Predicting Snow Layer Hardness with Meteorological Factors

Mark C. Kozak*[1], Kelly Elder[2], Karl Birkeland[3], and Phillip Chapman[4]
[1]Dept. of Earth Resources, Colorado State University, Fort Collins, Colorado
[2]Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colorado
[3]National Avalanche Center, USDA Forest Service, Bozeman, Montana
[4]Dept. of Statistics, Colorado State University, Fort Collins, Colorado

Abstract: The majority of slab avalanche accidents occur when the victim triggers the slide. Slab hardness is an important property affecting skier-triggered avalanches because hardness partially determines whether sufficient stress reaches the weak layer to cause failure and/or fracture. This study examines how new and old snow layer hardness varies with aspect and which meteorological variables most influence those changes. 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, Wyoming. Continuous weather data were obtained from weather stations at Jackson Hole Mountain Resort. Analyses were carried out on new and older near-surface snow layers. A temperature index was calculated for the south and north aspects to describe the delayed effect of increasing temperature on increasing hardness through sintering, settlement, and densification. The south temperature index, maximum daily temperature, and the interaction between maximum daily temperature and incoming shortwave radiation were the most significant predictors of new snow layer hardness on the south aspect. The north temperature index, maximum daily temperature, and the previous day's wind speed were the most significant predictors of new snow layer hardness on the north aspect. The temperature index was the only significant predictor of old snow layer hardness on both the north and south aspects. The results of this research suggest that it may be possible to use meteorological factors to predict changes in snow hardness – an important component in predicting skier-triggered avalanches.

Keywords: skier-triggered avalanches, hardness, temperature index

1. Introduction

On a yearly basis, avalanches kill many backcountry recreationalists such as skiers, snowboarders, and snowmobilers. The majority of those caught and killed in avalanches trigger the slide. In the Swiss Alps, ten years of avalanche statistics (1987 – 1997) found that 85% of the victims caught in avalanches trigger the slide. That rate could be even higher in North America where snowmobilers contribute to the avalanche death toll (Jamieson and Johnston, 1992; Westwide Avalanche Network, 2001). The concept of the victim triggering the slide is often referred to as skier triggering (Schweizer and Camponovo, 2001). Any load, whether it is skier, snowmobiler, or the addition of new snow, results in deformation to the snowpack. Hardness, which is defined as the initial resistance to deformation per square unit area, controls deformation in a layer (McClung and Schweizer, 1996). Schweizer (1993) found that slab thickness, slab hardness, and the layering within the slab appear to be the primary slab properties that affect skier triggering.

The ability to accurately assess instability is also complicated by the spatial and temporal variability of snowpack characteristics (Schweizer, et al., 1995; McClung and Schweizer, 1999). These variations can be partly attributed to terrain effects, including how the energy balance varies with aspect as well as variations in mesoscale and microscale meteorology.

Because of the importance of hardness to skier-triggered avalanches, this study focuses upon the spatial and temporal variability of snow layer hardness and the meteorological properties influencing snow layer hardness. Accordingly, based upon previous studies and their interpretations, we hypothesize that a quantitative relationship should exist between the hardness of snow layers on north and south aspects and meteorological conditions such as temperature, wind speed, and incoming shortwave radiation.

* *Corresponding author address*: Mark Kozak, P.O. Box 1462, Wilson, WY 83014; tel: 307-413-1000; e-mail: kozakmail@usa.net

2. Literature Review

Hardness is not a physical parameter, but a state characterized 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).

McClung and Schweizer found that temperature affects slab properties. While cold temperatures increase hardness and slab strength, warm temperatures decrease hardness – a decrease that allows deformation to result deeper in the slab and thus increases the chances of failure in the weak layer. Over time, however, this warming increases strength and hardness due to settlement, densification, and sintering (McClung and Schweizer, 1999).

