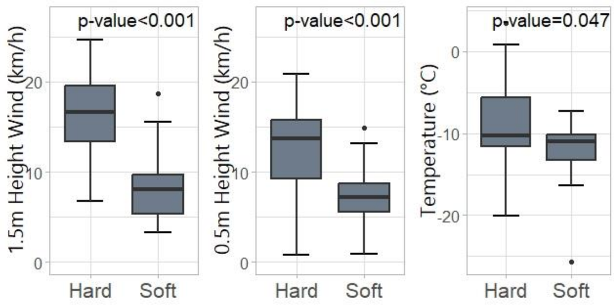

Figure 5: Box plots showing all variables that were significantly different between hard wind slab and soft wind slab formation (hard n = 24, soft n = 17). Each box shows the maximum, median, minimum and interquartile range.

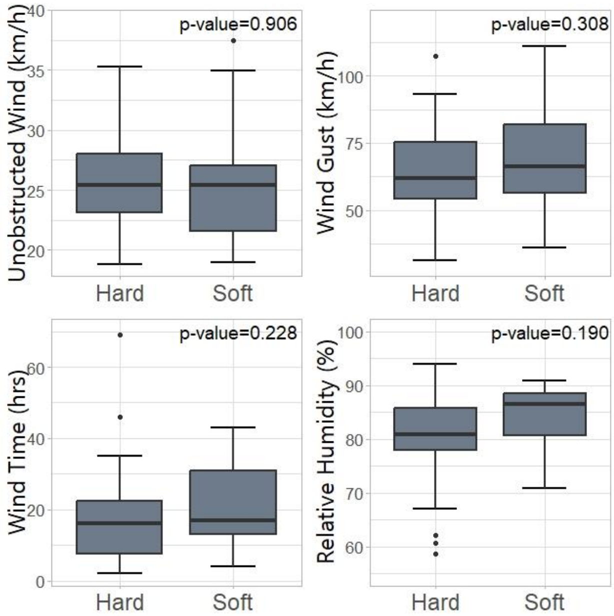

Figure 6: Box plots showing all variables that were not significantly different between hard wind slab and soft wind slab formation (hard n = 24, soft n = 17). Each box shows the maximum, median, minimum and interquartile range.

Simple linear regression provided strong evidence that average 1.5m wind speed was positively correlated with wind slab density, (p=0.033) though it only explained 15% of the variance (r^2=0.15) (Figure 7).

All other meteorological variables produced SLR models which were not significant (Table 3).

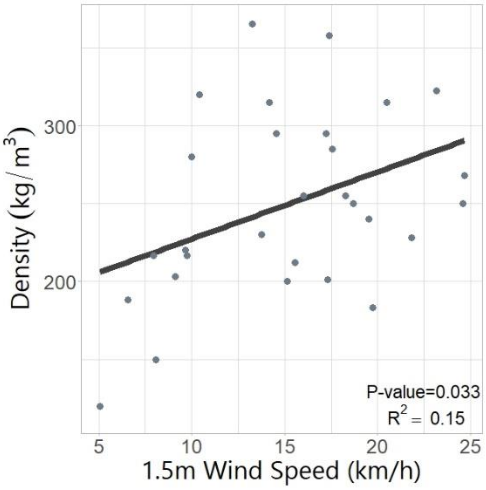

Figure 7: Positive linear relationship between 1.5m wind speed and wind slab density.

Table 3: Each meteorological value and its associated density SLR p-value.

Variable	P-Value
Mean unobstructed (~10m height) wind speed	0.681
Mean 1.5m height wind speed	0.033
Mean 0.5m height wind speed	0.714
Maximum unobstructed (~10m height) wind gust	0.679
Time period during which snow was transport by wind	0.483
Temperature	0.265
Relative Humidity	0.215

After removing variables with VIF values greater than five, the first MLR model was significant with six different explanatory variables ($p=0.003$, $r^2=0.56$), of which only one was independently significant. The relatively high r^2 value (compared to subsequent models), lack of independently significant variables, and low number of datapoints led us to suspect this could be an instance of overfit, which occurs when a model begins to describe random error (Akinwande et al., 2015). We decided to continue with significance of all individual variables as the endpoint for the MLR, which resulted in the elimination of all variables except for 1.5m wind speed, and thus a return to the original SLR model using 1.5m speed.

5. DISCUSSION

Our results show that given the presence of snow available for transport, wind speed is the most important meteorological variable to forecast wind slab formation. This is consistent with the general rule of thumb applied by avalanche workers. The dramatic difference in average unobstructed wind speed when wind slabs formed and when they did not (Figure 3), demonstrates that the 5 m/s (18 km/h) unobstructed wind speed cut-off was an appropriate choice to constrain wind slab formation time periods in this study. Wind speed measured at 1.5m and 0.5m above the surface both had lower cut-offs of around 8 km/h and 6 km/h respectively (Figure 3), as wind speed tends to increase with height above the ground (Schmidt, 1982). Previous studies on snow entrainment by wind were measured at an unobstructed height, which explains this discrepancy. The difference in the number of observations in each category (windslab n = 41, null n=14) was a relic of the study design, where data collection was prioritzed on days when a new wind slab was expected in at least one study site, and so the data collection of null layers was not prioritized. However, the large difference in median values between the two categories inidicates that the relationship would likely remain significant even with an equal number of observations between categories.

