SNOWPACK MODELING EFFORTS AT THE COLORADO AVALANCHE INFORMATION CENTER

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ABSTRACT: The Colorado Avalanche Information Center started investigating operational applications of the Swiss Federal Institute for Forest, Snow and Landscape Snowpack model in 2013. Driving the snowpack model with numerical weather prediction output allows the generation of snowpack profiles at remote locations where observational data is non-existent. Following several years of development, a system to update snowpack profiles daily using a 2-km grid covering the Colorado mountains was implemented for the 2022-23 season. Results are presented followed by plans to utilize snowpack profile averaging and clustering techniques.

KEYWORDS: Snowpack modeling, numerical weather prediction, avalanche forecasting.

1. INTRODUCTION

The Colorado Avalanche Information Center (CAIC) switched from fixed-zone to dynamic forecast regions for issuing daily avalanche forecasts in 2022. An objective of dynamic forecasting regions is that each forecast region represents similar avalanche problems across the region. As avalanche problems change with time, the dynamic regions change in area. The paradigm shift required the definition of 103 polygon regions that can be clustered together into larger forecast regions.

The operational forecaster is now tasked each day to combine smaller polygons with similar avalanche problems into regional avalanche forecasts, which added a significant workload to an already busy forecaster schedule. CAIC is developing methods to help the forecaster's decision-making process. Snowpack modeling using the Swiss Federal Institute for Forest, Snow and Landscape (SLF) Snowpack (SP) (Bartelt & Lehning, 2002) model is a part of that effort.

2. SNOWPACK MODELING AT CAIC

2.1 History

An in-house implementation of the open-source Weather Research and Forecasting (WRF) (Skamarock & Klemp, 2013) model has provided numerical weather forecasts since 2011 (Snook, et. al., 2005; Snook, 2016). The SLF Snowpack model was implemented at CAIC in 2013 (Morin et al., 2020). WRF is configured to output meteorological forecasts as input into the SP model. SP profiles were generated at all WRF grid points located within the CAIC forecast zones.

An initial assessment of WRF profiles showed larger than expected height of snow (HS) that resulted in reduced depth hoar generation and a more stable snowpack when compared to field observations. SP profiles were then generated for a select number of point locations where observed meteorological data is available. A two-year comparison of SP profiles using observations and WRF forecasts confirmed that WRF profiles had consistently greater HS than observed. Next, CAIC generated SP profiles using observed HS combined with WRF forecasts and the profiles compared much better to observations.

2.2 Latest Operational Configuration

For the 2022-23 winter season, CAIC generated SP profiles using HS analysis data merged with WRF forecasts, which allows SP profile generation at any location where WRF forecasts are available. CAIC generates WRF predictions four times per day using a double-nested gridded domain system with 6- and 2-km grid sizes (Figure 1). The inner 2-km grid covers all polygon forecast regions. In addition to generating standard hourly forecasts, WRF is configured to output special forecast files at 10-minute increments with only surface parameters needed by SP. The 10-minute forecast data is then averaged into hourly input data for SP. The averaging process helps to smooth the meteorological data, especially the SP-required radiation forecasts. A continuous stream of forecast data is pieced together by using the 6–12-hour forecasts from each successive WRF run.

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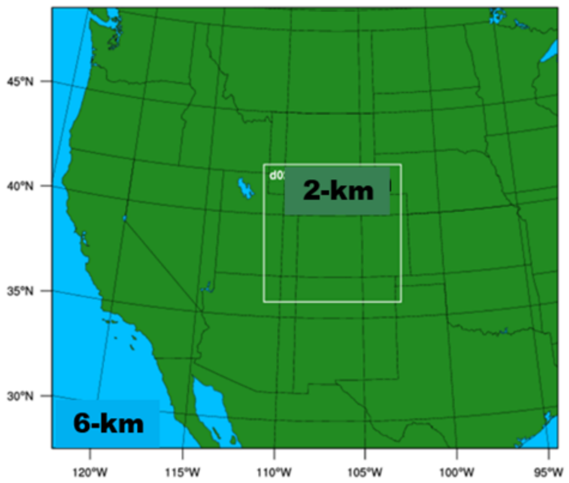

Figure 1: CAIC WRF domain configuration. The inner domain uses a 2-km grid that covers all the forecast polygon regions.

