# HOW SNOWMICROPEN RECORDINGS ARE INTEGRATED INTO DAILY FORECASTING WORK BY THE SOFTWARE FRAMEWORK AWSOME

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ABSTRACT: During the assessment process of avalanche danger forecasters rely on enormous amounts of different data. Most of this data connects only indirectly to the factors defining avalanche danger and requires additional interpreation skills by the forecaster. In contrast, there are very direct bits of information that offer more direct links to snowpack stability, e. g. a snow pit observation including a stability test. Unfortunatly this kind of information is often spatially scarce, time consuming to collect, and subject to personal skills. In order to offer a more objective way of assessing snow stratigraphy and measuring mechanical properties of snow, the SLF introduced the SnowMicroPenetrometer (SMP), an electronical rammsonde measuring the penetration resistance of snow by vertically driving a cone into it. Its advantages lie in quick objective and high-resolution sampling of the snowpack. Its disadvantage when taken out of the software lab is that it measures micro-parameters that are quite far removed from what a practitioner would record in the field. The operational goal is to take the SMP out in a challenging environment, quickly record multiple observer-independent profiles, and feed them into a computer as they are to instantly and fully automatically produce snow stratigraphy and stability forecasts making SMP data accessible for daily forecasting procedures. To achieve this we have developed a new module in our general-purpose snow modeling toolchain called the Avalanche Warning Service Operational Meteo Environment (*AWSOME*).

*Keywords:* avalanche forecasting, SnowMicroPenetrometer, SNOWPACK, model chains, AWSOME

## 1. MICROMECHANICAL PROPERTIES - A SHOT NOISE MODEL

Löwe and van Herwijnen (2012) showed with a shot noise approach that some microstructural parameters of the snowpack can be be deduced from the analytical solution of a stochastic model. To this end the penetration force $F$ of the SMP cone can be interpreted as a Poisson shot noise process and can be simulated as such, giving a statistical but principally rigorous solution.
The following quantities are commonly derived from the SMP signal and are also computed as a first step in its user software *snowmicropyn* (via statistical moments of the dataset):
$f$ ... The rupture strength.
$\lambda$ ... Intensity of the Poisson point process.
$\delta$ ... The deflection at rupture. The entire one-point statistics of the penetration force $F$ solely depend on the product $\lambda * \delta$. Hence, to estimate both parameters a higher order correlation function is chosen: the force covariance. The simplest estimate for delta can be inferred from the slope of the correlation function at origin.
$L$ ... The element length. This is the average distance between neighboring elements. Since the (projected) area of the SMP $A$ is fixed the element size and intensity can be related by

$$\lambda = A/L^3 \quad (1)$$

This relation quantifies assumptions about the spatial distribution of snow grains when propagating the information from the one-dimensional force characteristics to the three-dimensional snowpack.
In short, first the non-central moments of the SMP force are estimated in a finite window. Second, an estimate of the cumulants can be obtained from their relation to the non-central moments. From these, $\lambda * \delta$ and $f$ can be calculated from combinations of the mean and variance, and finally $\delta$ through the covariance of the force signal.

## 2. MACRO PARAMETERS - REGRESSION

Relating stratigraphic parameters to physical properties of snow is a topic of ongoing research. However, the importance of density and grain size as fundamental characteristics of the snow samples become clear in many applications including numerical snowpack models. With these two morphometric measures, key properties such as thermal conductivity, dielectric permittivity or air permeability can be computed.
The underlying idea of the statistical model employed in the SMP's software is that repeated elastic increases of the force followed by small elastic deflections of length $\delta$ correspond to the SMP cone breaking through snow crystals separated by air gaps.
Ground truth measurements about density and specific surface area (SSA) were originally sampled by means of Micro-CT. Meanwhile however *snowmicropyn* offers a couple of parameterizations that were obtained by various methods for different SMP

