ADOPTING SNOWPACK MODELS INTO AN OPERATIONAL FORECASTING PROGRAM: SUCCESSES, CHALLENGES, AND FUTURE OUTLOOK

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ABSTRACT: Physical snowpack modelling has become an operational forecasting tool used by Avalanche Canada over the last decade. This paper reflects on the process of adopting modelling into the forecasting workflow, highlighting both successful implementation and challenges faced. Additionally, we present an outlook on future developments based on feedback from forecasters who have used the tools. The process of adopting modelling at Avalanche Canada involved close collaboration between the SFU Avalanche Research Program and other forecasting operations. Collaborative efforts focused on developing computer infrastructure to run SNOWPACK at a regional scale, designing effective ways to present model output, and delivering ongoing training. Over time, gradual exposure to this new source of information resulted in increased trust, especially after specific cases where the model offered insights into snowpack conditions that traditional data sources could not provide. However, limitations in understanding model uncertainty and the lack of meaningful verification data currently limit the weight placed on model predictions. To address this issue, future efforts should integrate the models with traditional data sources and establish workflows to regularly monitor model output and facilitate real-time validation. Despite these challenges, physical snowpack models have the potential to improve the accuracy and reliability of avalanche forecasting. The insights gained from this process may be applicable when adopting other new technologies into forecasting programs.

KEYWORDS: snowpack modelling, avalanche forecasting, dashboard, workflow

1. INTRODUCTION

In recent years, avalanche forecasters have shown growing interest in using numerical snowpack models to complement conventional data sources. Models like SNOWPACK and Crocus use meteorological data from weather stations or numerical weather prediction (NWP) models to simulate snowpack stratigraphy (Morin et al., 2020). While these models are widely used for snow and avalanche research, uptake by forecasting operations has been limited.

Developments in Canada were spurred by interest in producing avalanche forecasts in data sparse regions (Storm and Helgeson, 2014), which led to a collaborative effort between Avalanche Canada, the University of Calgary, the SFU Avalanche Research Program, and the Canadian Avalanche Association. The result was an operational snowpack modelling tool that is now used by public forecasters at Avalanche Canada and several other avalanche safety operations.

The core of these developments has been user-centric designs based on the specific needs and constraints of forecasters. The groundwork was laid during a workshop held at the 2016 ISSW in Breckenridge, where snowpack model developers and forecasters discussed barriers to adopting models. These discussions led to a status report by Morin et al. (2020) that emphasized the importance of improving the accessibility, interpretability, relevance, and accuracy of operational tools. In addition to these recommendations, we have drawn valuable insights from how meteorologists have implemented NWP models into forecasting operations over recent decades, as outlined by Benjamin et al. (2019).

The objective of this paper is to reflect upon and share the progress made towards the adoption of snowpack modelling in Canada. The paper begins by outlining the key developments over the past decade, followed by a summary of forecasters' responses to these developments. Finally, we present an outlook for future steps that could further improve our snowpack modelling tools and their integration into forecasting programs.

2. DEPLOYMENT INTO OPERATIONS

The deployment of operational snowpack modelling in Canada can be split into three periods (Table 1).

2.1 *Early prototypes (2011-2017)*

The first operational prototypes were developed by the Applied Snow and Avalanche Research group at the University of Calgary starting in the

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2010-11 winter. The SNOWPACK model was forced with a NWP model to address challenges in data sparse regions (Bellaire et al., 2011; 2013). Meteorological forcings were originally taken from the RDPS model (15 km resolution) until 2014, at which point we switched to the HRDPS model (2.5 km) (Schirmer and Jamieson, 2015). Simulated profiles were produced at 10 to 80 relevant grid point locations across western Canada and displayed with timeline and hardness profiles using early versions of niViz software (Fierz et al., 2016). Profiles were originally accessed through an ftp site, then later added to a map-based data viewer (ARFI). Between 2014 and 2017, additional operational prototypes were developed to experiment with topographic classes that averaged meteorological forcings across regions and applied lapse rate adjustments to different elevations (Morin et al., 2020), as well as gridded simulations of surface hoar formation (Horton et al., 2014).

