VALIDATION OF SNOWPACK SIMULATIONS USING A LOW-COST WEATHER STATION IN SOUTHERN NORWAY

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ABSTRACT:

Snow-cover models are increasingly used to support avalanche forecasting, but their reliability must be demonstrated under prevailing climatic conditions before they can become part of operational workflows. We present a first validation of the SNOWPACK model for Norway using repeated snow-profile observations collected during the winter of 2025/26 at two sites representing continental and maritime snow climates. Simulations forced with numerical weather prediction (NWP) data and measurements from low-cost weather stations were compared with observed snowpack evolution. The results show that errors in meteorological forcing, particularly a cold bias in NWP air temperature, strongly influence simulated snow depth and snowpack structure. Including explicit soil layers improved the simulation of temperature gradients and depth-hoar formation, while modifications to melt-freeze crust metamorphism improved agreement with observed grain-type evolution. Across both sites, however, simulations tended to overestimate the occurrence of melt forms and rounding facets relative to observations. Overall, SNOWPACK reproduced the main characteristics of the observed snowpacks when appropriate forcing data and model settings were used. The study provides an important first step toward the operational use of SNOWPACK in avalanche forecasting in Norway and highlights areas where further model development is needed.

KEYWORDS: Validation, Modelling, SNOWPACK, Norway, case-study.

1. INTRODUCTION

Snow-cover models are increasingly used to support avalanche forecasting. However, for forecasters to trust model predictions, the simulations must first be proven to be reliable. Validating a layered snowpack model is challenging because simulated layers do not always correspond directly to observed layers. Differences in model parameterizations, observational uncertainty, and observer subjectivity can all contribute to this mismatch. As a result, objective comparison is difficult, although recent studies have introduced quantitative methods to assess snow-profile similarity (Herla et al. 2021; Viallon-Galinier et al. 2020; Hagenmuller et al. 2016).

A further challenge is that snowpack-model errors accumulate throughout the season. Errors in one period influence the evolution of the snowpack in subsequent periods. For example, an overestimation of snowfall can produce excessive snow depth, weaker temperature gradients, and consequently less faceting. In numerical weather prediction, this problem is addressed by regularly re-initializing models with observations. For snowpack models, this is generally not feasible because snow-profile observations are sparse and difficult to interpolate across complex terrain. Nevertheless, methods for initializing point simulations from observed snow profiles have been developed by Viallon-Galinier et al. (2020) and Binder et al. (2024), and have been shown to improve short-term model performance.

Layer-scale validation studies remain relatively rare. Most validation efforts focus on bulk snowpack properties. For example, Wever et al. (2015) compared SNOWPACK simulations driven by automatic weather station data at Weissfluhjoch (WFJ), Switzerland, against multi-year observations of snow depth (HS), snow water equivalent (SWE), snow temperature, liquid water content, density, grain size, and other variables. Similarly, Calonne et al. (2020) evaluated density, specific surface area (SSA), and critical cut length at the same site. More commonly, however, studies focus on stability metrics and avalanche-relevant indicators rather than directly validating simulated physical properties (Richter et al. 2019; Schweizer et al. 2023; Herla et al. 2024b; Bellaire et al. n.d.).

Most of these studies have been carried out in the Alps, many of them at WFJ. In addition, several SNOWPACK parameterizations were developed using observations from WFJ. It remains unclear

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how well these parameterizations perform in other snow climates, although recent work indicates that differences do exist (Herwijnen et al. 2024).

This study is a first step towards validating SNOWPACK for operational use in Norway, where efforts are underway to integrate the model into the national avalanche forecasting workflow (Herla et al. 2024c). We focus on physical snowpack properties in order to establish a robust foundation for model-based forecasting. During one winter season, repeated snow profiles were collected at two study sites equipped with low-cost weather stations. Simulations driven by both weather-station observations and numerical weather prediction (NWP) data were compared with these observations to assess SNOWPACK performance across a range of model configurations.

