Spatial predictions of surface hoar and crust formation

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ABSTRACT: Understanding the distribution of critical snowpack layers is important when assessing avalanche hazard. Two common critical layers, surface hoar and melt-freeze crusts, form under specific weather conditions. This study explores the possibility of modelling the formation of these layers with forecasted weather data. Surface hoar and sun crusts were tracked at study sites on two mountains in the Columbia Mountains of Canada. Weather data from automated stations near these sites were compared to forecast data from two numeric weather prediction (NWP) models (15 and 2.5 km grids). The latent heat flux and net shortwave radiation were modelled with the snow cover model SNOWPACK and related to observed surface hoar crystal size and sun crust thickness. Surface hoar formation was then predicted across western Canada with NWP data. Comparing these predictions with observations made by avalanche professionals at 112 study plots found that surface hoar occurrence was generally over-predicted. Spatial predictions with forecast data could help avalanche forecasting in data sparse areas.

KEYWORDS: surface hoar; sun crust; surface energy balance; avalanche forecasting; numeric weather prediction

1 INTRODUCTION

Destructive snow slab avalanches often result from failure in persistent layers such as surface hoar, facets on crust and depth hoar. These layers are spatially variable making their presence and stability hard to predict. Most persistent layers in Columbia Mountains of Canada are associated with surface hoar or melt-freeze crusts (Haegeli et al., 2003).

Surface hoar often forms when near surface air is cooled below its dew-point. This process is often simulated by modelling the energy associated with phase change, known as the latent heat flux (Föhn, 2001). This process is sensitive to wind speed making it difficult to model (Hachikubo, 1997). Crystal size is believed to be an important property of surface hoar layers, and has been shown to be an indicator of weakness and persistence (Horton et al., 2013). Large crystals often bond poorly and are attributed to high fracture propagation propensity.

Melt-freeze crusts usually form when near surface snow is melted by the sun, rain, or warm air and then refreezes. Phase changes and movement of liquid water make this process difficult to model as well (Mitterer et al., 2011). Wet snow forming crusts can provide favourable conditions for facet growth including a vapour supply and strong temperature gradients (Jamieson, 2006). Crusts can also provide a bed surface for avalanche release and flow.

Formation of these layers on a regional scale is affected by synoptic weather patterns such as precipitation and cloud cover. Haegeli et al. (2003) showed the spatial extent of layers that caused avalanches was on the order of hundreds of kilometres. Formation on a slope scale is affected by local vegetation, ground roughness, radiation and wind patterns. Variations in weather and terrain make modelling difficult (Feick et al., 2007).

Processes that form and change these layers over time can be simulated with weather driven snow cover models (e.g. Brun et al., 1989; Lehning et al., 2002). These models are operationally used in Europe to simulate snow profiles with data from automated weather stations. In Canada, there are large data sparse regions without weather stations. Using forecasted data from numeric weather prediction (NWP) models in these regions has shown promise (Bellaire et al., 2011; 2013). The overall snow stratigraphy can be simulated well, but thin weak layers were sensitive to weather inputs (Bellaire and Jamieson, 2013). In this study we examined how well coupled weather and snow cover models could simulate the surface energy balance, surface hoar, and sun crust formation. To test the models we used detailed weather and snow observations from two sites in the Columbia Mountains, then used snow observations from mountain ranges across western Canada.

2 METHODS

2.1 Field methods

Field studies were done on Mt. Fidelity and Mt. St. Anne in the Columbia Mountains of Canada (Figure 1). Layers of surface hoar and melt-freeze crusts were tracked during the 2011-
2012 and 2012-2013 winters. Each mountain had three uniform open study sites at treeline elevation (south aspect, north aspect and flat). The flat sites were equipped with automated weather stations that took measurements of snow surface temperature and shortwave and longwave radiation.

Each site was visited one to three times per week to monitor surface hoar and melt-freeze crust formation. When surface hoar was present on the surface, the average and maximum crystal sizes were measured (CAA, 2007). Over two winters we observed 17 layers of surface hoar and made 31 crystal size measurements at flat sites. When a frozen melt-freeze crust was present at or near the surface its thickness and hand hardness were measured. We observed 13 sun crusts and made 30 thickness and hardness measurements at south sites.

2.2 InfoEx dataset

Avalanche operations in western Canada share daily observations on the Canadian Avalanche Association’s daily industrial information exchange (InfoEx). A database of InfoEx observations was queried to find the presence or absence of surface hoar at 112 InfoEx study plots over the 2012-2013 winter (Figure 1).