2.2 Regional-scale prototypes (2018-2020)

Snowpack modelling research began at the SFU Avalanche Research Program in 2017-18 to directly address barriers to adoption. Based on feedback from forecasters (Floyer et al., 2016), the main theme was to provide simplified regional-scale summaries of snowpack conditions that relate to avalanche problems. This required developing infrastructure for large-scale gridded simulations where SNOWPACK could run on a continuous 2.5 km grid across all forecast regions (over 25,000 profiles). To display these profiles, research into visualization design principles helped develop interactive dashboards that provided simple overviews of the data while allowing forecasters to drill into more details on demand (Horton et al., 2020a). Refinements were made to reduce the redundancy and computational cost of gridded simulations, leading to stratified sampling of roughly one profile for each vegetation band within 10 to 20 km^2 cells. Methods to align, average, and cluster snow profiles were developed

Table 1. Timeline for the deployment of operational snowpack models in Canada.

Period	*Year*	*Operational milestone*
Early prototypes (2011-2017)	2011	Point profiles with SNOWPACK forced with RDPS (15 km) at 10 locations
	2014	Switched meteorological forcings to HRDPS (2.5 km)
	2014	Maps of modelled surface hoar formation available to professionals on InfoEx
	2015	Topographic classes introduced by averaging NWP inputs across vegetation bands
	2016	Outputs available on map-based dashboard (ARFI) and visualized with niViz
	2017	Number of profiles increased to 80 popular recreation locations
Regional-scale prototypes (2018-2020)	2018	Deployment of large-scale gridded simulations across western Canada
	2018	Interactive Tableau dashboards tested by Avalanche Canada and several heliskiing operations
	2019	Gridded simulations at all grid points in all forecast regions (over 25,000 locations)
	2020	Visualizations designed to emphasize avalanche problems in simulated profiles
	2020	Implemented profile processing code using the sarp.snowprofile package for R
	2020	Gridded simulations reduced to 2000 locations with stratified sampling
Operational dashboard (2021-2023)	2021	Computations moved to Amazon Web Services and maintained by Avalanche Canada
	2021	Operational dashboard with map views, regional summaries, and select point locations released and shared with 25 partner operations
	2021	Training videos published on YouTube
	2022	Produced average profiles for each region & tested regional clustering
	2022	Weekly snowpack model briefings with forecasters focused on current conditions
	2023	Assimilation of snow depth observations to correct snowfall amounts
	2023	Expansion of domain to USA (AK, WA, ID, MT) and eastern Canada (NL, QC, Baffin) and 40 partner operations
	2023	Combination of HRPDS (2.5 km) and RDPS (10 km) used in each region

over this period to improve the display of regional-scale model outputs (Herla et al., 2021; 2022).

2.3 Operational dashboards (2021-2023)

For the 2020-21 winter, the infrastructure developed at SFU was transferred to Avalanche Canada's operational servers and Avalanche Canada developed an interactive dashboard based on previous prototypes. This allowed forecasters to view snowpack model output on the same website as other observations such as avalanche occurrences and automated weather stations (Figure 1). Forecaster use was encouraged with training videos on YouTube, pre-season workshops, and weekly briefings where the model output was discussed in the context of the current avalanche conditions. Working closely with SFU, the latest research developments were implemented into the operational system in an ongoing basis, including clustering and averaging snow profiles (Herla et al., 2022) and assimilating snow depth observations (Horton and Haegeli, 2022). By the 2022-23 winter, access to the dashboard was shared with over 40 operations in western Canada and the USA.