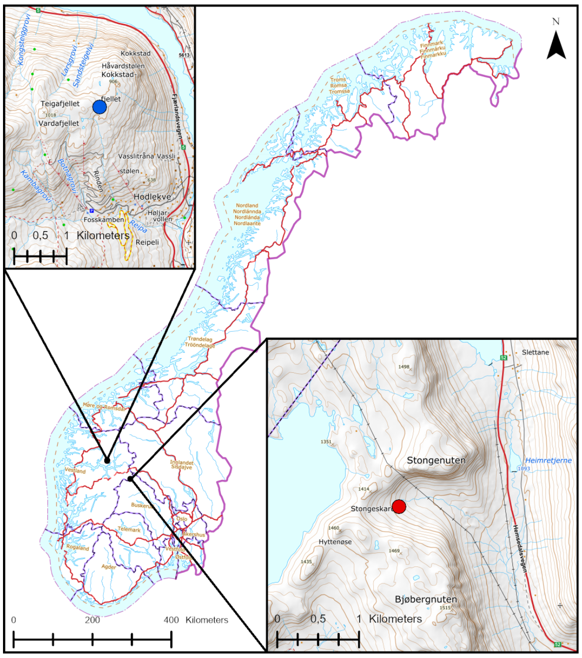

Figure 1: Location of the test sites Stongenuten (red) and Kalvavatni (blue) within Norway.

2. METHODS

2.1. SNOWPACK Model and Setup

SNOWPACK is a one-dimensional, physically based snowpack model that simulates the evolution of a layered snow cover by solving the energy balance equations along a vertical column. Each layer is characterized by microstructural properties such as grain type, grain size, bond size, and dendricity/sphericity. These properties evolve over time and determine the thermal and mechanical behaviour of the snowpack (Bartelt et al. 2002; Wever et al. 2015).

SNOWPACK requires meteorological forcing data, which can be obtained either from weather stations or from numerical weather prediction (NWP) models. In this study, we use simulations driven by several NWP configurations as well as simulations forced by measurements from SNOWER weather stations. Comparing these simulations allows us to distinguish errors originating from the forcing data from those arising within SNOWPACK itself. SNOWER is a low-cost weather station with a radar-based snow depth sensor (Nieminen et al. 2024). Since SNOWER does not measure radiation, the incoming shortwave and incoming longwave radiation are taken from the Numerical Weather Prediction (NWP) model The MetCoOp Ensemble Prediction System (MEPS) (Müller et al. 2017). This same model is used to force the NWP-based simulations in two different configurations. In the fully distributed configuration, NWP model data at 1-km resolution is used to force SNOWPACK at each NWP grid point. In the semi-distributed configuration, this same weather data are aggregated to 20 x 20km 'pixels' at 100 m wide elevation bands at 300 m intervals (Herla et al. 2024c). All the simulations described here are conducted within the AWSOME framework (Herla et al. 2024a).

Apart from simulations with different input data, we also present simulations with different model configurations in order to demonstrate the model's capabilities (Table 1). At the 1-km resolution, a simulation with largely default setting for the various parameterizations is presented as a baseline. Next is a 1km simulation with settings optimized for Norway. This simulation, identified with *1km NO* contains several additions since Wever et al. (2015) and Bavay et al. (2024) related to the effects of wind on snow (Kruyt et al. 2026). It also uses 7 explicit soil layers and Richard's solver for both snow and soil to improve water percolation (Wever et al. 2014).

From simulations in both, Norway and the Alps, it has been observed that refrozen melt forms (MFcr) often persist in simulated profiles long after these layers have transformed into facets in observed profiles. Therefore the faceting behavior of MFCr layers was recently modified in SNOWPACK. MFCr layers are now "allowed" to resume faceting at normal rates after having been exposed to reduced faceting rates following refreeze. Simulations with the MFcr relaxation behavior are identified as *1km MFcr* or *20km MFcr*.

An overview of included simulations is provided in Table 1. Due to limited space here, we do not show

Table 1: Overview of the different Simulations.

ID	input	SNOWPACK settings
snower	AWS	default settings
1km def	NWP 1km	default settings
1km NO	NWP 1km	wind-related changes(Kruyt et al. 2026), 7 soil layers Richard's equation
1km TA+1	NWP 1km +1°K TA	as 1km NO
1km MFcr	NWP 1km	as 1km NO, plus MFcr relaxation
20km NO	NWP 20km agg.	as 1km NO
20km MFcr	NWP 20km agg.	as 1km NO, plus MFcr relaxation

all possible combinations of model improvements that were simulated in order to attribute changes to changes in model settings, nor do we show a comparison of individual profiles to investigate density differences.

