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SYNTHESIZING REGIONAL SNOWPACK STABILITY AND AVALANCHE PROBLEMS IN THE OPERATIONAL AWSOME FRAMEWORK

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ABSTRACT: Snowpack simulations can enhance avalanche forecasting by providing more continuous spatial and temporal assessments, offering short-term forecasts, and serving as an objective second opinion. The open-source framework AWSOME (Avalanche Warning Service Operational Meteo Environment) has been developed to streamline and automate these computations for both avalanche warning services and researchers. This paper highlights AWSOME's post-processing toolbox, focusing on recent and ongoing enhancements. These include a redesigned dashboard, performance improvements to the `avapro` module for avalanche problem prediction, aggregation of simulated profiles based on the `aggregatepro` module, and the integration of new features, such as interactive hazard charts provided by the `qmah` module. By incorporating these tools, which have all emerged from recent research, into an accessible framework, we aim to facilitate their practical application in operational settings to ultimately help improve the consistency and accuracy of avalanche hazard assessments.

Keywords: Avalanche forecasting, snowpack modeling, avalanche hazard assessment modeling, large-scale operational model chain, forecaster dashboard, AWSOME.

1. INTRODUCTION

Snowpack models can complement the standard human information sources used by avalanche forecasters by producing spatially and temporally more continuous assessments, providing short-term forecasts, and offering an alternative and potentially more objective second opinion (Bellaire et al., 2017; Mayer et al., 2023; Herla et al., 2023a). Substantial research has recently provided various approaches to harness and synthesize the vast information generated by these simulations in ways that are informative and relevant to practitioners, such as numerically processing snow profiles, predicting avalanche problems, estimating likelihoods of avalanches, and more. While numerical snowpack and avalanche hazard assessments offer invaluable insights for avalanche forecasting, the integration of new tools into practice is often slow, taking several seasons to become widely accessible to different warning services.

The recently developed open-source framework AWSOME (Avalanche Warning Service Operational Meteo Environment, AWSOME Core Team, 2024) offers a range of snow model toolchains designed to automate and streamline operational computations for both avalanche warning services and researchers. As a comprehensive modeling suite, AWSOME addresses all stages of the modeling chain, from pre-processing to post-processing and data visualization on a dashboard. While Herla et al. (2024c) and Reisecker and Mitterer (2024) provide a high-level overview of AWSOME and explain how the framework was used to establish an operational weather and snowpack model chain in Norway and how SnowMicroPen measurements are used to initialize snow cover simulations, respectively, this paper highlights recent updates to AWSOME's post-processing workflow.

Key updates include the redesign of the AWSOME dashboard, performance improvements to the avalanche problem algorithm by Perfler et al. (2023), and the integration of a Python interface for the averaging algorithm by Herla et al. (2022a), which computes representative snow profiles and their underlying instability distributions. Additionally, we developed a new Python package to extract avalanche problem characteristics from large-scale simulations by merging existing approaches (Herla et al., 2024b). By incorporating these tools into an accessible open-source framework, we aim to facilitate their transition to operational use and promote

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broader, quicker adoption among practitioners and researchers.

2. THE DASHBOARD

AWSOME started out with a Python/Leaflet-driven dashboard that featured map-based pop-up windows. However, as this setup ran into capability limitations, current efforts focus on redesigning the dashboard using JavaScript. To support avalanche forecasters within the Euregio collaboration (Mitterer et al., 2018) with a forecaster dashboard for snow and avalanche observations, Lanzanasto et al. (2018) developed the JavaScript-driven Admin GUI.

The Admin GUI offers an interactive map with a side panel containing charts that provide a fast overview of all observations within a specified time frame. The charts fulfill two purposes. They offer a quick overview of the data point distributions across various parameters (e.g., elevation, aspect, stability class, and more) and enable users to filter, color, or label data points within the map according to these criteria.

An extended version of this dashboard will be implemented as a separate JavaScript project to meet the requirements for AWSOME. Due to the heterogeneity of the post-processing output within AWSOME, it is necessary to create the charts flexibly based on the available data. To achieve this, we defined a GeoJSON data structure that allows all necessary information for visualizing the results (parameters, value ranges, colors, labels, etc.) to be included directly in the files themselves as an output from the post-processing packages. This information is dynamically loaded from the dashboard, potentially using multiple sources, and the corresponding diagrams, filters, and visualizations are generated.

Although all post-processing packages documented in this paper are standalone and generate independent outputs, the ultimate goal is to feature all their relevant results within the dashboard. To enable maximum flexibility, data sources can be specified separately for each instance of the dashboard, allowing it to serve as both a development dashboard and a component of a production system.