Observed HS is derived from the US National Weather Service National Operational Hydrologic Remote Sensing Center (NOHRSC) national gridded snowfall analysis (NOHRSC team, 2022). The snowfall analysis is updated daily at 1200 UTC. CAIC downloads the updated analysis grid daily and then interpolates HS values to all WRF grid points. Hourly HS is temporally-interpolated between daily analyses using WRF accumulated snow predictions.

SP model profiles were updated daily at all 2-km WRF grid points above 2800 meters within the 103 polygons for a total of 11,430 SP profile locations (Figure 2). Five profiles are generated at each point location representing a flat surface plus four aspects (north, east, south, west) with a slope angle of 38 degrees. Thus far the profiles appear reasonable for the Colorado continental climate (Figure 3). Of note is the improved representation of the depth hoar layer, which likely results from incorporating the HS analysis. Comparison to field observations is ongoing. Figure 4 illustrates a flow diagram of the complete operational process.

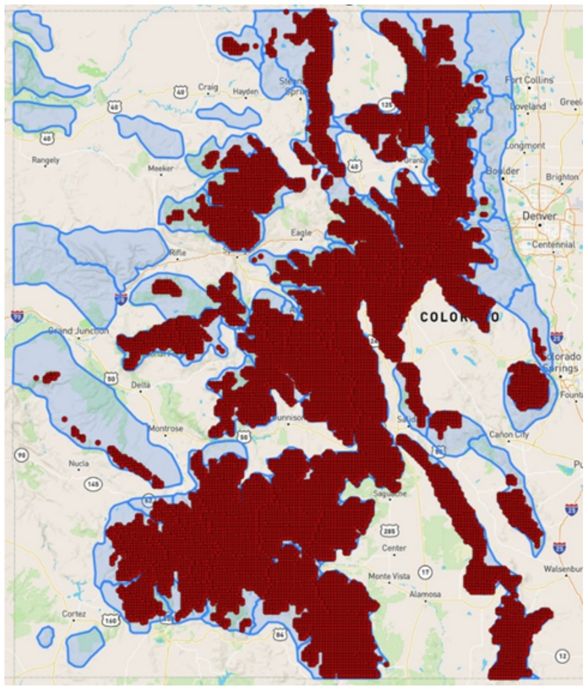

Figure 2: Forecast polygon areas with red dots indicating snowpack profile locations.

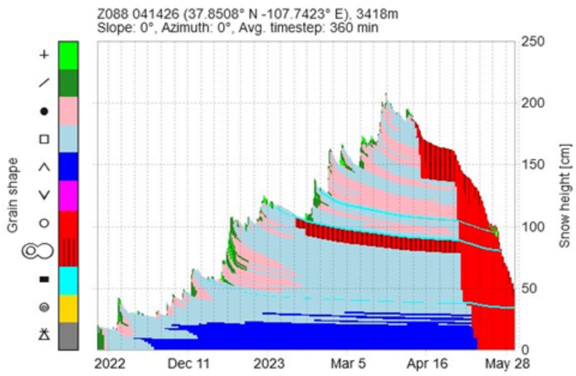

Figure 3: Example of snowpack profile time series for 2022-23 season from a single WRF grid point in polygon 88, which is in the northern San Juan Mountains. Color coding represents grain type, where dark blue is depth hoar, aqua is facets and pink is rounds.

