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Variability of snow layer hardness by aspect and prediction using meteorological factors

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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. New snow layer hardness increased most rapidly on the south aspect due to accelerated settlement and densification from warming by incoming shortwave radiation. With the exception of the surface layer, old snow layers, 2 months after deposition, became harder on the north aspect in comparison to the south aspect. 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, which is 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, 10 years of avalanche statistics (1987–1997) found that

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85% of the victims caught in avalanches triggers 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, 1999). 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; Birkeland and Landry, 2002). 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 not only should snow hardness for the same snow layer vary spatially by aspect and over time, but also 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.

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, 1999).

McClung and Schweizer (1999) 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 the 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. Recent research on a single slope by Birkeland and Landry (2002) suggests that stability varies 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, Wyoming (Fig. 1). North and south study plots were established at elevations between 2400 and 2600 m 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

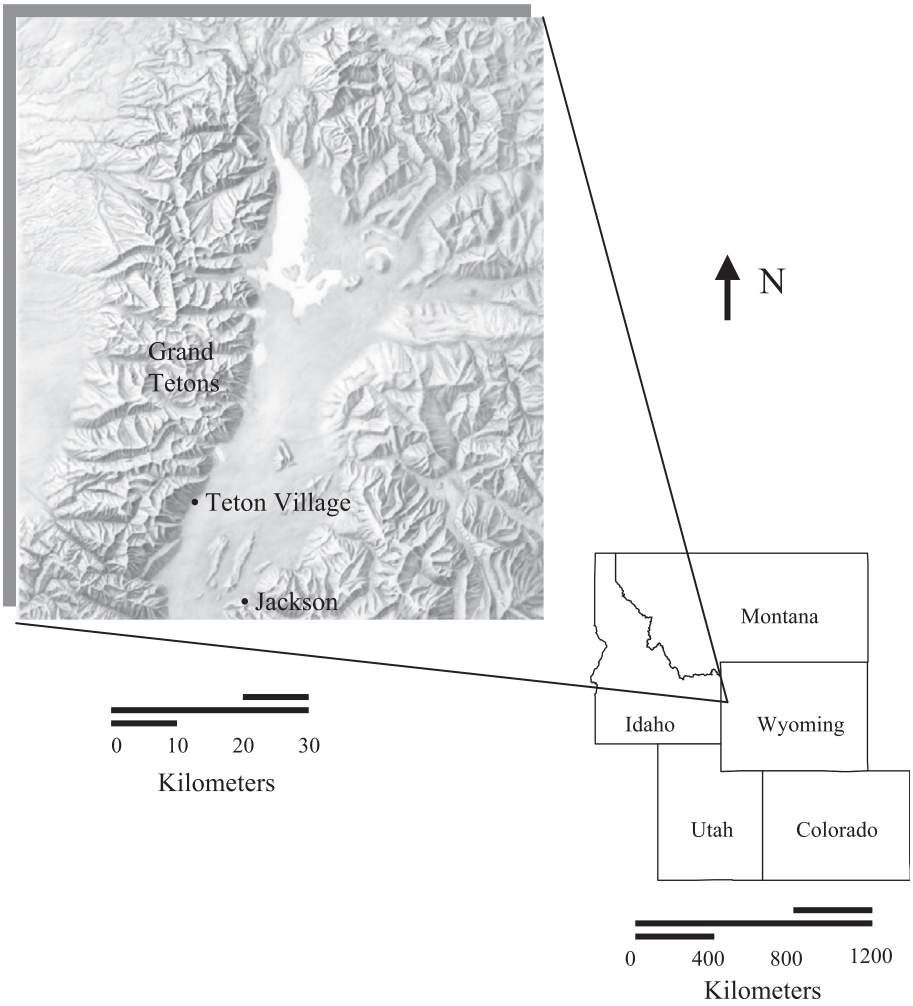

Fig. 1. Contiguous map of the Rocky Mountain states with a relief map of the Jackson Hole region (source: http://www.nps.gov/grte/pphtml/maps.html, 2001). North and south study plots are located (514, 200 E/4, 828, 500 N UTM) at the Jackson Hole Mountain Resort in Teton Village.

measured with a pyranometer at a single weather station at approximately 2750 m 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 had 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. Incoming solar radiation

Although actual radiation was not measured at the different sites, a FORTRAN algorithm (Whiteman, 2000) made it possible to calculate the theoretical amount of incoming solar radiation that was being received on a daily basis for the south and north study sites. A theoretical daily total of incoming shortwave radiation (MJ/m^2) was calculated for each study site for the 15th day of the month for December, January, February, and March. These calculations were used as an index of differences in potential incoming shortwave radiation with aspect. These calculations were performed in order to explain how the difference in incoming shortwave radiation might affect development of certain snowpack properties on different aspects.

