A QUANTITATIVE MODULE OF AVALANCHE HAZARD—COMPARING FORECASTER ASSESSMENTS OF AVALANCHE PROBLEMS WITH INFORMATION DERIVED FROM DISTRIBUTED SNOWPACK SIMULATIONS

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ABSTRACT: Avalanche forecasting is a human judgment process with the goal of describing the nature and severity of avalanche hazard based on the concept of avalanche problems. Snowpack simulations can help improve forecast consistency and quality by extending qualitative frameworks of avalanche hazard with quantitative links between weather, snowpack, and hazard characteristics. Building on existing research on modeling avalanche problems, we present the first spatial modeling framework for extracting the characteristics of storm and persistent slab avalanche problems from distributed snowpack simulations. Grouping of simulated layers based on regional burial dates allows us to track them across space and time and calculate insightful spatial distributions of avalanche problem characteristics.

We applied our approach to ten winter seasons in Glacier National Park, Canada, and compared the numerical predictions to human hazard assessments. Despite good seasonal agreement, the comparison of the daily assessments of avalanche problems revealed considerable differences. Best agreements were found in the presence and absence of storm problems and the likelihood and expected size assessments of persistent problems. Even though we are unable to conclusively determine whether the human or model data set represents reality more accurately when they disagree, our analysis indicates that the current model predictions can add value to the forecasting process by offering an independent perspective. Our study contributes to a growing body of research that aims to enhance the operational value of snowpack simulations and provides insight into how snowpack simulations can help address some of the operational challenges of human avalanche hazard assessments.

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Keywords: Avalanche forecasting, snowpack modeling, avalanche problems, model evaluation

1. INTRODUCTION

Avalanche forecasting is a human judgment process where a wide range of observations are synthesized into an overall picture of the nature and severity of avalanche hazard (LaChapelle, 1980; McClung, 2002a,b). The North American Conceptual Model of Avalanche Hazard (CMAH, Statham et al., 2018a) and similar standards in Europe (EAWS, 2023) set the foundation for a common language and qualitative framework for assessing avalanche hazard based on the concept of avalanche problems.

Operational experience and recent research has shown that there is considerable variability in how the avalanche danger rating, the CMAH, and the concept of avalanche problems are applied by avalanche forecasters (Lazar et al., 2016; Statham et al., 2018b; Techel et al., 2018; Clark, 2019; Horton et al., 2020; Hordowick, 2022). Since these inconsistencies can lead to serious miscommunications among forecasters themselves and with avalanche forecast users, there is a need for improving the consistency and quality of the operational use of these cornerstones of avalanche hazard assessments.

Snowpack simulations that numerically link weather, snowpack, and hazard have great potential to present avalanche forecasters with an independent and reproducible perspective on the possible characteristics of the expected avalanche problems. Extensive research in snowpack modeling for avalanche forecasting dates back over two decades and has led to a variety of operational modeling chains (Morin et al., 2020). While data overload issues and validity concerns have traditionally been the primary hurdles preventing the operational use of snowpack models in Canada (Morin et al., 2020; Herla et al., 2021), several recent studies have focused on making the simulated data more accessible and operationally more relevant (Herla et al., 2023b). Furthermore, a growing body of

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research provides insights into the validation of snowpack simulations from a variety of different angles (e.g., Morin et al., 2020; Calonne et al., 2020; Viallon-Galinier et al., 2020; Horton and Haegeli, 2022; Herla et al., 2023a).

While these studies help forecasters better understand the strength and weaknesses of the simulated snowpack information and integrate into their workflows, they do not address the existing challenges in the human analysis process that synthesizes the information into a comprehensive hazard assessment. To address this issue, Reuter et al. (2021) recently introduced a prescriptive approach for modeling avalanche problem types from simulated snowpack information based on the current understanding of snow instability. In addition, Mayer et al. (2023) developed data-driven models for predicting the probability and size of dry-snow avalanches in the vicinity of weather stations from observation-driven snowpack simulations using verified data sets of natural avalanche activity and stability tests related to human triggered avalanches. Both of these studies demonstrate the potential of snowpack models for providing avalanche problem information.

