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Modelling hazardous surface hoar layers across western Canada with a coupled weather and snow cover model

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ABSTRACT

Destructive snow avalanches in western Canada are often caused by failure in buried surface hoar layers. Numerical snow cover models can simulate the formation and evolution of these layers, which could help avalanche forecasters assess the location and timing of avalanches. To investigate this application, we compared modelled surface hoar layers with snow and avalanche observations from the Coast, Columbia, and Rocky Mountains of western Canada. Surface hoar formation and evolution was modelled by forcing the snow cover model SNOWPACK with data from a high-resolution numerical weather prediction model. Surface hoar formation was verified with daily snow surface observations at 88 observation sites over two winters, and the evolution of buried layers was verified with avalanche observations and persistent weak layer assessments from 67 avalanche forecast regions. The frequency of surface hoar formation was overpredicted by 40%, although since modelled crystal sizes were moderately correlated with observed sizes, the more hazardous layers were often distinguished. A structural stability index in SNOWPACK often identified surface hoar layers during storm slab avalanche activity, but identifying layers during persistent slab avalanche activity was more difficult. Model limitations included uncertain meteorological inputs, errors in SNOWPACK's snow surface energy balance, and representing the necessary spatial scales. Despite these limitations, the coupled model resolved differences between major Canadian mountain ranges and could improve avalanche forecasts in data-sparse regions.

1. Introduction

Failure in buried surface hoar layers causes many destructive snow slab avalanches in western Canada (Haegeli and McClung, 2007). Surface hoar crystals form when water vapour deposits on the snow surface. While formation is common on clear, calm, and humid nights (Colbeck, 1988), the distribution of surface hoar is affected by complex mountain weather and topography (Feick et al., 2007, Horton et al., 2015). Once buried, surface hoar crystals form thin layers prone to releasing avalanches (Jamieson and Johnston, 1992, Jamieson and Schweizer, 2000).

Surface hoar layers release avalanches because of their unique structural properties. Schweizer and Jamieson (2007) found most skier-triggered avalanches released on layers with persistent grain forms, large grain sizes, and low hardness. Buried surface hoar layers often satisfy all three conditions, as crystals can reach several centimetres in length, much larger than the 1.3 mm threshold reported by Schweizer and Jamieson (2007). Large grains persist in the snowpack for weeks to months and can form weak truss-like structures prone to fracture propagation (Jamieson and Schweizer, 2000, Lutz et al., 2007).

Avalanche forecasters have used numerical models to simulate mountain snow covers since the 1990s. The French CROCUS model (Brun et al., 1992) and the Swiss SNOWPACK model (Lehning et al., 1999) use meteorological inputs to simulate the structural, thermal, and mechanical stratigraphy of the snow cover. Models predicting vapour deposition rates for surface hoar formation are implemented in both CROCUS and SNOWPACK (Hachikubo, 2001, Lehning et al., 2002). The SNOWPACK model calculates surface hoar size from the accumulated mass of deposited vapour. Stössel et al. (2010) and Horton et al. (2014) found modelled surface hoar sizes were moderately correlated with sizes observed at study plots. SNOWPACK also identifies potential avalanche failure layers with algorithms based on modelled grain size, layer hardness, and shear strength (Chalmers and Jamieson, 2003, Monti et al., 2014, Schweizer et al., 2006). Schirmer et al. (2010) and Monti et al. (2012) successfully identified critical surface hoar layers in simulated snow profiles with these algorithms.

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Although snow cover models can simulate critical weak layers, avalanche forecasters are usually already familiar with snow conditions at weather stations where simulations are run. However, forcing snow cover models with data from numerical weather prediction (NWP) models could provide valuable information about snow conditions in remote areas (e.g. Storm, 2012). Bellaire et al. (2011, 2013) tested this method at the Mt. Fidelity snow study plot in western Canada, finding coupled weather and snow models approximated the overall snow stratigraphy, including critical surface hoar and melt-freeze crust layers. Further verifications highlighted the need to address compounding errors with coupled models, as NWP model errors affected modelled surface hoar layers (Bellaire and Jamieson, 2013, Horton et al., 2014).

Recently, increasing horizontal resolution of NWP models has improved weather forecasts in complex terrain (Schirmer and Jamieson, 2015, Vionnet et al., 2014). For example, Schirmer and Jamieson (2015) found high-elevation snowfalls in western North America were modelled substantially better with a high-resolution NWP model (2.5 km) than with a regional-scale NWP model (15 km). Previous verifications of coupled weather and snow cover models in Canada used regional-scale NWP models, suggesting errors could be reduced by switching to higher resolution models. Furthermore, past verifications of critical layers focused on the Mt. Fidelity snow study plot, giving limited confidence in extrapolating the results to other mountain ranges.