3.3. New snow layers

Fourteen new snow layers were analyzed over the course of this study period. Changes in hardness were observed and measured between 2 and 8 days after deposition. The average period over which new snow layer hardness was measured was 4 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.

While numerous predictors are 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. How-

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
$T_{\mathrm{N}}S$	interaction between north maximum daily temperature and incoming shortwave radiation
$T_{\mathrm{S}}S$	interaction between south maximum daily temperature and incoming shortwave radiation

ever, 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 transport breaks grains down into smaller particles. As a result, grains are deposited closer together which encourages sintering and hardening of the wind-deposited layer (Miller, 2002). Wind direction and terrain influence which slopes and aspects are affected by strong wind speeds (Whiteman, 2000). 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.

3.4. Old snow layers

The hardness of five old snow layers was tracked over the course of the 3-month study period, and was 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 and discussion

4.1. New snow layers

4.1.1. Qualitative analysis

The rate of change in hardness was used as the primary means to qualitatively compare new snow layer hardness on north and south aspects. Fig. 2 shows wind direction (true), 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 $\mathrm{d}R/\mathrm{d}t$ fall in the middle of an observation period that often lasted 7–8 days. Although the process of hardening occurred over the entire observation period, the point is plotted in the middle of the observation period for visual convenience.

When compared to the north aspect, hardness of new snow layers generally increased more rapidly on the south aspect and ultimately reached a higher value