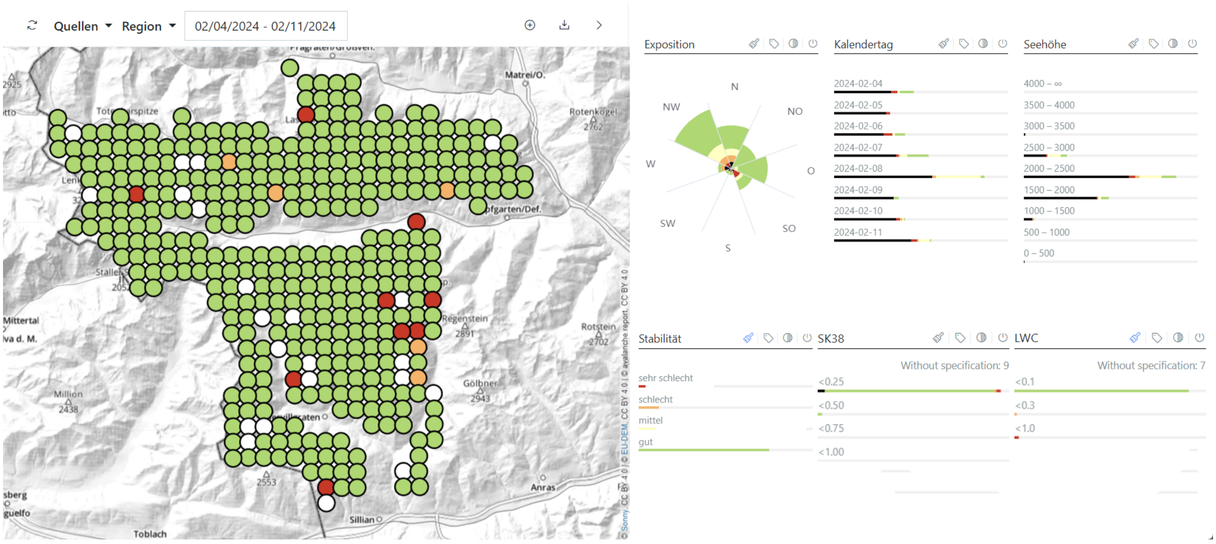


Figure 1: The main *AWSOME* dashboard. It can handle multiple spatial domains with different model configurations and different calculation modules enabled. Shown is the Tyrol domain with markers for SNOWPACK runs on gridded NWP data. In the future SMP measurements will be selectable as data source.

devices and climate settings. In any case SMP measurements were performed together with hand profiles at the observation sites to calibrate the density and SSA models with.

### 2.1 Density

The statistical model for the snow density has evolved to include more than just the (logarithm of) the penetration force. Which parameterization to use depends on the version of the SMP device and wide-scale snow conditions. Early successful attempts to estimate the density are of the bilinear form:

$$\rho = a_0 + a_1 * \ln(F) + a_2 * \ln(F) * L + a_3 * L \quad (2)$$

A couple of parameter sets for this model are provided in *snowmicropyn*.

### 2.2 Specific Surface Area (SSA)

The SMP length scale $L$ lends itself to start a regression on, and indeed already a direct comparison reveals a correlation to the length scales derived from independent measurements. To account for varying snow types (e. g. different densities in different climate settings) a linear regression for the SMP variables $L$ and $\ln(F)$ can be used which is what's implemented in *snowmicropyn*.

### 2.3 Hardness

The force needed for the SMP's cone to break up the crystal structure and drive through the snow is not the same as when measuring snow hardness via the hand hardness index where snow is being displaced horizontally. The hand hardness index (from "new snow" to "ice") is estimated with a power law fit through a graph connecting SMP to manual hand hardness index measurements using a few data points from a dedicated experiment by Pielmeier and van Herwijnen (2016).

### 2.4 Grain size

The grain size is indirectely proportional to the SSA, so we have this already.

## 3. SNOW GRAIN SHAPES - MACHINE LEARNING

Current theoretical efforts hope to find a fundamental model to connect an SMP measurement with the observed type of snow. Until such methods are successfull we try to simulate the model with standard machine learning techniques.
There have been numerous experiments employing various machine learning algorithms to SMP datasets, e. g. Satyawali et al. (2009) and Havens et al. (2013). Common to all of these studies is that they are tailored to the climate settings and prerequisites of the dataset. For example, King et al. (2020) excluded new snow particles - something we can not do in the Alps and for avalanche forecasting purposes.
*Snowmicropyn* allows the user to choose from a set of different machine learning routines together with minimalistic algorithms for data pre-processing and resampling. Since the micro-parameters derived by the shot noise model have a physical meaning they are used together with the force signal to fit a machine learning model to the data and predict the snow type, i. e. the grain shape. However, there

