A BETWEEN-STORM INDICATOR OF AVALANCHE ACTIVITY

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ABSTRACT: Earlier studies examining relationships between weather factors and avalanche activity showed that the important between-storm factors include an index related to the minimum and maximum daily air temperatures. The index helped explain the differences in avalanche activity with similar storms, but with different circumstances affecting the snow between storms. This study used the results of the previous investigation to guide case studies taking a closer look at the temperature index, which has the name vapor gradient index (VGI). The VGI accumulates each day between storms by adding the current day's value VGI' with the accumulated value from the previous day. During storms the value remains constant, and is reset to zero when the snow stops falling. To calculate the VGI' for the current day, one requires two temperatures, the daily minimum temperature and the value midway between the daily minimum and maximum. For each temperature the one then uses Clausius-Clapeyron equation to calculate the saturation vapor pressure at each temperature. The difference between the two vapor pressures becomes the VGI', the value of the current day. We used the SNTHERM model of snow processes to calculate grain growth during a 17-day period between storms in the early winter, 1994, at Mammoth Mountain, California. During this period the VGI showed a high correlation to grain growth.

KEYWORDS: Snow, metamorphism, avalanche activity

1. INTRODUCTION

The avalanche community has known for some time the conditions related to release of dry slab avalanches. Among these include factors that affect the strength of the old underlying layer and/or the relative degree of sintering between the slab and the old layer (Schweizer, 1999). Metamorphism in near-surface layers prior to snowfall may affect the degree of involvement of old snow in slab avalanches and/or the rate of bonding between the slab and old snow surface.

In analyzing avalanche activity in long-term datasets, one frequently finds circumstances with different avalanche response to similar storms, in terms of the number of releases and/or the maximum size (e.g., Davis et al., 1999). In particular, the longer duration between storms, the larger the avalanche response in many situations. Some of this difference can be attributed to processes near the snow surface during the between storm period.

Faceted crystals growing on the surface of a snow cover form during conditions of extreme temperature gradients (Colbeck, 1988). Once buried, these layers can cause persistent weakness contributing to avalanche release (Jamieson and Johnson, 1992).

Recent research has demonstrated that faceted crystals near the surface of a snow cover can affect avalanche release and size (Birkeland et al., 1998a). Faceted crystals in near-surface layers can grow in the presence of large gradients of vapor pressure, driven by 1) differing radiation regimes from solar and longwave radiation having an approximate balance, 2) presence of a melted layer beneath new snow, and 3) large diurnal temperature gradients (Birkeland et al., 1998b).

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The grain size of the old snow surface can affect the rate at which new snow becomes bonded to the old. While the processes controlling bonding are not well understood (Colbeck, 1997), it seems clear that the rate of bond formation is inversely proportional to grain size, so that fine grains bond more slowly to coarse grains than to other fine grains (Colbeck, submitted). Accordingly, new snow will bond more slowly to an old snow surface, other factors being the same, if the grains of the old surface are large.

The main factors controlling dry snow metamorphism include temperature, vapor flux and initial size of the grains (Colbeck, 1982). A temperature gradient gives rise to a gradient in vapor pressure, and the warmer the average temperature, the steeper the gradient in vapor pressure. In turn, grains grow in dry snow at a rate determined by the vapor flux, which is controlled by the gradient of water vapor and the geometry of the pore space.

Recent snow models have reached a stage of sophistication where one can estimate general changes to grain size and density within snow layers (Brun et al., 1989; Davis et al., 1993, 2001; Fierz et al., 1997; Fierz and Gauer, 1998; Fierz and Lehning, 2000; Jordan, 1991; Jordan et al., 1999; Gubler, 1998). The variables listed in Table 1 show the inputs generally required at frequent time intervals by snow models of this type (Davis et al., 2001).

Table 1. Variables required by models fully characterizing snow processes and properties.

1. Incoming (reflected*) solar radiation
2. Incoming longwave radiation (surface temperature*)
3. Air temperature
4. Humidity
5. Wind speed
6. Precipitation and type

* alternate variables used by Swiss SNOWPACK model.

On the other hand, ski areas, departments of transportation and other organizations in the US typically measure the variables listed in Table 2 on a daily basis.