2.3 Numeric weather prediction models

Forecasted weather data for western Canada was taken from two NWP models - the Canadian regional 15 km Global Environmental Multiscale model (GEM15) and the high-resolution 2.5 km Limited Area Model (GEM2.5) (Mailhot et al., 2006; 2012). Gridded data from each model were collected twice per day over the course of the 2012-2013 winter. The four closest grid points to each study plot were identified for each model and time series were made for each grid point. Forecast quality was assessed at grid points near Fidelity and St. Anne by comparing station measurements (STN) with forecasted values (GEM). Standard errors (SE) and biases were calculated over N time steps using:

\[
SE = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( \frac{GEM_i - STN_i}{N} \right)^2 \right]^{1/2}
\]

\[
BIAS = \frac{1}{N} \sum_{i=1}^{N} (GEM_i - STN_i)
\]

2.4 Surface energy balance

The snow surface energy balance was modelled with the snow cover model SNOWPACK (Lehning et al., 2002). This was done with both weather station data and forecasted data from the GEM15 and GEM2.5 models. SNOWPACK uses weather and radiation data to simulate the formation and evolution of snowpack layers. It also simulates the surface temperature, albedo, and surface heat fluxes (assuming a neutral atmosphere as done by Stössel et al. (2010)). Since the GEM models do not forecast surface temperature, SNOWPACK was set to predict it using modelled fluxes and radiation (Neumann boundary conditions). To verify how well the surface energy balance was modelled, we compared the snow surface temperatures measured at Fidelity and St. Anne with temperatures modelled by SNOWPACK (e.g. Fierz et al., 2003).

2.5 Surface hoar formation

Surface hoar formation was modelled using the latent heat flux predicted by SNOWPACK. To estimate the amount of sublimation, the latent heat flux was accumulated over clear weather periods (defined as periods with no precipitation). The accumulated latent heat was compared to crystal size observations from flat sites at Fidelity and St. Anne. Crystal size was estimated by multiplying the latent heat by the heat of sublimation (2.83 x 10^6 J kg^(-1)) and then dividing by density value for surface hoar.

2.6 Sun crust formation

The net absorbed shortwave radiation on south facing 30° slopes was predicted by SNOWPACK. This corresponded with our south sites at Fidelity and St. Anne. We correlated the thickness of sun crusts in the field with the accumulated net shortwave radiation.

3 RESULTS

3.1 Measured and forecasted weather

A clear weather period between 6 and 12 February 2013 caused surface hoar to form at both Mt. Fidelity and Mt. St. Anne. A sun crust
formed beneath the surface hoar at the south sites. Figure 2 shows the precipitation, incoming shortwave radiation, surface temperature, wind speed, and modelled latent heat flux over this period at Fidelity. Cold nighttime surface temperatures and strong daytime solar radiation provided good conditions for surface hoar and sun crust formation. The majority of surface hoar growth occurred on the nights of 9 and 10 February when the surface was cold and the latent heat flux was positive. This resulted in 12 to 15 mm crystals at each site on Fidelity. Cold nighttime surface temperatures and strong daytime solar radiation provided good conditions for surface hoar and sun crust formation. The majority of surface hoar growth occurred on the nights of 9 and 10 February when the surface was cold and the latent heat flux was positive. This resulted in 12 to 15 mm crystals at each site on Fidelity.

Figure 2 also shows forecasted values from the four nearest GEM15 grid points. Values from GEM2.5 are not shown. Discrepancies between measured and forecasted values are evident over this period.

Table 1. Average standard error of forecasted values at two weather stations (each with four grid points).

<table>
<thead>
<tr>
<th></th>
<th>GEM15</th>
<th>GEM2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (ºC)</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>10</td>
<td>11.5</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Incoming shortwave (W m⁻²)</td>
<td>45</td>
<td>59</td>
</tr>
<tr>
<td>Incoming longwave (W m⁻²)</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>Hourly precipitation (mm)</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Surface temperature (ºC)</td>
<td>3.3</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 2. Average bias of forecasted values at two weather stations (each with four grid points).