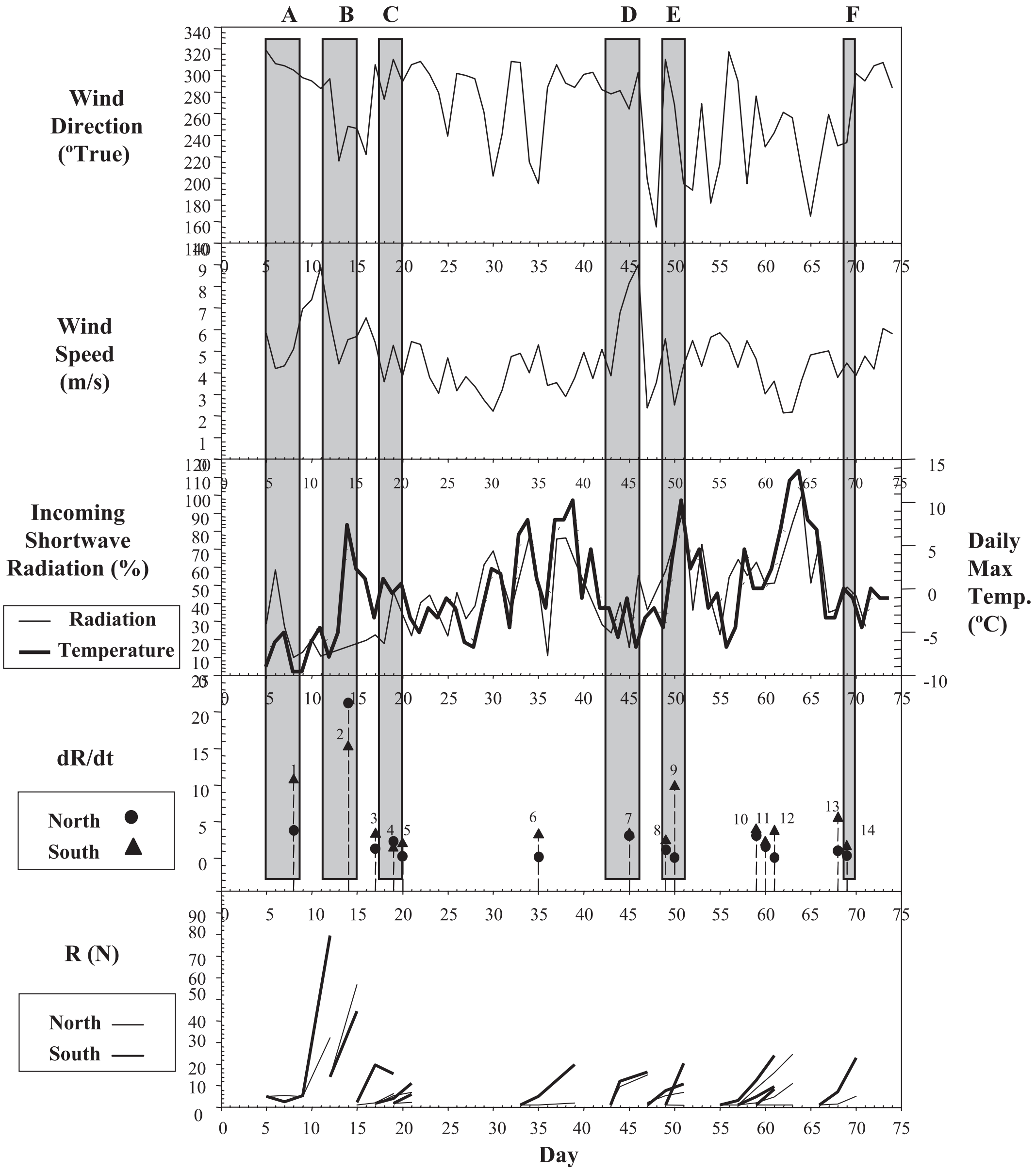

Fig. 2. Qualitative new snow layer analysis using wind direction (true), wind speed (m/s), maximum daily temperature (°C), incoming shortwave radiation (% of the maximum daily incoming shortwave radiation), d*R*/d*t* of new snow layer hardness for 1.4 new snow layers, hardness *R* as a ram number (*N*). Shaded areas A, B, C, D, E, and F are highlighted areas that are discussed in the text.

of hardness. Increases in hardness for new snow layers on the south aspect tended to accompany increases in shortwave radiation. The difference in rate of change between the south and north aspects became accentuated during periods of moderate-to-high input of shortwave radiation, maximum daily temperatures below 0 °C (on the north aspect), and low wind (A and E in Fig. 2). 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 maximum daily temperatures depicted in Fig.

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

Variable	Range	Mean	Standard deviation	p-value
T_{SI}	4–54	19	11.5	< 0.0005
T_S	7–8	− 1	3.9	< 0.0005
$T_S S$	− 225–657	41	262.7	0.011
R_S	1–80	10	14.5	< 0.0005

T_{SI}, T_S, and $T_S S$ are in °C.

2 were recorded at the Raymer Study Plot (Jackson Hole Mountain Resort's weather station).

The difference in rate of change between south and north aspects was smaller during periods of moderate-to-low incoming shortwave radiation, maximum daily temperatures above 0 °C (on the north plot), and moderate-to-heavy wind with a northerly component (B, C, and D in Fig. 2). This difference was also lower during periods of low incoming shortwave radiation, low maximum daily temperature, and low wind (F in Fig. 2). Multiple linear regression analyses corroborate findings from the qualitative analyses.

4.1.2. Quantitative analysis

4.1.2.1. 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 ($R^2 = 0.79$, $p < 0.0005$, $n = 42$):

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

where T_{SI} is the south temperature index, T_S is the maximum daily temperature for the south aspect, and $T_S S$ is the interaction between the average incoming shortwave radiation and the maximum daily temperature. Table 3 provides descriptive statistics for the variables used in Eq. (1). The negative sign in front of the 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.

4.1.2.2. 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, $n = 42$):

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

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 Eq. (2). 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

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

Variable	Range	Mean	Standard deviation	p-value
T_{NI}	2–37	12	8.1	< 0.0005
W_P	5–38	12	7.4	0.009
T_N	− 8–3	− 4	3.0	0.002
R_N	1–57	6	10.4	< 0.0005

T_{NI} and T_N are in °C, W_P is in m/s, and R_N is in N.

qualitative analyses (Kozak, 2002). The hardness of new snow layers on the north aspect significantly increased during periods of heavy wind from the north and northwest.

