IMPROVEMENT OF SNOWPACK MODEL OUTPUT THROUGH HAND PROFILES? – A CASE STUDY

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ABSTRACT: Modelling the layered snow cover offers a wide range of possibilities in snow and avalanche research and is an important piece of information for assessing the avalanche hazard on regional and local scales. One of the most established models is SNOWPACK. In order to use a model efficiently in avalanche warning it is crucial to know how well it performs and how much we can rely on its output, especially concerning weak layers. The cause for errors in model output is often inserted into the model at a certain point in time and can then remain there for the rest of the season. The question we pursued is whether the model's output can be improved by including manually taken snow profiles in the modelling routine during the winter season. At the Bavarian Avalanche Warning Service there is a high potential in this manner: twice a month, voluntary members of the avalanche warning service dig snow profiles at the exact spot of the automatic weather stations (AWS) used for the modelling routine. These profiles could initialize the routine based on current conditions. Seven manually recorded snow profiles were used in this study to validate the SNOWPACK model output at three different AWS. The snow profiles purely modelled based on AWS-data were compared with snow profiles that had been modelled with additional hand profiles as input data. The main focus lies on the analogy of both the existence and the characteristics of potential weak layers or crusts as published in Herla et al., 2021. The results indicate a high agreement close to the starting point of the integration of the manual snow profiles. The longer the model runs without another integration of a manual profile, the more the model output differs from reality. We found that the quality of the manually taken snow profile is crucial to prevent false information from interfering with the modeling. This study shows that by including high quality manual snow profiles, snow cover modelling can be more effectively used to forecast weak layer development and therefore the avalanche hazard in general.

KEYWORDS: Snowpack modelling, Integration of hand profiles, SNOWPACK

1. INTRODUCTION

Single snow layer characteristics such as grain type or liquid water content have a significant impact on snow stability and therefore on avalanche danger (Techl and Pielmeier, 2011; McClung and Schaerer, 2006). It is crucial to know the evolution of the layered snow cover to assess the possibility of avalanche release. Snowpack modelling offers huge potential regarding generating additional information in this matter. Model output can not only help to increase the quality of danger assessment in regions with sparse information. With its ability to forecast snow layering it is also able to contribute to all the avalanche bulletins that are of prognostic feature.

One of the most common snow cover models including snow stratigraphy is the SNOWPACK model (Bartelt and Lehning, 2002). The field of applications in avalanche warning services ranges from simple visualizations of the direct models' output to the automated suggestion of an avalanche danger level or avalanche-prone days based on snowpack modelling (Mayer et al. 2023).

SNOWPACK offers the possibility to include manually taken snow profiles as starting profiles from which the layered snow cover is simulated, driven by data from the automatic weather stations (AWS) or weather forecast information. Thus snowpack modelling is now possible at every time and location during the winter if only a manual snow profile and weather forecast data exist.

At the Bavarian avalanche warning service twice a month manual snow profiles are taken by voluntary members at sites of the automatic weather stations. These profiles could be used to set the model to actual conditions every second week, offsetting prior modelling errors. To evaluate the benefit of this proceeding two questions should be answered:

- Can the implementation of manual snow profiles as starting profiles improve the SNOWPACK model output?
- What limitations arise, and what needs to be considered?

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The adherence to the reliability of the information provided by snowpack models is crucial for the benefit these models can bring to avalanche warning.

2. DATA AND WORKFLOW

To validate the agreement of pure model output, model output with integrated hand-profiles and the actual stratigraphy of the snow cover at a single location, we compared all snow profiles of each site qualitatively and quantitatively. As quantitative method we used the Algorithm publishes by Herla et. al 2021 with the focus on avalanche danger related layers in the snowpack. These include layers of depth hoar and buried surface hoar as well as melt-freeze crusts (Herla et al., 2021). Crusts in combination with strong temperature gradients promote the evolution of facetted crystals (Jamieson, 2006). Layers of rounded grains and small facetted crystals are classified as bulk layers and given less emphasis (Herla et al., 2021).