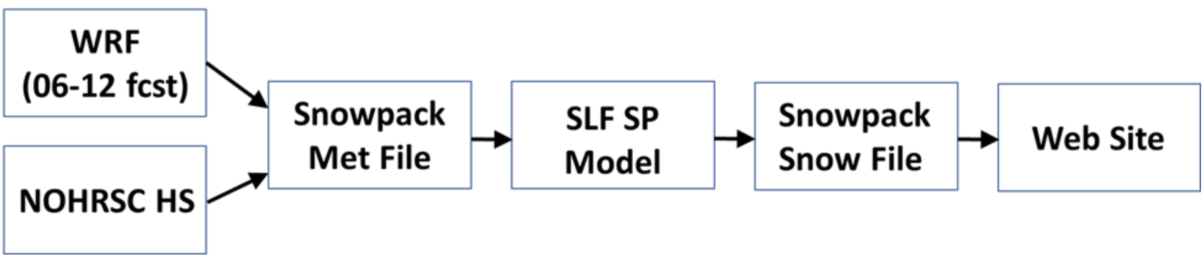

Figure 4: CAIC snowpack modeling flow chart.

3. SNOWPACK PROFILE ANALYSIS

3.1 Profile averaging by polygon

Fast computer processing power allows the over 57,000 SP profiles to be updated every day in a timely fashion. The enormous dataset is, however, too cumbersome to be of much use to the forecaster operating under strict deadlines. CAIC is investigating methods to generate polygon-averaged SP profiles, which can be evaluated quickly by the forecaster. Simon Fraser University (SFU) has led an effort to develop SP profile averaging techniques that are designed to facilitate meaningful explorations of data sets too large for human forecasters to analyze manually (Herla et. al., 2022).

The averaging methodology utilizes a technique known as Dynamic Time Warping Barycenter Averaging (DBA) (Petitjean et. al., 2011). DBA uses an iterative approach that starts with an initial condition (i.e., reference profile) and then updates the reference profile using averaged layer properties from the individual polygon profiles. After each iteration, similarity is evaluated with the previous iteration. The algorithm finishes when the similarity function reaches a specified threshold; in other words, the algorithm converges on the final solution. Herla et. al. (2022) notes a couple of advantages about this technique. Specifically, it is more suited to snow profile applications since it uses an average of all individual sequences as opposed to making pairwise comparisons. DBA uses less computing resources because it does not rely on pairwise comparisons.

SFU provided the open-source software for this process to CAIC. The SFU software package is a set of library routines designed for use with the open-source R project for statistical computing (R Core Team, 2020). The software can ingest any number of SLF SP profiles from which an average profile is generated. CAIC is testing the software on SP profiles that were generated during last (2022-23) winter season.

The initial focus is to develop scripts that generate average SP profiles for each forecast polygon area. Herla et.al. (2022) notes that DBA is sensitive to the initial condition. If the SP profiles for analysis can be grouped strategically, then the final averaged profile better retains the overall characteristics of the individual profiles. One such strategy is to group by similar HS. The CAIC implementation, therefore, groups SP profiles by elevation band: below treeline (BTL, 2800-3200 m), near treeline (NTL, 3200-3500 m) and above treeline (ATL, >3500 m). Averaging is also performed separately on the five available aspects for a total of 15 average profiles for each polygon. The overall strategy fits nicely with the operational CAIC forecast that includes avalanche problem identification by elevation band and aspect.

CAIC is currently testing the generation of two products, 1) average snow profiles for each polygon and 2) time series of average snow profiles for each polygon. Figure 5 shows a comparison of two average snow profiles for April 1, 2023 on a flat surface. The average profile for polygon 88, located in the northern San Juan Mountains, indicates deeper HS resulting in a shallower depth hoar layer and a mix of layers consisting of primarily rounded grains or facets. The polygon 34 profile, located in eastern Summit County, is shallower in depth. By comparison, the depth hoar layer is deeper, and the layers above are predominantly faceted grains.