Table 2. Typical weather measurements by avalanche practitioners in the US.

1. Total snow depth
2. New snow depth
3. New snow water equivalent
4. Minimum and maximum air temperature
5. Average wind speed.

We derived an index to roughly describe grain growth in the near surface of the old snow based only on the minimum and maximum air temperatures.

2. METHODS

This section describes the formulation of an index, which describes the potential for snow metamorphism at the snow surface and in near-surface layers during periods between storms. This section also describes a case study in which the SNTHERM model (Jordan, 1991) simulated grain growth to compare with the index.

2.1 *The Vapor Gradient Index*

We propose that the minimum daily air temperature forms a reasonable surrogate for the minimum surface temperature of dry snow near the site of the air temperature measurement. Further, we assume that the temperature midway between the minimum and the maximum daily air temperatures represents a crude approximation of dry snow temperature near the diurnal damping depth, several centimeters below the surface.

The Vapor Gradient Index (VGI) presents a cumulative expression of temperature gradient effects on the potential vapor gradient during periods with no significant snowfall. To formulate the VGI we calculated an individual daily interim value VGI', based on the difference in saturation vapor pressure between the two temperatures. Buck (1981) formulated modified expressions of the Clausius-Clapeyron relation to estimate the saturation vapor pressure $p_{v,sat}$ (mb) based on temperature T (°C):

$$p_{v,sat} = 6.138 \exp(22.452\,T/(272.55 + T))$$

The current-day value of the interim vapor pressure gradient VGI' comes from the difference between $p_{v,sat}$ at the two temperatures:

$$VGI' = p_{v,sat\,(Tmin)} - p_{v,sat\,((Tmin - Tmax)/2)}$$

For between-storm periods

$$VGI_{today} = VGI_{yesterday} + VGI'$$

During storms VGI = *constant* at the last value before snowfall. The first day after snowfall VGI = VGI' for the day. That is, the VGI comes from the cumulative sum of the daily values VGI' every day between avalanche/storm days. Functionally, the VGI has similarity to the estimation of near-surface gradients of vapor density proposed by Gubler (1998), except that Gubler's method requires much more measurement support and provides more frequent estimates of near-surface processes.

2.2 *Grain Growth Simulation with SNTHERM*

The simulation of grain growth used SNTHERM (Jordan, 1991; Jordan *et al.,* 1999), a physically-based 1-dimensional mass and energy balance model that simulates details in changing snow cover properties over time in response to meteorological forcing (Table 1).

Primary meteorological measurements came from the Mammoth Mountain cooperative snow study plot (Painter et al., 2000). This site lies in the Sierra Nevada at about 2926 m elevation (37° 39'N, 119° 02'W). We adjusted the meteorological measurements to account for a variety of notional starting zones with properties listed in Table 3.

Table 3. Conditions used for simulating grain growth using SNTHERM.

1. mean elevation 3200 m: air temperatures and humidity adjusted for a normal lapse rate;
2. three aspects: north, northeast and northwest;
3. mean slope: 35°;
4. solar illumination: two cases – 75% sunny and 75% shaded (periods during day)
5. length of simulation: 17 days
6. snow profile: themally semi-infinite with isothermal temperature set at the mean air temperature over the 5 preceding days;
7. model spin up period: 48 hours;
8. initial grain radius: 0.025 mm;
9. initial snow density: 125 kgm^{-3}

Further, we selected the 17-day period from the weather record during which the formation of near-surface facets seemed likely; high pressure dominated the synoptic weather with predominantly clear skies and low winds.

This study compared the VGI for this same 17-day test period, normalized to the maximum reached, with the grain growth from SMTHERM.

3. RESULTS

SNTHERM showed grain growth on sunny slopes as slow at first, then increasing at a steady rate until the next storm started. Figure 1 shows the trend in mean grain size from the three aspects under sunny conditions.

