MODELLING SURFACE HOAR FORMATION AND EVOLUTION ON MOUNTAIN SLOPES

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ABSTRACT: Predicting the spatial distribution and persistence of surface hoar layers is a challenge to avalanche forecasters and backcountry recreationists. This study evaluates surface hoar size predictions made with empirical weather based models and discusses how buried layers change over time. Surface hoar layers were observed during the 2011-2012 winter at flat, north and south facing slopes in the Columbia Mountains. Two models were developed to predict crystal size, one using a constant growth rate and the other estimating vapour deposit from the surface energy balance. Weather station data and forecasted data from the GEM15 numerical weather prediction model were used to simulate the growth of layers over seven winters. Reasonable size predictions were made with growth rates of 2.1 and 2.6 mm per day (r^2 = 0.44), although specific rates appeared to change with season. The surface energy balance model made good predictions of crystal size with real station data (r^2 = 0.74) and reasonable predictions with the output of GEM15 (r^2 = 0.49). Time series of shear frame and propagation saw test results were made from observations on a buried surface hoar layer that formed in February 2012. The large crystals in this layer showed a steady increase in shear strength while the potential for fracture propagation remained high. The results of this study show promise for modelling surface hoar formation and evolution in snow cover models.

Keywords: surface hoar; avalanche forecasting; snowpack stratigraphy; persistence; weak snowpack layer

1. INTRODUCTION

Surface hoar crystals form when water vapour deposits on the snow surface. Once buried, they can become a failure layer for slab avalanches and can persist for several weeks (Chalmers and Jamieson, 2001). Understanding both the formation and evolution of these layers are important steps for assessing snowpack stability.

The formation of surface hoar is driven by the surface energy balance. The balance depends on local weather and terrain, making the spatial distribution highly variable. The transport of moisture towards the surface is optimized during calm, clear, and humid nights with strong radiative cooling (Colbeck, 1988). The moisture supply must be replenished with either light winds (Hachikubo and Akitaya, 1997), valley cloud movement (Colbeck et al., 2008), or nearby creeks. Crystals often form over several days where they can be destroyed by wind (Feick et al., 2007), solar radiation (Shea and Jamieson, 2011), warm air advection, or rain.

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Terrain and vegetation also influence the local surface energy balance. Schweizer and Kronholm (2007) successfully used a set of terrain parameters including aspect and elevation to predict the presence or absence of surface hoar. Forest cover and undulations reduce the sky view for radiative cooling, causing a high degree of slope scale variability (Lutz and Birkeland, 2011). Despite small-scale variability, forecasters are interested in the regional-scale distribution of specific layers. Borrish et al. (2010) mapped the crystal sizes observed over a regional scale and explained much of the distribution from synoptic weather patterns.

Surface hoar formation is simulated in the snow cover model SNOWPACK (Lehning et al., 2002) by calculating the turbulent flux of moisture towards the surface. The latent heat flux Q_E is a measure of vapour transport (kg m^{-2} s^{-1}). At the snow surface Q_E corresponds to vapour deposition or sublimation depending on the direction of the flux, equating to surface hoar growth or shrinkage. The bulk aerodynamic approach provides a simple means of calculating Q_E from weather variables (Föhn, 2001). It compares the vapour pressure of the surface with that of the air and assumes down-gradient transport. The transport rate is proportional to wind speed and properties of the air. As several assumptions are made when

calculating turbulent fluxes, they have been found to give poor predictions of crystal size (Feick et al., 2007; Stossel et al., 2010). Limitations include the need for accurate and localized weather measurements and an accurate conversion from mass to crystal size.

