THRESHOLDS IN WIND SPEED, AIR TEMPERATURE AND RELATIVE HUMIDITY CONTROLLING SLAB FORMATION

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ABSTRACT: Weather variables including wind speed, air temperature and relative humidity have important controls on slab formation, influencing the dynamics of snow formation in the atmosphere, snow transport, and deposition. In this study we examine statistical thresholds in these variables that lead to formation of dry loose, soft slab, and hard slab avalanche events recorded by the Bridger-Teton Avalanche Center (Wyoming, USA). Using 43 seasons of historical 24-hr data from the Summit wind station at Jackson Hole Mountain Resort we quantify daily wind totals necessary to support slab formation. We then examine the distribution of hourly average wind speeds and max gusts during slab deposition by selecting wind data only during precipitation periods directly preceding slab avalanche events. To investigate potential thresholds between dry loose, soft slab, and shallow hard slab, we examine 15-minute weather data from ten case study periods between 1999 and 2017. Using five periods dominated by dry loose / very soft slab events, and five periods dominated by shallow hard slab events, we find characteristic weather conditions associated with these end-member types. In particular, these results show a distinct threshold in relative humidity associated with hard slab formation. Supporting previous work, we show that these weather variables have important controls on slab formation.

KEYWORDS: avalanche forecasting, slab formation, weather

1. INTRODUCTION

In this study, we attempt to isolate thresholds in wind speed, air temperature, and relative humidity that have controls on the transition between dry loose, soft slab, and hard slab conditions for single to multiday storm cycles in the northwest Wyoming snow climate (USA).

Many previous studies have investigated the influence of wind and air temperature on general avalanche hazard (e.g. Schweizer et al., 2003; McClung and Schaerer, 2006). Previous work has also demonstrated weather conditions that promote weak layer formation (e.g. Bellaire and Jamieson, 2013) or changes in slab mechanical properties (e.g. Reuter and Schweizer, 2012). A large body of previous work has also used statistical techniques to find significant weather variables related to avalanche events (e.g. McCollister et al., 2003; Marienthal et al., 2015).

There has been limited research, however, to quantify specific weather conditions that drive the transition from dry loose, to soft slab, to hard slab conditions. McCollister (2004) analyzed the spatial variability of hard slab and dry loose avalanches, using a nearest neighbor technique to find significant trends with wind speed, 24-hr maximum air temperature, and new snow density. This study found an increase in hard slab events with increases in new snow density, and an increase in dry loose events with decreases in new snow density and wind speed.

Kozak et al. (2003) also examined weather variables related to new snow layer hardness. This study found maximum daily air temperature and incoming shortwave radiation as the most significant predictors of new snow hardness on south aspects, and maximum daily air temperature and the previous day's wind speed to be most significant for north aspects.

In support of these previous efforts, our study attempts to use high-resolution weather data to resolve specific conditions during new snow deposition that can lead to slab formation. Although wind speed is an obvious driver of slab formation, we also identify thresholds in air temperature and relative humidity (RH) that support slab formation. We focus in particular on RH which, despite being a very common meteorological measurement, has only received very general remarks in previous work (e.g. McClung and Schaerer, 2006) or has been used primarily only as input to energy balance and snowpack models (e.g. Mitterer and Schweizer, 2013).

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2. METHODS

Data for 24-hr wind totals (1974–2017) and hourly average wind speed and max gust (1999–2017) are from the Summit wind station (3,185 m) at Jackson Hole Mountain Resort (JHMR). In addition, we use 15-minute data from automated weather stations at the Raymer Study Plot (2,853 m) and the Mid-Mountain Study Plot (2,493 m) at JHMR to analyze air temperature, relative humidity, and new snow density during precipitation periods (1999–2017).

Avalanche events are recorded daily in the BTAC database, including explosively triggered events at the ski resort and backcountry events. In this study we analyze dry loose (L), soft slab (SS), and hard slab (HS) events for all trigger types and all locations. To isolate events that represent slab formation during the previous storm, we limit crown depth for slab events to 76 cm (30 in) or less. This is particularly relevant for HS events, where we attempt to not include hard slabs that are higher density as a result of settlement from multiple storm cycles over weeks and months. Instead we focus on shallow hard slabs that have likely developed over one to several days in a single storm cycle.

