LOOKING BACK AT THE LAST 15 YEARS OF OPERATIONAL AVALANCHE WARNING WITH THE SNOWPACK MODEL IN SWITZERLAND

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ABSTRACT: From the start, the SNOWPACK model was created to address the needs of the avalanche warning in Switzerland based on a large network of Automatic Weather Stations (AWS). An energy balance approach was chosen that incorporated the modeling of the snow metamorphism in order to reproduce the stratigraphy, an arbitrary number of layers and the ability to simulate very thin layers. But a number of annoying issues remained for the daily use in an operational toolchain, linked to the handling of raw data coming from the AWS as well as the limitations of the AWS themselves. After the data preprocessing got separated from the SNOWPACK model itself as the MeteoIO library (in 2008), it experienced a sustained development effort over more than 15 years. Many typical data issues could be identified and addressed, often with timeseries filters in MeteoIO while a few had to be addressed in the SNOWPACK model itself. More flexibility was also allowed by new developments aimed at supporting operational constraints such as the inability to physically access some of the AWS in the winter, even to perform emergency maintenance.
This paper shows some of the limitations of the measurement network from the SNOWPACK point of view and some typical data problems that have been encountered in the last 15 years while forcing SNOWPACK with raw AWS data. Some of the solutions that have been implemented and the compromises that had to be made are presented as well as their remaining limitations.

Keywords: numerical modeling, snowpack, operational, avalanche warning, Automatic Weather Station

1. INTRODUCTION

The SNOWPACK model has originally been written to address the needs of the operational avalanche warning in Switzerland (Lehning et al., 1999), based on data provided by an ad-hoc network of Automatic Weather Stations (AWS) called the IMIS network. The model simulates the snow microstructure with an arbitrary number of layers in order to be able to simulate thin layers if necessary (Bartelt and Lehning, 2002; Lehning et al., 2002). It has been adapted by other countries for their own operational avalanche warning (Hirashima et al., 2008; Morin et al., 2020). As it started to be used more widely even outside the avalanche warning applications, new modules got developed: a drifting snow index (Lehning et al., 2000) for the avalanche warning, a soil module (Luetschg et al., 2003) that has been used for permafrost and soil temperature studies (Luetschg et al., 2008; Haberkorn et al., 2017), a simplified liquid water transport scheme and one based on the Richard's equation (Wever et al., 2014) to better simulate melting, soil moisture or rain on snow events (Wever et al., 2015; Würzer et al., 2016), a dual domain preferential flow module (Wever et al., 2016) as well as a module to simulate the formation of ice layers (Quéno et al., 2020), a water vapor transport module (Jafari et al., 2020) as necessary to simulate arctic snowpacks, a sea ice module (Wever et al., 2020) and a technical snow module (Hanzer et al., 2020).

In parallel, it was decided in 2008 to remove the data preprocessing from the SNOWPACK[1] source code and develop it as the independent MeteoIO[2] software library to ease and accelerate the development and maintenance (Bavay and Egger, 2014) of this part. This has allowed to support a much larger diversity of data sources (such as reanalysis datasets) and even more flexibility in the forcing parameters (Schmucki et al., 2014) and in turn, facilitated the usage of SNOWPACK in other areas of the world as well as for other fields of research. Thus the SNOWPACK model has been used for climate change impact studies (Bavay et al., 2009, 2013; Kobierska et al., 2011; Fischer et al., 2022; Willibald et al., 2021), reindeer herding sensitivity analysis (Rasmus et al., 2016), investigating the role of land use change versus carbon storage (Schwaab et al., 2015), feedback from dust radiative forcing on snow (Skiles and Painter, 2019) or to provide the initial conditions for avalanche dynamics simulations (Köhler et al., 2018). The continuous developments to the MeteoIO library allowed much more complex forcings scenarios (Bavay et al., 2018) such as merging data from various sources or spatially in-

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[1] `https://snowpack.slf.ch`
[2] `https://meteoio.slf.ch`

terpolating point-data on virtual stations. It has even taken a life on its own and has been further developed in the last few years as an essential component for an AWS data management system (Bavay et al., 2020) coupled with the current development of a web service interface (Bavay et al., 2023) that enforces datasets reproducibility (Bavay et al., 2022).
The interactions between the limitations of the network of AWS (based on compromises for costs and operational realities) and the limitations of the model itself have been experienced first hand over the last 15 years of managing the SNOWPACK simulations for the operational avalanche warning in Switzerland. This has in turn motivated many of the software developments of the last 15 years, both in the SNOWPACK model and in its MeteoIO preprocessor to offer some pragmatic solutions for the daily operations of the service.