2.1 Test Sites

We used snow profiles from three different locations in Bavaria and two winter seasons as initial snow cover states for the modeling routine and reference profiles. This includes two profiles from the end of February 2018 at Kühroint with an interspace of one week. Kühroint lies on an elevation of 1420 m in a flat section close to the Watzmann in the Berchtesgaden Alps. In the Ammergauer Alps three profiles from the 23rd of February, the 7th and the 28th of March 2018 at the location of the Pürschling AWS were used as starting and reference profiles at a similar elevation of 1370 m. To consider higher elevations, we used two snow profiles at the location of the Zugspitze AWS at 2420 m in an interval of two weeks in spring 2024.

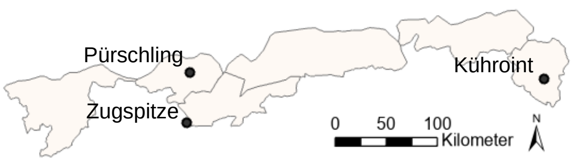


Figure 1: Map of the Bavarian Alps with the three test-sites at which manual snow profiles were taken.

2.2 Model setup

To generate an unaffected model output for the whole season up to the date of the last manual snow profile at each location, the SNOWPACK model is driven by the data of the AWS with a no-snow situation as starting point in October. The simulation is configured to match the measured snow height. As atmospheric stability model MO_MICHLMAYR was chosen as well as the water transport model BUCKET.

The manual hand profiles were translated into CAAML-format (Haegeli et al. 2023) and used as starting profiles based on their creating date. From this date on, the AWS data drives the model until the last manual snow profile at the particular location was taken. The simulation based on the hand-profile does not need to match the measured snow height to prohibit the occurrence of unrealistic new snow deposit due to the ambition of the model to reach the measured snow height. In addition, the CAAML maximum element thickness is not set.

2.3 Profile comparison workflow

As an initial step for each site, we compared the first hand-profile with the purely AWS-based simulation to identify the initial deviation between the observed profile and the model. After running the modeling chain based on the first hand-profile, we compared its output and the output of the purely AWS-based simulation with the second hand-profile.

For the Pürschling site, we conducted additional analyses. The third hand-profile was compared with three different simulations:

- the purely AWS-based simulation
- the simulation based on the first hand-profile
- the simulation based on the second hand-profile

In all comparisons we computed a similarity value between the two profiles ranging from 0 to 1, with 0 indicating no similarity. This similarity value was calculated using dynamic time warping, as proposed by Herla et al. 2021. The algorithm was modified to compare profiles at the same point in time by rescaling the queried profile to match the height of the reference profile. This adjustment accounts for deviations in snow height caused by uneven ground surfaces.

When the hand profiles are imported into SNOWPACK, the model adjusts some parameters, such as the hardness of melt-freeze crusts. These adjustments made by SNOWPACK influence the similarity coefficient when comparing snow profiles. This effect becomes visible when comparing the original hand profile with the same hand profile after SNOWPACK processing. For example, after processing the hand profile of the Pürschling site in 23.02.2018, the similarity value is 0.60.

