THE SPATIAL AND TEMPORAL VARIABILITY OF SLAB HARDNESS

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ABSTRACT

A slab avalanche occurs when a weak layer or interface below the slab fractures, causing the slab to release. A large percentage of accidents associated with slab avalanches result when the victim triggers the release. While it is recognized that avalanches are caused by the unique interaction between the weak layer and the slab, most research has focused on the composition of the weak layer and how its strength changes over time. Relatively few studies have examined how slab properties change over time and space. We expect slab properties to change over time and space because of both the inherent variations in the energy balance associated with aspect and the dependency of snow metamorphism on the energy balance. This research attempts to address the following research question: to what degree does slab hardness vary with aspect and time when elevation and slope are kept relatively constant?

Slab hardness was measured with a ram penetrometer on north and south aspects from January through March, 2000 at Jackson Hole Mountain Resort and Grand Teton National Park, WY. While hardness increased more rapidly on southern than northern aspects due to settlement and densification, solar radiation on southern aspects also contributed to greater heterogeneity in the snowpack.

KEYWORDS: Hardness, new snow-layer, incoming shortwave radiation, maximum daily temperature

1. INTRODUCTION

A large percentage of skiers, snowboarders, and snowmobiliers who are caught in avalanches trigger the avalanche themselves. The concept is often referred to as skier triggering and is highly dependent on slab hardness (Schweizer, 1993). How the mechanical properties of slab strength enhance and reduce snowpack stability is not well understood, and traditionally these properties have been overlooked in evaluating snowpack stability. An additional factor that complicates a forecaster's ability to accurately predict backcountry avalanches is the inherent spatial and temporal variation of snowpack characteristics and resulting stability (McClung and Schweizer, 1999). These variations can be attributed in part to terrain effects, including how the energy balance varies with aspect as well as variations in mesoscale and microscale meteorology.

The objectives of this paper are to:

- determine how the hardness of a new snow layer varies spatially and temporally while keeping slope and elevation relatively constant
- determine which physical weather-related properties – incoming shortwave radiation, maximum air temperature, wind speed, and wind

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direction – most influence changes in hardness with aspect

This study quantitatively examines changes that we intuitively expect to find in the snowpack, and reinforces insights about slab development. This study is still in progress.

2. LITERATURE REVIEW

Hardness can be thought of as the initial resistance to deformation per unit area (McClung and Schweizer, 1996). Hardness, however, is not a physical parameter, but a state described by degree of viscosity (Schweizer, 1993). A hard layer is in a state of high viscosity while a soft layer is in a state of low viscosity. The state of viscosity, which is highly dependent on temperature, has a bearing on how much deformation can occur within a layer (McClung and Schweizer, 1996). The larger the difference in viscosity between the relatively hard and soft layers, the more susceptible the slope is to avalanching (Schweizer, 1993).

The spatial variabilty of snowpack properties complicates accurately predicting where and when an avalanche will occur. Avalanche professionals recognize that spatial patterns exist across avalanche terrain (Birkeland, 1998). Dexter (1986) observed snowpack and strength patterns over seven study sites in the Front Range of Colorado. He found that strength increased with elevation on northerly aspects and decreased with elevation on southerly aspect. Snow stability patterns were also investigated by Birkeland (1998) in the Bridger Range in Montana. His study found that terrain can be correlated to snowpack stability and that stability decreases on northerly aspects as elevation increases. The study also found that this relationship changes over time.

3. METHODS

Snow hardness was measured with a ram penetrometer on north and south aspects from January through March, 2000 at Jackson Hole Mountain Resort and Grand Teton National Park, WY. North and south study plots were established at elevations between 2400 meters and 2600 meters. Both plots were sampled every other day, on the same day. Layer hardness, thickness, temperature, density, crystal size, crystal type, and stability (by means of several stuff block tests (Birkeland et al., 1996)) were also determined at each plot.

Weather data, including air temperature, wind speed, and wind direction, were recorded every hour at three on-mountain weather stations. Daily incoming shortwave radiation was measured with a pyranometer at approximately 2750 meters. Maximum, minimum, and current air temperature was also recorded from max/min thermometers at each of the study plots.