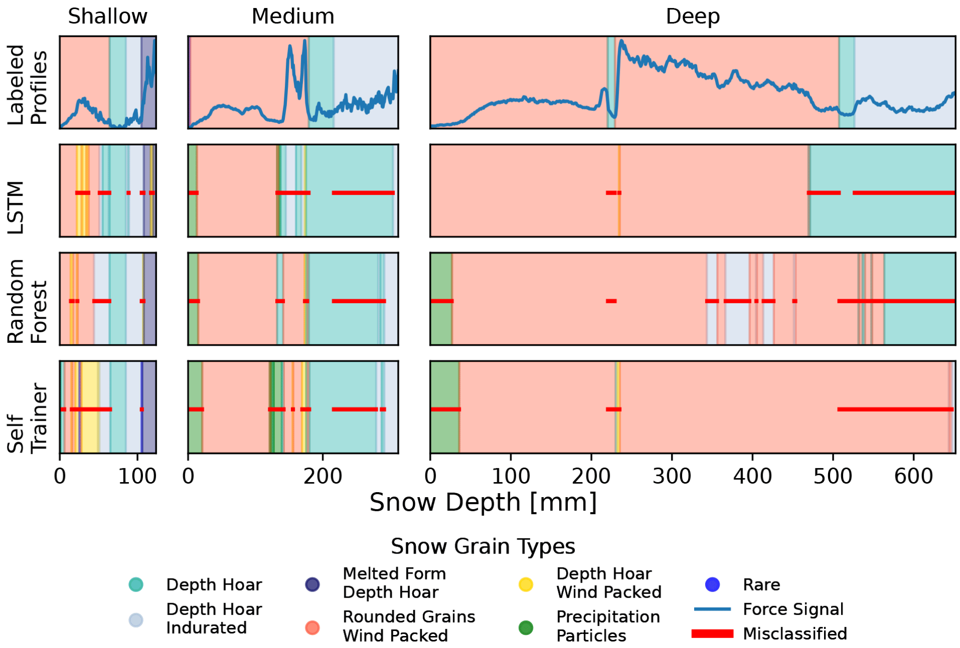


Figure 2: *Snowdragon* run for three randomly chosen SMP profiles of the MOSAiC dataset. Figure taken from Kaltenborn et al. (2023) - cf. therein for details.

exists another software package called *snowdragon* by Kaltenborn et al. (2023) which aims to handle this step transparently. *Snowdragon* was originally developed on the *MOSAiC* SMP dataset by Macfarlane et al. (2021) which is a collection of labelled SMP profiles on sea ice. Example output is shown in Figure 2. The involved parties are currently thriving to generalize this for use in arbitrary regions (Figure 3).

## 4. OPERATIONAL USE

A great benefit of having a "manual-like" profile at hand after performing SMP measurements is that certain snowpack models like SNOWPACK by Bartelt and Lehning (2002) can be started with this kind of information. It remains to be seen how quickly a snow model driven by SMP data will stabilize its own (probably different) microstructure parameters and produce reliable output in the form of macroscopical observables like the grain shape.

Apart from a whole range of practical challenges however the path is principally clear: we can take the SMP into the field and feed this data to a computer. *snowmicropyn* by SLF (2024) and *snowdragon* by Kaltenborn (2024) can then produce standardized CAAML output. This information together with meteorological weather forecast data assimilated by *AWSOME* can drive snowpack models to analyze and predict the snow stratigraphy for the observation site fully automatically.

## 5. THE AVALANCHE WARNING SERVICE OPERATIONAL METEO ENVIRONMENT (*AWSOME*)

The *AWSOME* framework by the AWSOME Core Team (2024) is an open source software distribution for snow cover modeling in the context of operational warning services as well as a simulation tool for theoretical research. It features a fully unsupervized operational toolchain for daily warning work. As such it provides numerous ways to drive snow stratigraphy forecasts. One of them is to initialize the respective toolchain with a manually observed snow pit profile, run a snowpack model on it and project the stratigraphy into the future via numerical weather prediction (NWP) data to get a forecast, see Binder and Mitterer (2023). The various toolchains' outputs are plotted on a map, shown in Figure 1.
In the scientific context *AWSOME* can be viewed as a framework providing all kinds of data and tools at hand. The immense burdon of setting up a research platform running some models is lifted from the scientist who is getting started with a research project. Finally, *AWSOME* also caters to all kinds of professionals working in a winter environment (Figures A.4 and A.7).
This comes in handy for the SMP toolchain: Now that we have estimated the grain shapes we still lack some mandatory temperature values to drive SNOWPACK with[1].