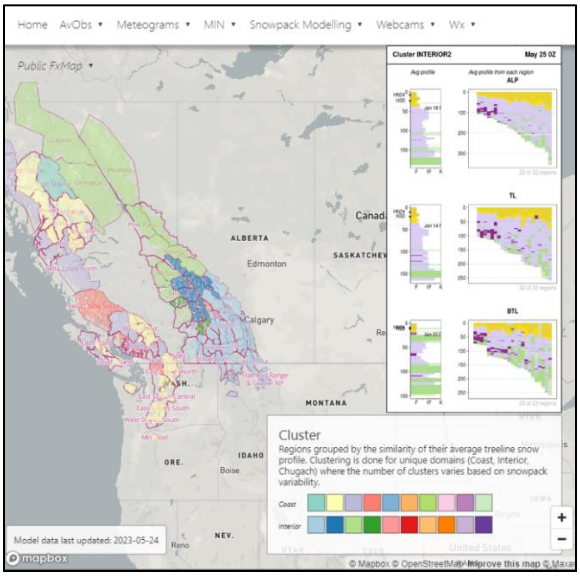

Figure 1. The operational dashboard from the 2022-23 winter has a map of regions with similar snowpack structure on the left and sidebar on the right showing a representative snow profile at three elevation bands for a selected region. Critical weak layers and three-day snowfall are identified on the profiles.

3. FORECASTER FEEDBACK

We conducted an informal survey with five Avalanche Canada forecasters of varying experience to gather their insights on integrating snowpack models into their workflows. This section summarizes key themes that emerged from their responses along with some insightful quotes.

3.1 Adoption into forecasting workflows

Integration into daily operations varied among individuals, primarily shaped by their familiarity with forecasting workflows. Experienced forecasters with established workflows generally integrated the tool slowly, while new forecasters immediately dedicated time to learning and using the tool. Initial encounters with snowpack models evoked skepticism due to concerns about accuracy and validation.

"I think we applied a lot of undue scrutiny to models in the early days due to a combination of skepticism toward weather models, protectiveness of our workflows, and existing ideas about what makes good data."

Forecasters gradually began incorporating models into their decision-making processes after observing their value in specific scenarios.

"Understanding where the models are calibrated well helps immensely. I have come to better understand over time when they are most useful."

Weekly briefings also played an important role in improving model comprehension and interpretation.

"Weekly briefings have addressed many of the issues behind understanding how the models work and how to interpret the output."

3.2 How the tool is currently used

The most sought-after information from the current tool is regional-scale snowfall patterns, which most forecasters use daily in combination with traditional weather observations. In contrast, the interpretation of more complex snowpack details, such as weak layer depths and distributions, is conducted more irregularly. Such in-depth analysis primarily occurs during periods of heightened uncertainty and for regions with limited field data.

Avalanche Canada implemented flexible forecast region boundaries for the 2022-23 season, at which point the regions suggested by the model clustering algorithm was frequently consulted to help define region boundaries. This feedback prompted further research at SFU into optimizing the clustering methods (Horton et al., in prep).

The shift of this tool from point-scale to regional-scale information was initially a challenge as it presented snowpack data in a new way, but eventually was found to be valuable. Extrapolating point-scale field observations to a regional-scale is cognitively demanding, whereas viewing snowpack data at a larger scale naturally fits with the scale of hazard assessments.

"Instead of making an extrapolation from a single professional operation to an entire region, we can make a much smaller leap toward a regional summary and then use professional observations to modify the summary."

Several forecasters drew analogies to weather forecast products, highlighting the need to establish ways to interpret the information and build anecdotal evidence of which models work best in different locations and scenarios. Importance is placed on interpreting and validating the models in conjunction with other available data, especially in data-rich areas. There has been a gradual realization that model data can outperform observation networks in certain situations.

3.3 Barriers to adoption

Time constraints were identified as the most common barrier to adopting any type of new tool, including snowpack models. Some forecasters also said the tool needs to be further integrated into the forecasting software to be used more regularly, and suggested they would use the tool more if parts of the forecast were auto populated with model output.