2.2. Test sites

We installed two validation sites for this project, both located in Southern Norway (Figure 1). The main validation site 'Stongenuten', is located in the region of Hemsedal, east of the watershed, at an elevation of 1200 m.a.s.l.. Most precipitation is associated with easterly and southeasterly weather systems. Under intense precipitation events west of the watershed divide, accompanied by strong winds, some spillover precipitation may extend into this area. The climate is continental. Typical precipitation amounts associated with low-pressure systems are 0-20 mm per 24 hours, while higher amounts are considered significant. Precipitation events are frequently accompanied by strong winds of 8-15 m/s. The area is generally characterized by high wind exposure, with prevailing westerly winds. Extended periods with air temperatures near −20°C are common. The snowpack is typically shallow, heavily influenced by wind redistribution, and characterized by poor snowpack structure with multiple persistent weak layers. A secondary site, 'Kalvavatni', is located near the town of Sogndal roughly 100 km to the North-West. This site lies at 900 m.a.s.l. and gets most of its precipitation from westerly flows. Its proximity to the fjords makes for a maritime snowpack with fewer weak layers than at Stongenuten. Both sites had a SNOWER station installed in December 2025, after the first snowfalls. From then on snow pits were dug at weekly intervals, with a few exceptions. As much as possible, we had a dedicated observer per site, but schedules forced some substitution of observers.

In the following, when we compare the modeled data to the observations, we refer to the nearest grid point from the selected model chain when we speak of the "1-km" or "20-km" model. In the case of Stongenuten, this is a grid point with a mean elevation of 1207 m.a.s.l for the 1-km model, and a pixel with an elevation band of 1150-1250 m for the 20-km model. For Kalvavatni, we use a grid point from the 1-km model at 921m, and an elevation band of 850-950m from the 20-km model.

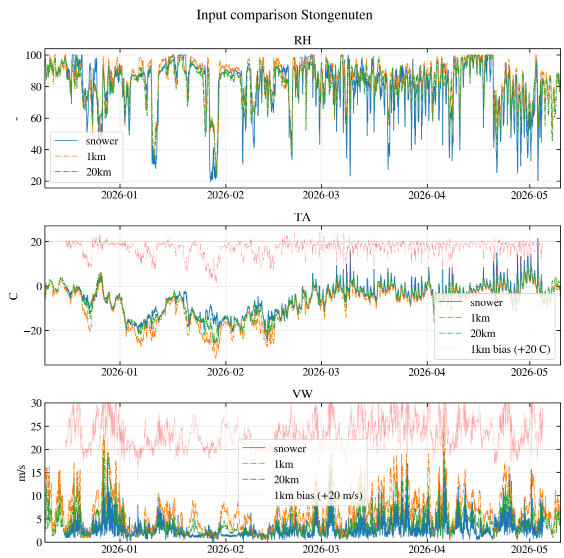

Figure 2: Comparison of modeled weather data with observed values from the SNOWER station at the test site Stongenuten. Relative humidity (top panel); 2m air temperature including (offset) bias of the 1-km NWP model (middle panel). Wind speed and its bias (offset by 20 m/s for clarity) are shown in the bottom panel.

3. RESULTS

3.1. Meteorological Input Data

Figure 2 shows the air temperature and relative humidity as measured by the SNOWER station at the Stongenuten site, compared to the NWP model data at 1km and 20km 'aggregated' resolution. There is a distinct cold bias in the NWP data, especially at 1km (mean bias -3.02 deg K for 1km, -0.50 deg K for 20km). This is most pronounced during cold periods in mid-winter in January and February. At the Kalvavatni location this bias is markedly less, and only occurs during those same cold spells (not shown). The NWP data also has a positive bias in relative humidity (4.4%), which may be a direct result of the temperature bias. Wind speed and direction (not shown) deviate significantly from measured values, but this is to be expected in complex terrain with NWP models at the kilometer scale. The 1km model has a significant positive bias of 3,67 ms^{-1} at Stongeskardet. At the Kalvavatni site, model biases are markedly less, with -1.44° C, 0.33% and -0.21 ms^{-1} for air temperature, relative humidity and wind speed, respectively. Given the large bias in air temperature at Stongenuten, we included a bias-corrected simulation, where a constant +1° C temperature correction was applied to the input data.