To identify hourly wind data that corresponds to precipitation periods preceding events, we use a custom "storm selector" algorithm that starts at the timestamp of an avalanche event that has occurred during or within hours after the end of a storm period. The program then steps backward in time in 1-hr increments until the 8-hr cumulative precipitation falls below 0.76 cm (0.3 in), marking the start of the storm cycle. This method allows for short breaks in precipitation, while still capturing hourly timestamps associated with the core of the storm event.

Soft slab events are the most common type in the historic record, whereas HS and L events comprise <10% of the historic event database. Because the sample size is so low for these types, and because HS and L events are often mixed with SS events, we have selected ten case study periods where the event record is dominated by either L or shallow HS events. These case studies span 1999 – 2017 and are used as end-members to define thresholds for slab-forming conditions. We have avoided case studies with deep hard slab events, with most HS events having depths ranging 25-61 cm (10-24 in). Analysis from case study periods use 15-minute air temperature, RH, and precipitation data from the Raymer Study Plot.

3. RESULTS

3.1 Wind speed

Analyzing 24-hr wind totals (total daily wind kilometers) for the Summit station using data spanning 1974 – 2017, we quantify the distribution of wind speed for periods preceding avalanche events. For the preceding 24-hr period, wind totals for slab events (SS and HS combined) are significantly higher than for loose events (Figure 1). Analysis using wind totals from preceding 48-hr and 72-hr periods shows very similar relative distributions between loose and slab events.

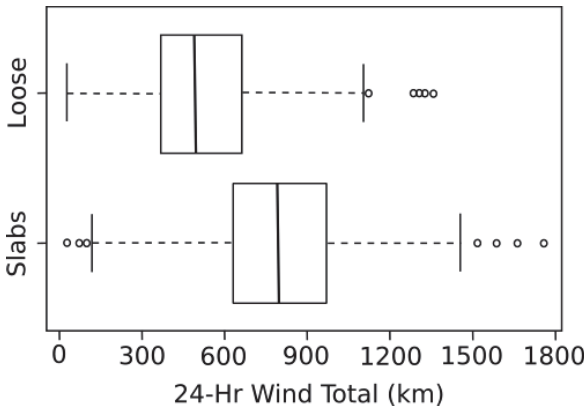

Figure 1. Distribution of 24-hr wind totals for periods preceding loose and slab events.

To further quantify the distribution of ridgetop wind speeds that result in slab formation, we use the "storm selector" algorithm to select hourly wind data only for precipitation periods preceding slab events (SS and HS). Because 24-hr data can often include wind speeds that are not directly associated with slab deposition (e.g. rapid frontal passages), this analysis is an attempt to better quantify winds during storm events that were slab-forming (Figure 2). This algorithm selected 102 storm periods with 872 hourly timestamps.

Using the ten case study periods, average wind speed and average max gust are calculated for loose and hard slab dominated cycles (vertical dashed lines in Figure 2). The labels and corresponding ranges applied to Figure 2 are intended to be general ranges based on the case study analyses, and are somewhat qualitative interpretations. Note that periods dominated by L events often include notes by the avalanche forecaster describing "very soft slab" events that are common for these periods. An example of a hard slab-dominated case study is shown in Figure 4.