"Due to time constraints, any prospective new tool or process has a high bar to meet in order for forecasters to be open to integrating it on more than a trial basis."

"I use them after I am a bit more familiar with the forecast regions and have more time to dedicate to fine-tuning the forecasts."

"The current dashboard is not built-in enough to my workflow to remember or want to use it."

Finally, there are still challenges with interpreting the information. Detailed snowpack properties are not easily interpreted by all, comparing model and observation data is a time-consuming and cognitively demanding task, and for some, the unique way of visualizing the snowpack at a regional scale is unnatural.

"They just don't work for my eye and the way I read things. I am not sure why. I really have to concentrate to pull meaning from them."

4. NEXT STEPS

4.1 Dashboards

While the current tools are semi-integrated into Avalanche Canada's forecasting software, improvements could be made to streamline the comparison of model and observation data. The development of such dashboards was instrumental in meteorology to allow forecasters to learn when and where models offer reliable predictions (Benjamin et al., 2019). Interactive dashboards are also key in allowing forecasters to explore data and perform specific queries. We have noted several common queries that could be developed into more interactive dashboards (e.g., displaying load on a specific layer, identifying elevation bands of specific problems, toggling the number of clustered regions).

4.2 Automation

Snowpack modelling could support computer-assisted forecasting, which has potential to improve efficiency, accuracy, consistency, and coverage (Floyer et al., 2016). Certain sections of avalanche forecasts could be auto populated with either text or graphics derived from model output. Automating avalanche problems and danger ratings is also a possibility, however research towards this goal has highlighted challenges in the training data and inconsistent application of problems and danger by forecasters (Horton et al., 2020b; Hordowick, 2022, Herla et al., 2023). Automated products should be supported with dashboards where forecasters can explore and verify the data used to produce them.

4.3 Training

Training is critical to successful adoption by forecasters, who are traditionally not familiar with computer-generated snowpack data. A structured training approach could follow the way weather forecasting is taught to avalanche workers. Adding snowpack modelling to the curriculum of professional avalanche courses could provide a foundational knowledge base, and then continued learning can be made possible by seasonal workshops and more regular briefings to apply the knowledge to the current situation. Making the tool more accessible to a border range of avalanche professionals through platforms such as the InfoEx would also improve adoption and learning.

4.4 Model configurations

The configuration of snowpack models should continue to progress based on the availability of quality NWP products. Trends in modern NWP include higher-spatial resolutions and ensemble or probabilistic models. As higher spatial resolutions become available, snowpack models could potentially provide more localized predictions. We find current NWP output is sufficient to distinguish regional-scale patterns across mountain ranges (e.g., the windward versus leeward sides of major ranges), however with higher resolutions, subrange and drainage-scale predictions will likely become possible. Similarly, ensemble model configurations should be further explored to provide probabilistic snowpack predictions (Vernay et al., 2015), and leverage recently developed snow profile processing methods to simplify the output.

4.5 Data assimilation

Assimilating snow and weather observations into operational model chains should improve the accuracy of model predictions. Horton et al. (2022) developed a simple routine to assimilate snow depth observations into the operational model, given the relatively abundant coverage of manual and automatic observations. Further assimilation of snowfall and precipitation observations could further improve model accuracy. Herla et al. (2023) explored methods of matching layers to critical layers identified in professional avalanche assessments, which could be implemented to assimilate observed or assessed layers into snowpack simulations.

However, there is growing evidence from related fields like hydrology that model data can outperform sparse observation networks in certain situations (Lundquist et al., 2019). The advantages and disadvantages of each information source should be carefully weighed when making regional-scale assessments.