The present study expands on these ideas with two main contributions. First, we present a spatial approach to extracting the characteristics of storm and persistent slab avalanche problems from distributed snowpack simulations that traces individual snowpack layers across space and time and allows the calculation of insightful spatial distributions of avalanche problem characteristics. We tailor the output of our numerical predictions to the needs of the North American avalanche community by mirroring concepts included in the CMAH and make the output tangible and relevant by summarizing the simulated information in the familiar format of hazard charts. Second, we examine the agreement between simulations and human assessments for persistent and storm slab avalanche problem situations. We start with seasonal patterns to compare our results to Reuter et al. (2021) and Mayer et al. (2023), but focus mainly on the comparison of daily assessments to simultaneously explore the capabilities of the model chain and gain further insight into the strengths and weaknesses of human avalanche hazard assessments.

2. DATA

The data sets used in this study consist of snowpack simulations and operational avalanche hazard assessments from avalanche forecasters in western Canada over ten winter seasons (2013–2022). The study focuses on the public avalanche forecast region of Glacier National Park, which is located in the Columbia Mountains of British Columbia, Canada.

2.1. Snowpack simulations

For our simulations, we feed the Canadian numerical weather prediction model HRDPS (Milbrandt et al., 2016, 2.5 km resolution) into the detailed snow cover model SNOWPACK (Bartelt et al., 2002; Lehning et al., 2002b,a) to simulate the snow stratigraphy at 100 treeline locations (i.e., 1800–2100 m asl) within the boundaries of Glacier National Park. All simulated snow profiles represent flat field conditions valid between 4–5 PM local time. For a detailed description of the snowpack simulations used for this study, the interested reader is referred to Herla et al. (2023a).

2.2. Avalanche hazard assessments

Avalanche hazard assessments used in this study were issued by public avalanche forecasters every day of the winter season. The assessments represent forecasters' best knowledge of the current conditions (i.e., nowcasts) and were issued in the afternoon for the treeline elevation band in Glacier National Park. Applying the CMAH (Statham et al., 2018a), forecasters partition the avalanche hazard into different avalanche problems and characterize each problem by its type, location, the likelihood of avalanches, and destructive avalanche size resulting from each avalanche problem. In addition to the avalanche problem information, the hazard assessments contain danger ratings that summarize the hazard from all avalanche problems using the five-level ordinal North American Public Avalanche Danger Scale (Statham et al., 2010).

3. METHODS

3.1. Grouping of layers by their burial dates

Since persistent weak layers and crusts can cause multiple avalanche cycles, one of the key tasks of avalanche forecasters is to maintain a mental model of where these layers exist and track their evolution over time. To facilitate both the tracking and communication of these layers, avalanche forecasters in Canada name these layers with date tags and their grain type(s) (e.g., "Jan 17th surface hoar layer"). Reported date tags mostly represent the beginning of snowfall periods that bury layers that were exposed to the snow surface before the snowfall and therefore likely contain weak grain types. Sometimes the date tags also represent rain events that form a crust at the snow surface.