Furthermore, when wind slabs did form, the average wind speed at lower heights (1.5m and 0.5m) was significantly higher during hard wind slab formation than during soft wind slab formation (Figure 5). In contrast, the average value and maximum gust of unobstructed wind speed did not significantly differentiate between periods of hard and soft wind slab formation (Figure 6). The lack of association between unobstructed wind speed and wind slab hardness demonstrates the importance of using localized and low-height wind information to predict specific wind slab properties. Many operations use unobstructed anemometers to observe wind speeds, and these may not reflect actual wind speeds or wind transport in most start zones. The lack of correlation between unobstructed and lower height wind speeds could be due to terrain features and their influence on wind. This implies that the extent of correlation between unobstructed and lower wind speeds may depend on wind direction. While our findings confirm that avalanche workers can use wind speed to forecast approximate wind slab hardness, they emphasize the critical importance of collecting local wind speed measurements from start zones at the slope-scale, rather than inferring localized wind speed and therefore wind transport, from unobstructed wind speeds.

Unfortunately, installing many low-height anemometers in start zones may be impractical for most operations. Low-height anemometers in areas prone to wind loading are likely to get buried, and maintenance of these sensors could be dangerous based on their location. Further, installing many quality anemometers could be prohibitively expensive. 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. An alternative to installing many anemometers could be to install a few temporary anemometers on representative slopes. This would help improve local knowledge and could bridge the gap between wind speeds at different heights in specific areas.

In this dataset the average temperatures during wind periods were significantly higher when hard wind slabs formed than when soft wind slabs formed (Figure 5). However, there was considerable overlap in the range of these two categories. Because of this, it may not be practical to use exact temperature values to predict wind slab hardness, but relative temperature could be a useful guide in predicting relative hardness. For example, with wind speeds remaining mostly constant, harder slabs may begin to form as temperatures rise. Results of this study indicate that in addition to wind speed, forecasters could look at temperature data for further clues about potential wind slab hardness.

This increase in wind slab hardness with increasing temperature agrees with previous literature stating that bond formation begins immediately upon deposition and increases with increasing temperature (Colbeck, 1982). However, a secondary and opposite relationship also exists between temperature and hardness, since material stiffness increases with decreasing temperature (McClung & Schweizer, 1999). This process may be more likely to occur at low temperatures (~ -25°C), where the role of stiffness begins to dominate over bonding and cohesion (Li & Pomeroy, 1997b). The results from this study indicate the need for further investigation, specifically at low temperatures, in order to determine the full extent of the usefulness of temperature in forecasting wind slab hardness.

Slab density, though less commonly measured by avalanche workers, is another useful physical property for understanding potential avalanche behavior. Slab density is typically positively correlated with hardness and strength (Colbeck, 1982). Our SLR analysis showed that wind speed at 1.5m had a significant positive linear relationship to wind slab density (Figure 7). Despite the significant relationship ($p=0.033$) the associated r-squared value was relatively low ($r^2=0.15$), explaining only 15% of the variance in wind slab density using 1.5m wind speed. So, while 1.5m wind speed may help avalanche forecasters understand relative changes in wind slab density, it is not practical to predict an actual wind slab density value from a known 1.5m wind speed. Despite this, it is encouraging that we were able to explain 15% of the variance given the complexity of wind slab formation in mountainous terrain.

Although the interaction of meteorological variables with each other and the snowpack is complex, our work provides promising approaches for predicting wind slab properties at the slope-scale. Conducting laboratory studies where variables can be controlled, or increasing the number of observations in a field setting could help eliminate some uncertainty and replicate findings. Despite the limitations inherent to field work, this study provides a step toward describing how avalanche workers can interpret wind and snow processes. When information on recent avalanche activity is unavailable, forecasters often rely on snowpack data to predict avalanche occurrence. When snowpack data is unavailable, they rely on meteorological data to predict snowpack data, and extrapolate this to potential avalanche occurrence. Unfortunately, forecast uncertainty increases with each step away from observing actual avalanches (LaChapelle, 1980). Therefore, any information establishing better links between meteorological variables and snowpack properties, such as in this study, reduces uncertainty and helps improve avalanche forecasts.

6. CONCLUSIONS

Being able to better forecast snowpack properties from meteorological variables helps 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. This study shows that while increasing wind speed is associated with increased wind slab hardness, this relationship only exists for localized wind speed close to the snow, and not unobstructed wind speed. Temperature could also be used to help forecast wind slab hardness, where increasing temperature is associated with increased wind slab hardness. While wind speed at 1.5m above the snow surface does a poor job of predicting actual wind slab density, this information could be used to understand relative differences in slab density. This enhanced understanding of the relationships between meteorological variables and wind slab properties will help forecasters better predict avalanches, particularly in windy areas.

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