3. SNOWPACKTOOLS.AVAPRO

In recent years, avalanche forecasting services have shifted towards a process-oriented approach to asses the regional avalanche danger, with the identification of prevailing avalanche problems playing a central role (EAWS, 2023b). To provide an objective starting point to assessing these problems, Perfler et al. (2023) adapted the algorithm by Reuter et al. (2021), which derives avalanche problems from numerical snowpack simulations, into the Python package `avapro` as part of the larger `snowpacktools` package (Binder et al., 2024). `avapro`, which has been integrated into the AWSOME framework, only requires SNOWPACK's native output, PRO and SMET files (SLF, 2024), as input, making it versatile enough to operate independently or within various model chains (Binder and Mitterer, 2023). The problem identification is grounded in physical and process-based failure criteria, as described by Reuter et al. (2021) and Mitterer et al. (2013). `avapro` is designed to meet operational needs and presents its output in intuitive visualizations.

To better serve recent developments in the AWSOME framework, such as the new toolchain for gridded snowpack simulations, we currently work on making the core algorithm more efficient, and restructure the output format into GeoJSON files. This update allows for seamless integration of visualizations into the new dashboard.

4. SNOWPACKTOOLS.AGGREGATEPRO

Avalanche forecasters have traditionally spent a considerable time studying snow profiles. With the advent of large-scale snowpack simulations, it became impossible to keep track of the flood of simulated profiles that forecasters could theoretically go through. Herla et al. (2022a) developed a numerical tool to compute a representative snow profile from a group of individual profiles that allows forecasters to study spatio-temporal snowpack patterns in the format of a snow profile. The resulting suite of snow profile processing tools has been openly accessible as an R package (Herla et al., 2022b, 2023b). However, the snow and avalanche community tends to use Python extensively and may hesitate to employ the existing tool. To address this, we have developed a Python wrapper `aggregatepro` as part of the existing `snowpacktools` package (Binder et al., 2024) that facilitates using the existing R code from a Python interface. `aggregatepro` is designed to seamlessly integrate with AWSOME's gridded snowpack simulations, but can be applied standalone to data sets of SNOWPACK's PRO and SMET files. While most advanced functionality still requires an R interface, `aggregatepro` primarily generates static PNG files with information geared towards operational avalanche forecasting.

For AWSOME's new dashboard, the representative profile will be pre-computed for static regions and specified combinations of elevation bands and aspects to give forecasters a quick overview of the snowpack conditions.

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5. QMAH

Recent snow model research has focused on exploring various process-based and data-driven approaches to deriving snowpack stability and avalanche hazard from snow cover simulations (e.g., Monti et al., 2016; Bellaire et al., 2017; Richter et al., 2019; Reuter et al., 2021; Viallon-Galinier et al., 2022; Mayer et al., 2022, 2023; Hendrick et al., 2023) and their far reaching uptake in research and application (e.g., Katsuyama et al., 2023; Mariani et al., 2023; Dick et al., 2023; AvaCollabra, 2024) demonstrates a strong need. However, to this date, no software package exists that aims to provide easy access to the full range of stability indices. As a result, assessing snowpack stability appears as a matter of paradigm choice, with only few studies making the effort to compare different approaches (Herla et al., 2023a; Schweizer et al., 2023).

5.1 Objective

The Python package qmah (Herla et al., 2024a, a quantitative module of avalanche hazard[1]) aims to provide an accessible, standalone solution, well-integrated into AWSOME, for computing various stability indices and other hazard-relevant characteristics. It compiles this information into a structured format for visualization on a dashboard or further processing. In particular, the package aims to implement state-of-the-art methods for assessing both dry and wet snow stability, accounting for natural or skier-triggered avalanches. It will include existing process-based stability indices (Reuter et al., 2021; Perfler et al., 2023) and data-driven models (Mayer et al., 2022, 2023; Hendrick et al., 2023), fused with a spatial framework that tracks specific layers across space and time (Herla et al., 2024b). qmah is designed to facilitate direct comparisons between these different stability assessment approaches, making it easier to evaluate their performance and formulate best-practices for operational applications. Its modular design allows for flexible processing tailored to custom needs.

5.2 Functionality

To organize the code in an intuitive and accessible way, qmah contains four subpackages, processing, instability, hazard, and datetags. The following description is arranged by functionality instead of these underlying subpackages.

Essentially, qmah post-processes a directory of SNOWPACK's PRO and SMET files (SLF, 2024) and organizes the results into a GeoJSON structure. This structure can be viewed on a dashboard and further processed either by qmah itself or by custom analysis scripts. The GeoJSON structure contains one georeferenced feature per (virtual) station, with different aspects stratified within each feature. Depending on the user's needs, the feature properties (i.e., data elements) provide information on general snowpack characteristics, hazard chart elements, and simplified snow stratigraphies.