2. TYPICAL ISSUES

On one hand, a model is a simplified vision of reality designed to simulate or predict some behavior of real-world or physical systems. As such, many compromises are made in order to reduce the complexity where a good match with the reality is not required and to increase the efforts where a good match is required. This means that behaviors that did not match the original intent of the model might be less accurately reproduced. Over time, as the usage of the model expands, some shortcomings might appear that are a direct consequence of this mismatch. Of course, there are also oversights and errors in the design and in the implementation.
On the other hand, measuring real-world physical properties is not as authoritative as it might seem. Automated measurement systems rely on sensors that convert the physical property of interest into an electric signal that is then digitized. This introduces room for errors at various levels: the digitization itself might experience signal saturation, loss of precision or accuracy limit. Then the conversion from the physical property of interest into the electrical signal introduces errors: the assumed relationship is a model in itself that might get more or less accurate and could even get out of its applicability range. Finally the property of interest as seen by the sensor might significantly differ from how the data user will interpret the signal: if an unventilated temperature sensor heats up in the sun would perfectly measure its temperature, it would still be widely different from the air temperature that it is expected to measure (Huwald et al., 2009).
As the SNOWPACK model as used for operational avalanche warning in Switzerland is forced by the data from AWS of the IMIS network, both sources of uncertainty have been experienced and actually often interact. Although the IMIS network has been specifically designed to support the avalanche warning service and shines with its spatial coverage and data quality, it still has some limitations compared to the best, state of the art, high end research AWS: first in order to reduce the costs (it is quite different to deploy a single AWS than a network of more than 100 identical stations) but also for technical reasons. As the stations are located in remote areas and a significant part of the network can not be accessed during the snow season, the whole design must be power autonomous (thus relatively low power) and the sensors must be robust enough to simply work for months without any manual intervention. A few of these issues are presented below as typical examples.

2.1 Precipitation forcings

As it provides the vast majority of the mass input, the precipitation forcings are a very important parameter for the quality of the numerical simulation. Unfortunately, the IMIS stations suffer from two severe limitations with respect to solid precipitation measurements: the rain gauges are unheated and exhibit undercatch (Larson and Peck, 1974). Using heated rain gauges would require too much energy for AWS that are off-grid while installing the right kind of wind shield to make the rain gauge a proper reference measurement is hardly feasible in remote, mountainous terrain (Larson, 1972).
A first, pragmatic solution consists in calibrating a correction function from a reference rain gauge (such as the one used at the Weissfluhjoch in Switzerland) and applying it to all identical rain gauges of the network. Although it works quite well for some years, some other years still exhibit a very significant undercatch. This is therefore not a proper solution for critical applications such as avalanche warning services.
The solution that has been implemented at SLF consists in measuring the snow depth under the AWS with a sonic sensor and then assimilating it in SNOWPACK (Lehning et al., 1999) as illustrated in Fig. 1. The measurement uncertainty (Egli, 2008) is much lower than from a rain gauge that would be installed at the same location with a small wind shield. But it is now sensitive to spikes in the snow height signal and also does not handle Rain-On-Snow events. The spikes (created during heavy snowfalls by parasitic reflections of the sonic pulse by the falling snow) are removed by a combination of min/max filter (enforcing the expected range of the data), rate of change (enforcing a maximum rate of change, both in the ascending and descending directions) and a Median Absolute Deviation filter (Hoaglin et al., 2000; Lehning et al., 2002).
As many stations still have a rain gauge that provides liquid precipitation input, it is possible to use it to handle Rain-On-Snow events, after some signal filtering: because snow might accumulate in the rain

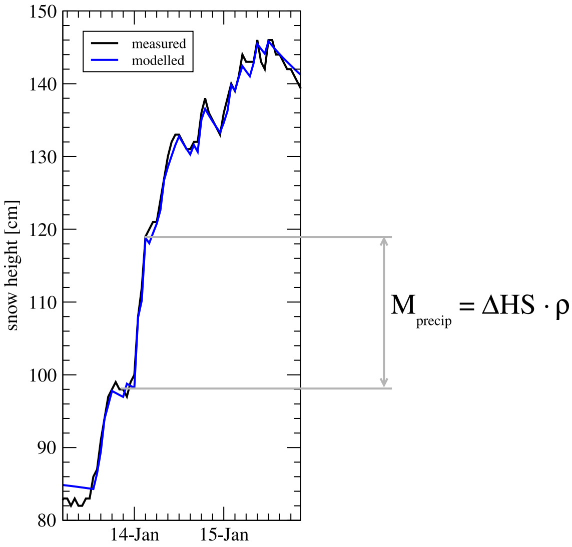

Figure 1: Principle of the assimilation of the snow height: positive snow height increases are multiplied by a parametrized new snow density in order to generate a precipitation amount.

gauge and melt later when exposed to the sun, a filter only accepts liquid precipitation measurements occurring at times deemed suitable for precipitation (relative humidity higher than a given threshold and air temperature close enough to the surface temperature). Figure 2 shows the impact of taking into account the liquid precipitation input: in panel (a) where there is no liquid precipitation, the snow settling is well reproduced in any case. But in panel (b) when there is a Rain-On-Snow event, not taking into account the liquid precipitation leads to a strongly underestimated snowfall amount for the immediately following snowfall (c) and later on an insufficient settling.