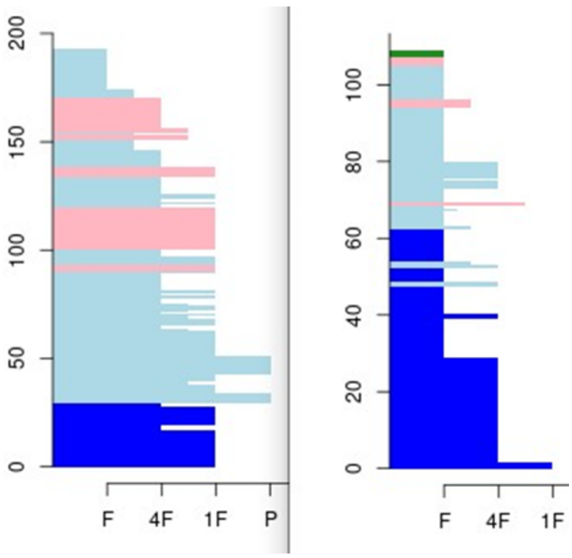

Figure 5: Two examples of snowpack profile averaging by zone. Polygon 88, located in the northern San Juan Mountains, is on the left and polygon 34, located in eastern Summit County, is on the right. Average profiles are on a flat surface from April 1, 2023. The y-axis is HS (cm) and the x-axis is hand hardness. Color coding represents grain type (see Figure 3).

Figure 6 shows an example of the average snow profile time series product. It compares the north- and south-facing aspects of polygon 88. As expected, the north-facing aspect shows a well-developed depth hoar layer while the south-facing aspect indicates several interlaced melt-freeze crust layers. The south-facing snow profile shows the transition to full-depth melt forms around April 9-12. A significant wet slab avalanche cycle occurred during this period.