Surface hoar is usually considered a persistent weak-layer in the snowpack, but it is difficult to know how long a specific layer will persist. The shape of large crystals may limit bonding to the underlying layer by preventing precipitation particles from falling between them (Davis et al., 1997). Loading causes crystals to eventually penetrate into adjacent layers and form stronger bonds (Jamieson and Schweizer, 2000). Zeidler and Jamieson (2006) found loading to be the best snowpack factor to explain changes in the shear strength of surface hoar layers. While the shear strength of a layer can be compared to the stress to required to cause failure (Chalmers and Jamieson, 2001), the potential for fractures to propagate is also important (Gauthier et al., 2008). Changes in the shear strength and propagation potential of a prominent surface hoar layer were tracked in this study.

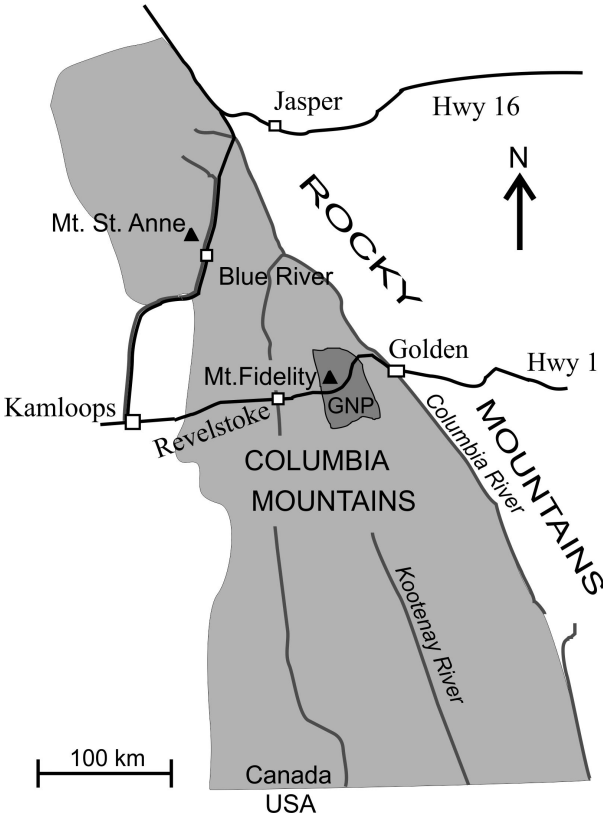

Figure 1: Map of the Columbia Mountains showing study sites at Mt. Fidelity and Mt. St. Anne.

2. METHODS

2.1 Field methods

Data were collected during the 2011-2012 winter at regular study sites in the Columbia Mountains of British Columbia, Canada. Uniform sites with an open sky view were chosen on north, south and flat aspects at treeline elevations on Mt. Fidelity in Glacier National Park and Mt. St. Anne near Blue River (Figure 1). Weather data were recorded at automated stations on each mountain including half-hourly measurements of temperature, relative humidity, wind speed, wind direction, incoming longwave radiation, incoming shortwave radiation, and precipitation. Forecasted weather data (3-hour time-steps) were obtained daily from the numerical weather prediction model GEM15 on a 15 km grid (Bellaire et al., 2011).

Surface observations were made on most potential formation days with detailed notes on crystal size, crystal type, microclimate and weather. After burial, layers were tracked once or twice per week at each site. Observations were made in snow pits successively spaced 2 m apart including grain size, layer thickness, layer temperature, adjacent layers, compression tests (CT), propagation saw tests (PST) and shear frames tests (CAA, 2007). A large layer that formed in early February 2012 was tracked for seven weeks while layers of smaller crystals were tracked as long as detectable.

2.2 Data analysis

The formation component of this study used data from seven winters (2005-2006 to 2011-2012) including surface observations from Mt. Fidelity, station weather, and forecasted weather from GEM15. Five winters were used for analysis and two for validation. Potential formation periods were identified as clear periods with no precipitation for at least 24 hours. Weather patterns were identified by comparing 39 precipitation-free periods that produced surface hoar over five years with 54 precipitation-free periods that did not. Weather predictors were identified with t-statistics, and a logistic regression model was used to predict when formation was expected to occur. The logistic model was not applied when predicting sizes in the subsequent models.