[1] The operator could record them on site, but then measuring air- and snow-temperatures again makes this a bit of a process. The SMP could measure the snow temperatures in its tip, but technically this proves to be extremely challenging. There could

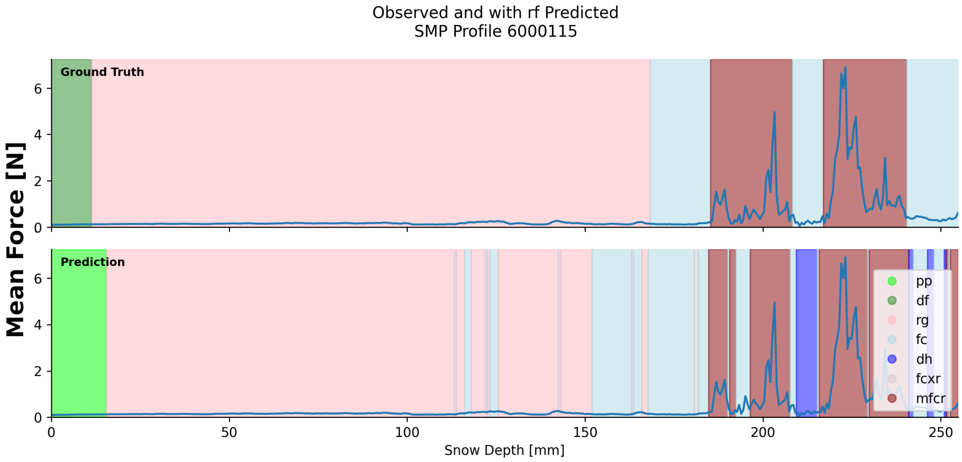


Figure 3: *Snowdragon* run for an alpine profile in Tyrol. The blue line is the (smoothed) SMP force signal.

*AWSOME* runs its own instance of the state of the art open source numerical weather prediction model WRF, see Skamarock et al. (2008). It has the Noah-MP land surface model enabled. The description reads: "Noah-MP contains a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze, and sublimation of the canopy-intercepted snow." Hence, over our experiment site we get a plethora of modeled weather and snow parameters, such as the needed air-, snow surface-, snow layer-, and soil-temperatures. *AWSOME* will also look for close-by weather stations and manual snow pit observataions measuring the snow surface temperature and extract it from there if available.

As a consequence, given the idea outlined above is to prepare SMP profiles to match hand profiles, once we have done our conversion we can use the same model setup as for the observed profiles and their visualizations. *AWSOME*'s automated analysis about avalanche problems (lower part of Figure A.6a) and various stability index distribution calculations can also run on top of it just the same.

The simplified setup is as follows: Manually observed profiles are downloaded from an online observations platform, and SMP measurements are uploaded via a dedicated web interface (Figure A.5a). Both data sources are pre-processed to provide a CAAML file that is suitable to start SNOWPACK with. A general purpose SNOWPACK engine will first perform the nowcast and then attach a forecast by fetching appropriate NWP data. Various analysis tools for avalanche hazard estimation are applied to the calculations (e. g. SK38 and other stability indices). Output is then passed to the dashboard via a geojson file which defines the types of plots and data filters to show and also includes meta data like the location and marker type, cf. Figure 1. Please refer to Appendix A for a few screenshots of *AWSOME* in the context of research and SMP probing. The main toolchains targeting snowpack modeling for avalanche forecasters are not part of this paper, for an overview consider Herla et al. (2024a), Perfler et al. (2023), Binder et al. (2024), and Herla et al. (2024b).

### *5.1 OUTLOOK*

Our operational toolchain to take a snow pit profile and produce snow stratigraphy forecasts with it has already been in operation throughout a winter season. Hence, once we can produce meaningful profiles from SMP measurements the processing and postprocessing of it is ready. The SnowMicroPen's software *snowmicropyn* has received some work by the authors lately and provides a rudimentary machine learning interface to achieve all that. However, recent efforts focused on integrating a revised *snowdragon* version for this task. In order to operate in the Alps we also simply need more data from our forecasting regions. Hence, we have all the pieces and for the upcoming season they just need to fall into place. *AWSOME* as a whole is currently also under very rapid development. Hopefully starting snowfall we will be ready to gather data, use the SMP operationally, and start validations.