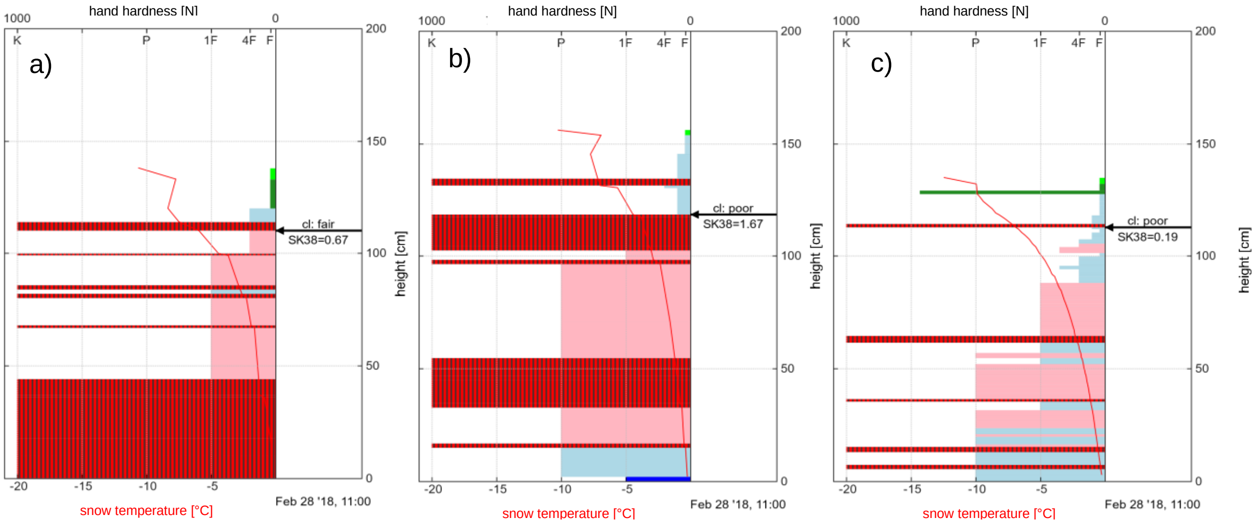
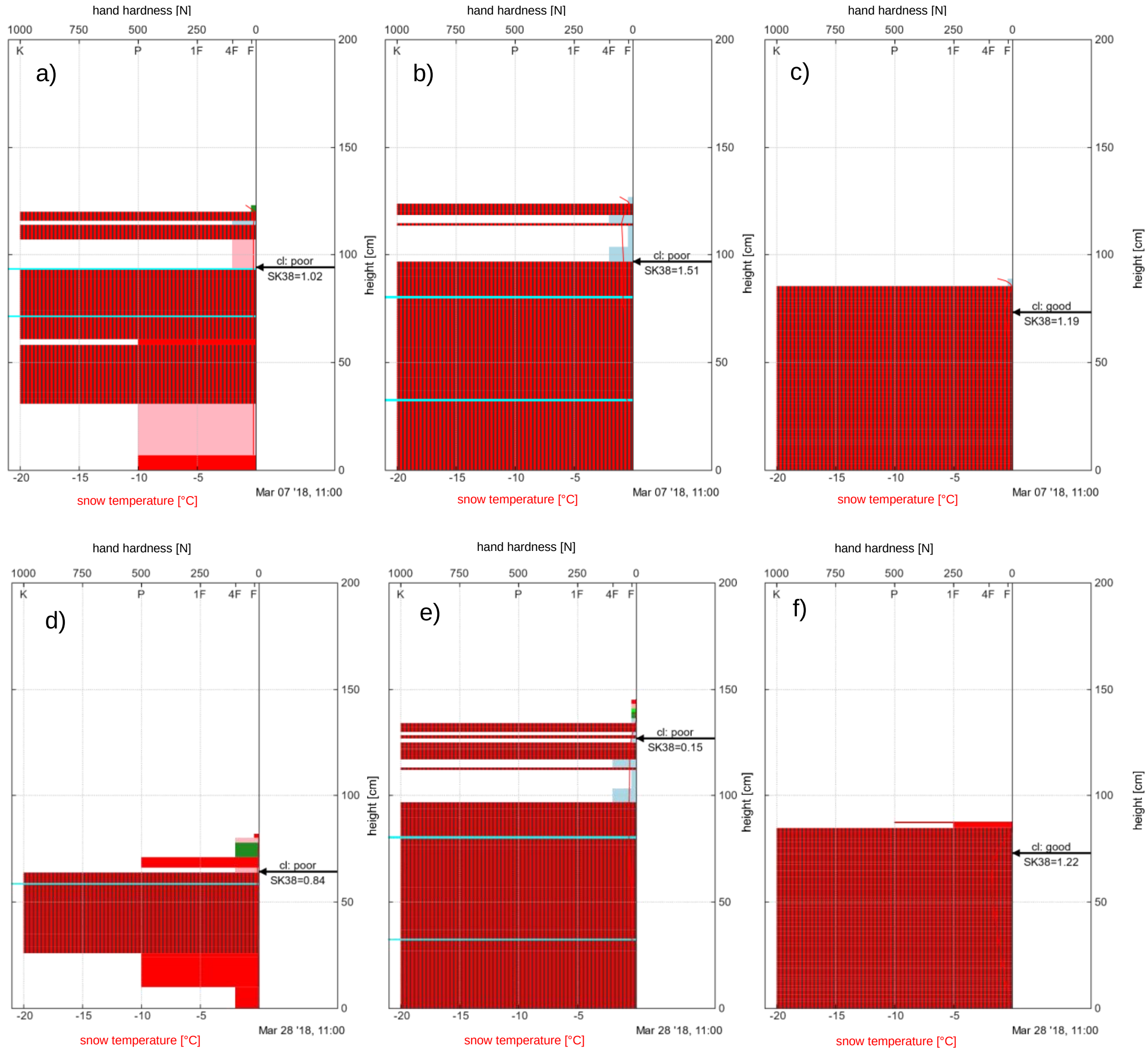