4.2. Old snow layers

4.2.1. Qualitative analysis

Three out of five old snow layers (A, B, C) (Figs. 3 and 4) 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 the study period. In addition to measuring hardness, other snowpack properties such as grain size, grain type, density, temperature, and location were also measured in order to deduce changes in settlement, densification, and possible sintering of a particular layer. Layer A is at the greatest depth beneath the surface of the snowpack because it was the first layer tracked. Layer E is the youngest layer and closest to the surface.

The thickness of layers A, B, and C for the south aspect is documented in Table 5 for the dates of January 21 through January 31 as a means of assessing the potential settlement on the south aspect. Despite the fluctuation (most likely due to spatial variability) in the thickness of layer A between January 25 and January 27, the thickness essentially remains the same over the four observation dates. The thickness of layer A most likely does not change because it is located at a great enough depth to be insulated from ambient air temperatures.

Table 5
Old snow layer thickness for layers A, B, and C on the south aspect with respect to date

South aspect			
Date	Layer A	Layer B	Layer C
January 21	92 − 44 = **48**	44 − 0 = **44**	NA
January 25	112 − 60 = **52**	60 − 27 = **33**	27 − 0 = **27**
January 27	112 − 64 = **48**	64 − 32 = **32**	31 − 0 = **31**
January 31	96 − 48 = **48**	48 − 19 = **29**	19 − 0 = **19**

Layer thickness, in cm and in bold print, was determined by subtracting the location of the upper boundary of the layer from the location of the lower boundary.

The majority of settlement appears to occur in the near-surface layers (B and C). The thickness of layers B and C decreases considerably between January 21 and January 31. While it is difficult to verify settlement without a fixed reference, this deduction seems to be a logical one.

The thickness of layers A, B, and C for the north aspect is documented in Table 6 for the dates of January 21 through January 31 as a means of assessing the potential settlement on the north aspect. Despite a reduction in thickness of layer A by 4 cm

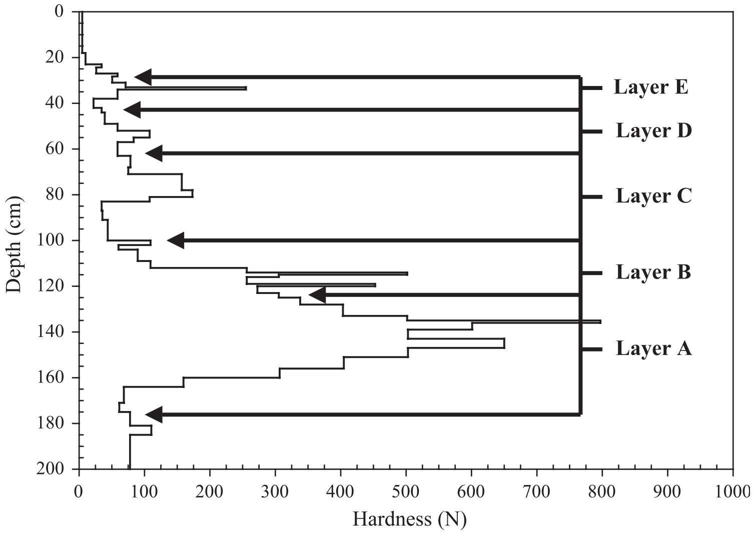

Fig. 3. Ram penetrometer profile of the south aspect on March 3, 2000.

Table 6
Old snow layer thickness for layers A, B, and C on the north aspect with respect to date

North aspect			
Date	Layer A	Layer B	Layer C
January 21	120 – 44 = **76**	44 – 0 = **44**	NA
January 25	146 – 74 = **72**	74 – 32 = **42**	32 – 0 = **32**
January 27	170 – 74 = **96**	74 – 32 = **42**	32 – 0 = **32**
January 31	NA	NA	NA

Layer thickness, in cm and in bold print, was determined by subtracting the location of the upper boundary of the layer from the location of the lower boundary.

between January 21 and January 25, the thickness of layer A on the north aspect is approximately 24 cm thicker on January 27. A probable explanation for this change in thickness is the spatial variability across the sampling slope as well as moderate wind speeds from the northwest that potentially transported and deposited additional snow on the sampling slope during this particular observation period.

That the upper boundary of layer A remains in the same location between the 25th and the 27th also supports the spatial variability explanation. There is minimal-to-no change in layer thickness for layers B and C. Settlement is not apparent on the north aspect from the data in Table 6.