The spatial variability of snowpack properties complicates prediction of where and when an avalanche will occur. Avalanche professionals recognize that spatial patterns exist across avalanche terrain (Birkeland, 2001). 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 (2001) in the Bridger Range in Montana. His study found that terrain can be correlated to snowpack stability, and that stability decreased on northerly aspects and at higher elevations on two sampling days.

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, Wyoming. North and south study plots were established at elevations between 2400 and 2600 meters above sea level. Both plots were sampled on the same day, every other day.

Ram numbers (N) were graphed against depth (cm) to create hardness profiles of the top 200 cm of the snowpack. Profiles were grouped by aspect and annotated by age of layer. The annotated profiles made it possible to compare layers of the same age on both aspects. A weighted-average value of hardness was calculated for each layer so that they could be statistically compared.

Weather data, including air temperature, wind speed, and wind direction, were recorded every hour at three on-mountain weather stations. Maximum, minimum, and current air temperature were also recorded from max/min thermometers at each of the study plots. Daily incoming shortwave radiation was measured with a pyranometer at approximately 2750 meters above sea level. The amount of incoming shortwave radiation was quantified in the form of an index as a percentage of maximum daily incoming shortwave radiation. We used an index since instrumentation was not available to measure absolute values of incoming shortwave radiation. This radiation index was calculated by digitizing the area under the scribed curve and dividing it by the maximum scribed area for a perfectly clear day (March 8, 2000).

3.1 Air Temperature

For this study, maximum daily temperature was used as the basis for all temperature indices created to assess the influence of temperature on snow layer hardness (Doeskin, 1999). A separate temperature index was also created to describe the delayed effect that temperature had on increasing hardness by increasing settlement, densification, and sintering (McClung and Schweizer, 1999). This index attempted to summarize a physical effect that was occurring over a multiple-day to monthly time period into a single index. The temperature index was used as a predictor to model layer hardness.

A degree-day method was used as the conceptual foundation for the temperature index. Degrees above a base temperature of –10 °C were accumulated for each day within the temperature index period. The base temperature of –10°C was chosen for the temperature index based on the finding that sintering increases rapidly above –10°C (Gubler, 1982). The index was calculated by subtracting -10°C from the maximum daily temperature when it exceeded –10 °C and then adding the degrees for each day after the layer was deposited or tracking it had begun. By this method, a warmer day would have a higher individual day index than a colder day. It was hypothesized that this temperature association would be indicative of the degree of settlement, densification, and sintering that occurred as ambient air temperatures increased. Adding the daily indices described the cumulative effect that temperature had on changes in hardness over a multiple-day period.

3.2 New Snow Layers

Fourteen new snow layers were analyzed over the course of this study period. Changes in hardness were observed and measured between two and eight days after deposition. The average period over which new snow layer hardness was measured was four days. These layers were tracked until they became buried by new snowfall or until it was too difficult to accurately differentiate the new snow layer from the older snow beneath it. A variety of predictors, summarized in Table 1, were used to try to effectively model new snow layer hardness.

Table 1. Independent variables used to predict new snow layer hardness.

Symbol	Independent Variable
(T)	maximum daily temperature
(T_N)	north maximum daily temperature
(T_{NP})	previous day's north maximum daily temperature
(T_S)	south maximum daily temperature
(T_{SP})	previous day's south maximum daily temperature
(T_{NI})	north temperature index
(T_{SI})	south temperature index
(S)	incoming shortwave radiation
(S_P)	previous day's incoming shortwave radiation
(W)	average wind speed
(W_P)	previous day's average wind speed
(D)	average wind direction
(D_P)	previous day's average wind direction
(T_NS)	interaction between north maximumdaily temperature and incoming shortwave radiation
(T_SS)	interaction between south maximum daily temperature and incoming shortwave radiation

While there are numerous predictors listed in Table 1, they can be divided into five categories. Four of the five categories include air temperature, incoming shortwave radiation, wind speed, and wind direction. These categories were chosen as predictors because they have all been identified in the scientific literature as factors affecting snow layer hardness (McClung and Schaerer, 1993). The fifth category, interaction, is created by multiplying two variables together and using it as a single variable to predict hardness. The interaction term is a statistical technique that attempts to explain a nonlinear relationship between two variables such as incoming shortwave radiation and maximum daily temperature. Combining the two variables into a single term describes the physical effect that both terms have as they work together to reinforce the effects of each other.