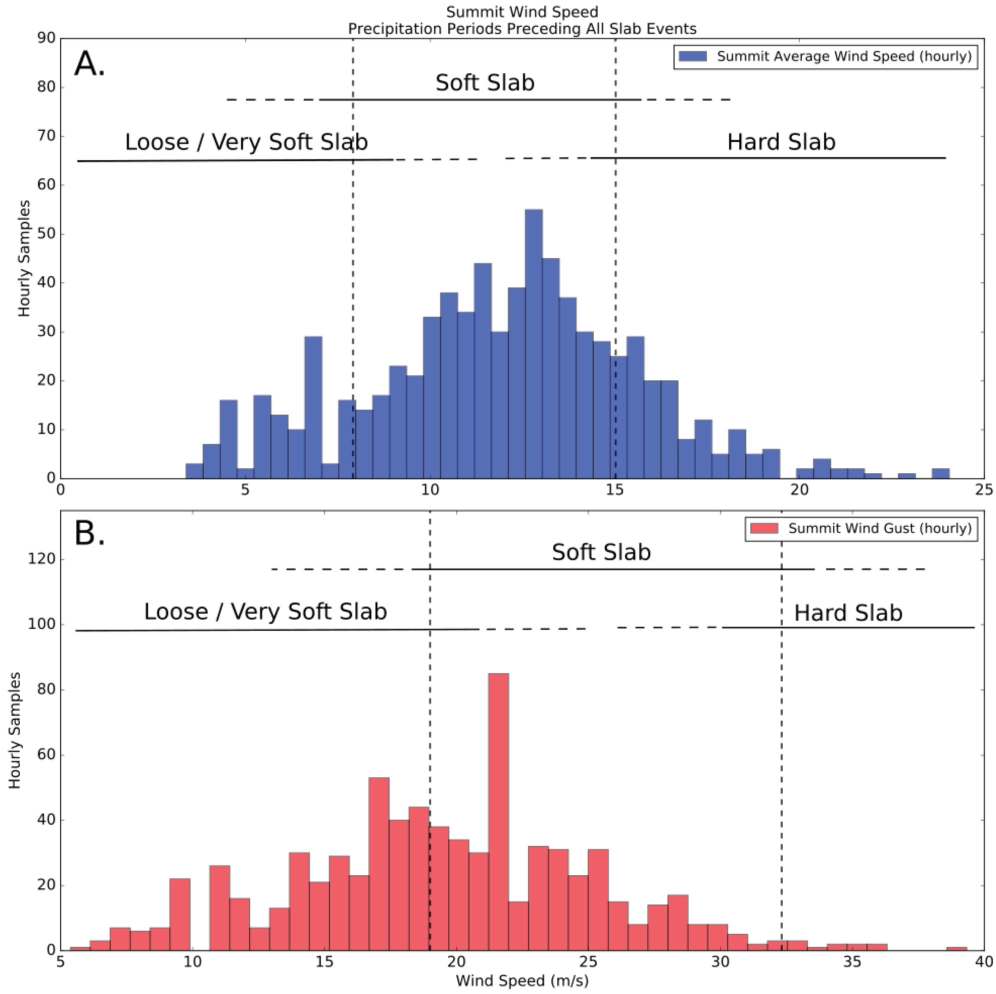

Figure 2. Distribution of hourly average wind speed (A.) and hourly max wind gust (B.) at the Summit Wind Station (3,185 m). Data is selected from precipitation periods directly preceding slab events (SS & HS) with depths < 76 cm (30 in) for the period 1999 – 2017. Vertical dashed lines represent average wind speed and average max gust from L-dominated and HS-dominated case study periods.

3.2 Air temperature and relative humidity

To analyze trends in air temperature and RH, we use the ten case study periods for loose-dominated or hard slab-dominated events. Figure 3 shows results for all 15-minute air temperature and RH data during precipitation periods directly preceding events. L events tend to follow periods of cold and dry precipitation, whereas HS events tend to follow precipitation from warmer, moist air masses. Although there is considerable overlap in the range of air temperatures between the two case study groups, RH conditions have a distinct threshold at ~90%.

New snow density measured at a 24-hr interval board for loose event periods ranges 0.04 - 0.09, and snow density for hard slab periods ranges 0.12 - 0.17.

4. DISCUSSION

Our results for wind speed distributions (Figures 1 & 2) confirm intuitive knowledge and previous work, and quantify the range of wind speeds necessary for slab formation. Higher wind speeds cause for mechanical breakdown of snow particles, allowing for wind-packing to higher densities and increased bond formation between grains (McClung & Schaerer, 2006).