<table>
<thead>
<tr>
<th></th>
<th>GEM15</th>
<th>GEM2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (ºC)</td>
<td>-0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>-3.6</td>
<td>-6.5</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>-1.8</td>
<td>-1.8</td>
</tr>
<tr>
<td>Incoming shortwave (W m⁻²)</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Incoming longwave (W m⁻²)</td>
<td>-17</td>
<td>-8.5</td>
</tr>
<tr>
<td>Hourly precipitation (mm)</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>Surface temperature (ºC)</td>
<td>-2.0</td>
<td>-0.7</td>
</tr>
</tbody>
</table>

temperature, which was modelled with SNOWPACK. Average errors and biases for each model are given in Tables 1 and 2. These do not show some of the systematic differences between Fidelity and St. Anne (e.g. wind speed and directions were forecasted better at Fidelity than St. Anne) or variations between adjacent grid points (which were mostly minor).

Grid point elevations were often lower than station elevations by 200 to 600 m. This explains the warm bias observed for GEM2.5, but not the cold bias for GEM15. A cold bias with GEM15 was also reported by Mailhot et al. (2012) and Bellaire and Jamieson (2013). Relative humidity was substantially under-predicted by both models. Wind speeds were over-predicted at Fidelity and under-predicted at St. Anne. Incoming shortwave radiation was over-predicted and by both models and longwave radiation was under-predicted. This was also found by Mailhot et al. (2005) and suggests that cloud cover was under-predicted.

The surface energy balance depends on many of these parameters. Modelled surface temperatures had cold biases and standard errors of 3.3 ºC with GEM15 data and 3.7 ºC with GEM2.5 data. Temperatures modelled with GEM15 data captured strong cooling on 9 and 10 February (Figure 2), which was important for surface hoar formation. However, the latent heat flux was over-predicted because in this case forecasted wind speeds were too high.

3.2 Surface hoar size and sun crust thickness at Fidelity and St. Anne

Field observations of surface hoar and sun crust from Fidelity and St. Anne we compared with modelled fluxes and radiation. The accumulated latent heat over clear weather periods was
compared to surface hoar crystal size at Fidelity and St. Anne (Figure 3a). A Pearson correlation of 0.77 resulted when comparing 31 observations with the latent heat modelled from station data over two winters.

A density value is needed to predict crystal size from latent heat. Horton et al. (2013) found a density of 30 kg m\(^{-3}\) using a large dataset from Fidelity, while this dataset found a density of 20 kg m\(^{-3}\). St. Anne is typically windier than Fidelity, so the different values suggest an effect of wind climate on modelled fluxes.

Accumulated shortwave radiation on south facing slopes was compared to the thickness and hardness of sun crusts (Figure 3b). A Pearson correlation of 0.63 resulted when comparing eight thickness observations from south sites with shortwave measurements from weather stations. Thin crusts were generally softer than thick crusts.

The same observations were also compared when NWP data were used instead of weather station data (Table 3). The correlations suggest the models were less accurate at modelling surface hoar formation, but were comparable at modelling sun crust formation. In both cases GEM2.5 performed better than GEM15. GEM2.5 actually had a stronger correlation than station measurements for sun crusts, but the sample size was small.

### 3.3 Surface hoar presence at InfoEx sites

Forecasted NWP data were used to predict surface hoar formation at InfoEx sites. Predictions of crystal size for a layer that formed in February 2012 is shown in Figure 4. Over this period surface hoar was reported at 42% of the InfoEx study plots, but crystal size was not reported with most observations. The GEM models predicted surface hoar at 92% of the study plots, with a median size of 5 mm for GEM15 and 9 mm for GEM2.5. Although it is difficult to verify these sizes, they appear to highlight regions where formation was more developed (e.g. south central regions).

The presence or absence of surface hoar at each study plot was compared to whether it was predicted at nearby GEM grid points (Tables 4 and 5). Over the entire 2012-2013 winter surface hoar was observed 11% of the time (base rate). The probability of detecting surface hoar was 81% with GEM15 and 79% with GEM2.5. The probability of a false alarm was 80% with GEM15 and 79% with GEM2.5. This suggest both models could predict surface hoar, but often over-predicted it.

### 4. DISCUSSION

The surface energy balance and heat fluxes are important drivers for surface hoar and melt-freeze crust formation. Coupling SNOWPACK with the GEM15 and GEM2.5 models resulted in
Validations of NWP models in the Coast Mountains of Canada. Validation at our two stations supported many of their findings. While the higher resolution model (GEM2.5) did not necessarily improve the forecast of individual weather variables (Tables 1 and 2), it did improve predictions of surface hoar and sun crust (Table 3).