Figure 2: a) manually taken hand-profile of the 28.02.2018 at Kühroint; b) simulated snow profile of the 28.02.2018 based on the hand-profile from the 21.02.2028; c) simulated snow profile of the 28.02.2018 purely based on AWS-data. Both snow profiles b) and c) are compared with the reference hand-profile a) in this study.



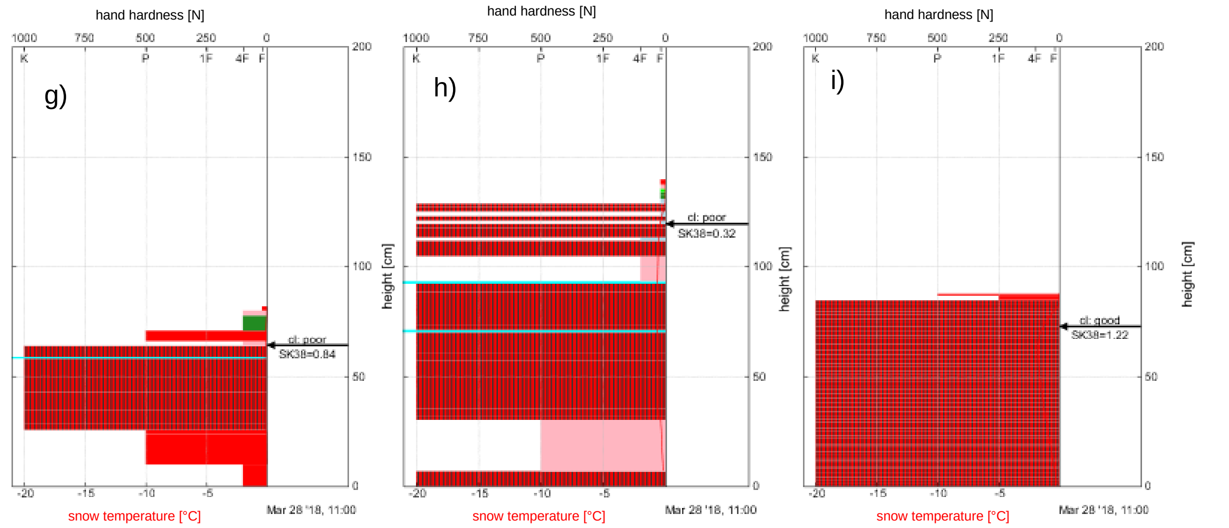


Figure 3: a) manually taken hand-profile of the 07.03.2018 at the Pürschling site; b) simulated snow profile of the 07.03.2018 based on the hand-profile from the 23.02.2018; c) simulated snow profile of the 07.03.2018 purely based on AWS-data. Both snow profiles b) and c) are compared with the reference hand-profile a) in this study. d) manually taken hand-profile of the 28.03.2018 at the Pürschling site; e) simulated snow profile of the 28.03.2018 based on the hand-profile from the 23.02.2018; f) simulated snow profile of the 28.03.2018 purely based on AWS-data. Both snow profiles e) and f) are compared with the reference hand-profile d) in this study. g) manually taken hand-profile of the 28.03.2018 at the Pürschling site; h) simulated snow profile of the 28.03.2018 based on the hand-profile from the 07.03.2018; i) simulated snow profile of the 28.03.2018 purely based on AWS-data. Both snow profiles h) and i) are compared with the reference hand-profile g) in this study.

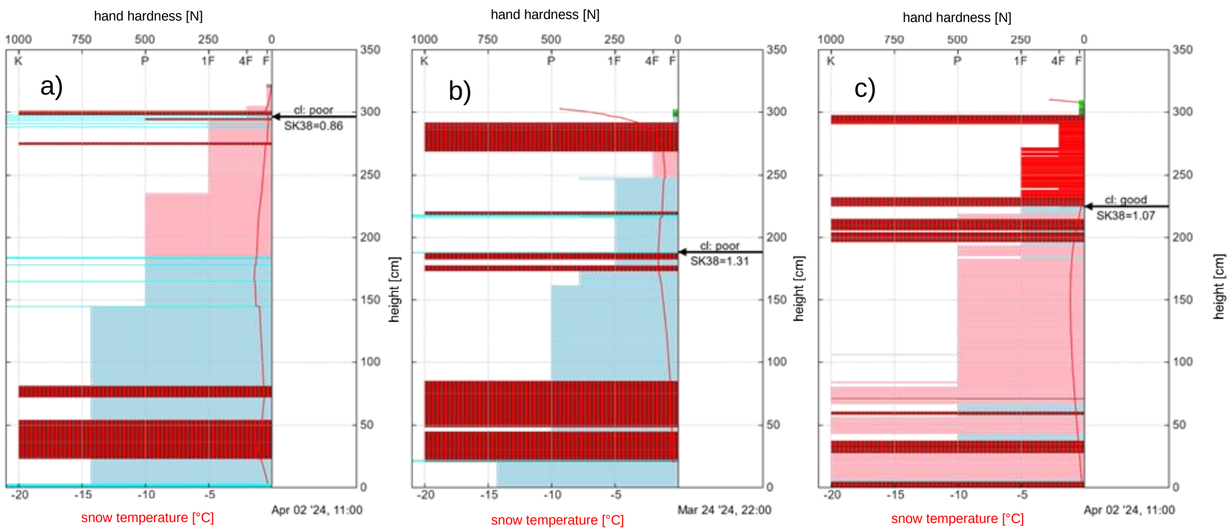


Figure 4: a) manually taken hand-profile of the 02.04.2024 at the Zugspitze; b) simulated snow profile of the 02.04.2024 based on the hand-profile from the 14.03.2024; c) simulated snow profile of the 02.04.2024 purely based on AWS-data. Both snow profiles b) and c) are compared with the reference hand-profile a) in this study. The colour convention for main morphological grain shape classes of "The International Classification for Seasonal Snow on the Ground" of Fierz et al. 2009 is used in all graphes.

compared to the original hand profile. This means that in this case the processing of SNOWPACK adds 40% of the deviation between the profiles. To prohibit a falsification in calculating the similarity value by this fact, the hand-profiles taken for the comparisons are the profiles one timestep after importing.

3. RESULTS

The simulated and the manually taken snow profiles were opposed to each other. First, we compared them with a qualitative approach. Afterwards the comparison is executed quantitatively.

3.1 Qualitative Comparison

Kühroint:

All simulated profiles show too distinct kinetic metamorphism due to a slightly higher temperature gradient than measured in the field. Also, melt forms in the lower part of the snowpack and close to the ground are missed and replaced by facets or in case of the hand-profile based simulation by depth hoar (figure 2).