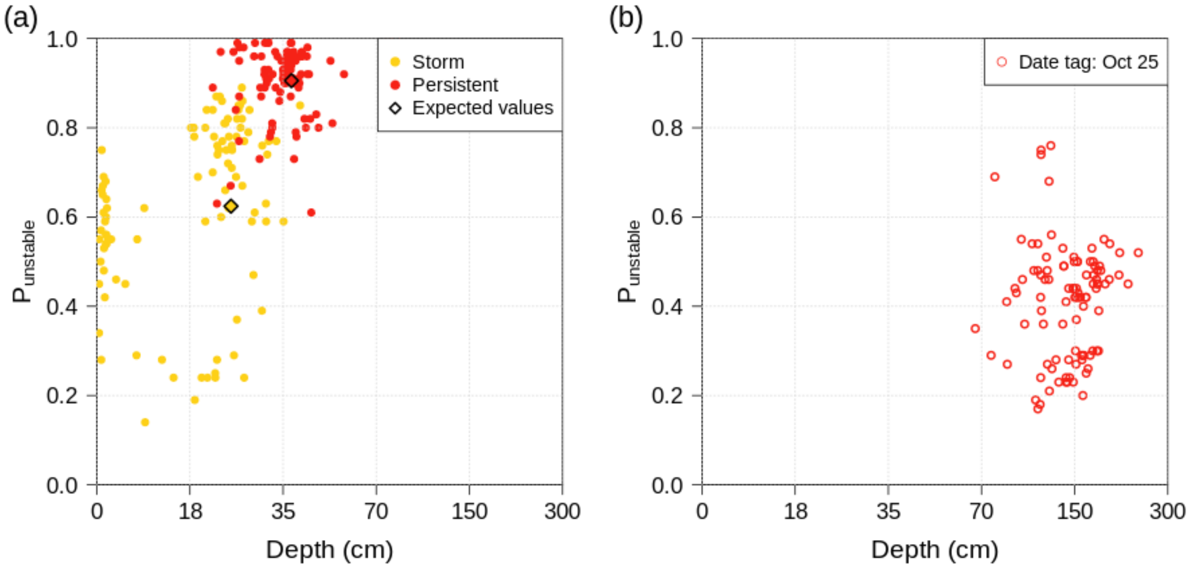

Figure 1: Numerical hazard charts derived from snowpack simulations that are similar to the ones produced by forecasters following the CMAH. As described in the text, the data can be subset by avalanche problem types and date tags, such that each data point corresponds to one grid point location showing the weakest instability ($p_{unstable}$) and the relevant failure depth for the given subset of layers. (a) Showing storm snow and persistent weak layer problems, (b) showing the subset for a specific date tag. Both panels are valid for Feb 04, Glacier National Park at treeline.

We use the concept of date tags to group all layers from our snowpack simulations from different locations and times. First, we create a list of all possible date tags for the season based on a) layers that were explicitly tracked by forecasters, and b) simulated precipitation patterns across the region. Analogously to forecaster practice, each date tag represents a date when the snow surface got buried by new snow. We then label all simulated snowpack layers that got deposited by the same storm and were exposed to the same subsequent dry period with one date tag based on knowledge of the layers' formation dates. The interested reader is referred to Herla et al. (2023a) for more detailed descriptions of exact rules and thresholds.

3.2. Modeling storm/persistent avalanche problems

Our strategy of extracting avalanche problem characteristics from the simulations first evaluates all problem characteristics for individual layers at each model grid point separately before aggregating these individual evaluations by date tags, problem types, and finally across all grid points within the region. In this study, we apply this approach to assess storm and persistent (including deep persistent) slab avalanche problems. These problem types were identified using modeled grain types: instabilities within layers of precipitation particles were designated as storm problems, while instabilities within layers of surface hoar, depth hoar, or facets were designated as persistent problems. To characterize the likelihood of avalanches, we employ the stability classifier $p_{unstable}$ developed by Mayer et al. (2022) for artificial triggering of dry snow. As suggested by Mayer et al. (2022), we considered layers with $p_{unstable} \geq 0.77$ as critical avalanche layers with poor stability. To characterize avalanche size, we extract the depth of the expected failure layer.

To aggregate the problem information at each grid point by date tag or by problem type, we compute the weakest instability of the corresponding groups of layers to characterize the likelihood of avalanches and the depth of the weakest instability (or the depth of the most deeply buried critical layer with poor stability) to characterize their destructive potential. The simulated avalanche problem information can now be visualized in a similar way to the hazard charts known from the CMAH. The information either characterizes the contribution from each problem type (Figure 1a) or the contribution from a subset of layers with a specific date tag (Figure 1b). Data points that are located close to the upper right corner correspond to deeply buried layers that are expected to be triggered easily. Since every data point corresponds to one grid point, the spatial distribution can be gauged from the distribution of the point cloud on the chart.