Increased settlement on the south aspect was speculated to be the result of warming due to increased solar radiation. Results from FORTRAN algorithms found that while both aspects received increasing shortwave radiation through the study period from January 5 through March 15, 2000, incoming shortwave radiation also varied with aspect. The south aspect received considerably more incoming shortwave radiation than the north study site (Table 7). Although the study period did not include December, incoming shortwave radiation for the month of December is included in the table for general interest. The magnitude of difference in incoming shortwave radiation between the north and south study sites decreased considerably toward the end of the study period.

Table 7
Difference in incoming shortwave radiation between the north and south study sites for the 15th of December, January, February, and March

Date	South study site	North study site	Ratio south/north
December 15	28.2	0.8	37:1
January 15	29.4	1.5	20:1
February 15	33.2	5.5	6:1
March 15	36.2	12.4	3:1

Daily incoming shortwave radiation is in MJ/m^2.

Table 8
Weighted average of old snow hardness (N) for layers A, B, and C on the south aspect with respect to date

South aspect			
Date	Layer A	Layer B	Layer C
January 21	64	8	NA
January 25	62	13	2
January 27	137	22	2
January 31	115	24	3

While the weighted average values of hardness of old snow layers are similar on south and north aspects, layers A and B on the south aspect are slightly higher (Tables 8 and 9). Interestingly, the rate of change of hardness between the north and south aspect for layers A and B from January 21 to January 27 is roughly equal (12 N/day for layer A, 2 N/day for layer B).

By March 3 (58th day of the study period), the lower boundary of layer A on the south aspect was at a depth of approximately 175 cm below the surface of the snow (Fig. 3). This location is a little more than 50 cm deeper than the location of the lower boundary of layer A on January 31 despite the addition of approximately 180 cm of new snow. The weighted-average of hardness of layer A also increased to 356 N. These two changes indicate that considerable settlement and densification occurred on the south aspect between January 31 and March 3. While hardness measurements were performed on a daily basis through the entire study period, March 3rd was chosen as a random date for comparison purposes.

Table 9
Weighted average of old snow hardness (N) for layers A, B, and C on the north aspect with respect to date

North aspect			
Date	Layer A	Layer B	Layer C
January 21	50	4	NA
January 25	88	9	1
January 27	120	16	2
January 31	NA	NA	NA

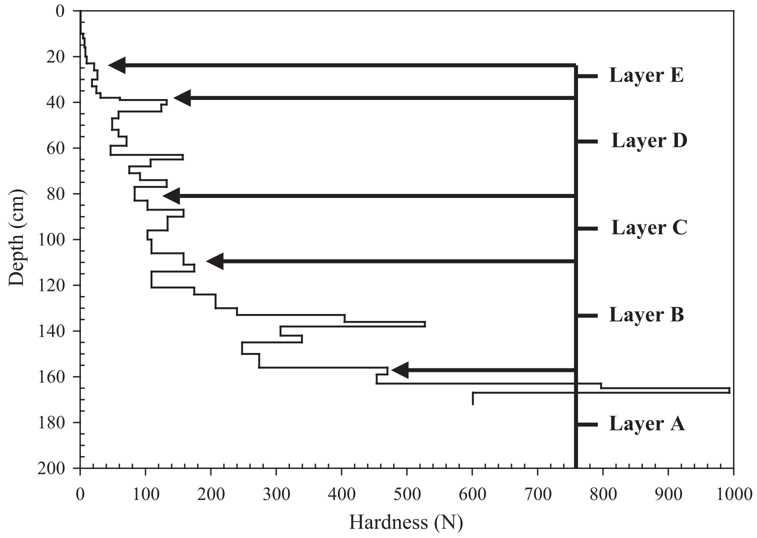

Fig. 4. Ram penetrometer profile of the north aspect on March 3, 2000.

The thin hard layer at a depth of 32 cm below the snow surface on the south aspect is most likely a melt-freeze crust that formed as a result of incoming shortwave radiation. While thin hard layers on the south aspect appear to generally become substantially harder than thin hard layers on the north aspect (Fig. 4), the snow bordering these thin hard layers on the south aspect is usually less hard than the surrounding snow on the north aspect. Thin hard layers on the north aspect were generally the result of wind hardening.