The wind speed threshold transitioning from loose snow to soft slab formation (Figure 2, Panel A) generally agrees with McClung and Schaerer (2006), who cite wind speeds in excess of 7 m/s for wind packing to begin. These authors also cite wind speeds of 10-25 m/s as optimal for drifting

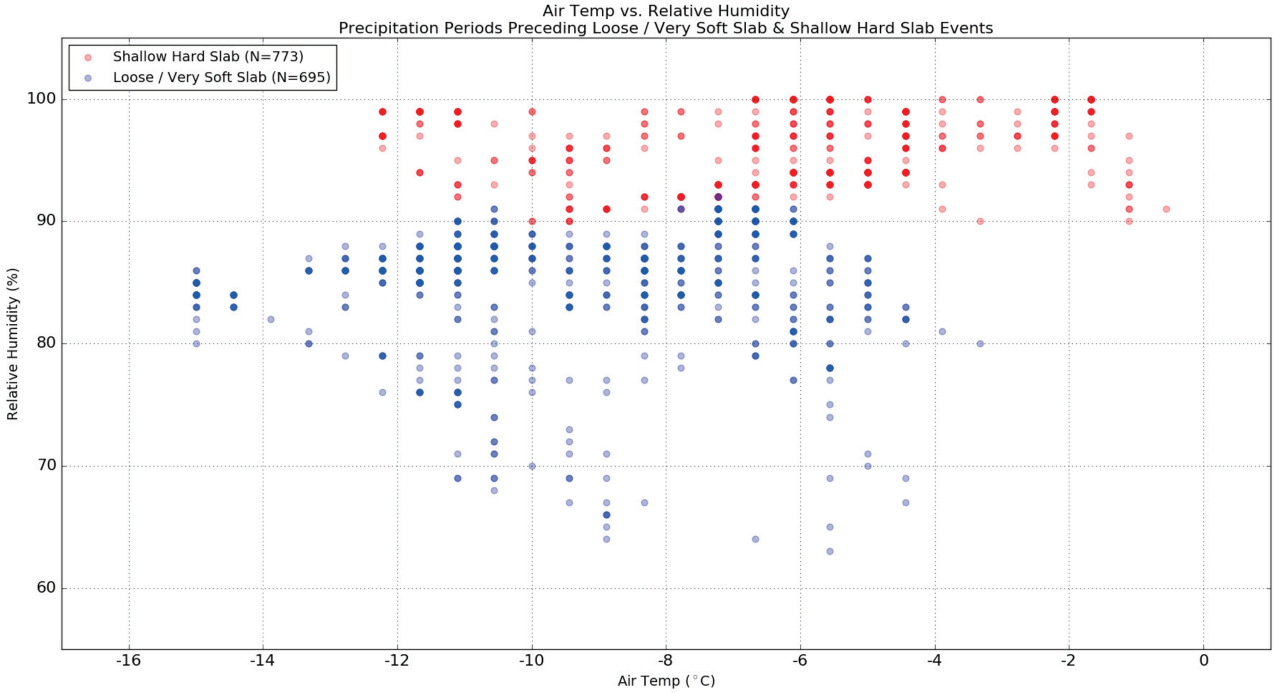

Figure 3. Air temperature vs. relative humidity for precipitation periods preceding Loose / Very Soft Slab and shallow Hard Slab events. Data is 15-minute resolution from the Raymer Study Plot (2,853 m). Individual points are plotted with transparent color, such that solid red or blue shows higher data density.