All in all, both simulated snow profiles show a similar level of agreement with the reference profile.

Eminent was the fact that the grain size of new snow and decomposed snow had to be adjusted in the manually taken profile to create realistic model output for the near-surface layers. A grain size of 5 mm of new snow in the hand-profile resulted in large depth hoar crystals at the snow surface, which could not be found in the field. Reducing the grain size in the starting profile to 0,5 mm showed much more alignment with the actual situation in the field and was used for the comparisons.

Pürschling:

At Pürschling, the simulations overestimate the melting and refreezing process significantly. Briefly after the date of the first hand-profile on the 23th of February the entire snowpack is simulated as a compact melt-freeze crust with the hand hardness “knife” (figure 3). In the field we found some more differentiation in hardness and grain types as melt forms or rounded grains. In contrast near the surface the kinetic metamorphism in the simulations is stronger than in the reference hand-profile.

Integrating the hand profiles into the simulation has a clear positive effect at the Pürschling site. The differentiations of single layers stay closer to the layers detected in the field.

Zugspitze:

Like at the Pürschling site, the melting process is simulated too strongly for the Zugspitze. On the 2nd of April the moisture already penetrates the near-surface layers and transforms them into melt forms where they are classified as dry rounded grains in the field (figure 4).

The melt forms in the hand-profile based simulation reach a few layers deeper than in the unaffected simulation. The lower part of the snowpack found in the field aligns better with the hand-profile based simulation instead. Overall, both simulations show a good agreement with the manual taken snow profiles.

3.2 Quantitative Comparison

The similarity values calculated as published by Herla et al. 2021 are shown in table 1.

Kühroint:

At Kühroint at the 28th of February the similarity value between the reference hand-profile and the simulation based on the hand profile from the 21st of February is with 0,60 slightly higher than the value for the comparison with the pure SNOWPACK simulation over AWS data with 0,59.

Pürschling:

Two weeks after the integration of the first hand-profile in the Pürschling simulation the similarity value of this simulation with the reference hand-profile is with 0,42 higher as for the pure SNOWPACK simulation with 0,39. The low value of 0,39 drops further for the pure simulation after two weeks to 0,20. In contrast the value of the hand-profile based simulation raised up to 0,46 four weeks after the integration. It can be even improved by the reintegration of a hand-profile two weeks after the first to 0,52.

Zugspitze:

At the Zugspitze the similarity value between the hand-profile of the 2nd of April and the simulation based on the hand-profile from the 14th of March is 0,48. It is slightly lower than the value for the pure SNOWPACK simulation with 0,49.

Table 1: Similarity values for each manually taken snow-profile with its corresponding modelled snow-profile based purely on AWS-data, based on the model output one or two weeks after the integration of the first hand profile into the simulations and, in case of the Pürschling-site, even on a second manually taken profile after five weeks.

Test site	Date	Purely AWS-based	1. hand-profile-based	2. hand-profile-based
Kühro-int	21.02 .2018	0,50	-	-
Kühro-int	28.02 .2018	0,59	0,60	-
Pürsch-ling	23.02 .2018	0,56	-	-
Pürsch-ling	07.03 .2018	0,39	0,42	-
Pürsch-ling	28.03 .2018	0,20	0,46	0,52
Zug-spitze	14.03 .2024	0,46	-	-
Zug-spitze	02.04 .2024	0,49	0,48	-

4. DISCUSSION

In most cases SNOWPACK overestimates the temperature gradient and hence the kinetic metamorphism. This coincides with findings of J.-B. Madore et al. 2016. Also, an overestimation of the melting processes by the model is shown. These circumstances have to be taken into account when deducing information regarding snowpack stability from the model output. At the Pürschling site the combination of a strong modelled humidity penetration into the snowpack and lower temperatures in the simulation than measured in the field, lead to a major discrepancy between simulated and measured conditions. In this case, the integration of a hand profile in the seasonal simulation of the snowpack can help handle these biases.