Changes in hardness for new snow layers were determined on north and south aspects over a period of seven days or until the layer was no longer discernable from the rest of the snowpack. These layers were tracked and their ram numbers calculated from both ram and stratigraphy profiles of the snowpack. Ram numbers for each layer were plotted over time. Rate of change of hardness (dR/dt) for each layer was determined by fitting a linear regression line to the ram number versus time curve. These data were then graphically compared with incoming shortwave radiation, maximum daily temperature, wind speed, and wind direction to qualitatively explain variations in rate of change of hardness with aspect. Incoming shortwave radiation was determined as a percent of the maximum daily radiation recorded during this study period.

Regression analysis was used to quantitatively describe which weather-related physical property or interaction of properties most influenced changes in hardness with aspect. A logarithmic transformation was used on the rate of change of hardness to improve the linear fit of the data.

4. RESULTS

Figure 1 shows wind direction (magnetic degrees), wind speed (m/s), maximum daily temperature (°C), incoming shortwave radiation (%), hardness (N), and rate of change of hardness over the study period (days) in order to relate changes in weather and incoming shortwave radiation with changes in hardness. The points (triangles and circles) describing dR/dt fall in the middle of an observation period that often lasted 7-to-8 days. While the process of hardening occurred over the entire observation period, the point is plotted in the middle of this period for visual convenience.

We found that compared to the north aspect, hardness of new snow layers generally increased more rapidly on the south aspect and ultimately reached a higher value of hardness. Significant increases in hardness for new snow layers on the south aspect tended to parallel increases in shortwave radiation. The difference in rate of change between the south aspect and the north aspect became accentuated during periods of moderate-to-high input of shortwave radiation, below 0 °C maximum daily temperatures (on the north aspect), and low wind (see A and E in figure 1). Despite the high maximum daily temperatures shown in box E, the maximum daily temperature recorded from the max/min thermometers at the north plot was around –5 °C.

The difference in rate of change between south and north aspects was reduced during periods of moderate-to-low incoming shortwave radiation, above 0 °C maximum daily temperature (on the north plot), and moderate to heavy wind with a northerly component (see B, C, and D in figure 1). This difference was also reduced during periods of low incoming shortwave radiation, low maximum daily temperature, and low wind (see F in figure 1).

The 14 pairs of points are north and south new snow layers that represent the 14 significant snow events observed over this study period. A detailed explanation for the development of hardness of each layer is given below.

- <u>Layer 1</u> – substantial incoming shortwave radiation and low maximum daily temperatures over the previous days, some moderate wind out of the NW which raised hardening rates on the north aspect. dR/dt was 2.8 times greater on the south aspect than the north aspect.

- <u>Layer 2</u> – six days of strong wind out of the NW with low incoming shortwave radiation and low maximum daily temperatures. dR/dt was 1.4 times greater on the north aspect than on the south aspect.

- <u>Layer 3</u> – low incoming shortwave radiation, above 0 °C maximum daily temperature over the previous days, and wind-affected snow on the south aspect from moderate winds out of the SW (field notes). dR/dt was 2.5 times greater on the south aspect than on the north.

- <u>Layer 4</u> – low incoming shortwave radiation, above 0 °C maximum daily temperature over the previous days, moderate-to-strong gusty wind out of the NW. "Wind is moving the top few cm's of snow – quite wind-affected – ripples (field notes)." dR/dt was 1.6 times greater on the north aspect than on the south aspect.