Two models were developed to predict surface hoar size. One model assumed a constant growth rate between periods of precipitation. The growth rate was determined by fitting observations from five winters to the number of preceding hours

without precipitation. The other model predicted the mass of vapour deposited using Q_E calculated with the bulk aerodynamic approach (Föhn, 2001). The calculation used wind speed, relative humidity, air temperature, and snow surface temperature from station and GEM15 data. In cases where snow surface temperature was missing it was estimated with a multivariable regression on air temperature and incoming longwave radiation. Other parameters used in the calculation included standard atmospheric values for air density, air pressure, and the average turbulent transport coefficient reported by Hachikubo and Atikaya (1997). The accumulated vapour deposit or loss (kg m^{-2}) was found by integrating Q_E over time. Density was needed to convert the predicted mass to a crystal size. Since measuring surface hoar density is difficult in the field (Föhn, 2001), an apparent density was found by fitting predicted masses from five winters to field observations.

3. RESULTS AND DISCUSSION

3.1 Weather trends during formation

Precipitation-free periods that produced surface hoar at Mt. Fidelity were found to be longer, more humid, and clearer than those that did not (Figure 2). Most layers formed over periods lasting at least two days. Periods producing surface hoar had average relative humidity between 81% and 88%, average temperature between -11 ºC and -5 ºC, and average incoming longwave radiation between 200 and 230 W m^{-2}. Humidity during formation periods was significantly higher than non-formation periods (t-statistic, $p < 0.05$). Incoming longwave radiation was significantly lower, corresponding to less cloud cover and stronger radiative cooling. The maximum wind speed during non-formation periods was significantly higher, but the average wind speed was not. Differences in air temperature and incoming solar radiation were minor. These trends agree with our general understanding of the formation process.

A logistic regression model with five statistically significant weather predictors was used to predict the probability of surface hoar formation. A total of 50 layers were observed when weather data were available for the five model building years and two validation years. The model correctly classified 36 of these layers (72% producers accuracy) and only 2 of the 14 misclassified layers had crystals larger than 3 mm. The model also worked with GEM15 data, correctly classifying 47 of 60 layers observed when weather data were available (78% producers accuracy). The ability of the regression model to predict surface hoar formation shows the potential for weather based rules in forecasting surface hoar formation.

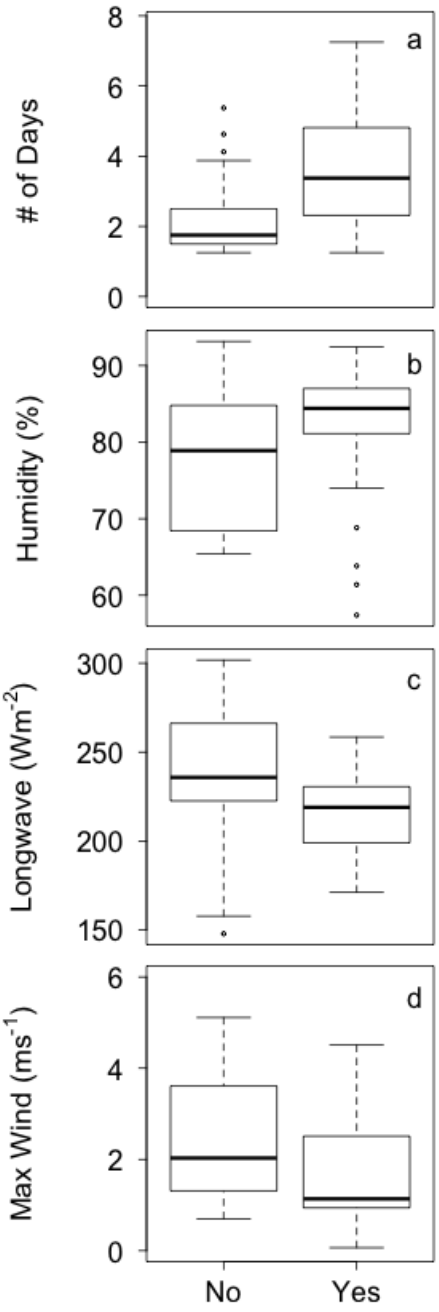

Figure 2: Boxplot comparisons of precipitation-free periods that produced surface hoar (Yes) and those that did not (No). Differences included (a) the number of precipitation-free days, (b) the average relative humidity, (c) the average incoming longwave radiation and (d) the maximum wind speed.