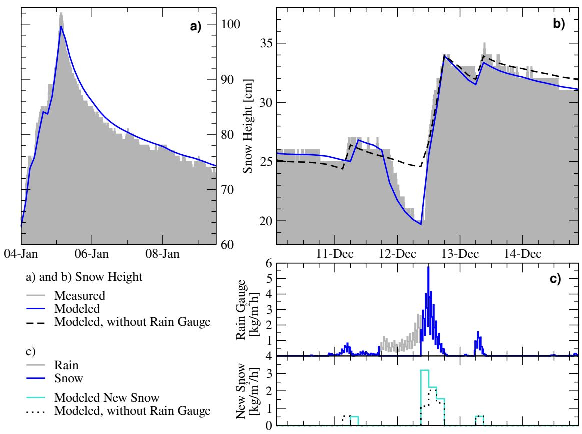

Figure 2: Impact of considering the liquid precipitation measurement for Rain-On-Snow events.

However, the general snow depth assimilation scheme requires to use a new snow density model. As the processes responsible for part of the new snow density experienced happened in the atmosphere well above the AWS (and are therefore not measured by the station), such a model will always stand on fragile ground. It is of course possible to develop a parametrization that works well most of the time, but there is always a risk of generating a parametrized value that is very different from the reality. This in turn leads to mismatch in the snow settling between the simulation and the reality (because the density is wrong) and therefore differences in the new snow amount that will be simulated at the next snow fall (as the initial snow height before the snow fall will be different from the measurements). In order to get better estimates of the new snow fall amount, the operational version of SNOWPACK at the SLF applies a scaling factor on the whole snow profile when it deviates too much from the measured snow height (the scaling factor actually varies over the height of the profile in order to apply a bigger correction close to the surface where the error mostly happened and decreasing as is goes down, with an exponential decay over the height).

Because of the remoteness of the stations, the standard WMO recommendations (measurements on a stable and controlled surface, WMO (2014)) are not enforced and therefore some grasses and plants might grow under the station. Therefore relying on snow height measurements introduces the problem of snow accumulating on low vegetation that grew under the station's sensors during the summer. At the start of the snow season, the snow accumulates first on this vegetation until it gets compacted to the ground, leading to a surprising behavior of the measured snow height: it might go down over the first few snowfalls before it goes up for good. The solution has been to model in SNOWPACK the vegetation as a spring that gets loaded by the snow mass until it reaches the ground[3].

2.2 Long wave radiation forcings

SNOWPACK as a surface energy balance driven land surface model, needs estimates of all energy fluxes crossing the surface (Neumann boundary conditions). Contrary to the short wave radiation fluxes that only play a role during daylight time (which, depending on the time of year and the latitude might be very short or very large), the long wave radiation fluxes are always active. Unfortunately, the accurate measurement of the Incoming Long Wave Radiation (ILWR) is too expensive for a

[3]There are actually two methods that have been implemented in order to detect and "remove" the vegetation growing under snow height sensors. The one refereed to here is implemented in SNOWPACK and relies on the full mass and energy balance capabilities of SNOWPACK to extract a good estimate of the true snow depth while a purely statistical method calibrated for the Alps (Tilg et al., 2015) has been implemented in MeteoIO and only removes snow height measurements that are attributed to vegetation growth.

large network of AWS and requires too much electrical power for such power autonomous stations. Thus such sensors have not been installed on the IMIS network but instead a Dirichlet boundary conditions is used, based on the snow surface temperature. This actually fits well with the surface energy balance approach in SNOWPACK that is tightly coupled to the heat transport in the snow (Fourteau et al., 2024). As a non-contact temperature measurement, it has been calibrated for the emissivity of the snow surface. It also means that any measurement error on the snow surface temperature (such as an offset resulting from a bad calibration or from sensor drift) has a direct impact on the simulated energy balance.