## 6. SUMMARY

An SMP measurement is quick and objective, and *AWSOME* can collect the necessary snowpack properties needed to drive operational forecasting tools (with varying complexity and trustworthiness of the estimated parameters). The authors are involved in development on all the needed software

be an auxiliary probe doing this job, but we don't have that (yet). *AWSOME* provides a web service to handle all these scenarios, but it can also utilize its strength and provide the missing data fully automatically.

products, namely *AWSOME*, *snowmicropyn* and *snowdragon*.


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Thanks to Christoph Mitterer and the whole Avalanche Warning Service Tyrol for putting together a team to develop these operational toolchains, Henning Löwe and Matthias Jaggi for projects and discussions around their SMP, Julia Kaltenborn and Jil Lehnert for their work on *snowdragon*, and the whole open source ecosystem and the *AWSOME* team especially, namely including Florian Herla, Michael Binder, and Norbert Lanzanasto, for contributions to the community.


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SLF: Snowmicropyn: A Python package to read, export and post process data (*.pnt files) recorded by SnowMicroPen, URL https://github.com/slf-dot-ch/snowmicropyn, 2024.


## Appendix A SCREENSHOTS OF *AWSOME* AND DIFFERNENT STAGES OF THE SMP STRATIGRAPHY FORECAST TOOLCHAIN

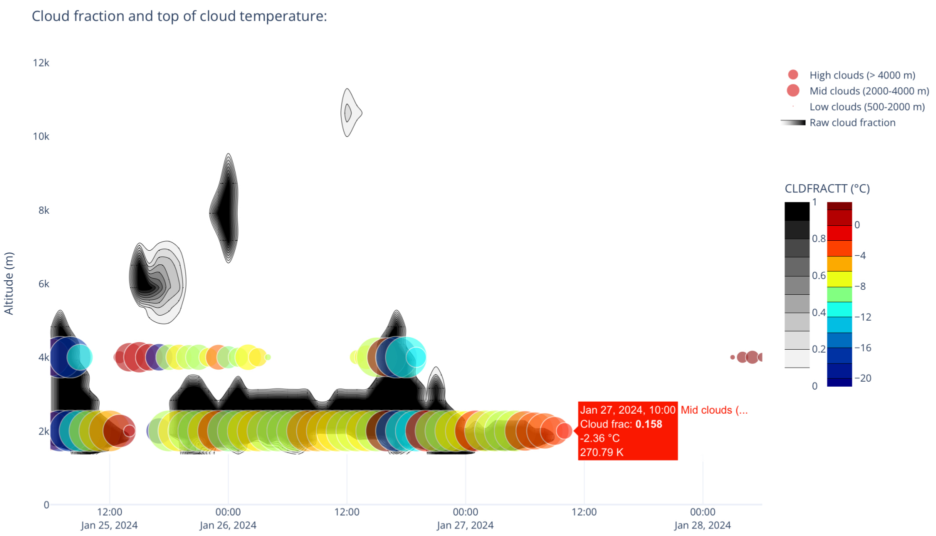
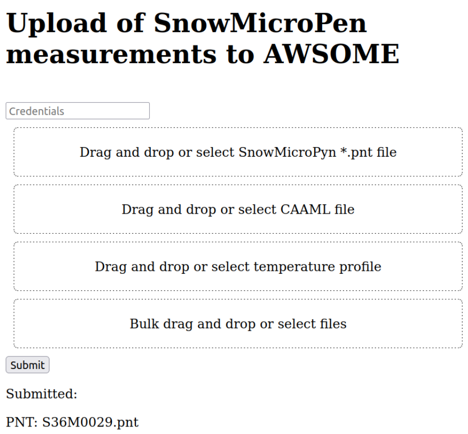
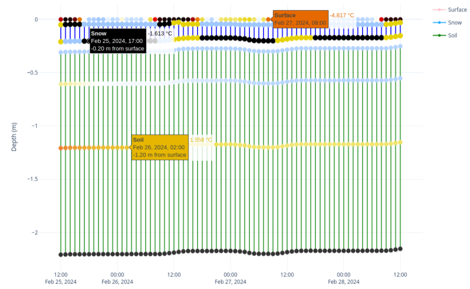



Figure A.4: Example of an *AWSOME* meteogram showing top of cloud temperatures which could be of interest for a snow scientist or meteorologist researching or estimating snow formation in the atmosphere.

