Modeling variation of surface hoar and radiation recrystallization across a slope

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ABSTRACT: Faceted ice crystals (plane faced grains) are frequently observed in investigations of slab snow avalanches. Morphologies of this sort can develop while near the snow surface. When subsequently buried, these faceted crystals may form a weak interface layer leading to an avalanche. For this reason, researchers at Montana State University in collaboration with snow safety personnel from the Yellowstone Club Ski Patrol have been investigating environmental conditions associated with near surface metamorphism. Two meteorological stations were used to correlate conditions with daily observations of grain structure at the snow surface. The field sites, one with a northern the other with a southern exposure, are meadows of 30^{o} slope surrounded by trees and rock. In addition, radiation recrystallization and surface hoar morphologies have been replicated in the laboratory by simulating natural conditions.

An energy balance model was used to estimate variations in near surface temperature conditions. LIDAR data was used to produce digital elevation maps at a one meter spatial scale. The model accounts for thermal properties of the vegetation and rock outcropping as well as snow, sun position, shadowing and surface to surface or surface with sky radiation. The modelling emphasis presented is on days when radiation recrystallization and surface hoar were observed. Based on field and laboratory results metamorphic development is assumed to be driven by the magnitude of the near surface temperature gradient in the case of radiation recrystallization and mass deposition for that of surface hoar. Calculation of these indicators reveals a spatial variation in the metamorphism across the slopes.

KEYWORDS: snow, metamorphism, near surface faceting, surface hoar.

1 INTRODUCTION

Slab avalanche initiation is often the result of a weakly bonded layer within the snowpack stratigraphy. This layer may originate when environmental conditions facilitate the development of faceted crystals (plane faced grains) on or near the snow surface. These layers can be problematic when subsequently buried by additional snowfall.

Such crystals may be characterized into three sub-surface processes; radiation-recrystallization (LaChapelle, 1970), melt-layer recrystallization (Birkeland, 1998; Jamieson and van Herwijnen, 2002), and diurnal recrystallization (Birkeland, 1998), and one onto the surface process, which forms surface hoar (Seligman, 1936).

Of this group, surface hoar has been the most intensively investigated. (e.g. Seligman,1936; Lang et al. 1984; Colbeck, 1988; McClung and Schaerer, 2006; Hachikubo and Akitaya, 1998; Cooperstein et al. 2004)). Processes involving melt layer recrystallization have been addressed as well (Armstrong, 1985, Fukuzawa and Akitaya 1993, Jamieson et al. 2001, Jamieson and van Herwijnen 2002). A study by Cooperstein et al. (2004), found that subsurface recrystallization was often more fully developed on the south study slope and surface hoar crystals were larger on the north. Radiation recrystallization has been examined by Morstad et al. (2007), Slaughter et al. (2008, in press) and McCabe et al. (2008).

Birkeland et al. (1996, 1998) measured near surface temperature gradients in snow that transitioned due to diurnal recrystallization and formally emphasized the importance of this process relative to avalanches. The significance of layers of faceted crystals within the snowpack to avalanches has been documented in a number of studies (Birkeland et al., 1996, 1998; Schweizer and Lutschg, 2001; Schweizer and Jamieson, 2000; Jamieson and Langevin, 2004).

The sensitive thermodynamic nature of snow leads to spatial variability within these thin weak layers due to even slight variations in topography and surroundings (Landry et al. 2004; Schweitzer et al. 2008). Ultra-weak zones or flaws in a weak layer are considered potential

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initiation regions leading to slab failure. A fracture may emanate from such a zone then propagate through the weak layer (McClung, 2009; Heierli, 2008).

2 METHODS

The notion behind this ongoing study is to carefully monitor changes at and near a snow surface in topographically varied terrain to thereby better understand the dominant environmental parameters leading to specific morphologies. By combining detailed observations with meteorological data, a primary goal is to utilize a first principles physics approach to extrapolate spatially to a larger area through computational modelling.

2.1 Field Data

Two field sites are maintained at the Yellowstone Club ski area in southwest Montana, USA. Each of these ~30^{o} slopes are on clearings surrounded by trees; one north facing, one south facing. These sites have been utilized in previous investigations (Cooperstein, et al., 2004, Staples, et al., 2006, McCabe et al., 2008, Slaughter et al., in press). Each site has a meteorological station measuring: air temperature, humidity, snow depth, snow surface temperature (non-contact sensor), slope parallel longwave and shortwave radiation, wind speed and direction and a thermocouple array to measure snow temperature at 2cm depth intervals. In addition, horizontally oriented incoming shortwave and longwave radiation sensors were placed on a ridge above both sites ridge to provide a generally unobstructed sky view for the modelling.