3.2. Snow Depth

Snow depth, as measured by the SNOWER radar sensor, as well as modeled snow depth from different SNOWPACK simulations are shown in Figure 3 for both test sites. For the location at Stongenuten, the default settings overestimate the snow depth significantly. The *1km NO* simulation improves this somewhat, likely due to wind compaction and higher new snow densities. The largest improvement however appears to come from a 1 degree bias correction in the input air temperature (simulation *1km TA+1*), which leads to a very good match with observed snow depths. Although the mean bias in air temperature was 3 degrees, a higher bias correction led to too little snow (not shown). Finally the regional, 20 km simulation also shows good agreement.

The second test site, Kalvavatni, is shown in the right panel of Figure 3. All simulations tend to underestimate the snow depth, although this seems to stem predominantly from the underestimation of two large snowfall events (mid-December and end of February). The melt phase of the season aligns well in all included simulations.

3.3. Grain Type Evolution

Figures **??** and **??** show the grain types of the observed and simulated profiles. In both test sites, the snower weather station was installed after the first snowfall. As a consequence, the simulations driven by SNOWER data show a mismatch in grain types at the start of the simulation. At Stongenuten (Figure **??**), the first profiles show small melt-freeze crusts that are not simulated, since the model initializes the existing snow depth as new snow (PP). At Kalvavatni this is also the case, and the SNOWER-driven simulation misses the melt forms from the early season, that are evident in the first few observed profiles. These melt forms (MF & MFcr) are present in the NWP forced simulations, albeit more as MFcr than MF, which could be due to model parameterization or observer subjectivity. Melt forms are also present in the NWP-forced simulations at Stongeskardet, however at this location they are not observed as frequently as they are simulated. The *1km NO* (as well as *1km def*, not shown) runs simulate too many melt forms in the lower half of the snow cover, which is slightly alleviated in the bias corrected run *1km TA+1* and the *1km MFcr*.

Temperature measurements showed sub-zero temperatures at the soil-snow interface. This was not reproduced by SNOWPACK using the default 1-km configuration without explicit soil layers. We found that adding several soil layers improved the simulated temperature profile, and resulted in faceting near the interface (Figure **??**).

In general, at both locations the SNOWPACK simulations forced with NWP data show too many MF and MFcr layers, as well as rounding facets (FCxr) compared to observations. Furthermore, the transition from PP and DF to RG does not align well between simulations and observations.

3.4. Individual Profile Comparison

Although a comparison of all individual profiles is beyond the scope of this current work, we present a single profile and its corresponding simulations in Figure 5. A manual profile observed on 2026-01-12 at the Stongenuten site is compared to the simulated profiles at 1km resolution to showcase the improvements by including various aspects in the model. First, the inclusion of soil layers in the simulation (1km NO, TA+1, MFcr) improves the temperature profile near the bottom, and leads to the accurate simulation of depth hoar that does not occur without soil layers (1km def). Based on the analysis of several profiles not shown in this work, it appears that the inclusion of Richard's equation improves the formation of low density layers in between large melt form layers, although further work is needed to substantiate this claim. Adding the correction of input temperatures in 1km TA+1 to these aforementioned changes gives the