- <u>Layer 5</u> – moderate incoming shortwave radiation, below 0 °C

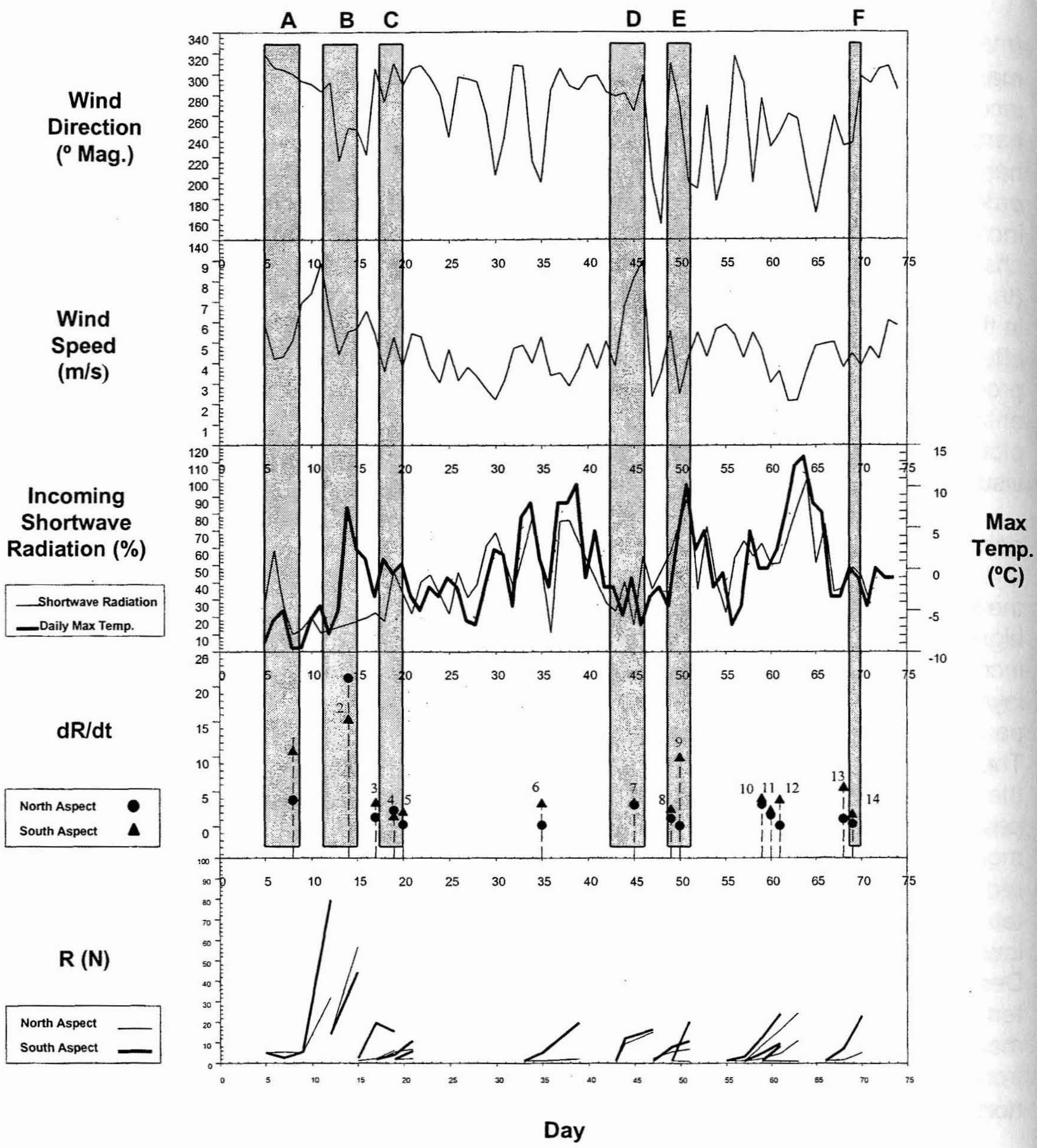

Figure 1 shows wind direction (magnetic degrees), wind speed (m/s), maximum daily temperature (°C), incoming shortwave radiation (%), hardness (N), and dR/dt of hardness over the study period (75 days).

maximum daily temperature on the north aspect, wind-affected snow on the south aspect (field notes). dR/dt was 8 times greater on the south aspect than on the north.

- Layer 6 – high incoming shortwave radiation, above 0 °C maximum daily temperature on the south aspect, below 0 °C on the north, and low wind. dR/dt was 17.8 times greater on the south aspect than on the north.