Table 1: Crystal sizes (mm) observed as surface hoar was forming on the snow surface in February 2012. The crystals were buried on February 8th at Mt. Fidelity and February 12th at Mt. St. Anne.

	Mt. Fidelity			Mt. St. Anne	
	Feb 4	Feb 6	Feb 8	Feb 6	Feb 9
North	5-10	12-24	20-30	6-9	6-12
Flat	6-14	9-21	12-24	6-9	5-10
South	6-12	12-21	15-27	2-3	1-4

3.2 Formation of the February 2012 layer

Surface hoar grew at each study site in early February 2012 (Table 1). On Mt. Fidelity sizes were similar on each aspect, while on Mt. St. Anne crystals were much smaller at the south site. A sun crust formed underneath the surface hoar at both south sites. The precipitation-free period lasted from February 2nd to 8th at Mt. Fidelity with the majority of growth occurring between February 3rd and 6th. Crystal sizes typically increased each day, suggesting a constant growth rate could be applied over this period. Less growth was observed near the start and end of the period, likely due to retreating and approaching clouds. A model based on the surface energy balance should simulate realistic growth.

3.3 Modelling formation

Growth rates were determined from five winters of data from Mt. Fidelity. Fits differed between the station and GEM15 data due to differences in precipitation timing. Least squares fits found a growth rate of 2.1 mm per day for the station data, 2.6 mm per day for the GEM15 data, and 2.3 mm per day when averaging between the two (r^2 = 0.44). These growth rates were used to model formation.

Apparent surface hoar densities were found by fitting the deposit mass predicted with Q_E to field observations. Least squares fits were applied to 120 surface hoar observations from five winters, resulting in a strong fit for the station data (r^2 = 0.74) and a reasonable fit for the GEM15 data (r^2 = 0.49). Apparent densities of 31 kg m^{-3} and 35 kg m^{-3} were found for the two sources, respectively. These densities are lower than previously published values (Föhn, 2001), but are influenced by assumptions made in the calculations.

Modelled and observed surface hoar sizes for the 2009-2010 winter are compared in Figure 3, which had more notable layers than other winters in this study. Predicted sizes at the time of burial for seven large layers are compared to the last size observed before burial in Table 2.