By March 3, layers A, B, C, and D on the north aspect had strengthened considerably since January 31 and surpassed hardness values on the south aspect (Table 10). Although the lower boundary of layer A is deeper than 200 cm, it is still possible to speculate that the weighted average of hardness also increased for this layer. Settlement does not appear to have occurred as much on the north aspect in comparison to the south aspect. It is interesting to note that while the hardness values of layers B, C, and D on the north aspect surpassed the hardness values of the same layers on the south aspect, layer E on the north aspect remained considerably less hard than layer E on the south aspect. This discrepancy between aspects suggests that different factors (e.g. energy balance) affect the hardness of surface layers on the north and south aspects. Layer E was probably densifying due to increased incoming shortwave radiation on the south aspect. Near-surface faceting (diurnal recrystallization) may possibly have kept layer E soft on the north aspect. Density of old snow layers also increased on both north and south aspects (Table 11). Density values continued to increase on the north aspect after February 26 while values on the south aspect, although maintaining an increasing trend, often fluctuated. By early March, lower layers on the north aspect

Table 10
Weighted average of old snow layer hardness with aspect on March 3, 2000

Layer	South aspect	North aspect
A	356	NA
B	195	248
C	85	126
D	61	85
E	62	28

Hardness is in N.

Table 11
Density of old snow layer B on north and south aspect with respect to date

Date	South aspect	North aspect
January 27	180	170
February 16	300	240
February 26	270	300

Density is in kg/m^3.

achieved a density that made it difficult to accurately measure without distorting the 250-cm^3 density cutter.

While settlement and densification were probably the dominant factors contributing to increases in hardness on the south aspect and to some extent on the north aspect, the level of hardness and density that was achieved on the north aspect must have been caused by sintering. Although sintering was not measured in this study, temperature gradients were measured; temperature gradients are related to vapor pressure gradients which in a general sense reflect the kind of snow metamorphism occurring in the snowpack.

On January 27, the snowpack on the north aspect (Fig. 5) was considerably colder than the snowpack on the south aspect, particularly at the surface. While a critical temperature gradient of approximately 10 °C/m existed within the top 20 cm of the snowpack on the north aspect, a relatively smooth transition in temperature existed down to 150 cm below the surface—another possible indication of sintering. A substantial temperature gradient (20 °C/m) existed in the active layer (top 30 cm) of the snowpack on the south aspect. It also appears that sintering was likely occurring in select layers at deeper depths on the south aspect. Since these temperature measurements were not made at the same time of day (13:00 MST on the south aspect and 16:00 MST on the north aspect), there is the potential for error between these temperature gradient comparisons.

Temperature gradients were also measured on north and south aspects on February 20, 2000 (Fig. 6). Similar temperature gradient conditions to the ones observed in January were also found in the active layer (30 °C/m) and between 50 and 60 cm (20 °C/m) on the south aspect. Near-surface faceting most likely occurred as a result of these gradients (Birkeland, 1998). These cases suggest that while faceting was likely occurring in the active layer on the south aspect and to some degree on the north aspect, sintering was probably occurring within deep old snow layers on both aspects. These settlement, density, and temperature results suggest, like the findings by McClung and Schweizer (1999), that hardness increases due to sintering, settlement, and densification.

We initially conducted a qualitative analysis to investigate the relationship between physical weather properties such as incoming shortwave radiation, maximum daily temperature, wind speed, and wind direction and old snow layer hardness. Even though wind speed and wind direction were not expected to have much of an influence on buried snow layers,