Maximum daily temperature was used as a predictor to model new snow layer hardness because hardness initially decreases as air temperature increases. However, over a longer time scale, hardness increases due to sintering, settlement, and densification (McClung and Schweizer, 1999). The temperature indices and the previous day's maximum daily temperature are predictors that attempt to describe this delayed hardening effect.

Incoming shortwave radiation has been found to affect ambient air temperatures and snowpack properties including hardness (Whiteman, 2000). The snowpack absorbs and reflects incoming shortwave radiation, and this causes changes in snowpack properties as well as near surface ambient air temperatures (Male and Granger, 1981; Gubler, 1992; Whiteman, 2000). Daily and previous day's incoming shortwave radiation are both used to predict changes in the hardness of new snow layers.

Previous studies have suggested that wind is an important factor regarding snow transport and hardening. Wind speed affects the carrying capacity of the wind in addition to the wind's ability to scour and compact snow surfaces (McClung and Schaerer, 1993). Wind direction influences which slopes and aspects are affected by strong wind speeds. Previous day's conditions are also considered for both wind speed and direction predictors.

Interactions between many of these variables were also used as single predictors to model new snow hardness. Because of the inherent complexity of an interaction, several combinations of temperature, incoming shortwave radiation, and wind predictors were tested without our having a preconceived understanding of how the interaction of two particular independent variables might affect the dependent variable.

3.3 Old Snow Layers

The hardness of five old snow layers were tracked over the course of the three-month study period, and were qualitatively and statistically analyzed to understand which physical-related weather properties (temperature, incoming shortwave radiation, wind speed, and wind direction) most influenced changes in the hardness of old snow layers. Layers of the same age were determined by comparing precipitation, grain type, and ram profiles between aspects. Weighted-averages of hardness (N) were calculated from profiles of ram numbers plotted over time. Simple and multiple linear regression analyses were used to determine which weather variables most influenced changes in hardness.

Variables were logarithmically transformed in order to normalize and improve the linear fit of the data where appropriate. Predictors used to model old snow layer hardness are summarized in Table 2.

Table 2. Independent variables used to predict old snow layer hardness.

Symbol	Independent Variable
(T)	maximum daily temperature
(T_N)	north maximum daily temperature
(T_{NP})	previous day's north maximum daily temperature
(T_S)	south maximum daily temperature
(T_{SP})	previous day's south maximum daily temperature
(T_{NI})	north temperature index
(T_{SI})	south temperature index
(S)	incoming shortwave radiation
(S_P)	previous day's incoming shortwave radiation

4. Results

4.1 New Snow Layers

4.1.1 South Aspect

The multiple regression model that predicts new snow layer hardness (R_S) on the south aspect can be described by the following linear relationship (R^2 = 0.79, $p < 0.0005$, n = 42):

$$\log R_S = 0.056T_{SI} - 0.14T_S + 0.001T_SS - 0.44 \qquad (1)$$

where T_{SI} is the south temperature index, T_S is the maximum daily temperature for the south aspect, and T_SS is the interaction between the average incoming shortwave radiation and the maximum daily temperature. Table 3 provides descriptive statistics for the variables used in equation 1. The negative sign in front of south maximum daily temperature implies that as temperature decreases, hardness increases. This inverse relationship describes the short-term effect of how warming air temperatures decrease snow layer hardness. The south temperature index term helps to explain the delayed effect that temperature has on hardness. The interaction between incoming shortwave radiation and the temperature term explains the combined effect of two nonlinear variables in increasing layer hardness on the south aspect by encouraging settlement and densification. Direct exposure to incoming shortwave radiation on the south aspect can raise ambient air and snow temperatures on the south aspect without causing similar effects on the north aspect.