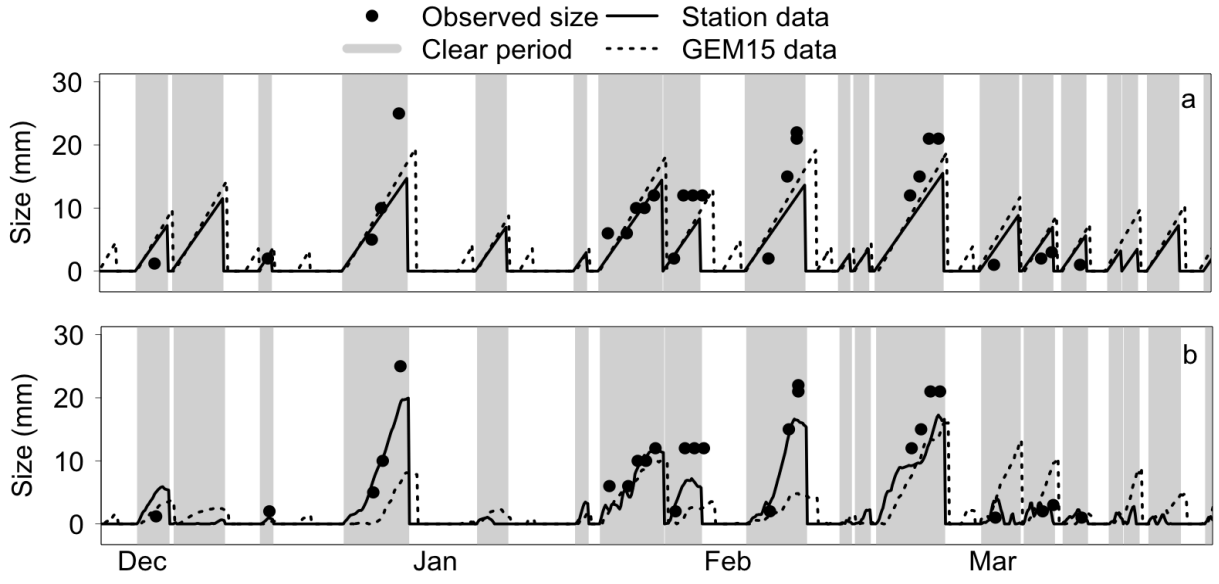

Figure 3: Predicted surface hoar sizes during the 2009-2010 winter using (a) a constant growth rate and (b) the surface energy balance. Clear weather periods are shaded grey, surface observations are marked with circles, predictions are shown with a solid line for station data and a dashed line for GEM15 data.

Table 2: Predicted sizes for seven large surface hoar layers at Mt. Fidelity using the growth rate model and the surface energy balance model with station (STN) and GEM15 (GEM) data.

Burial Date	Modelled Size (mm)				Observed Size (mm)
	Growth Rate		Surface Balance		
	STN	GEM	STN	GEM	
2007-02-04	24	15	18	11	15
2008-03-08	8	10	8	9	8
2009-12-29	15	19	20	8	25
2010-02-10	14	19	15	4	22
2010-02-24	16	19	17	16	21
2012-02-08	22	19	26	21	24
2012-02-16	6	7	13	5	7

The constant growth rate model made reasonable predictions when large layers formed, but predicted numerous false layers. False layers likely occurred when the weather was unfavourable for growth (e.g. too cloudy, dry or windy) and may have been prevented by applying the logistic regression model from Section 3.1. The constant growth rate model generally underestimated sizes in midwinter and overestimated sizes in the fall and spring. For example, the February 2012 layer had growth rate of 3.8 mm per day at Mt. Fidelity, which was higher than the rate used in the model. This seasonal effect was likely a result of stronger solar radiation and rain occurring in fall and spring.

Predictions with the surface energy balance model were close to observed sizes with fewer false layers. The model also appeared to simulate crystal shrinkage and stoppage of growth during unfavourable conditions. Layers were modelled best with the station data, while the GEM15 data underestimated many layers. This could be due to systematic errors in the GEM15 forecast (Bellaire et al., 2011) or occasional bad forecasts. The growth rate model had comparable accuracy to the surface energy balance model when using GEM15 data, suggesting advanced formation models may not be necessary with forecasted data.

3.4 Evolution of the February 2012 layer

The February 2012 surface hoar layer became a persistent weak layer in the Columbia Mountains causing avalanche activity until late March. Observations from each study site are shown in Figure 4. While the layers became thinner over time, the observed maximum crystal size changed little. The size two weeks after burial was on average 30% smaller than before burial, and crystals remain close to this size for the remainder of the study period. Shear strength increased in response to loading at each site, with greater snowfall amounts at Mt. Fidelity resulting in faster strength increases.

Fractures initiated in the PSTs after cutting through less than half of the column in 31 of 36 tests and fractures propagated to the end of the column in 34 of 36 tests. These results are suggestive of high propagation potential in this layer (Gauthier et al., 2008). PST results changed little over time, especially at Mt. Fidelity where crystals were larger. Cut lengths slightly increased, but occasionally decreased. Improved shear strength from shear frame results did not appear to affect the propagation potential of this layer.