- Layer 7 – low incoming shortwave radiation, below 0 °C maximum daily temperature, and high wind out of the NW. dR/dt was 1.1 times greater on the south aspect than on the north.

- Layer 8 – moderate incoming shortwave radiation, low maximum daily temperatures, and moderate wind out of the NW. dR/dt was 2.1 times greater on the south aspect than on the north.

- Layer 9 – moderate-to-high incoming shortwave radiation, above 0 °C maximum daily temperature on the south, below 0 °C on the north, and low winds. dR/dt was 98 times greater on the south aspect than on the north.

- Layer 10 – moderate incoming shortwave radiation, slightly above 0 °C maximum daily temperatures over the previous days, and moderate wind out of the NW over the previous days. dR/dt was 1.3 times greater on the south aspect than on the north.

- Layer 11 – moderate-to-low incoming shortwave radiation, slightly above 0 °C maximum daily temperatures over the previous days, and moderate wind out of the NW over the previous days. dR/dt was 1.4 times greater on the south aspect than on the north.

- Layer 12 – moderate incoming shortwave radiation, 0 °C maximum daily temperature on the south aspect, below 0 °C on the north aspect, and low wind. dR/dt was 37 times greater on the south aspect than on the north.

- Layer 13 – high incoming shortwave radiation, above 0 °C maximum daily temperature on the south aspect, below 0 °C on the north aspect, and low wind. dR/dt was 5.5 times greater on the south aspect than on the north.

- Layer 14 – low incoming shortwave radiation, low maximum daily temperature, and low wind. dR/dt was 4.4 times greater on the south aspect than on the north.

Preliminary statistical analysis has not yielded any significant results. Statistical models, however, show promise for describing a quantitative relationship between hardness and weather: the analyses are ongoing.

5. CONCLUSIONS

- Rates and levels of hardness for new snow layers generally increased more rapidly on the south aspect in comparison to the north aspect. Increased input of incoming shortwave radiation increased hardening on the south aspect.
  - This increase occurred during times when clear skies predominated. The difference in hardness between aspects became accentuated when maximum daily temperatures remained below 0 °C on the north aspect despite the predominance of clear skies. Wind speeds also

needed to remain low if blowing from a northerly direction.

- Hardening rates and values on the north aspect approached rates of those on the south aspect when cloudy skies predominated in conjunction with relatively high maximum daily temperatures. Relatively high maximum daily temperatures increased hardening on the north aspect. Hardening on the north aspect tended to surpass the hardening rates and levels on the south aspect if subjected to relatively strong wind with a northerly component.

While this study presents results that we intuitively understand, it provides a quantitative look at the relationship between weather and incoming shortwave radiation and snow-layer hardening with aspect. As a result, it helps to reinforce and calibrate our understanding of slab development. This study is still in progress.

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REFERENCES
Birkeland, K.W., 1998, Snow stability patterns in the Bridger Range, Montana, *Proceedings of the International Snow and Science Workshop,* Sun River, OR, Washington State Department of Transportation, 362-367.

Birkeland, K.W., R.F. Johnson and D. Herzberg, 1996, The stuffblock snow stability test, Technical Report 9623-2836-MTDC. U.S. Department of Agriculture Forest Service, Missoula Technology and Development Center, Missoula, Montana, 20 pp.

Dexter, L.R., 1986, Aspect and Elevation Effects on the Structure of the Seasonal Snowcover in Colorado, Ph. D. dissertation, Dept. of Geography, University of Colorado, Boulder, Colorado, 1986.

McClung, D., and J. Schweizer, 1996, Effect of snow temperatures on skier triggering of dry slab avalanches, *Proceeding of the International Snow and Science Workshop*, Banff, Alberta, The Canadian Avalanche Association, 113-117.

McClung, D., and J. Schweizer, 1999, Skier triggering, snow temperatures and the stability index for dry-slab avalanche initiation, *Journal of Glaciology*, 45(150), 190-200.

Schweizer, J., 1993, The influence of the layered character of snow cover on the triggering of slab avalanches, *Annals of Glaciology*, 18, 193-198.