To aggregate avalanche problem characteristics over a spatial domain, we compute averages (diamond shapes in Figure 1a, b, and black lines in Figure 3c–f) as well as various percentiles (grey shading in Figure 3c–f) of likelihood of avalanches and depth across all individual model grid points (i.e., 10th, 25th, 50th, 75th, and 90th percentiles) taking advantage of our regionally connected layers, both stable and unstable. While all data points contribute to the computation of the expected likelihood of avalanches, only data points with poor stability (i.e., $p_{\text{unstable}} \geq 0.77$) are considered for the computation of the expected failure depth.

3.3. *Comparing modeled and human assessments*

After extracting and aggregating avalanche problem information from the simulations, this information can be compared to the human avalanche hazard assessment data set. Figure 3 illustrates all hazard characteristics from the two data sets for the 2018/19 season. We examined active/inactive times of the problems, trends and absolute magnitudes of the likelihood and size of avalanches, as well as how the danger rating relates to the more specific individual assessments.

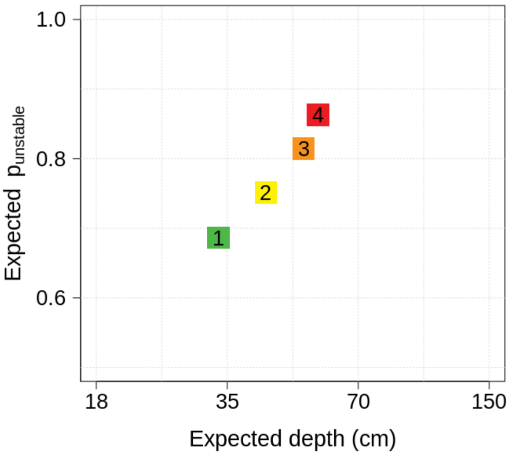

Figure 2: Multi-seasonal evaluation of the numerical hazard chart. The colored square labels highlight the median values of expected problem characteristics for different danger ratings as per human assessments.

4. RESULTS

4.1. *Seasonal patterns*

Our ten-year data set contained 1289 days of forecaster assessments that assigned a total of 780 persistent slab avalanche problem days and 572 storm slab avalanche problem days. Using a threshold for the expected $p_{\text{unstable}} \geq 0.77$ to classify a problem as modeled, the simulations identified considerably fewer days with avalanche problems, namely 558 and 328 persistent and storm slab avalanche problem days, respectively. However, the relative frequency between the two avalanche problems is similar between both data sources. Hence, our results are in line with Reuter et al. (2021), whose modeling approach also suggested fewer problems than actually assessed but also found good agreement in the relative frequency of avalanche problems.

Stratifying the predictions of the numerical hazard chart by the assessed danger rating of the day reveals a steady increase of the median expected values of both failure depth and likelihood of avalanches (Figure 2).

4.2. *Daily agreement*

Our qualitative examination of the ten season summaries (like Figure 3) initially revealed more disagreement than agreement. For many individual hazard cycles, the majority of hazard characteristics showed substantial differences between the human and simulated assessment data sets. For most cycles, only one or two characteristics, such as either absolute magnitudes or trends of different variables of interest, would agree between the two data sets while the other characteristics showed divergent patterns. Hazard cycles with higher levels of agreement in the majority of characteristics were rare. However, a more detailed analysis of the time series that took operational considerations into account revealed more valuable insight.

We use the 2019 winter season (Figure 3) to illustrate our observations with a few examples. The 2019 operational forecasting program started on Dec 01 and instantly reported a persistent weak layer problem. At first sight, this assessment is at odds with the distribution of p_{unstable} which remained at its seasonal minimum for about one week. However, the instability was modeled to be triggerable for the entire week before the forecasting program started and relaxed during the first two days of operations. The human assessments during that period most likely took a conservative approach and included the problem due to limited data availability at the beginning of the season, but acknowledged the dormant character of the problem at the same time by publishing a *Low* danger rating. Once the persistent layer was loaded with several storm cycles between Dec 10 and Jan 05, both data sources agree on the presence of both storm and persistent problems, show comparable trends in hazard characteristics, and suggest a correlation between modeled instability and reported danger rating. A short storm cycle starting on Jan 10 led to storm and persistent problems in the human assessment data set. However, since no new snow was modeled during that time period, the modeled hazard characteristics deviated from the assess-