Surface hoar layers vary on a wide range of scales from individual slopes to entire mountain ranges (Schweizer and Kronholm, 2007). Field campaigns by Feick et al. (2007) and Borish (2014) observed spatial correlations on scale of several hundred metres (i.e. basin scale), later supported by spatial patterns modelled on a 30 m grid by Helbig and van Herwijnen (2012). Gridded NWP models do not resolve weather conditions at these scales, suggesting snow cover properties could only be resolved at similar scales to the NWP models. Horton et al. (2015) investigated spatial weather patterns modelled by a 2.5 km NWP model across a small mountainous region. They found air temperature, humidity, and longwave radiation patterns that affected surface hoar distributions were resolved over different elevation bands on a regional scale, but finer scales were not resolved (e.g. basin or slope scales), primarily because local wind patterns had a substantial effect on surface hoar formation. Accordingly, coupled NWP and snow cover models are most suitable for regional-scale applications and should be further verified at those scales.

In this study, we modelled surface hoar layers at various locations in western Canada by coupling a high-resolution NWP model with SNOWPACK. The formation and evolution of modelled surface hoar layers over two winters was verified with a large data set of snow observations, avalanche observations, and persistent weak layer assessments. This paper reports the benefits and limitations of modelling hazardous surface hoar layers at scales relevant for avalanche forecasting with coupled weather and snow cover models.

2. Verification data

2.1. Surface grain observations

Snow grain observations were collected at weather observation sites operated by Canadian avalanche forecasting programs (e.g. ski resorts, backcountry skiing operations, parks, and transportation corridors). Observations were made at 14 sites in the Coast Mountains, 50 sites in the Columbia Mountains, and 24 sites in the Rocky Mountains (Fig. 1). Observations were collected for operational forecasting purposes and shared on the Canadian Avalanche Association's Information Exchange (InfoEx) database (Haegeli et al., 2014). Most observation sites were flat sheltered fields chosen to represent conditions in nearby avalanche starting zones (Canadian Avalanche Association, 2014). The form and size of surface snow grains were observed daily following standard observation guidelines (Fierz et al., 2009). A total of 7147 surface grain observations were collected between 1 December and 31 March during the 2013–2014 and 2014–2015 winters.

2.2. Avalanche observations

Avalanche observations were compiled from 15 avalanche forecasting programs in the Coast Mountains, 35 programs in the Columbia Mountains, and 17 programs in the Rocky Mountains (Fig. 1). The programs had defined regions that ranged in size from 2.5 to 8540 km^2, including ski resorts, backcountry skiing tenures, and national parks. Avalanches were observed by professionals travelling through their forecast regions and reported on the InfoEx following standard guidelines (Canadian Avalanche Association, 2014).

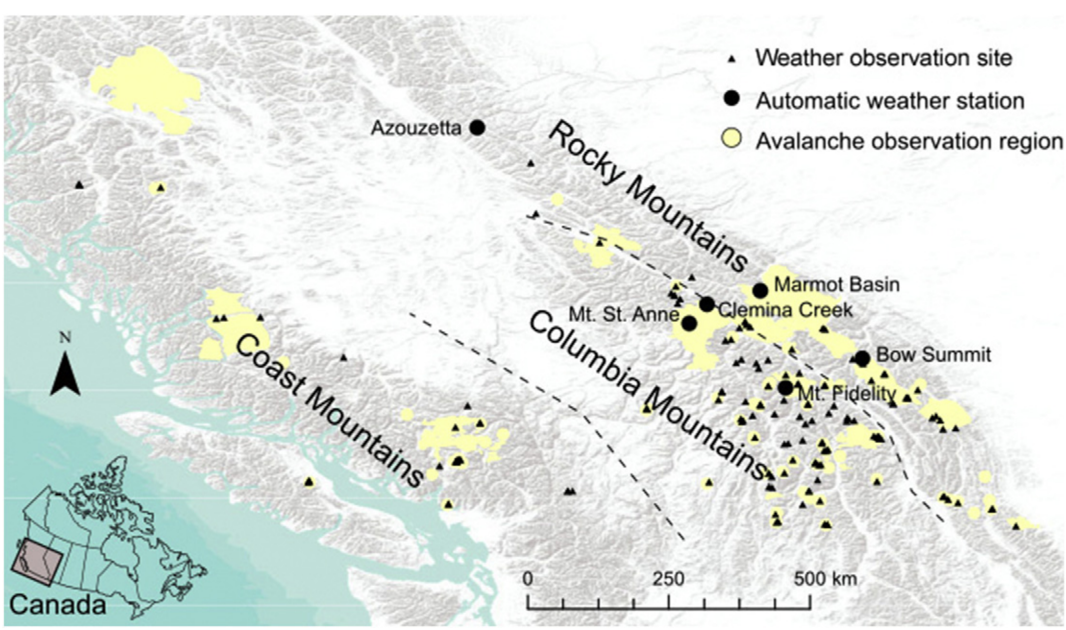

Fig. 1. Map of southwestern Canada with locations of mountain ranges, weather observation sites, automatic weather stations, and avalanche observation regions (ESRI basemap).