EXPLORING REGIONAL SNOWPACK PATTERNS WITH GRIDDED MODELS

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ABSTRACT: Although weather forecast models play a key role in avalanche forecasting, snowpack models have had limited uptake. As the quantity of weather and snowpack data grows with increasing computer power, methods to distill meaningful patterns will become more important. We generated spatially distributed snowpack data for over 15,000 km2 of western Canada during the 2017-18 winter. The snow cover model SNOWPACK was forced with meteorological data from a numerical weather prediction model on a 2.5 km grid. We developed visualization software to explore multiple snow profiles at the same time and shared it in real-time with six avalanche safety organizations. The visualization tool revealed common features in the profiles that could be aligned according to their deposition date. A case study at Mike Wiegele Helicopter Skiing found the visualizations contained many of the snowpack features described in their operational hazard assessments. Improvements to the visualizations and further post-processing of the model output could allow practitioners to interact with snowpack models in more meaningful ways.

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KEYWORDS: Snowpack model, forecasting, data aggregation, snow profile

1. INTRODUCTION

Physical snowpack models simulate the structural properties of the mountain snowpack using meteorological data. However, compared to weather forecast models, snowpack models have had limited uptake by avalanche practitioners. Likely barriers to adoption include limited confidence in model accuracy, being overwhelmed by the amount of detailed output, and lacking user-friendly interfaces for exploring the model output.

The past decade has seen an increase in the coupling of numerical weather prediction (NWP) models with physical snowpack models (Morin et al., In preparation). Examples include coupling operational weather models with the SNOWPACK model in Canada (Bellaire et al., 2011; 2013) and the CROCUS model in France (Vionnet et al., 2016) and Norway (Luijting et al., 2018). These model chains can simulate snowpack conditions in data-sparse areas, provide short-range snowpack forecasts, and make probabilistic forecasts with ensemble weather or climate models (Verfaillie et al., 2018). The model output is usually presented as snow profiles at individual locations (Fierz et al., 2016), and in some cases presented as maps. These visualizations may be difficult for operational decision making because they provide an overwhelming amount of information and can make it hard to understand the relevant information.

To improve the communication of snowpack model data, we explored ways to aggregate and simplify multiple simulated snow profiles. This paper presents a case study with snowpack simulations produced on a NWP model grid and presents new ways of visualizing the data with the intention of delivering the information in a meaningful way.

2. METHODS

2.1 Study area

A coupled weather–snowpack model was run in daily operational mode during the 2017-18 winter for seven regions in western Canada covering an area of over 15,000 km^2. This paper analyzes the profiles simulated in Mike Wiegele Helicopter Skiing's tenure in the Cariboo and Monashee mountain ranges of British Columbia (Fig. 1). Ski guides at the operation perform daily avalanche hazard assessments to select terrain that offers safe and enjoyable skiing. The process involves tracking snowpack conditions across an area that covers 4,535 km^2. The area has a transitional snow climate and the terrain ranges from densely forested valleys to expansive glaciated alpine terrain. While they collect large amounts of weather and snowpack data, additional information from numerical models could help during times of uncertainty.

2.2 Snowpack model

Snowpack simulations were produced using gridded meteorological data from a NWP model. Meteorological data was downloaded four times a day from the Canadian High-Resolution Deterministic Prediction System, which provides gridded forecasts at 2.5 km resolution (Milbrandt et al., 2016). Nowcast snow profiles were simulated by forcing the

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snow cover model SNOWPACK with precipitation, temperature, wind, humidity, and incoming solar and longwave radiation data. Flat field profiles were simulated at 482 grid points in Mike Wiegele Helicopter Skiing's tenure (Fig. 1). The grid points were assigned to below treeline (1500-1800 m, $n = 286$), treeline (1800-2100 m, $n = 168$) and alpine (>2100 m, $n = 25$) elevation bands.