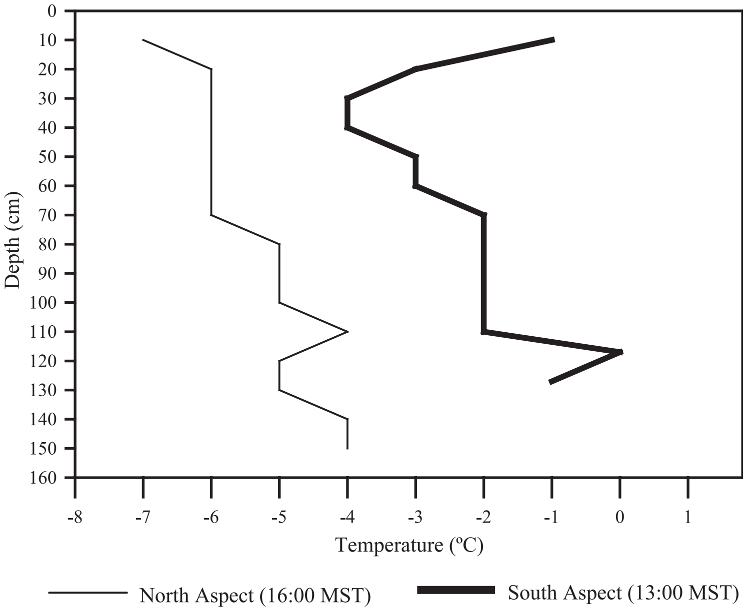

Fig. 5. Temperature profile of north and south aspects on January 27, 2000.

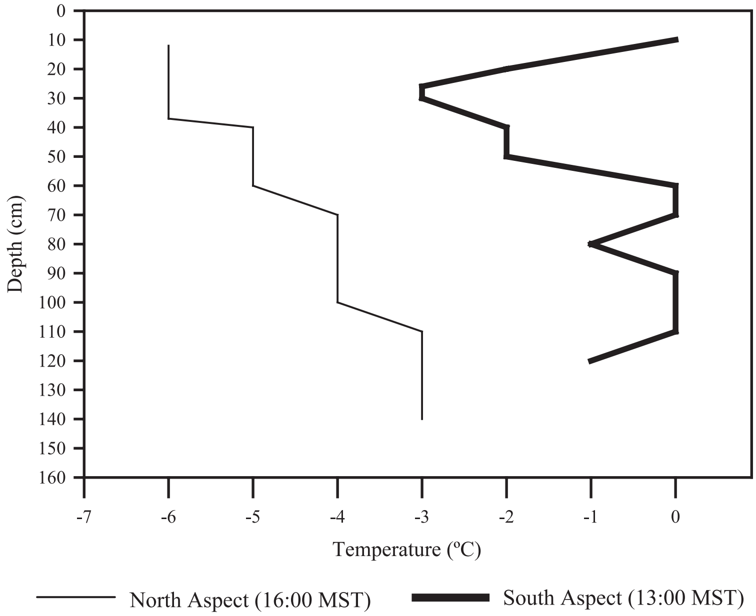

Fig. 6. Temperature profile of north and south aspects on February 20, 2000.

there was also no obvious apparent relationship between maximum daily temperature and old snow layer hardness. We, however, suspected a delayed hardening effect associated with maximum daily temperature. The same temperature index that was used for the new snow layer hardness was also applied to the old snow layer analyses.

4.2.2. Quantitative analysis

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.

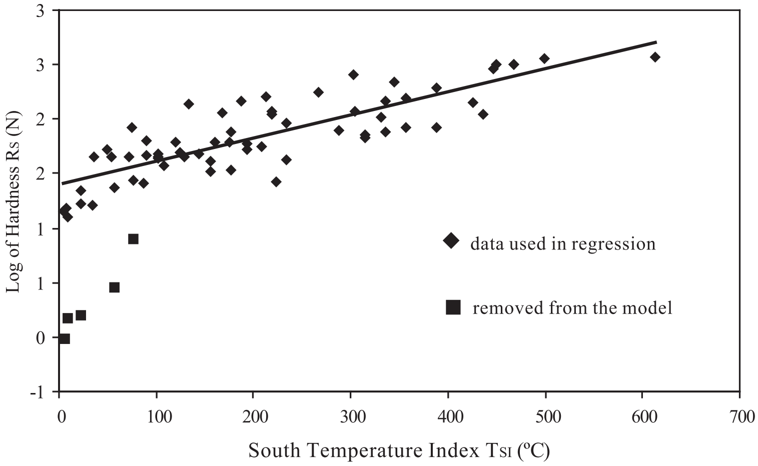

Fig. 7. Log of old snow layer hardness vs. south temperature index on the south aspect. Five points were removed from the model because they were physically different from the other points (see text for details). ($R^2 = 0.70$, $p < 0.0005$, $n = 60$).

Table 12
Summary statistics for old snow layer hardness on the south aspect

Variable	Range	Mean	Standard deviation
T_{SI}	4–613	214	151.2
R_S	1–376	101	94.9

R_S is in N.