Table 3. Summary statistics for the south temperature index, maximum daily temperature, the interaction between maximum daily temperature and incoming shortwave radiation, and new snow layer hardness on the south aspect. T_{SI} and T_S in °C, T_SS is in °C.

variable	range	mean	standard deviation	p - value
T_{SI}	4 to 54	19	11.5	< 0.0005
T_S	-7 to 8	-1	3.9	< 0.0005
T_SS	-225 to 657	41	262.7	0.011
R_S	1 to 80	10	14.5	< 0.0005

4.1.2 North Aspect

The multiple regression model that predicts new snow layer hardness (R_N) on the north aspect can be described by the following linear relationship (R^2 = 0.42, p-value < 0.0005, n = 42):

$$\log R_N = 0.049T_{NI} + 0.026W_P - 0.08T_N - 0.75 \qquad (2)$$

where T_{NI} is the north temperature index, W_P is the previous day's wind speed, and T_N is the north study site's maximum daily temperature. Table 4 provides descriptive statistics on variables used in equation 2.

Table 4. Summary statistics for the north temperature index, previous day wind speed, maximum daily temperature, and new snow layer hardness on the north aspect. T_{NI} and T_N are in °C, W_P is in m/s, and R_N is in N.

variable	range	mean	standard deviation	p-value
T_{NI}	2 to 37	12	8.1	< 0.0005
W_P	5 to 38	12	7.4	0.009
T_N	-8 to 3	-4	3.0	0.002
R_N	1 to 57	6	10.4	< 0.0005

Similar to the models that predict hardness on the south aspect, the negative sign in front of the maximum daily temperature implies that as temperature decreases, hardness increases.

The temperature variables are both important predictors of hardness due to the varying time effects of temperature on layer hardness. While the short-term effect of higher temperatures causes a decrease in hardness (the negative sign in front of the adjusted north maximum daily temperature), the delayed effect from higher temperatures causes an increase in hardness due to settlement, densification, and possibly sintering (the positive sign in front of the north temperature index).

Previous day's wind speed was also a significant predictor of new snow layer hardness on the north aspect. These findings agreed well with field observations as well as with conclusions drawn from the qualitative analyses (Kozak, 2002). The hardness of new snow layers on the north aspect significantly increased during periods of heavy wind.

4.2 Old Snow Layers

Three out of five old snow layers (A, B, C) were observed over the course of the entire study period. The remaining two layers (D, E) were only observed through the final one-third of the study period because these two layers did not originate until two-thirds of the way through.

4.2.1 South Aspect

All the old snow layer data are combined to create a model that predicts old snow layer hardness on the south aspect. After combining all the data, a logarithmic transformation is also performed on the hardness data to equalize the variance and to improve the linearity of the model. The resultant model is:

$$\log R_S = 0.002T_{SI} + 1.40 \qquad (3)$$

where T_{SI} is the south temperature index. This model has an R^2 of 0.70 with an associated p-value < 0.0005 (n = 60) (Figure 1). Table 5 provides descriptive statistics on variables used in equation 3.

Table 5. Summary statistics for old snow layer hardness on the south aspect. R_S is in N.

variable	range	mean	standard deviation
T_{SI}	4 to 613	214	151.2
R_S	1 to 376	101	94.9

Five points depicted as "squares" in Figure 1 were removed from the model because they were physically different from the other data. Four of those five points came from layer C and the remaining came from layer E. Those five points represented the hardness of a new snow layer. Layers C and E were the only layers that were sampled while the layer was solely composed of new snow. The starting hardness for all other layers (A, B, and D) tended to be significantly higher than layers C and E because those layers were already buried and were comprised of older, harder snow.