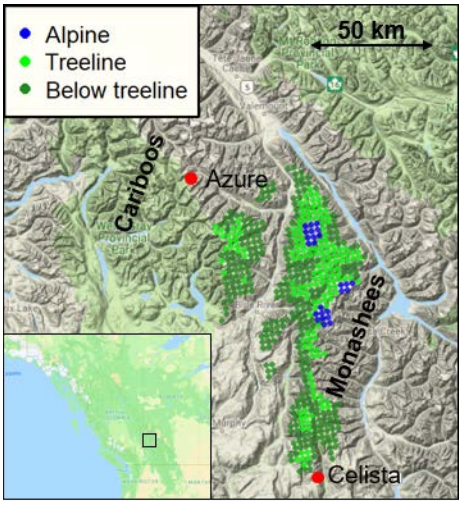


Figure 1: Mike Wiegele Helicopter Skiing operates in the Cariboo and Monashee Mountains of British Columbia. Coloured dots show the locations and elevation bands of NWP model grid points used in this study. Red dots show the location of the Azure River and Celista Mountain automated snow weather stations.

2.3 Visualization

A series of visualizations were produced following the visual information-seeking mantra: overview first, zoom and filter, then details on demand (Shneiderman, 1996). An interactive visualization tool was developed with Tableau® software and shared with partnering avalanche safety operations during the 2017-18 winter. The tool provided an overview of the distribution, shape, and outliers for a group of simulated snow profiles (Fig. 2). Features included a map-based browser to select locations and a profile viewer that showed side-by-side grain profiles sorted by either snow height or grid point elevation. A hovering tooltip allowed users to explore detailed layer properties such as their depth, grain size, and deposition date.

Visualization revealed snow profiles often had common features that formed on the same date (such as a crust, slab, or weak layer), however the depth of these features varied throughout the region. Hagenmuller (2016) and Bouchayer (2017) presented a method for matching features in snow profiles by adjusting layer thicknesses. Following this idea, a similar profile matching algorithm was developed using the deposition date of each layer. To align common features, we registered snow profile layers according to their deposition date. Every profile was resampled into a common set of dates. In cases where multiple layers had the same deposition date, these layers were aggregated by taking the mean of numeric variables (e.g. depth) and the mode of categorical variables (e.g. grain type). In cases where no layers existed for a given date, values were interpolated from the nearest dates (testing found interpolation gave meaningful results because related features often formed on consecutive days).

Once registered by deposition date, snow profile data was visualized with boxplots showing the range of properties for each date and aggregated hardness profiles with the average hardness, average depth, and most common grain type for each date. For example, amongst a set of profiles the layers deposited on December 5 could have an average depth of 78 cm, average hardness of 2.1, and the most common grain type as facet crystals.

2.4 Validation

The visualization tools were compared with operational snow safety data recorded by Mike Wiegele Helicopter Skiing. Data included assessments of avalanche problems and hazard, representative snow profiles drawn on whiteboards in their guides meeting room, and textual snowpack summaries. The snowpack summaries provide a concise overview of the range of conditions encountered during the day (CAA, 2014). Precipitation measurements were taken from two automated snow weather stations: Azure River at 1310 m in the Cariboo Mountains and Celista Mountain at 1551 m in the Monashee Mountains (Fig. 1).

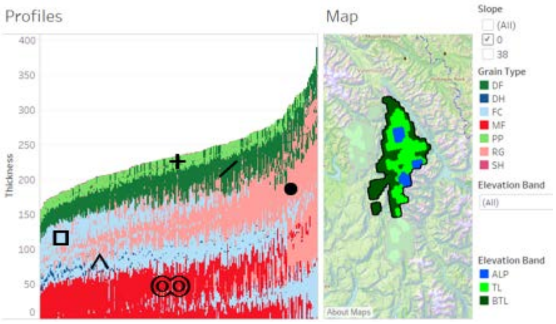
The case study focuses on February 15 2018, a day in which the avalanche danger was high and the guides identified a storm slab problem associated with new snow and a deep persistent slab problem associated with surface hoar layers from December and January. The combination of problems made for challenging mountain travel conditions and presented an interesting case to evaluate the accuracy of the model and the relevance of the visualizations.

3. RESULTS

3.1 Viewing multiple profiles

The Tableau® visualization tool provided an overview of common snowpack features by stacking profiles side-by-side. For example, on February 15 the simulated snowpack structure was similar throughout the region despite the fact the modelled snow depth ranged from 155 to 390 cm and the number of layers ranged from 30 to 74 (Fig. 2). By visual inspection, the snowpack can be summarized as 20-30 cm of fresh snow, 40-50 cm of recent storm snow, a mid-pack that was faceted in shallow areas and rounded in thick areas, a weak depth hoar layer 100-160 cm below the surface, and two melt-freeze crusts near the base of the snowpack.