General snowpack characteristics can include any bulk property of interest, such as total snow height or new snow amounts over various accumulation periods. Additionally, the characteristics encompass information on each stability index's weakest value and the corresponding relevant depth.

Hazard chart elements consist of the data necessary to create interactive hazard charts (Statham et al., 2018; Herla et al., 2023c, 2024b). These scatterplots visualize the three central components of avalanche hazard: snow(pack) stability, the frequency distribution of snowpack stability, and avalanche size (EAWS, 2023a). Snow stability is represented by a stability index (y-axis), avalanche size is approximated by the anticipated failure depth (x-axis), and the frequency distribution is depicted by the point cloud on the chart, with each point corresponding to the simulation at a (virtual) station (Fig. 1a).

A hazard chart can be compiled for each avalanche problem type, currently covering new snow, persistent weak layer, and wet snow problems (EAWS, 2023b). Users can select which stability index to query for each problem type. For example, the persistent weak layer problem might be assessed by the process-based criteria of failure initiation (SK38) and crack propagation (r_c) (Reuter et al., 2021), or by the random forest model p_unstable (Mayer et al., 2022). The new snow problem could be assessed by the process-based expected-time-to-failure (Reuter et al., 2021) or a regression based on three-day new snow amounts and p_unstable (Mayer et al., 2023). The wet snow problem could be assessed by the liquid water content index (Mitterer et al., 2013; Bellaire et al., 2017), or by the random forest model for wet snow avalanches by Hendrick et al. (2023).

The simplified stratigraphy is what makes the hazard charts interactive (aside from filtering stations). While the hazard chart elements are pre-compiled for the entire snowpack (Fig. 1a), they can be *re*-compiled for any subset of simplified layers (Fig. 1b). This feature is particularly valuable for assessing the hazard potential of a single layer

[1] A playful nod to the Conceptual Model of Avalanche Hazard that is well-established in North America (Statham et al., 2018)

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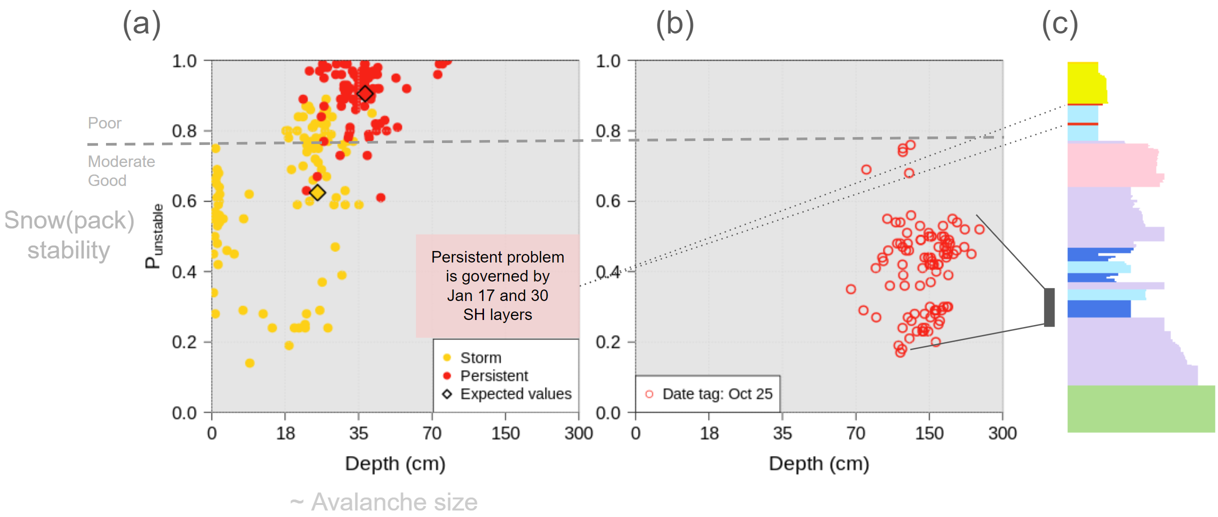

Figure 1: A hazard chart derived from snowpack simulations, showing the snow(pack) stability, anticipated failure depth, and frequency distribution (a) for the new snow and persistent weak layer problems, and (b) zooming in on a layer subset that was buried on Oct 25. (c) shows a representative profile to illustrate which layers influence the positions of the circles on the charts.

or excluding a layer that is known to cause less avalanche activity than modeled. Additionally, the simplified stratigraphy provides further context to the hazard chart, indicating which layers influence each data point's stability and depth assessment. For each stability index, the simplified stratigraphy at an individual (virtual) station consists of multiple groups of layers. Each group represents a package of layers that was exposed to the same processes at the snow surface before getting buried by the same snowfall event. Therefore, each group can be characterized by the dates of these events, which we call datetags—a concept widely used in the North American practitioner community.