Throughout the season, daily visits to the sites are carried out to observe/photograph near surface morphologies and for station maintenance. Meteorological data is downloaded weekly.

2.2 Modelling Energy Balance

RadThermRT, the program used in this study, is based on a first principles energy balance approach. It has its origin in codes developed to identify the infrared/thermal signatures of vehicles (Johnson, 1991; Johnson, 1995, PRISM:3.0, 1991). The concept was extended to topographically complex terrain and snow by Adams and McDowell (1991). RadTherm is now a commercial software product developed for structures, using these same IR signature principles (Curran, 1995; Johnson, 1995). In collaboration Montana State University and ThermoAnalytics Inc. enhanced the program to include topographically complex terrain.

Terrain for the study sites are defined using high resolution (1m) digital elevation maps derived from lidar data. Terrain type (e.g. rock, grass, trees, snow, etc.) are assigned appropriate thermal properties. The model accounts for shadowing and surface to surface radiation exchange. In this presentation, the snow is assumed to be 1 m deep superimposed on the clearing, but not covering the trees. Surface temperature, temperature profiles and surface mass fluxes are calculated and surface temperature and mass flux maps can be displayed through time.

3 RESULTS

From among the daily observations in 2009, one event each for surface hoar growth and near surface faceting are examined. These events are examined considering observations, meteorological data and RadThermRT.

3.1 Surface Hoar

Daily logs indicate that in the afternoon of 4 February on the north study site surface hoar crystals on the scale of 5 mm were observed (Figure 1). The model utilizes the breadth of meteorological energy input to calculate the snow temperature and mass flux to the surface.

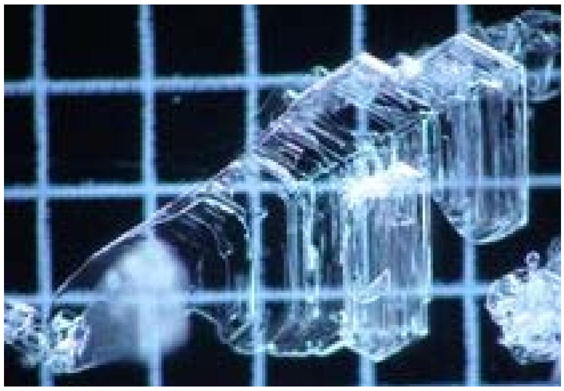

Figure 1 A surface hoar crystal collected near the north station on 4 February. (1 mm grid)

Since our interest here is to calculate the mass flux to the snow surface, the measured air temperature and relative humidity, which are primary contributors to the process, are displayed in figure 2. It should also be noted in the figure that there is a tendency for the model to calculate the snow surface temperature as colder than the measured value.

The calculation of mass flux is based on the snow surface temperature, the humidity of the air above and the wind speed. For the period considered here, the measured station air velocity varied generally between 0.5 and 1.6 m/s.

The mass flux calculated at the station is displayed in figure 3. A positive value for the flux indicates deposition, a negative sublimation.

We assume here that deposition will occur in the form of surface hoar and thus gives a measure of growth rate. In addition, since one of the issues of interest is the spatial distribution, fluxes at two other points are presented.

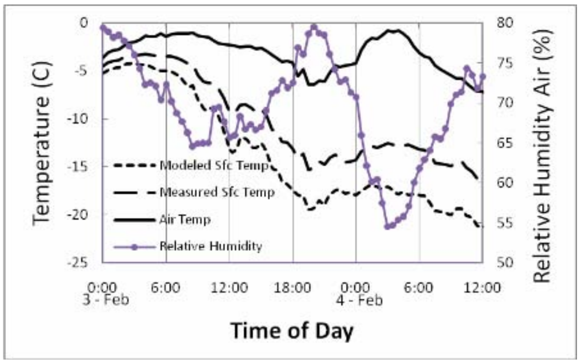

Figure 2 Modelled and measured surface temperature (IR thermometer), air temperature and relative humidity of the air on the north site.