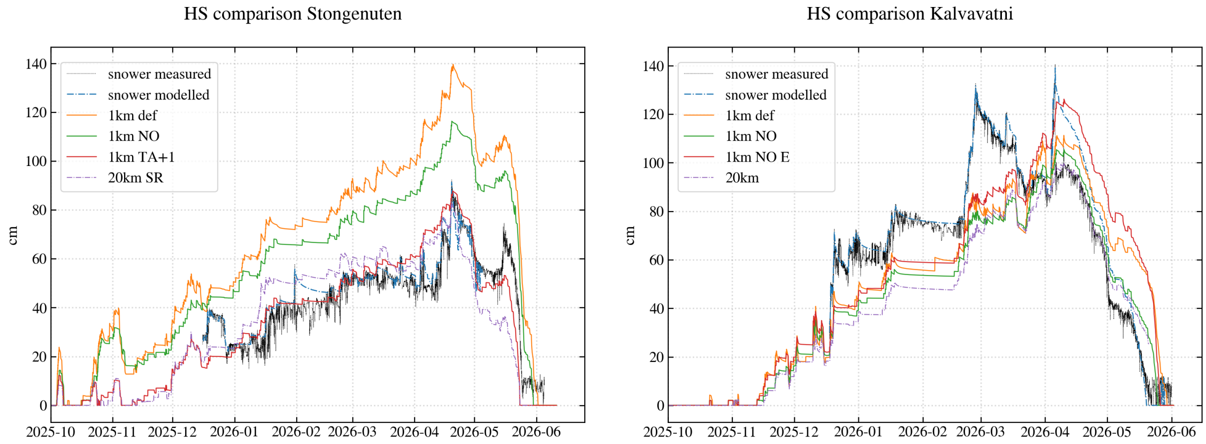

Figure 3: Snow depth at two test sites: Stongenuten (L) and Kalvavatni(R). Shown are observations (snower measured, black dotted), a simulation forced with measured snow depth (snower modelled, blue dashed), and several simulations forced with NWP data at either 1- or 20-km resolution. Both measurement stations were installed in December 2025, when there was already some snow on the ground.

best agreement with the observed profile, where we start to see the same general outline as the observed profile, at least in the bottom half.

4. DISCUSSION

Validating a model as complex as SNOWPACK is a challenging task, and the work presented here is only a first step in an ongoing effort to build a robust forecasting toolchain. It has nevertheless provided valuable insights, both for the improvement of the SNOWPACK model as well as the experimental setup itself. Since the installation of the SNOWER at both locations occurred after the season start, simulations forced with the SNOWER data suffered from fundamental flaws. Melt forms had already formed, while the SNOWER-forced simulations assumed fresh (PP) snow. This led to a mismatch in grain types that persisted throughout the season, especially at the Kalvavatni site.

The ground at the test sites was uneven and rocky. Combined with a thin snowpack, there was significant variability between profiles from the same site, that could not be attributed to temporal evolution. For future studies, it would probably be a good idea to prepare the soil at the test locations to be even, so that the snowpack is more homogeneous throughout the entire test area.

Grain types in the SNOWPACK model are defined by a combination of sphericity, dendricity and grain size, while a complex set of rules describes the evolution of these parameters. These parameterizations come from different studies, conducted in different climates. Together they may not represent the most accurate parameterization for Norway. Combined with the fact that there might be some subjectivity in the observations, leads us to believe that the occurrence of FCxr where RG or FC are observed should not be interpreted as a complete model failure.

This work has also highlighted the challenge of accumulating errors. At Stongenuten, an early-season melt-crust that was simulated erroneously, remained in place throughout the season and affected the metamorphism in the months following. In the future, data assimilation such as those pioneered by Binder et al. (2024) may provide valuable for identifying model errors in seasonal simulations.

Calonne et al. 2020 (Calonne et al. 2020)

5. CONCLUSIONS

In this work we have presented a comparison of simulated snowpack characteristics with observed snow profiles at two test sites in Southern Norway. By including a low-cost weather station at both locations, we were able to attribute some of the model error to errors in NWP input data. Correcting the bias in air temperature at the Stongenuten site improved both the simulated snow depth as well as the simulated grain forms. Nevertheless, all NWP-forced simulations at this location show too many MF layers. Similarly at both locations, simulations show too many rounding facet (FCxr) layers compared to observations. This overrepresentation of FCxr occurs mainly where either RG or FC are observed. It could therefore be due