For each simplified layer, we store key attributes such as its datetag, the weakest stability index value, the depth of the deepest unstable layer beyond a specified stability threshold, and the corresponding grain types. The grain types, in conjunction with the stability index, ultimately determine the avalanche problem that the layer may contribute to. While the simplified stratigraphy requires a considerable amount of disk space, it offers the most granular data extracted from the post-processed simulations and allows for insightful interpretation and rearrangement of the hazard charts. Using datetags to reference layers, in addition to their depths, creates a stronger connection between real-world and model outputs. Observed layer depths can vary greatly across terrain and may differ substantially from modeled depths. Therefore, when forecasters receive information about "the potentially unstable January 17th surface hoar layer down 75 cm", they gain a lot more information than if they had only known the depth alone, and are actually empowered to critically evaluate the model predictions.

qmah generates one GeoJSON file for each day, containing all (virtual) stations across the entire domain. To enable the plotting of time series from hazard chart elements, another GeoJSON file is necessary that stores the distributional information of these elements based on user-defined polygons or forecast regions. The expected snowpack stability and failure depth within a given region are calculated using the median stability index of all (virtual) stations, along with the median depth at stations identified as unstable (i.e., those exceeding a specific stability index threshold) (Herla et al., 2024b). This approach is also applied to other percentiles.

The interested reader is referred to Herla et al. (2024b) for more detailed information about the general calculations.

5.3 Limitations

Currently, wind slab avalanche problems are not addressed by qmah, despite the substantial need for this type of information from various avalanche warning services (AvaCollabra, 2024). Reach out if you are interested in implementing a viable solution.

Datetags to characterize the simplified stratigraphy can be provided manually, automated, or extended manually after automation. This flexibility is particularly valuable for zooming in on specific layers of interest and creating datetags that align transparently with forecasters' mental models of recent snowfall sequences. Currently, the automated datetag computations rely solely on daily information from 24- and 72-hour accumulations

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of rain and snow (Herla et al., 2024b) and process datetags for snowfall and rain events separately. While this method is effective for regions and elevations dominated by dry precipitation events, incorporating information about the snow surface could improve the processing of simulations in areas where rain and melt-freeze crusts frequently form. Furthermore, the current version processes all datetags, regardless of their hazard potential and age. To improve efficiency, rules could be implemented to select only those simplified layers for further processing and storage that could contribute to the overall hazard potential.

At this stage, `qmah` does not provide suggestions regarding the presence or absence of avalanche problems, but rather offers the hazard-relevant data that is needed to make that decision independently. However, a future version may incorporate this feature, potentially offering suggestions for avalanche problems within a given (dynamic) forecast region, for specific elevation bands and aspects.

While Herla et al. (2024b) demonstrated a proof of concept, the corresponding Python package is brand new and its development is still in progress. If you are interested in applying the package soon, get in touch to avoid potential beta-version pitfalls. And reach out if you want to contribute.

The potentially most impactful limitation stems from SNOWPACK's native file formats. While `qmah` efficiently processes the individual (virtual) stations by reading each file only once, even when handling multi-day time periods, the text-based nature of these files imposes substantial reading times, and, more importantly, the station-wise file arrangements force the processing into iterative loops. This is unfortunate, as many simple calculations could otherwise be vectorized across the entire dataset, speeding up computations. Consequently, `qmah` employs parallel processing to maintain managable runtimes. Recently started collaborative efforts to design a Python base package with more efficient data classes could potentially address this limitation in the future (AvaCollabra, 2024).

6. CONCLUSION

In just a few years, AWSOME has grown into a comprehensive modeling suite that covers every stage from pre-processing to post-processing and data visualization. It turned out that the interdisciplinary collaboration between natural scientists, computer scientists, and snow and avalanche professionals has fostered a motivating and inspiring work environment that drove AWSOME's rapid and successful development. With its open-source, collaborative spirit, and modular, adaptable design, AWSOME offers an attractive solution for operational and research applications in avalanche forecasting. Warning services can either integrate AWSOME's post-processing outputs into their own dashboards or adopt AWSOME's dashboard altogether to save resources. Researchers can start exploring and evaluating their data interactively right away, before moving on to more detailed analyses. This paper highlighted the current capabilities of AWSOME's post-processing toolbox, focusing on recent and ongoing enhancements.

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