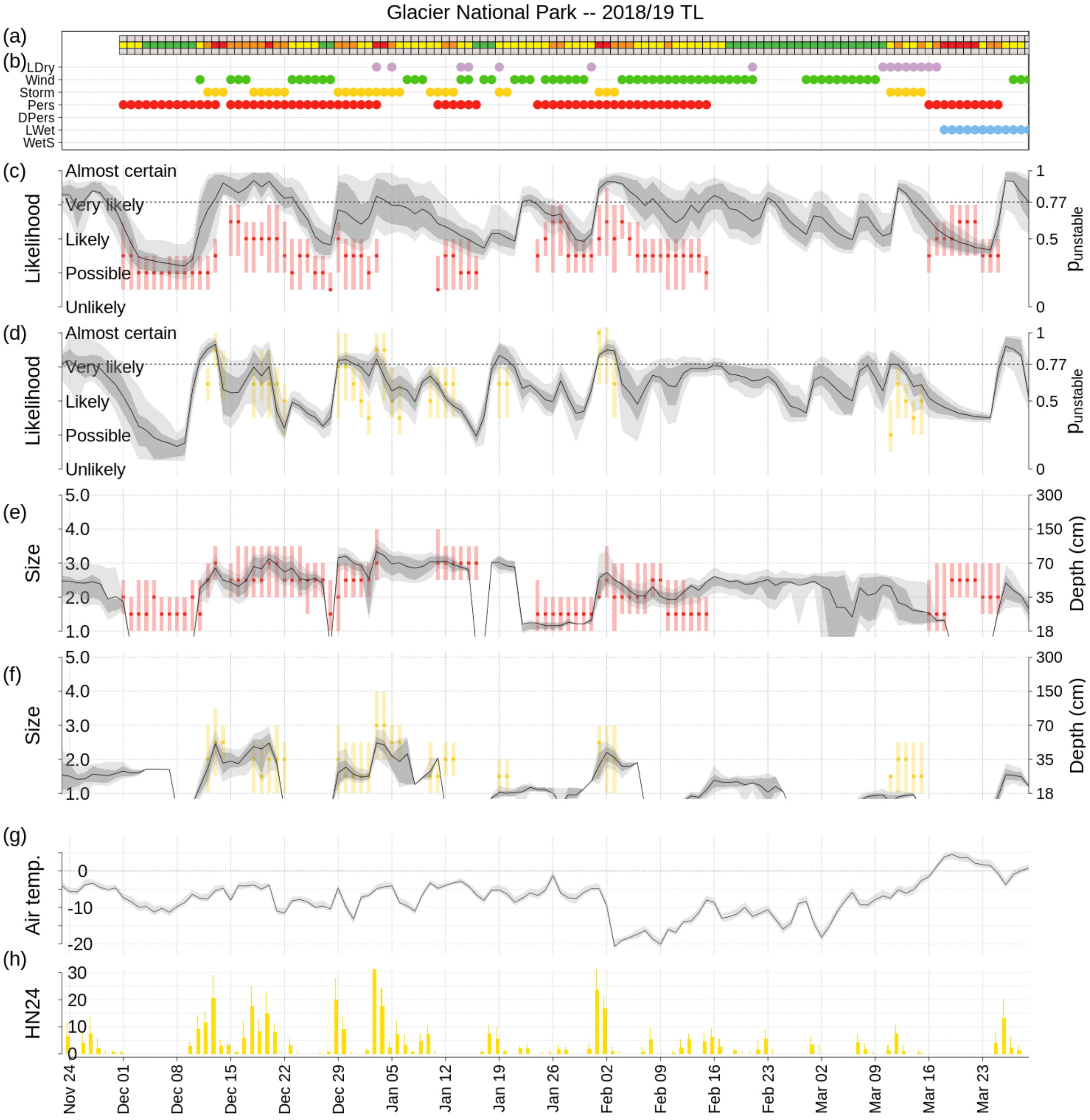

Figure 3: Season summary 2018/19 of human hazard assessments and modeled hazard characteristics for Glacier National Park. (a) Reported danger rating and (b) avalanche problems at treeline elevation, (c), (d) Reported likelihood of avalanches from persistent (red) and storm (yellow) slab avalanche problems, respectively. In addition, modeled distribution of p_{unstable} with the envelope of the 10–90th percentiles (light gray shading), the interquartile range (dark gray shading), and the expected value (black line). (e), (f) Analogous to the previous two panels, but showing the reported size of avalanches and the modeled failure depth. (g) interquartile range and median air temperature in units of °C. (h) median height of new snow within 24 hours in units of cm (HN24).

ments for several days. Another brief two-day storm problem starting on Jan 19 was captured by the instability predictions, and the resulting persistent problem was anticipated by the simulations two days earlier than in the assessments. Despite these two problems, the danger rating remained mainly at *Moderate* until the simulated depth of the weakness increased strongly on Feb 01 when the danger rating also increased to *High*. After this short-lived peak of instability, the danger rating, the reported likelihood of avalanches from persistent problems, and p_{unstable} decreased simultaneously. After the initial two days of decreasing hazard, the distribution of p_{unstable} started to span a wider range suggesting more variable conditions for triggering. The persistent problem was removed by the forecasters on Feb 15, a week after the modeled interquartile range of p_{unstable} values had decreased below the threshold of 0.77. In the subsequent weeks, several short and moderate peaks of modeled instability were not reflected in the human assessments. Each of the peaks was caused by little snowfall amounts below daily averages of 10 cm. A final hazard cycle of the season between Mar 16 and 23 was entirely missed by the simulations. Forecasters issued loose wet avalanche problems and temperatures rose above the freezing level. Although human assessments reported persistent problems, modeled p_{unstable} values remained very low, highlighting that the instability classifier was trained for dry snow conditions, not for wet ones.