4.6 Predict stability, problems, and danger

The current tool summarizes snowpack structure, but methods exist to extend this to predict the stability of specific layers (Mayer et al., 2022) and avalanche problem types (Reuter et al., 2021; Herla et al., 2023). While these concepts have a clear link to avalanche hazard assessments, they should be implemented gradually in a way that allows forecasters to learn their limitations. Given the lack of validated hazard datasets to train statistical models, we suggest developing predictive models based on physical principles, or expert systems that combine human analysis with computer-assisted predictions. Forecasters will need carefully designed tools to get familiar with such models and should play a role in their calibration.

5. CONCLUSIONS

The adoption of snowpack modelling tools by forecasters at Avalanche Canada has been a gradual process. Initially facing friction due to unfamiliarity and difficulty in verification, years of prototypes and iterative feedback have resulted in a tool that has now become regularly used in operational forecasting. However, future upgrades, such as higher spatial resolution, ensembles, data assimilation, and automated assessments, will encounter similar challenges. To overcome these challenges and facilitate successful adoption, we recommend the following:

- Collaboration: Foster international collaboration between researchers, forecasters, and organizations involved in snowpack modelling to share knowledge, resources, and best practices.
- User-centric design: Continuously engage with forecasters to understand their needs and design intuitive and accessible tools aligned with existing workflows.
- Integrate with existing tools: Integrate snowpack modelling tools with familiar data sources and formats and develop effective visualization techniques to highlight relevant information and communicate uncertainty.
- Validation: Integrate models with traditional data sources and establish workflows for real-time validation to enhance trust in model predictions.
- Training: Provide comprehensive training and ongoing support to improve forecasters' understanding of snowpack models.

Following these recommendations can accelerate the adoption of snowpack modelling, improving the accuracy and reliability of avalanche forecasting. Moreover, the lessons learned from this process can hopefully guide the successful adoption of other emerging technologies.

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REFERENCES

Bellaire, S., Jamieson, B., and Fierz, C.: Forcing the snow-cover model SNOWPACK with forecasted weather data, Cryosphere, 5, 1115-1125, https://doi.org/10.5194/tc-5-1115-2011, 2011.

Bellaire, S., Jamieson, B., and Fierz, C.: Corrigendum to “Forcing the snow-cover model SNOWPACK with forecasted weather data” published in The Cryosphere, 5, 1115-1125, 2011, Cryosphere, 7, 511-513, https://doi.org/10.5194/tc-7-511-2013, 2013.

Benjamin, S., Brown, J., Brunet, G., Lynch, P., Saito, K., and Schlatter, T.: 100 years of progress in forecasting and NWP applications, Meteorol. Monogr., 59, 13.1-13.67, https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0020.1, 2019.

Fierz, C., Egger, T., Gerber, M., Techel, F., and Bavay, M., SnopViz: an interactive visualization tool for both snow-cover model output and observed snow profiles, in: Proceedings of the International Snow Science Workshop, CO, 3-7 October 2016, 637-641, 2016.

Floyer, J., Klassen, K., Haegeli, P., and Horton, S.: Looking to the '20s: Computer-assisted avalanche forecasting in Canada, in: Proceedings of the International Snow Science Workshop, Breckenridge, CO, 3-7 October 2016, 1245-1249, 2016.

Herla, F., Horton, S., Mair, P., and Haegeli, P.: Snow profile alignment and similarity assessment for aggregating, clustering, and evaluating snowpack model output for avalanche forecasting, Geosci. Model Dev., 14, 239-258, https://doi.org/10.5194/gmd-14-239-2021, 2021.

Herla, F., Haegeli, P., and Mair, P.: A data exploration tool for averaging and accessing large data sets of snow stratigraphy profiles useful for avalanche forecasting, Cryosphere, 16, 3149-3162, https://doi.org/10.5194/tc-16-3149-2022, 2022.

Herla, F., Haegeli, P., Horton, S., Mair, P.: A quantitative module of avalanche hazard — Comparing forecaster assessments of avalanche problems with information derived from distributed snowpack simulations, in: Proceedings of the International Snow Science Workshop, Bend, OR, 8-13 October 2023, 2023.