On the other hand, the integration of a manual taken snow profile can cause new sources of errors as seen at Kühroint. The information of big new snow crystals with the size of 5 mm misled the simulation to the, under the given circumstances, unrealistic occurrence of depth hoar crystals near the surface. Nevertheless, new snow crystals classified in the field by this size are unusual, but could occur as input data. Accordingly, both output and input data should be checked regularly on their plausibility.

It stands out that single parameters of the input hand-profile are affecting the model output massively. A high quality of the manually taken snow profiles is therefore a requirement for reliable simulations.

The fact that SNOWPACK neglects certain parameters from the input snow profile/CAAML-File and further adjusts values according to its internal ruleset is mentionable. For example:

- SNOWPACK classifies any faceted crystals with a grain size bigger than 1,5 mm as depth hoar (Herla et al. 2021).
- The secondary grain type of the input profile is discarded.
- The measured layer hardness is neglected and an internal parametrization (Monti et al., 2014) is used to calculate the hardness. Melt-freeze crusts, for example, always get the hardness “knife”.
- Layers with temperatures < 0°C are set to “dry”.
- Occasionally, grain types are adjusted to match the strict physical rules implemented in SNOWPACK.

Inaccuracies of measurements in the field can therefore have a big impact on the characteristics of a snow layer in the model or on the other hand could be corrected by the model.

Nevertheless, the qualitative approach in some cases shows an improvement of the agreement between the reference hand-profile and the simulation, when the simulation is based on a prior hand-profile. The similarity values support these findings. For all sites the integration of hand profiles shows almost equal or better results than the simulation based on AWS data only. In the case of the melting situation at Pürschling, the hand-profile approach significantly improves the agreement with the reference profile. These findings indicate that the simulation of the layered snowpack in SNOWPACK, supported by integrating hand profiles, produces stable results and can effectively generate additional information, especially concerning the prognostic aspect. Running the SNOWPACK model from manual snow profiles reported to an avalanche warning service from the field can add a significant benefit as the information density is increased. Model errors caused by the accumulation of uncertainties in the weather forecast can thus be corrected. This is particularly helpful if the modeling is based on a snow-free situation in autumn and run only by weather forecasting data.

In addition, in certain situations, it is possible to improve the results even at sites where SNOWPACK is supplied with AWS-data. Thus, the information from the field is included in the simulation. Overestimated melting processes or kinetic metamorphism can be corrected for a certain point in time until the simulation process overrules again. Especially in deeper parts of the snowpack this has a long-term effect, which can be seen in the Zugspitze data. Here the layers align quite well deep down in the snowpack. Differences arise trough the simulated processes and can additionally be caused by inconsistencies by taking the hand-profile.

5. CONCLUSION

Starting snowpack simulations from manually taken snow profiles adds additional fields of applications to snowcover models. We found that the integration of hand-profiles as starting profiles into the SNOWPACK simulation leads to stable results one, two or five weeks after the integration. The results are equally good or even better than the simulation of the snowpack purely driven by AWS-data from the winterstart on. But it reqiures high quality hand-profiles as input-data, since errors in the input data inevitably lead to errors in the model output. Some deviation of the situation in the field can additionally occur due to the routine SNOWPACK imports and processes the manually taken snow profiles. The possability to take the hardness and the secondary grain type information into account could improve the benefit of the hand-profile integration even more. But even at the present state the integration of hand-profiles can be used to improve purely AWS based simulations in certain situations or to start a snowpack simulation besides the AWS-sites with weather forecasting data. We assume that the benefit of the integration is even higher closer to the date on wich the manual hand profile was taken. To verify this hypothesis further surveys are needed. Nevertheless the model output should always be questioned in order to detect errors due to the simulation process or low qualitiy input data. Bearing this in mind, the integration of hand-profiles into the snowpack simulation of SNOWPACK can increase the amount of high quality information regarding snow stratigraphy and can also be impotant additional information in avalanche warning.

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