After combining all the old snow layer data, the south temperature index proves to be the only significant predictor, for it represents in part the delayed effect that temperature has on increasing hardness by encouraging settlement, densification, and sintering.

4.2.2 North Aspect

Combining all the old snow layer data in one scatter plot reveals that two of the five layers (layers C and E) on the north aspect were physically different from the other three old snow layers. Unlike layers A, B, and D, layers C and E were separated from the model because they were measured while still on the surface of the snowpack and were physically different from the other three old snow layers. Separating these layers produced distinctly better results (Figure 2). Layers A, B, and D can be described by the following simple linear relationship:

$$\log R_N = 0.0040T_{NI} + 1.25 \qquad (4)$$

where T_{NI} is the north temperature index. The R^2 for this model is 0.78 with an associated p-value < 0.0005 (n = 50) (Figure 2). Table 6 provides descriptive statistics on variables used in equation 4.

Table 6. Summary statistics for old snow layer hardness on the north aspect. R_N is in N.

variable	range	mean	standard deviation
T_{NI}	2 to 316	146	93.8
R_N	6 to 380	114	100

Layers C and E can be described by the following simple linear relationship:

$$\log R_N = 0.0066T_{NI} + 0.24 \qquad (5)$$

where T_{NI} is the north temperature index. The R^2 for this model is 0.81 with an associated p-value < 0.0005 (n = 32) (Figure 2). Table 7 provides descriptive statistics on variables used in equation 5.

Table 7. Summary statistics for old snow layer hardness for layers C and E on the north aspect. R_N is in N.

variable	range	mean	standard deviation
T_{NI}	4 to 342	155	99.5
R_N	1 to 182	48	52.3

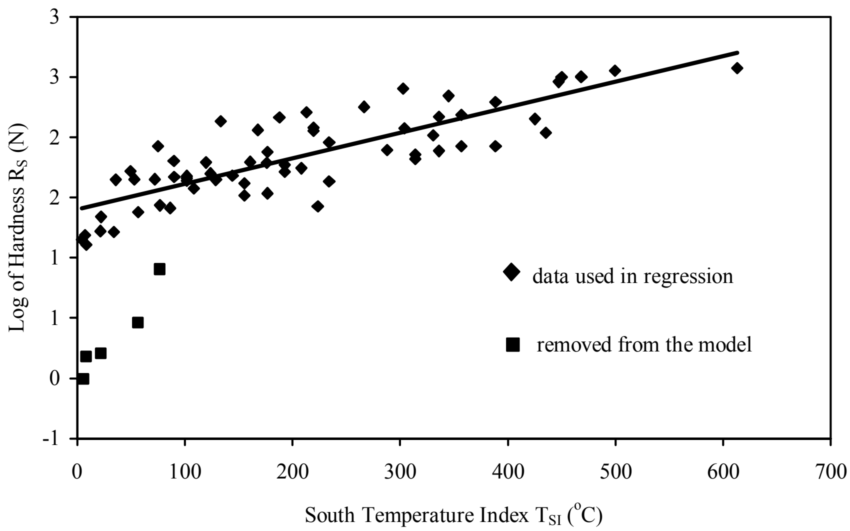

Figure 1. Log of old snow layer hardness vs. south temperature index on the south aspect. Five points were removed from the model because they were physically different from the other points (see text for details). The line represents the best fit line for the simple linear regression ($R^2 = 0.70$, $p < 0.0005$, $n = 60$).