Relying on the snow surface temperature instead of the ILWR in the energy balance has a big limitation: when the snow surface reaches melting temperature, it can not be used to compute the energy fluxes as the temperature will remain constant while all energy exchanges will lead to either surface melt (if more energy comes into the snowpack) or refreeze (if the snow is emitting more than it is receiving). Thus an additional strategy had to be implemented for these phases (which will be found over most of the ablation phase of the snowpack).

So in complement, the ILWR is parametrized from a cloudiness that is estimated from the comparison between the measured Incoming Short Wave Radiation (ISWR) and the potential radiation, that is the theoretical estimate of the clear sky solar radiation reaching this specific place on Earth at this specific time. Since the IMIS stations don't measure the ISWR but the Reflected Short Wave Radiation (RSWR), the snow albedo (as modeled by SNOWPACK) must be used in order to recompute what should have been the measured ISWR. This is of course another source of uncertainty. Furthermore, the cloudiness can not be estimated during the nighttime (as there is no short wave radiation).

As shown in Fig. 3, there have been two different approaches to handle the nights: fallback to a clear sky ILWR parametrization, which introduces a negative bias in the energy inputs (and negative temperature bias). Another approach is to linearly extrapolate over the night the last cloudiness values from before the last sunset. Because generally the stations don't have an absolutely unobstructed view of the sky, they often find themselves in the shadows cast by the surrounding terrain when the sun is low over the horizon. This gives very low RSWR, that are (wrongly) interpreted as very high cloudiness and then so interpolated over the night, leading to a positive bias in the energy inputs (and a positive temperature bias) during the ablation season. In order to prevent such behavior, it is necessary to provide a terrain horizon for each station so only the cloudiness values computed when the sun is really

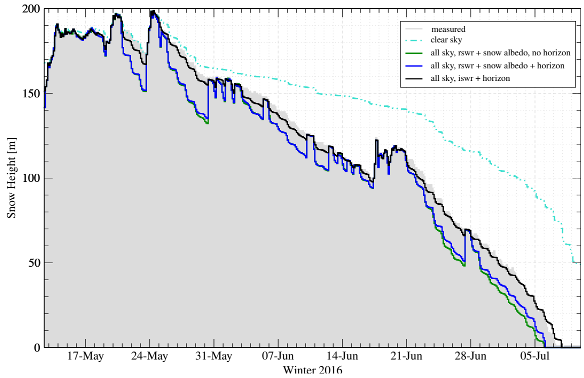

Figure 3: Comparison of measured and simulated snow heights using different strategies to parametrize the ILWR forcings during the ablation season 2016 at Davos Weissfluhjoch (46.829641, 9.809293, 2536): clear sky parametrization, all sky parametrization using the measured RSWR without and with the shading from a computed horizon, all sky parametrization using the measured ISWR with the shading from a computed horizon.

above the horizon are taken into account. Finally, when running SNOWPACK operationally, the model will run as long as there are forcing data available, then stop and wait for new data in order to run again. This can be problematic as if such a restart happens at night, SNOWPACK won't be able to get past values of the cloudiness and as a consequence won't be able to use an all sky ILWR parametrization. The usual fallback to a clear sky parametrization will lead to a cold bias in such simulations. In order to avoid this bias, it is necessary to restart SNOWPACK from a date when cloudiness values can be extracted.

2.3 Maintenance issues

The IMIS stations are usually located at remote places that might be too dangerous to reach during the snow season. This means that if a sensor fails, it will remain so for the rest of the snow season. Therefore, it is important to have a toolbox to mitigate as much as possible such issues. This toolbox is provided by the input data editing capability of MeteoIO and its data generators ability. Over the years, some stations have relied on a constant value generator for a relative humidity sensor (in order to allow SNOWPACK to accept positive rain gauge signal and generate precipitation, at the cost of the simulation producing too much surface hoar). Some other stations have relied on taking the measurements from the sensors of a nearby station with a *merge* command (this works quite well for radiation data). It has also been possible to merge Numerical Weather Prediction (NWP) data to fill the gaps of a missing sensor or to spatially interpolate some forcing parameters from neighboring stations at the location of interest.

3. CONCLUSION

As the SNOWPACK model has seen ever broader use, both for operational applications and for research applications, the model and its associated tools have been continuously developed further to address the associated challenges. Nowadays, the model and its tools are quite flexible and can handle a broad variety of input data configurations in a robust and reproducible way. Simultaneously, the interactions between the forcing data limitations and the modeling limitations have also resulted in further improvements to the model as well as precious experience in how to handle many special situations: these interactions can exhibit surprising side effects that are at first hard to comprehend. The numerical model is imperfect and so are the measurements! *"But since our measurements and observations are nothing more than approximations to the truth, the same must be true of all calculations resting upon them"* (Karl Friedrich Gauss, 1809)

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