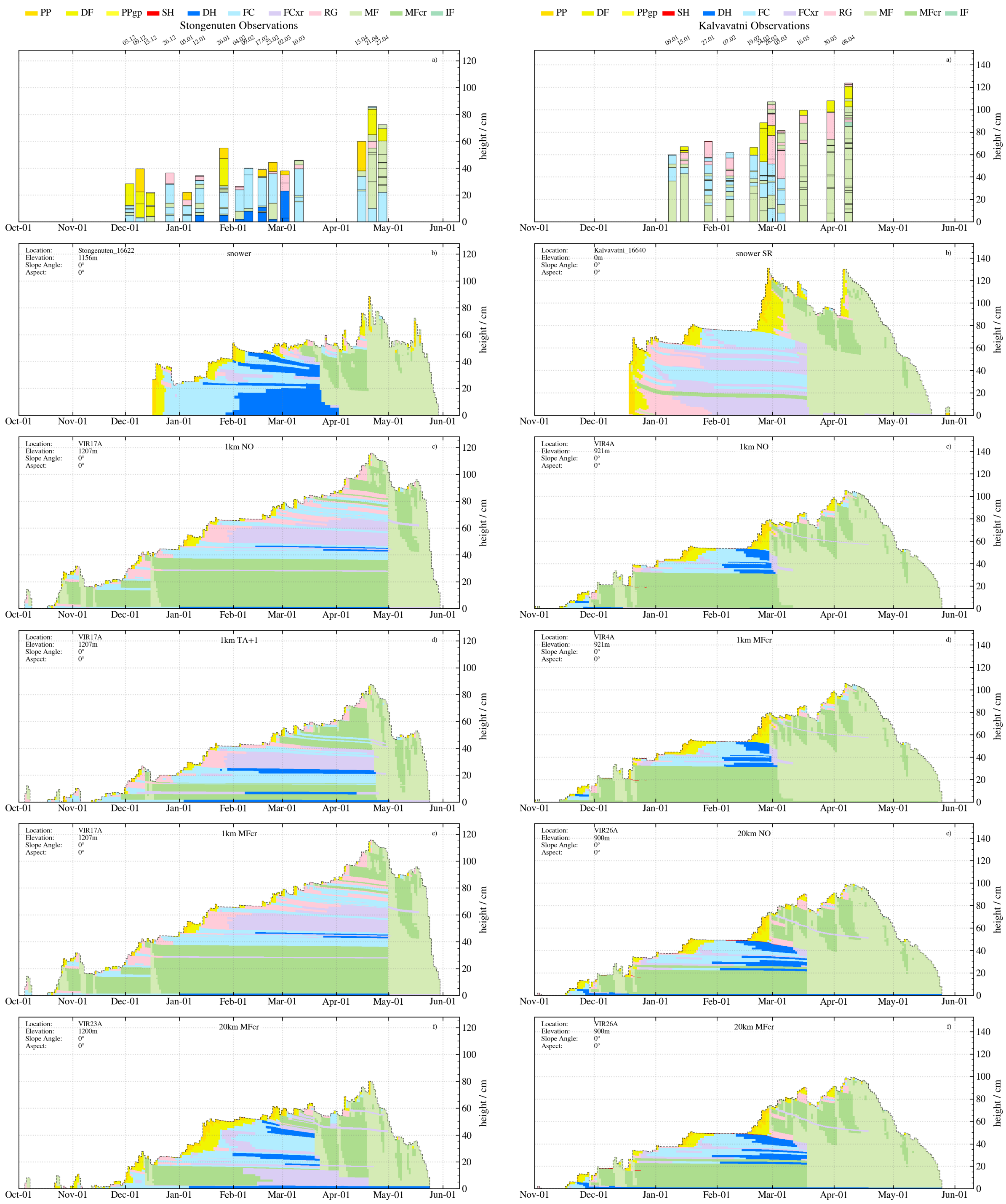

Figure 4: Comparison of seasonal evolution between observed snow profiles, a simulation forced with locally measured data (SNOWER), and several simulations forced with NWP data at either 1- or 20-km resolution. For test location Stongenuten (left) and Kalvavatni (L)

to observer subjectivity, or inaccurate parameterizations of grain shape. Furthermore, the transition from PP and DF to RG does not align well between simulations and observations, where often the simulations show rounded grains when PP or DF are observed.