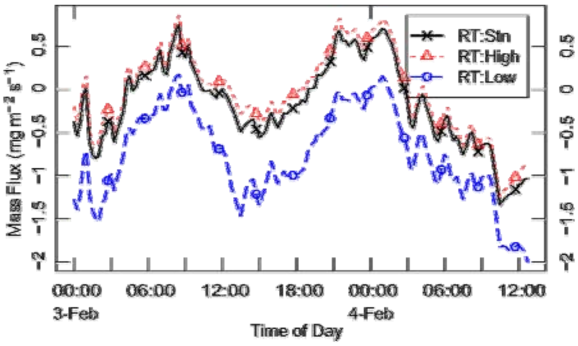

Figure 3 Time variation of mass flux at three points on the north site. Stn (X) is at the meteorological station, High (Y) is at a high accumulation area, Low (Z) is at a low accumulation area. X, Y, Z are positions noted in figure 4.

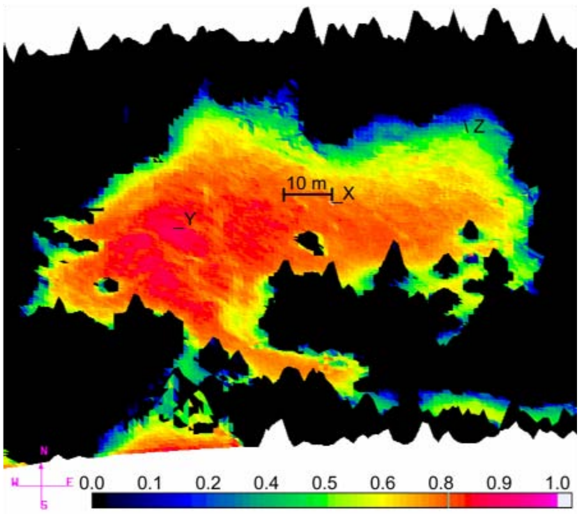

Figure 4 Modelled mass flux (mg/(m^{2}s)) distribution on the north facing slope at 08:30 on 3 February. The snow covered clearing has a generally uniform slope of ~ 30^o. The black represents trees, which are not considered to experience a mass flux. Width of total displayed area is ~ 120 m.

3.2 Near Surface (sub-surface) Faceting

Daily logs for the south study site report near surface facets on the 12th, 13th and 14th of February (figure 5). A melt-freeze crust was noted at 2-3 cm below the surface on 13 February.

For radiation recrystallization, the balance between shortwave and longwave radiation are critical factors (LaChapelle, 1970). Radiation data from a ridge station (with unobscured sky view) on 13 February are used in modelling. The day was clear with midday peak incoming short wave radiation of approximately 600 W/m^2 and consistent longwave radiation of approximately 180 W/m^2.

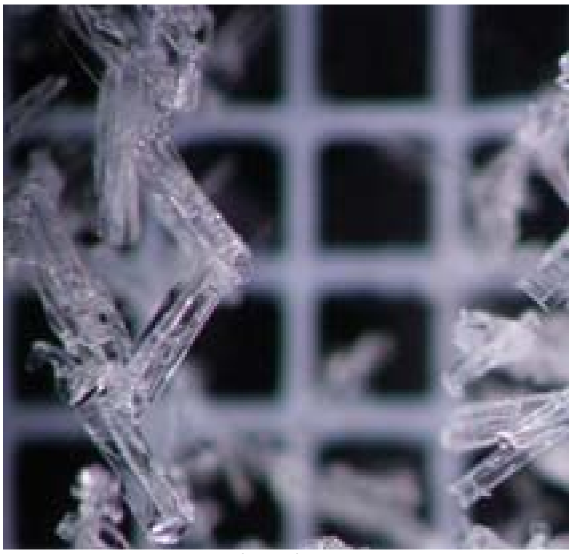

Figure 5 Near surface facets observed 13 February on the south study site. 1 mm grid.

Modelled temperature profiles are presented in figure 6. The shortwave radiation penetration is evident as the day progresses with near surface temperature gradients developing.

A “snapshot” of the modelled surface temperature map at near the time of the maximum near surface temperature gradient is displayed in figure 7.