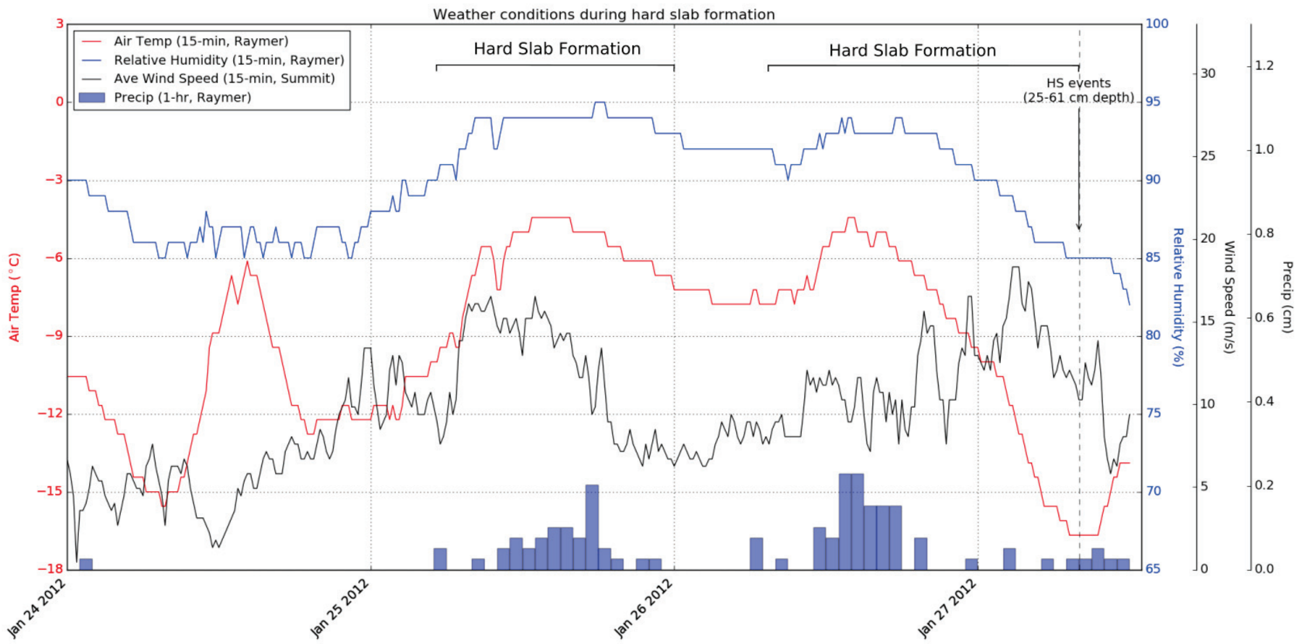

Figure 4. Weather conditions during a hard slab-dominated case study period. Note the increase in air temperature and RH to > 90% during the precipitation periods (denoted with “Hard Slab Formation”). Measurements are at 15-minute intervals from the Raymer Study Plot (2,853 m).

and slab formation, and speeds greater than 25 m/s resulting in scour at ridgetop locations.

Our results for air temperature and RH indicate that precipitation from warmer, moister air masses promotes harder slabs (in combination with increased wind speeds). Increased air temperature could increase settlement rates and grain sintering, resulting in higher slab density. Previous work has shown that both wind speed and air temperature are related to higher snow density (Wright et al., 2016), however RH also appears to be a contributing factor that was not included as an additional predictor variable in this previous work.

It is important to consider these results in the context of terrain variability. McCollister (2004) and Morrison (2004) found that terrain can cause significant variability in the spatial pattern of avalanche events and slab formation for a given “free air” wind speed and direction. Even if ridgetop winds, air temperature, and relative humidity are sufficient to support slab formation in high-elevation starting zones, it is common to have loose to very soft slab conditions at lower, more sheltered locations.

The wind speed thresholds defined in Figure 2 and the data presented in Figure 3 are derived from ten case study periods. By choosing distinctive end-member case studies for L and HS dominated cycles, we are better able to isolate the effects of the air mass that is characteristic for each case study group. However, we caution that these are preliminary results with small sample sizes. Future work will identify and add additional case studies to this analysis.

5. CONCLUSION

Using 43 seasons of historical 24-hr data from the Summit wind station at JHMR we quantify daily wind totals necessary to support slab formation, finding significant increase in the distribution of 24-hr wind totals preceding slab events compared to loose events.

Analysis of hourly average wind speeds and max gusts for precipitation periods directly preceding slab avalanche events (1999-2017) quantifies the distribution of wind speeds during deposition. Ten case study periods are used to derive wind speed thresholds between loose, soft slab, and hard slab conditions. These results generally agree with previous work, where a threshold in average wind speed in the range of 5-10 m/s corresponds with a transition from loose to slab-forming conditions. We caution that these wind speed thresholds are derived from small sample sizes and likely have large variability depending on location within complex terrain.

Analysis of 15-minute weather data from ten case study periods shows loose-dominated avalanche cycles resulting from precipitation during cold, dry conditions, and hard slab-dominated cycles resulting from warmer conditions with increased RH. In particular, we find a distinct threshold of ~90% RH when comparing loose / very soft slab and hard slab conditions.

Although wind speed is a primary driver of slab formation, these results show that air temperature and relative humidity can also have important controls. In particular, the transition to hard slab-dominated deposition during single storm cycles will likely require increases in air temperature and RH.

ACKNOWLEDGEMENT

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