Our qualitative analysis of the seasonal summaries of all winters revealed the following findings. The modeled instability predictions of persistent problems appear more sensitive to recurrent snow loading than forecaster assessments of likelihood of avalanches. Particularly subtle day-to-day variations in modeled instability seem to agree better with the reported danger rating than the reported likelihood of persistent avalanches. The 2017 season contained an interesting case when a heavy prolonged snowfall lasting for more than two weeks led the modeled instability of persistent layers to decrease considerably, while the instability in storm snow remained high. Not surprisingly, the forecaster assessments listed both problems with peak likelihoods of triggering avalanches and the danger rating fluctuated between *Considerable* and *High*. Another notable situation occurred in 2018 when a persistent weak layer problem was dominating the bulletin for nine weeks and simultaneously kept the modeled instability in persistent layers well above the threshold. We also found several instances when an increase in the range of the distribution of p_{unstable} coincided with a decrease of the reported likelihood or danger rating. Although more nuanced, layer-specific information, such as average snow profiles (Herla et al., 2022, 2023a) or date tag subsets (Figure 1b), was often helpful to better understand times when persistent problems were added. We also found that the distribution of p_{unstable} added value to the process of understanding the different phases of individual hazard cycles for both storm and persistent problems.

5. DISCUSSION

5.1. Insights from the comparison

Although the seasonal and multi-seasonal comparisons of simulated and reported avalanche problem characteristics presented in this and other studies (Reuter et al., 2021; Mayer et al., 2023) show encouraging agreement, our in-depth comparison of their temporal evolution revealed mixed results. Taking operational considerations into account helped explain the observed differences at times. This general finding is in line with the results of Herla et al. (2023a) who validated snowpack simulations for their capabilities to capture critical layers of operational concern. While they found reasonable patterns overall, the agreement in their seasonal validation was substantially higher than in the validation using daily observations. Our analysis also showed that the simulated characteristics of storm slab avalanche problems seem better suited to assist forecasters determining their presence and absence, whereas the modeled characteristics of persistent problems are better at informing the likelihood and size of persistent slab avalanches.