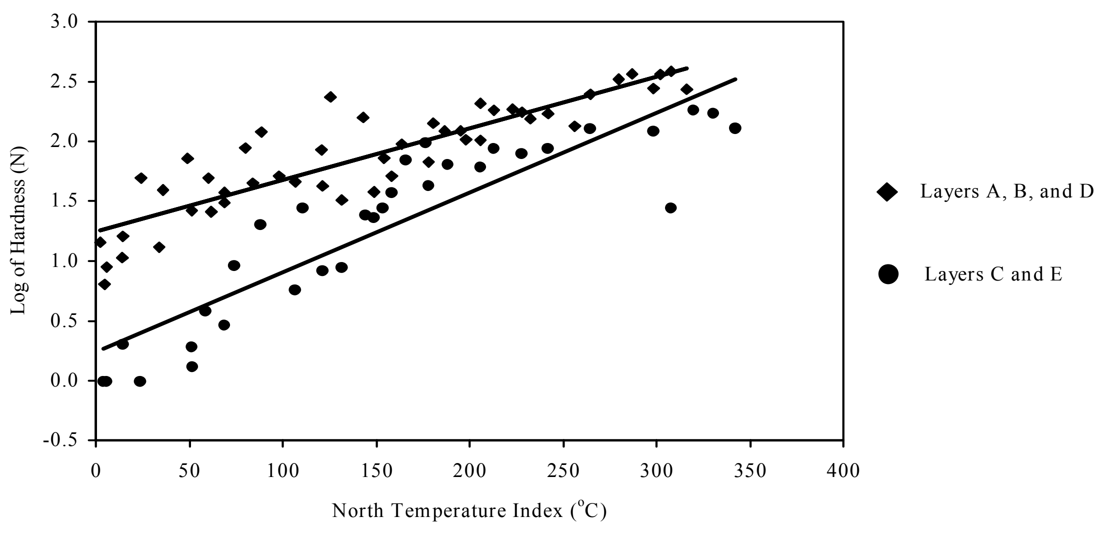

Figure 2. Log of hardness vs. north temperature index on the north aspect. The lines represent the best fit lines for the simple linear regressions ($R^2 = 0.78$, $p < 0.0005$, $n = 48$) for layers A, B, and D and ($R^2 = 0.81$, $p < 0.0005$, $n = 32$) for layers C and E.

After combining all the old snow layer data, the north temperature index remains the only significant predictor of old snow layer hardness. The temperature index attempts to describe the delayed and cumulative effect that temperature has on increasing hardness by encouraging settlement, densification, and sintering over an extended period of time. A likely reason why the temperature index is the only significant predictor is that, like old snow layer hardness, the index also increases over time and varies with temperature. These results support McClung and Schweizer's (1999) findings on the effect of temperature on snow layer hardness.

5. Conclusion

5.1 New Snow Layer Hardness

The most significant predictors of new snow layer hardness on the south aspect were the south temperature index, south maximum daily temperature, and the interaction between south maximum daily temperature and incoming shortwave radiation. This model found that an inverse relationship exists between the south maximum daily temperature and new snow layer hardness. A positive relationship exists between new snow layer hardness and the interaction between south maximum daily temperature and incoming shortwave radiation. The model also indicates that a positive relationship exists between the south temperature index and new snow layer hardness.

The linear multiple regression model created to predict new snow layer hardness on the north aspect indicates that the most significant predictors of new snow layer hardness were the north temperature index, previous day's wind speed, and north maximum daily temperature. A positive relationship exists between both the north temperature index and the previous day's wind speed and new snow layer hardness.

5.2 Old Snow Layer Hardness

The same temperature index that predicts new snow layer hardness also describes the delayed effect that temperature has on increasing old snow layer hardness. Despite the fact that warming temperatures reduce snow layer hardness at the time of warming, the long-term effect is an increase in hardness due to a suspected increase in sintering, settlement, and densification. The models indicate that as maximum daily temperature increases, hardness decreases. The models also consistently indicate a positive relationship between the temperature index and hardness. The temperature index is the only significant predictor of old snow layer hardness in all of the models.

Hardness is found to increase over time and to be affected by air temperature and the influence of incoming shortwave radiation. The results of this research suggest that it may be possible to use meteorological factors to remotely predict changes in snow hardness, an important component in predicting skier-triggered avalanches.

6. References

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