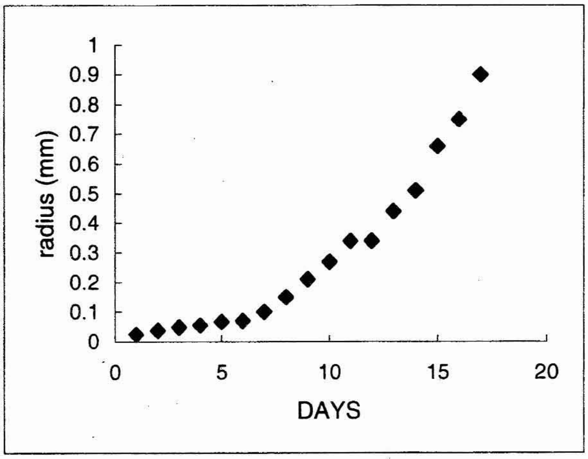

Figure 1. Grain growth simulated by SNTHERM on sunny slopes under conditions specified in Table 3.

The simulated grain growth showed minor variations across the different aspects, with the major difference between sunny and shaded slopes. Figure 2 shows that the grains on the sunny slopes grew at about twice the rate as the grains on the shaded slopes.

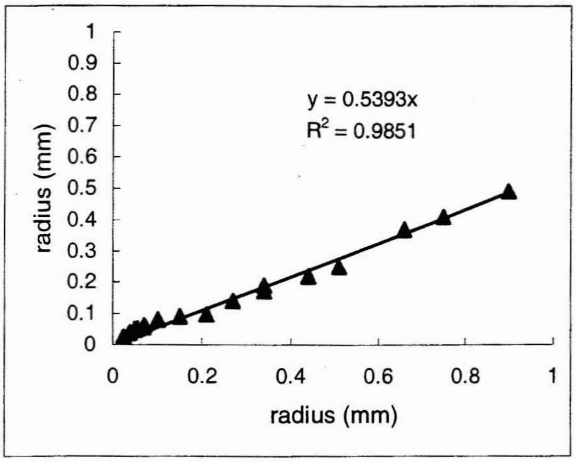

Figure 2. Comparison between simulated grain growth on sunny and shaded slopes.

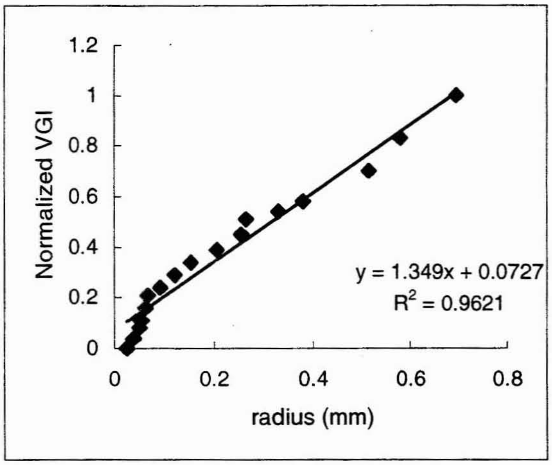

Figure 3. Comparison between the mean grain growth across all conditions list in Table 3 and the normalized VGI during the test period.

The normalized VGI showed a high correlation with the mean grain growth from all model simulations, as shown in Figure 3.

4. DISCUSSION AND FUTURE DEVELOPMENT

We consider this limited case study as offering reasonable evidence that the VGI can provide a simple surrogate to conditions controlling metamorphism. Though the VGI used air temperature measurements from the study plot, we still found good correlation to conditions in the notional avalanche starting zones and paths. The specific rates and values reached by the VGI, as related to actual grain growth and potential formation of faceted crystals, will clearly prove site specific. However, this simple index offers another piece in the puzzle of avalanche release characteristics. One can calculate the VGI using a simple spreadsheet application and the equations presented above.

The VGI does not distinguish between types of surface or near-surface crystal formation in snow. Further development might incorporate wind speed as an additional factor, which may allow site-specific separation between cases of rounded grain growth, surface hoar growth and the formation of near-surface facets within the snow cover.

5. CONCLUSIONS

This study described the Vapor Gradient Index, a simple parameter that may provide important clues to the conditioning of old snow prior to storm cycles. Using a limited case study we showed that the VGI can have a high correlation to grain growth, at least as simulated by the SNTHERM model under conditions described in Table 3.

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