Viewing multiple profiles at a time gives a better overview of the snowpack structure and eliminates some of the unnecessary details that exist in individual profiles. This could inspire greater confidence in the model, provide insight into snowpack variability, and prompt further detailed investigations of the data.


Slope
☐ (All)
☑ 0
☐ 38

Elevation Band
(All)

Figure 2: Screenshot of Tableau® visualization tool showing a sub-region of Mike Wiegele Helicopter Skiing's tenure on 15 February 2018. Profiles for a subset of locations were selected on the map are sorted by snow depth in the profile viewer.

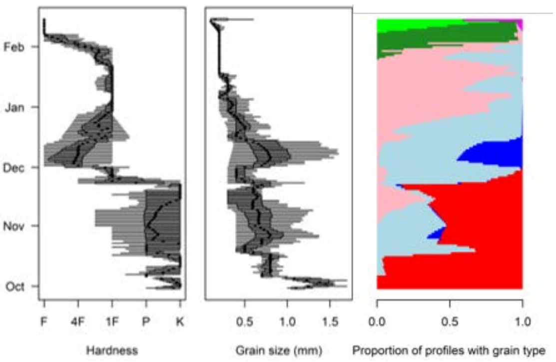


Figure 3: Range of hardness, grain size, and grain type for layers with same deposition date for all the treeline profiles on February 15.

3.2 *Features by deposition date*

To further understand these common features in the snowpack, the properties of layers that formed on the same day were compared (Fig. 3). For example, out of the treeline profiles on February 15 about 50% had new snow on the surface while the other 50% had surface hoar, the December weak layer was depth hoar in about 50% of the profiles, and about 75% of the profiles had early season crusts. Hardness and grain size was most variable for features that formed early in the season (Fig. 3), suggesting any deep persistent slab problems may have only existed in certain locations. Viewing the variability of snowpack features prompted further questions about their spatial distribution.

3.3 *Aggregated profiles*

Model output was presented in a format more familiar to practitioners by plotting hardness profiles with the average properties for each deposition date (Fig 4). The aggregated profiles were conceptually similar to whiteboard profiles drawn by the guides, as they represent the typical conditions in the region. The profiles provide a summary and overview of the data in an easy to understand format. The aggregation can be done by selecting various groups of grid points such as sub-regions or elevation bands. Grouping profiles by alpine, treeline, and below treeline elevation bands on February 15 revealed the snowpack was deeper and more consolidated at higher elevations and the December weak layer was most prominent at lower elevations (Fig. 4).

Figure 4: Snowpack summaries at three vegetation bands drawn by guides at Mike Wiegele Helicopter Skiing on February 15, along with aggregated profiles from snowpack simulations in these three bands.

3.4 *Critical weak layers*

Patterns emerged when analysing the stability indices predicted by the SNOWPACK model. The model identifies a primary critical weak layer for each profile using a structural stability index (a function of structural and mechanical properties). On February 15, the primary instability was in the recent storm snow for about half of the profiles, while the other half of the profiles had a primary instability in the deeper December weak layers composed of facets and depth hoar (Fig. 5). These two types of weak layers corresponded to the storm slab and deep persistent slab problems assessed by the guides.

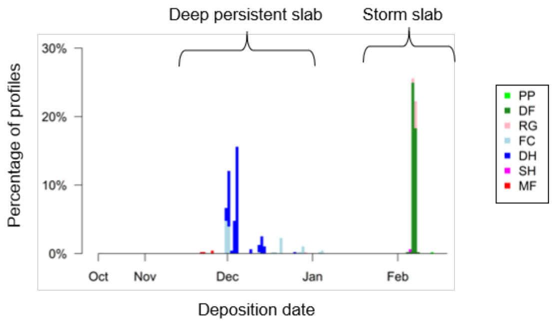


Figure 5: Grain types and deposition dates of critical layers for 482 simulated profiles on February 15.

Information about these two problems emerged when partitioning the profiles into two corresponding groups. For example, the depth of the critical weakness in profiles with the storm slab problem ranged from 23-50 cm while the depth of the critical weakness in profiles with the deep persistent slab problem ranged from 101-143 cm. Mapping the location of the profiles in these two groups revealed the storm slab problem was more prevalent at higher elevations and in southern parts of the region while the deep persistent slab was more prevalent at low elevations in the northern part of the region (Fig. 6). Further analysis of critical weak layers could lead to the complete identification and characterization of avalanche problems including their type, location, size, and likelihood.