Table 13
Summary statistics for old snow layer hardness on the north aspect

Variable	Range	Mean	Standard deviation
T_{NI}	2–316	146	93.8
R_N	6–380	114	100

R_N is in N.

4.2.2.1. 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:

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

where T_{SI} is the south temperature index. This model has an R^2 of 0.70 with an associated p-value < 0.0005 ($n = 60$) (Fig. 7). Table 12 provides descriptive statistics on variables used in Eq. (3).

Five points depicted as "squares" in Fig. 7 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.

4.2.2.2. 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 (Fig. 8). Layers A, B, and D

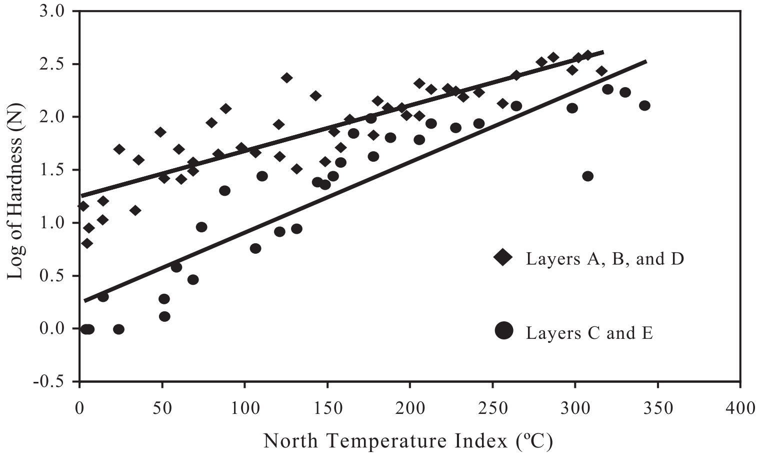

Fig. 8. Log of hardness vs. north temperature index on the north aspect. The lines represent the best fit lines for the simple linear regressions ($R^2 = 0.78$, $p < 0.0005$, $n = 48$) for layers A, B, and D and ($R^2 = 0.81$, $p < 0.0005$, $n = 32$) for layers C and E.

Table 14
Summary statistics for old snow layer hardness for layers C and E on the north aspect

Variable	Range	Mean	Standard deviation
T_{NI}	4–342	155	99.5
R_N	1–182	48	52.3

R_N is in N.

can be described by the following simple linear relationship:

$$\log R_N = 0.0040 T_{NI} + 1.25 \tag{4}$$

where T_{NI} is the north temperature index. The R^2 for this model is 0.78 with an associated p-value < 0.0005 ($n = 50$) (Fig. 8). Table 13 provides descriptive statistics on variables used in Eq. (4).

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

$$\log R_N = 0.0066 T_{NI} + 0.24 \tag{5}$$

where T_{NI} is the north temperature index. The R^2 for this model is 0.81 with an associated p-value < 0.0005 ($n = 32$) (Fig. 8). Table 14 provides descriptive statistics on variables used in Eq. (5).

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 layers

5.1.1. Qualitative analysis

Qualitative analysis found that rates and levels of hardness for new snow layers generally increased more rapidly on the south aspect in comparison to the north aspect. Increased incoming shortwave radiation appeared to increase hardening on the south aspect. This increase occurred during times when skies were clear. The difference in hardness between aspects became accentuated when maximum daily temperatures remained below 0 °C on the north aspect despite clear skies. The difference became less accentuated during periods when high wind speeds occurred out of the northwest. Hardening rates and values on the north aspect also approached rates of those on the south aspect under cloudy sky conditions in conjunction with high maximum daily temperatures around 0 °C.

5.1.2. Quantitative analysis

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

5.2.1. Qualitative analysis

Initially, layers, particularly near-surface layers, became harder on the south aspect in comparison to those on the north aspect. However, with the exception of the surface layer, layers on the north aspect, after 2 months, became harder than their corresponding layers on the south aspect. While minimal settlement was recorded on the north aspect, considerable settlement occurred on the south aspect. Settlement on the south aspect possibly resulted from increased incoming shortwave radiation. The densification of old snow layers was approximately the same on both aspects. Sintering was also another mechanism that possibly increased hardness on both aspects.

5.2.2. Quantitative analysis

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.

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