Simulating soil layers has been shown to be important in simulating a correct temperature profile in the lower part of the snow cover. Without explicit simulation of soil layers, the temperature at the snow-soil interface is 0° C by default, while our profiles clearly show subzero temperatures at this interface. Getting this temperature profile right by including soil layers also improves the formation

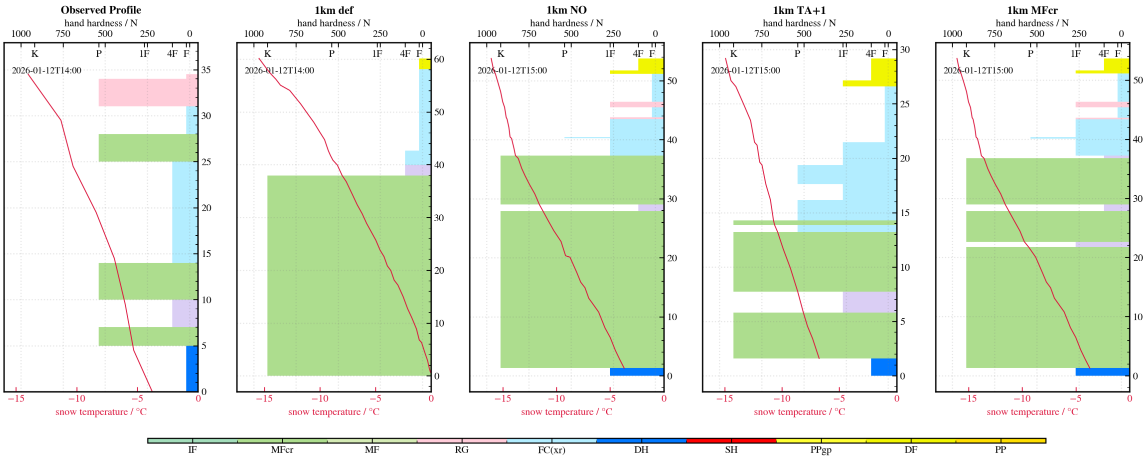

Figure 5: Individual snow profiles from 12-01-2026 at Stongenuten. From left to right: Observed profile, 1km default settings, 1km NO , 1km TA+1 and 1km MFcr.

of depth hoar in the simulations. The inclusion of Richard's equation is less obvious, but it does appear to improve overall layering, and reduce the formation of large homogenous MF(cr) layers that are simulated too much. The melt crust relaxation algorithm, which allows for MFcr grains to resume normal faceting rates appears to improve the agreement with observations, although the exact tuning of this model feature requires further investigation. In general, the model seems to struggle with an over-representation of large layers of melt forms, while thin crusts are often missing in the simulations. Lastly, though not the focus of this paper, the semi-distributed method where weather data is aggregated to representative elevation bands seems to produce results that are very close to the higher resolution model. Validation studies with a larger spatial scope will be conducted in the future to assess the validity of this approach, but initial findings are promising.

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REFERENCES

Bartelt, P. and Lehning, M. (2002). A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model. en. In: https://doi.org/10.1016/S0165-232X(02)00074-5.

Bavay, M., Wever, N., Fierz, C., and Lehning, M. (2024). LOOKING BACK AT THE LAST 15 YEARS OF OPERATIONAL AVALANCHE WARNING WITH THE SNOWPACK MODEL IN SWITZERLAND. en. In.

Bellaire, S., Schweizer, J., Fierz, C., Lehning, M., and Pielmeier, C. (n.d.). PREDICTING SNOW COVER STABILITY WITH THE SNOW COVER MODEL SNOWPACK. en. In: ().

Binder, M., Perfler, M., Herla, F., Techel, F., and Mitterer, C. (2024). INITIALIZING AND EVALUATING SNOWPACK SIMULATIONS WITH RECURRING SNOW PROFILE OBSERVATIONS. en. In.

Calonne, N., Richter, B., Löwe, H., Cetti, C., Ter Schure, J., Van Herwijnen, A., Fierz, C., Jaggi, M., and Schneebeli, M. (June 2020). The RHOSSA campaign: multi-resolution monitoring of the seasonal evolution of the structure and mechanical stability of an alpine snowpack. en. In: The Cryosphere 14.6, pp. 1829–1848. ISSN: 1994-0424. https://doi.org/10.5194/tc-14-1829-2020.

Hagenmuller, P. and Pilloix, T. (May 2016). A New Method for Comparing and Matching Snow Profiles, Application for Profiles Measured by Penetrometers. en. In: Front. Earth Sci. 4. ISSN: 2296-6463. https://doi.org/10.3389/feart.2016.00052.