5 CONCLUSIONS

Properties of surface hoar and sun crust layers are closely coupled with meteorological influences. We used weather data from automated stations and NWP models on 15 and 2.5 km grids to model the surface energy balance with SNOWPACK. Surface hoar crystal size was related to accumulated latent heat (correlation of 0.77 with station data) and sun crust thickness was related to accumulated shortwave radiation (0.63). Coupling NWP models with SNOWPACK tended to over-predict surface hoar due to cold surface temperature biases and poor wind forecasts. Sun crusts were predicted well with NWP data. In both cases the higher resolution model performed better. By studying these errors and biases we hope to improve predictions of critical avalanche layers in data sparse regions.

6 ACKNOWLEDGEMENTS

For collecting data we thank the subscribers of the InfoEX, the ASARC field staff, and Ben Shaw. For logistic support we thank the Avalanche Control Section of Glacier National Park and Mike Wiegele Helicopter Skiing. For their help with the GEM and SNOWPACK models we thank Sascha Bellaire, Charles Fierz and Mathias Bavay. For their support of this research we thank Tecterra, Canadian Pacific Railways, NSERC, HeliCat Canada, Canadian Avalanche Association, Canadian Avalanche Foundation, Parks Canada, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association, Backcountry Lodges of BC Association, Association of Canadian Mountain Guides, Teck Mining Company, Canadian Ski Guide Association, Backcountry Access and the BC Ministry of Transportation and Infrastructure Avalanche and Weather Programs.

7 REFERENCES


Bellaire, S., Jamieson, B., 2013. Forecasting the formation of critical snow layers using a coupled models in the Coast Mountains of Canada. Validation at our two stations supported many of their findings. While the higher resolution model (GEM2.5) did not necessarily improve the forecast of individual weather variables (Tables 1 and 2), it did improve predictions of surface hoar and sun crust (Table 3).

Table 4. Contingency table for the presence of surface hoar (SH) predicted by GEM15 at 112 study plots in western Canada.

<table>
<thead>
<tr>
<th></th>
<th>SH present</th>
<th>No SH present</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH modelled</td>
<td>411</td>
<td>1665</td>
</tr>
<tr>
<td>No SH modelled</td>
<td>96</td>
<td>2344</td>
</tr>
</tbody>
</table>

Table 5. Contingency table for the presence of surface hoar (SH) predicted by GEM2.5 at 112 study plots in western Canada.

<table>
<thead>
<tr>
<th></th>
<th>SH present</th>
<th>No SH present</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH modelled</td>
<td>403</td>
<td>1499</td>
</tr>
<tr>
<td>No SH modelled</td>
<td>104</td>
<td>2510</td>
</tr>
</tbody>
</table>

modelling snow surface temperatures with standard errors of 3.3 and 3.7 °C. This may lead to reasonable simulations of surface processes.

The GEM-SNOWPACK chain did a fair job of modelling surface cooling at night. There was a slight cold bias that usually resulted in larger latent heat fluxes and over-prediction of surface hoar. Wind speed errors also resulted in inaccurate fluxes. Despite these limitations, GEM data appeared to provide reasonable predictions of surface hoar (Table 3). The resolution of NWP grids (15 and 2.5 km) are far too coarse to resolve a process like surface hoar formation. However, nighttime cooling can usually be predicted on a widespread scale during high pressure systems. This makes it possible for predictions at NWP grid points to be representative of surrounding areas. We found surface hoar formation was generally over-predicted at InfoEx study plots (Tables 4 and 5). This could be due to model errors and biases (e.g. cold surface temperatures) or possibly because some sites were less prone to surface hoar formation.

The net absorbed shortwave radiation on south slopes was related to sun crust thickness. The thickness and hardness of sun crusts should be related to the amount of melting, and therefore net solar radiation. Greater solar radiation generally resulted in thicker and harder crusts (Figure 3b), which was also reported by Buhler (2013). Solar radiation forecasted by the GEM models was also closely related to crust thickness (Table 3). Other factors including the initial snow type, density, and the melting and flow of liquid water affect crust properties. Other types of melt-freeze crusts (e.g. rain and temperature crusts) are likely more challenging to model with NWP data because their formation is affected by local atmospheric conditions (e.g. inversions).

Validations of NWP models in mountainous regions are valuable to snowcover simulations. Mailhot et al. (2012) found appreciable errors in humidity and wind when validating several
snow cover and weather model. Cold Regions Science and Technology 94, 37-44.
Buhler, R., 2013. Formation and Evolution of Melt-freeze Crusts in the Columbia Mountains. MSc Thesis, Department of Civil Engineering, University of Calgary, Canada.