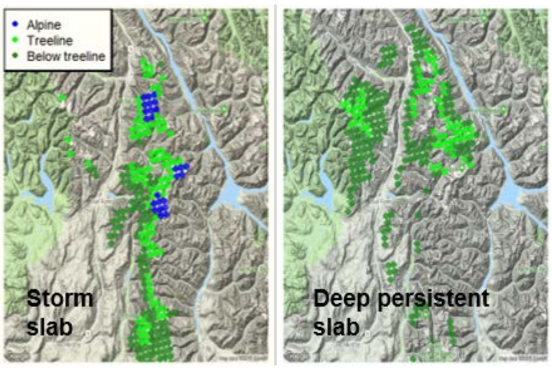


Figure 6: Location of simulated profiles with primary storm slab and deep persistent slab problems on February 15.

3.5 Validation

The snowpack summary written by Mike Wiegele Helicopter Skiing guides on February 15 identifies some strengths and weaknesses of the visualizations:

"*Up to 50 cm of low density snow in the last 48 hours, new Feb 13 surface hoar difficult to find mixed in with new snow, slight upside-down density change down 60 cm at places. Sun crust down 35 at steep solar aspects. Old surface hoar layers still evident in lower elevation profiles but increasing in strength with shovel tests*."

The simulated profiles only had 20-30 cm of storm snow, and the storm snow was decomposed at many locations as opposed to the "*low density*" snow reported by the guides. Errors in storm snow amounts are likely a result of errors in the NWP model's precipitation forecast (Schirmer and Jamieson, 2015). However, the model offers some additional information about the storm snow, including patterns over different elevations and horizontal gradients across the region. Sparse weather station records suggest the storm was likely more intense to the south. Snow pillow measurements at Celista Mountain in the Monashees reported 67 mm of snow water equivalent over the week compared to 45 mm at Azure River in the Cariboos. Guides often depend on a few point measurements of snowfall before heading into the field, and so these visualizations could potentially help localize storm slab problems.

The "*February 13 surface hoar*" appeared in a minority of the profiles (Fig. 3) and thus did not appear in the aggregated profile (Fig. 4). However, the guides said it was difficult to find and thus may not have been a relevant or problematic layer at the time.

The "*sun crust*" is not predicted in any of the profiles, as only flat field simulations were produced. Subtle localized features such as wind slabs and sun crusts may not be resolved with this model setup. This could be improved by running SNOWPACK on virtual slopes, but the results would still be limited by the ability of NWP models to resolve small-scale processes.

The "*old surface hoar layers*" mentioned by the guides refer the December weak layers, which was one of the prominent features in the simulated profiles. The simulated profiles correctly reveal the layer was most prevalent at low elevations (Fig. 4 and 6). Most profiles represent this layer as depth hoar rather than surface hoar, which is a known behaviour of the SNOWPACK model. Buried surface hoar layers will often evolve into depth hoar in the model (Horton and Jamieson, 2016), which was found to be the case after inspecting profiles from the same locations earlier in the season.

Regardless of grain type, the fact this weak layer existed was evident from the hardness and grain size profiles. The depth of the layer was underestimated (101-143 cm versus 150-180 cm), as was the overall snow depth and storm snow amounts in this region. Fig. 6 suggests the problem was prevalent in the northern part of the region, but none of the validation data localizes this problem by geographic area. In this case the visualizations may have offered some additional insight into the spatial distribution of the deep persistent slab problem.

4. CONCLUSIONS

New visualizations for coupled weather and snowpack models were developed to explore regional-scale snowpack patterns. The focus was to provide quick overviews of large sets of snow profile data, followed by detailed investigations of specific snowpack features. Deposition date proved to be a useful means to identify common snowpack features and summarize multiple snow profiles. For a case study in the tenure of Mike Wiegele Helicopter Skiing, the visualizations helped characterize a storm slab and a deep persistent slab avalanche problem. In the upcoming year we will work with practitioners to develop operational products that simulate the snowpack across large regions of western Canada and visualizations that promote meaningful interactions with the model output.

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