Herla, F., Binder, M., Lanzanasto, N., Perfler, M., Widforss, A., Reisecker, M., Müller, K., and Mitterer, C. (2024a). Synthesizing regional snowpack stability and avalanche problems in the operational AWSOME framework. In: Proceedings of the International Snow Science Workshop, Tromsø, Norway.

Herla, F., Haegeli, P., Horton, S., and Mair, P. (Aug. 2024b). A large-scale validation of snowpack simulations in support of avalanche forecasting focusing on critical layers. en. In: Nat. Hazards Earth Syst. Sci. 24.8, pp. 2727–2756. ISSN: 1684-9981. https://doi.org/10.5194/nhess-24-2727-2024.

Herla, F., Horton, S., Mair, P., and Haegeli, P. (Jan. 2021). Snow profile alignment and similarity assessment for aggregating, clustering, and evaluating snowpack model output for avalanche forecasting. en. In: Geosci. Model Dev. 14.1, pp. 239–258. ISSN: 1991-9603. https://doi.org/10.5194/gmd-14-239-2021.

Herla, F., Widforss, A., Binder, M., Müller, K., Horton, S., Reisecker, M., and Mitterer, C. (2024c). Establishing an operational weather \& snowpack model chain in Norway to support avalanche forecasting. In: Proceedings of the International Snow Science Workshop, Tromsø, Norway.

Herwijnen, A. van, Muccioli, M., Wever, N., Saiet, E., Mayer, S., and Pugno, N. (2024). IS ARCTIC SNOW DIFFERENT FROM ALPINE SNOW? DELVING INTO THE COMPLEXITIES OF SNOW COVER PROPERTIES AND SNOW INSTABILITY. en. In.

Kruyt, B., Wever, N., and Müller, K. (2026). "Modeling WInd Slabs With the SNOWPACK Model". In: Proceedings of the 2026 INTERNATIONAL SNOW SCIENCE WORKSHOP, WHISTLER, CANADA.

Müller, M., Homleid, M., Ivarsson, K. I., Køltzow, M. A., Lindskog, M., Midtbø, K. H., Andrae, U., Aspelien, T., Berggren, L., Bjørge, D., Dahlgren, P., Kristiansen, J., Randriamampianina, R., Ridal, M., and Vignes, O. (Apr. 2017). AROME-MetCoOp: A nordic convective-scale operational weather prediction model. In: Weather and Forecasting 32.2, pp. 609–627. ISSN: 15200434. https://doi.org/10.1175/WAF-D-16-0099.1.

Nieminen, L., Valasma, H., and Valasma, S. (2024). DETECTING SNOWPACK WITH LOW-COST RADAR – CASE STUDY IN PYHÄTUNTURI, FINLAND. en. In.

Richter, B., Schweizer, J., Rotach, M. W., and Van Herwijnen, A. (Dec. 2019). Validating modeled critical crack length for crack propagation in the snow cover model SNOWPACK. en. In: The Cryosphere 13.12, pp. 3353–3366. ISSN: 1994-0424. https://doi.org/10.5194/tc-13-3353-2019.

Schweizer, J., Reuter, B., Mitterer, C., Monti, F., and Mayer, S. (2023). ON STABILITY MEASUREMENTS AND MODELING. en. In.

Viallon-Galinier, L., Hagenmuller, P., and Lafaysse, M. (Dec. 2020). Forcing and evaluating detailed snow cover models with stratigraphy observations. en. In: Cold Regions Science and Technology 180, p. 103163. ISSN: 0165232X. https://doi.org/10.1016/j.coldregions.2020.103163.

Wever, N., Fierz, C., Mitterer, C., Hirashima, H., and Lehning, M. (Feb. 2014). Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model. en. In: The Cryosphere 8.1, pp. 257–274. ISSN: 1994-0424. https://doi.org/10.5194/tc-8-257-2014.

Wever, N., Schmid, L., Heilig, A., Eisen, O., Fierz, C., and Lehning, M. (Dec. 2015). Verification of the multi-layer SNOWPACK model with different water transport schemes. en. In: The Cryosphere 9.6, pp. 2271–2293. ISSN: 1994-0424. https://doi.org/10.5194/tc-9-2271-2015.