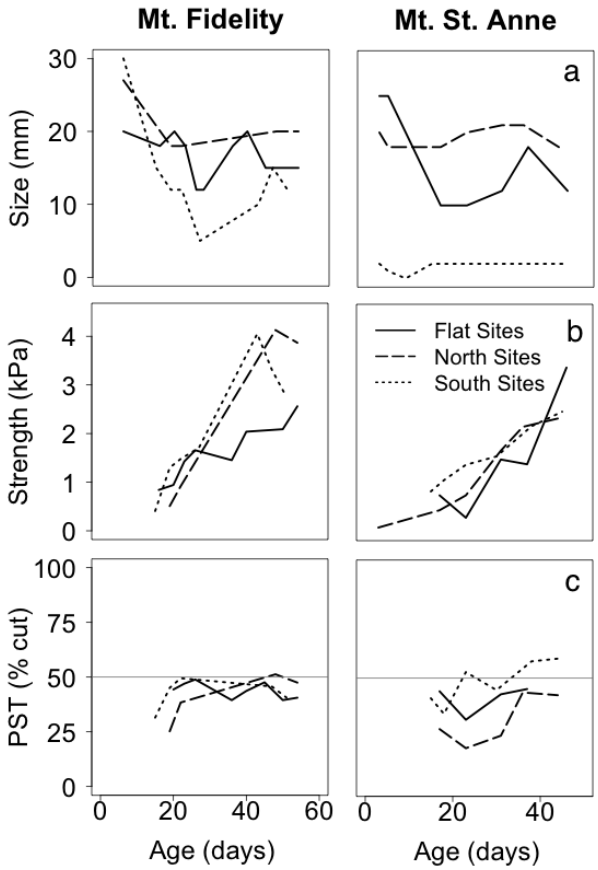

Figure 4: Time series of (a) maximum crystal size, (b) shear frame strength, and (c) propagation saw test % cut length for the early February 2012 surface hoar layer at each study site.

Changes in propagation potential are speculated to be attributed to thinning of the layer, stiffening of the overlying slab, and spatial variability across the study slope. The much smaller crystals at the Mt. St. Anne south site (2 mm) gave comparable shear frame and PST results to other sites. This was likely due to poor bonding to the underlying sun crust.

4. CONCLUSIONS

Modelling surface hoar formation over terrain is inherently challenging because slight differences in weather and location can change the size or even presence of crystals. We know to expect formation on calm, clear humid nights, but would also like to know the size and distribution of a layer. Analysis on 50 surface hoar layers over the last seven years at Mt. Fidelity found formation was common after two days without precipitation. Crystals grew at an average rate of 2.3 mm per day, but the rate for a specific layer depended on aspect and the time of year. A constant growth rate produced reasonable crystal size predictions in most cases ($r^2 = 0.44$).

Modelling formation with the surface energy balance required accurate weather measurements. Densities in the range of 30 to 35 kg m^{-3} were found to work best when converting mass to crystal size. The model made good predictions when using real station data ($r^2 = 0.74$), and reasonable predictions when using forecasted GEM15 data ($r^2 = 0.49$). The calculation of Q_E is very sensitive to wind speed, which likely accounts for the difference between the two data sources. Being able to model such a sensitive phenomenon with GEM15 data is promising for future snow cover modelling. Future work will be done to predict sizes at different locations in the Columbia Mountains. Extrapolating predictions into complex terrain will be attempted by making aspect specific predictions for north and south facing slopes.

Making realistic size predictions is important as size is believed to affect the persistence of a layer. The February 2012 surface hoar layer had large crystals and was a persistent avalanche problem. Although the strength of this layer steadily increased, the propagation potential remained high in PST tests – likely because of the large crystals. In future work this layer will be compared to other layers and changes in strength and propagation potential will be related to regional avalanche activity.

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