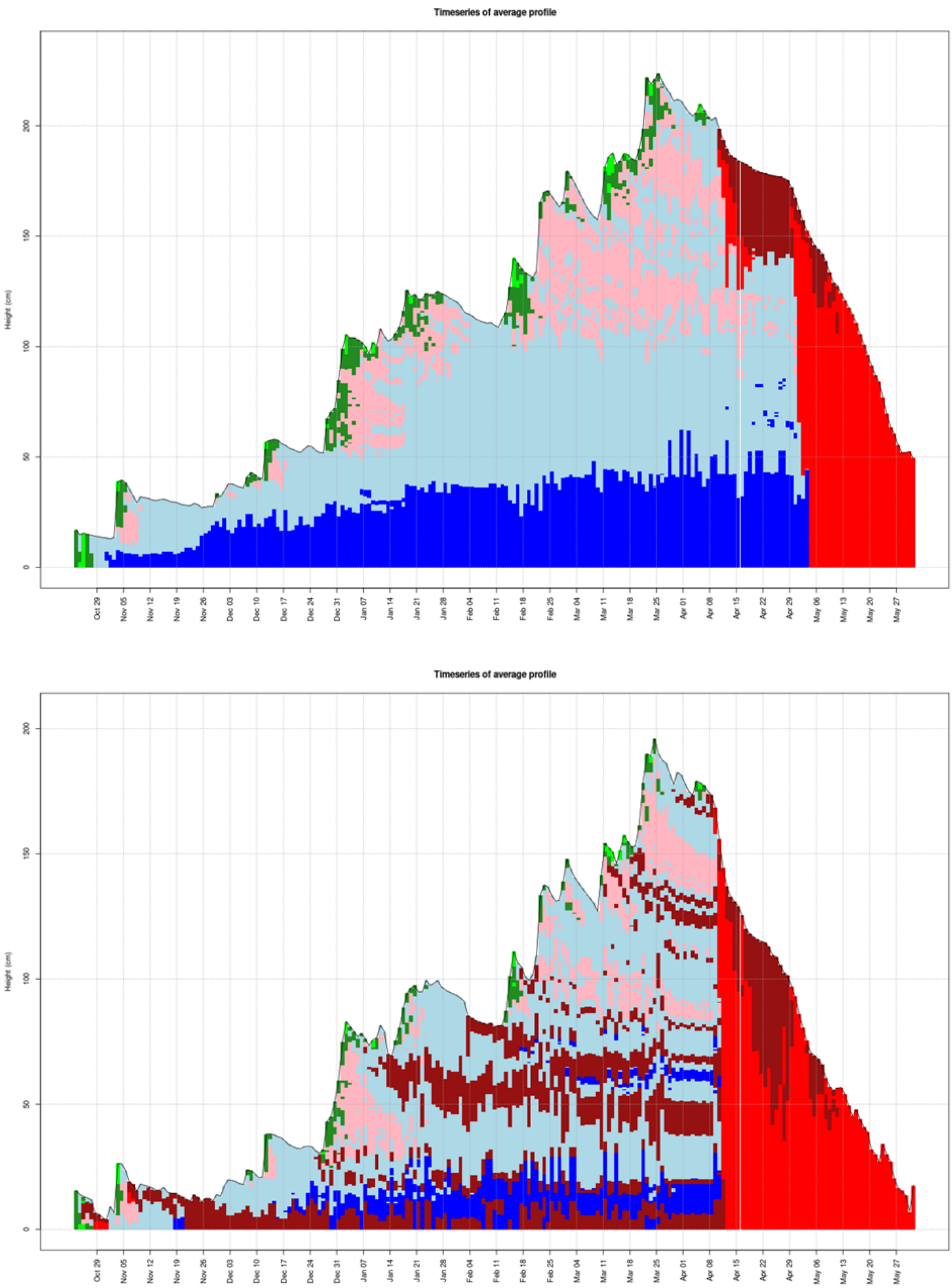

Figure 6: A comparison of average snow profile time series (polygon 88 in the northern San Juan Mountains) for north (top) and south (bottom) facing aspects at 38 degrees slope angle. Color coding represents grain type (see Figure 3).

3.2 Clustering of polygon profiles

CAIC forecasters are tasked with combining polygon areas with similar avalanche problems into single forecast regions. These forecast regions are updated daily and may not have the same areal extent from day-to-day. The next step for CAIC is to implement a technique to objectively cluster polygon-averaged snow profiles with similar characteristics. SFU is currently investigating snow profile clustering methods. CAIC plans to collaborate with SFU and test this methodology during the upcoming season.

4. OPERATIONAL PLAN FOR 2023-24 SEASON

CAIC plans to have a prototype system fully implemented for the upcoming 2023-24 winter season. Average polygon snow profiles and time series will be updated daily. A website interface is under development to best summarize the information. Figure 7 shows a snapshot of an interactive map where users can browse and visually compare polygon-averaged snow profiles. Snowpack averaging by polygon should provide valuable guidance to the operational forecaster in the dynamic region decision-making process.

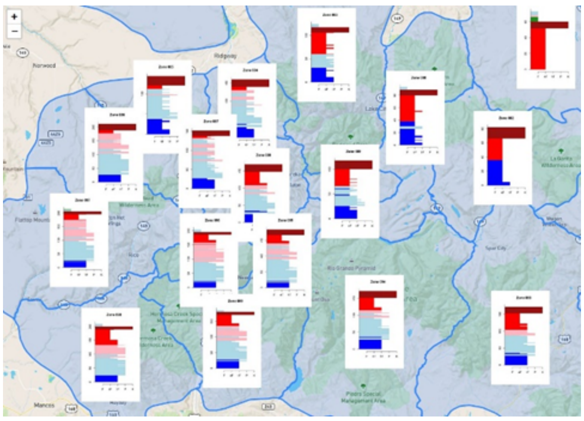

Figure 7: An example of the web interface under development to allow interactive browsing and comparison of polygon-averaged snow profiles.

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