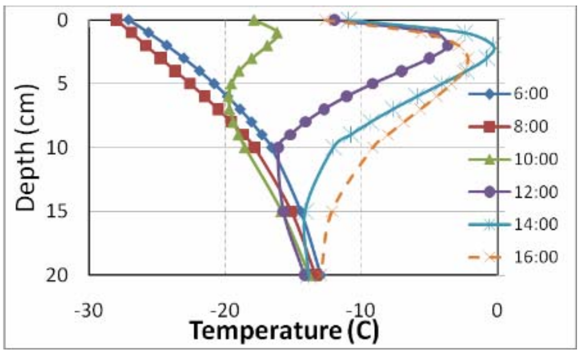

Figure 6 Temporal variation of 13 February south site modelled temperature profiles.

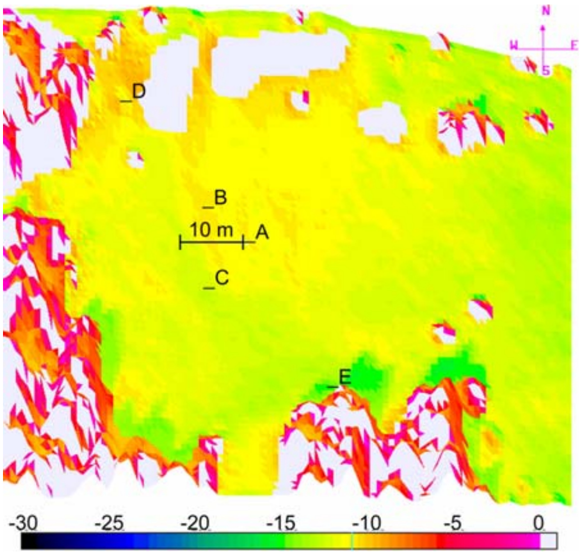

Figure 7 Spatial variation in modelled surface temperature at 14:00, 13 February. Note that the warmer sections generally surrounding the slope are trees and rock. The total width of the image represents 70 m. Calculation of the near temperature gradients at this time yield 805, 851, 636, 885 and 54 C/m for points A, B, C, D and E respectively.

5 DISCUSSION

Our interest in this study is the development of a tool that may be of assistance in ascertaining conditions leading to the development of weak layers formed near or on the surface that may lead to an avalanche stability problem. In addition to determining if an event might be expected on a specific slope, the location of the ultra-weak zone is of practical concern.

Modelling of the surface hoar event presented above does indicate that we would expect to have experienced growth for the observed event. The values for mass flux are lower than what would be expected based on the data collected by Hachikubo and Akitaya (1997) for similar size crystals (3.7mg $m^{-2}s^{-1}$). As presented in the results, the temperature tended to be lower than the measured, although this would not explain the lower than expected growth rates. In fact, taken in isolation this would have a tendency to increase the calculated rate. From the perspective of spatial distribution, the model provides insight into areas that would be expected to experience higher growth rates. Samples collected near the weather station were in a relatively high growth area, whereas the areas with slightly different topographic orientation or near trees have substantially different growth rates.

The near surface faceting event of 13 February falls into the category of radiation recrystallization. The modelling here also indicates that the event observed would have been expected based on the large near surface temperature gradients. It is worth noting that a thermocouple array placed in the snow showed a definite knee, analgous to that displayed in figure (6), indicating measurable subsurface heating. However, the thermocouples themselves were thermally contaminated, heating to several degrees above freezing. Consequently, they could not be used for comparison. In this case, again, the modelled snow surface temperature was lower than the IR measured temperature. The temperature profile shapes are similar in character to the laboratory radiation recrystallization profiles presented in Morstad et al. (2007). The peak gradients calculated at the weather station occurred at 14:00. These peak values were somewhat high, which may be a consequence of the generally colder than appropriate surface temperature.

The calculated temperature at 3 cm (figure 6) is near melt, corresponding to the melt-freeze crust that was observed.

It is particularly interesting to observe the significant change in near surface temperature gradients over relatively short distances. Again these values are highly influenced by subtle topographic differences and surrounding trees or rocks.

6 CONCLUSIONS

From the perspective of avalanche forecasting, the implementation of the model presented, or other such spatially oriented efforts, would be of significant utility to the practitioner community. Results from this model are promising and the essential physics and program should be sufficiently robust to provide a useful tool. The magnitudes and rates calculated are based on rather general values for the thermal and optical properties of the snowpack. A more accurate representation of these values should lead to more accurate results. However, given the very encouraging, reasonable trends, and understanding the bias, the model may be useful in areas with sufficient resolution digital elevation maps and appropriate proximity to meteorological data.

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