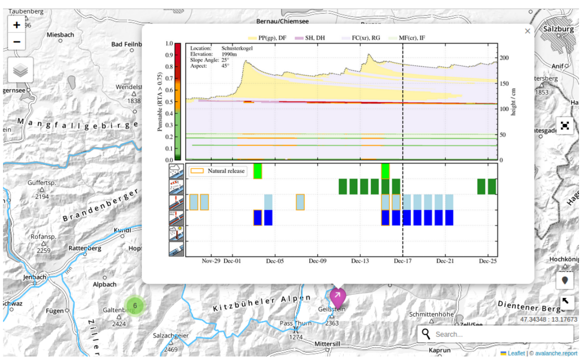



(a) Upload form for batch raw SMP file processing.

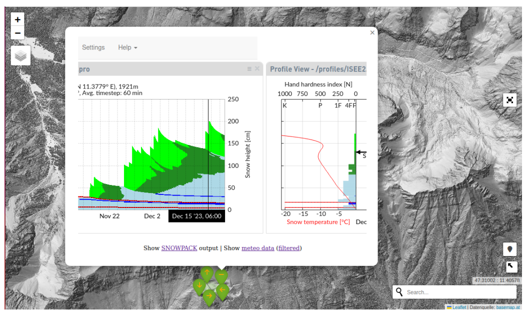


(b) Concept plot for *AWSOME* extracting snow layer, surface, and soil temperatures at an arbitrary given location.

Figure A.5: Two steps of the SMP toolchain: (a) Upload form for SMP profiles (plus additional measurements if available) provided by a Python web application. (b) Visualization of soil, snow, and surface temperatures as they will be assimilated into the recorded SMP profile's CAAML output.

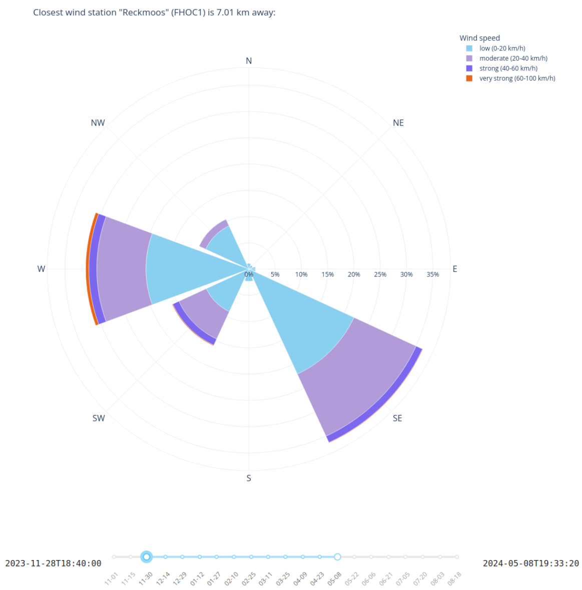


(a) Snowpack stratigraphy forecasts based on snow pit profiles.

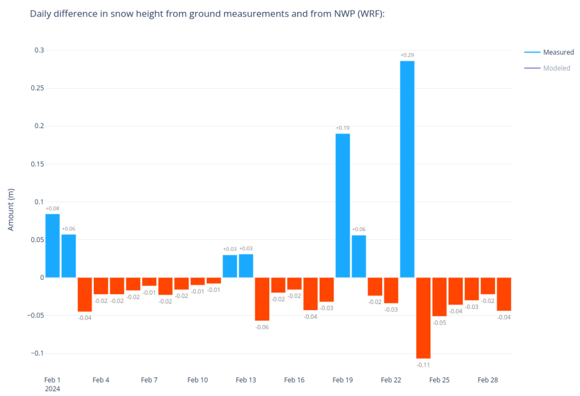


(b) Snowpack nowcast based on ground measurements by automated weather stations.

Figure A.6: *AWSOME* provides numerous toolchains for snow stratigraphy estimations. Two are shown here: (a) SNOWPACK is initialized with a manually observed snow pit profile and calculated into the future by using NWP data. (b) SNOWPACK nowcast based on ground measurements by automated weather stations. For gridded simulations and stability index maps see e. g. Herla et al. (2024a).




(a) Wind compass rose as an example for *AWSOME* finding the closest usable weather station and fetching its data.




(b) Measured and modeled (not shown) daily differences in snow height.

Figure A.7: Sample plots for *AWSOME* for practitioners and field work: (a) A compass rose showing the frequency distribution of wind strength and direction. (b) Daily differences in snow height as measured and modeled. Both plots are fully interactive in their online versions.