Herla, F., Haegeli, P., Horton, S., and Mair, P.: A large-scale validation of snowpack simulations in support of avalanche forecasting focusing on critical layers, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-420, 2023.

Hordowick, H.: Understanding avalanche problem assessments: A concept mapping study with public avalanche forecasters, MRM, School for Resource and Environmental Management, Simon Fraser University, Burnaby, BC, 2022.

Horton, S., Schirmer, M., Jamieson, B., and Kulyk, E.: Online tool for visualizing surface hoar layers, in: Proceedings of the International Snow Science Workshop, Banff, AB, 28 September - 3 October 2014, 547-549, 2014.

Horton, S., Nowak, S., and Haegeli, P.: Enhancing the operational value of snowpack models with visualization design principles, Nat. Hazards Earth Syst. Sci., 20, 1557-1572, https://doi.org/10.5194/nhess-20-1557-2020, 2020a.

Horton, S., Towell, M., and Haegeli, P.: Examining the operational use of avalanche problems with decision trees and model-generated weather and snowpack variables, Nat. Hazards Earth Syst. Sci., 20, 3551-3576, https://doi.org/10.5194/nhess-20-3551-2020, 2020b.

Horton, S. and Haegeli, P.: Using snow depth observations to provide insight into the quality of snowpack simulations for regional-scale avalanche forecasting, Cryosphere, 16, 3393-3411, https://doi.org/10.5194/tc-16-3393-2022, 2022.

Horton, S., Herla, F., Haegeli, P.: Clustering simulated snow profiles to produce avalanche forecast regions, manuscript in preparation, 2023.

Lundquist, J., Hughes, M., Gutmann, E., and Kapnick, S.: Our skill in modeling mountain rain and snow is bypassing the skill of our observational networks, Bull. Am. Meteorol. Soc., 100(12), 2473-2490, https://doi.org/10.1175/BAMS-D-19-0001.1, 2019.

Mayer, S., van Herwijnen, A., Techel, F., and Schweizer, J.: A random forest model to assess snow instability from simulated snow stratigraphy, Cryosphere, 16, 4593-4615, https://doi.org/10.5194/tc-16-4593-2022, 2022.

Morin, S., Horton, S., Techel, F., Bavay, M., Coléou, C., Fierz, C., Gobiet, A., Hagenmuller, P., Lafaysse, M., Ližar, M., Mitterer, C., Monti, F., Müller, K., Olefs, M., Snook, J., van Herwijnen, A., and Vionnet, V.: Application of physical snowpack models in support of operational avalanche hazard forecasting: A status report on current implementations and prospects for the future, Cold Reg. Sci. Technol., 170, 102910, https://doi.org/10.1016/j.coldregions.2019.102910, 2020.

Reuter, B., Viallon-Galinier, L., Horton, S., van Herwijnen, A., Mayer, S., Hagenmuller, P., and Morin, S.: Characterizing snow instability with avalanche problem types derived from snow cover simulations, Cold Reg. Sci. Technol., 194, 103462, https://doi.org/10.1016/j.coldregions.2021.103462, 2021.

Schirmer, M. and Jamieson, B.: Verification of analysed and forecasted winter precipitation in complex terrain, Cryosphere, 9, 587-601, https://doi.org/10.5194/tc-9-587-2015, 2015.

Storm, I., and Helgeson, G.: Hot-spots and hot times: exploring alternatives to public avalanche forecasts in Canada's data sparse Northern Rockies region, in: Proceedings of the International Snow Science Workshop, Banff, AB, 28 September - 3 October 2014, 91-97, 2014.

Vernay, M., Lafaysse, M., Mérindol, L., Giraud, G., and Morin, S.: Ensemble forecasting of snowpack conditions and avalanche hazard, Cold Reg. Sci. Technol., 120, 251-262, https://doi.org/10.1016/j.coldregions.2015.04.010, 2015.