One of the situations where simulated avalanche problem characteristics could be particularly helpful for forecasters is the removal of persistent slab avalanche problems. Both Horton et al. (2020) and Hordowick (2022) found that forecasters struggle with the decision to remove persistent slab avalanche problems. Our analysis also found evidence of this issue as it identified several instances where the timing of forecasters' removal of reported persistent problems was much later and sometimes appeared arbitrary when compared to the simulated avalanche problem characteristics. Hence, in these difficult to assess situations, the simulations might provide valuable information about the instability of the relevant weak layers. Another advantage of the numerical predictions is that they depict the evolution of instability and depth more continuously and at a higher resolution than human assessments using relatively coarse, ordinal scales. This presents forecasters with a more subtle perspective on the evolution of the hazard characteristics.

5.2. Benefits of the grouping by date tags

The modeling approach presented here expands on previous methods (Reuter et al., 2021; Mayer et al., 2023) by extracting information from spatially distributed snowpack simulations in a way that takes advantage of layers that are linked across space and time. The approach adopts concepts from the practitioner community to make the output of numerical predictions of avalanche problems from large-scale simulations more organized, transparent, and informative for forecasters. By splitting the overall hazard into contributions from different regional layers as identified by their burial date tags, the model predictions cater to the existing sensemaking process of forecasters, which aims to simplify the integration of the simulated information into their mental model.

This approach also makes it easier for forecasters to identify times when the modeled predictions deviate from reality, like when a specific hazard-driving weak layer is absent in the simulations or a non-existing layer is modeled. In these situations, our modeling approach allows forecasters to keep using the simulations as information source for all other regional layers since they are all assessed separately. Other advantages include the capability for extracting the entire distribution of instability associated with each date tag across all grid points, and the tracking of layer characteristics during the transitions from instability to stability while maintaining information about the depth distribution or regional layers after they have gone dormant.

6. CONCLUSIONS

We presented a spatial approach for extracting the characteristics of storm and persistent slab avalanche problems from distributed snowpack simulations by grouping individual layers based on their regional burial dates. Our approach allows for computationally efficient tracking of instabilities across space and time to compute spatial distributions of hazard characteristics that are consistent with existing avalanche forecasting practices. We applied the approach to ten winter seasons in Glacier National Park, Canada, and compared the numerical predictions to human hazard assessments to evaluate seasonal and daily agreements.

Although the seasonal summaries of the numerically predicted avalanche problems showed strong similarities with human hazard assessments and agreed with the results of existing research (Reuter et al., 2021; Mayer et al., 2023), our comparisons of the daily characteristics of the avalanche problems revealed considerable discrepancies. The best agreements were found in the presence and absence of storm slab avalanche problems and in the likelihood and expected size assessments of persistent slab avalanche problems. However, our qualitative examination also suggested the numerical predictions might have a better handle on the removal of persistent slab avalanche problems than human forecasters, which is a known operational challenge (Hordowick, 2022).

While differences between human assessments and simulated data sets are expected, an important caveat of our study is that it is unclear which of the two data sets represents reality better. Interestingly, our analyses showed that both data sets have their own strengths and weaknesses, and they can both contribute to a better understanding of the conditions. However, it is beyond the present comparison to explain in detail *why* the two data sources disagree. To answer this question and properly evaluate the performance of numerical predictions, we need validated, scientific-grade data sets of complete avalanche hazard assessments, which is currently not available in Canada.

To further strengthen avalanche forecasters' familiarity with the strengths and weaknesses of large-scale snowpack simulations, we encourage the use of dashboards that facilitate real-time comparisons between human assessment and model data sets. Understanding their current capabilities requires careful study of context and the consideration of operational practices that differ from the purely physical computations of the simulations. Since higher-level hazard characteristics can often be assessed more easily, it is possible for forecasters to gauge the current value of the simulations by comparing high-level characteristics and—if appropriate—integrating more intricate numerical predictions into their reasoning process. Even at times when forecasters disagree with the numerical predictions, they can be a valuable independent information source that triggers critical reflection.

A manuscript that presents the more detailed analysis of this research project is in preparation to be submitted for peer-review.

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