SAFE - A LAYER-BASED AVALANCHE FORECAST EDITOR FOR BETTER INTEGRATION OF MODEL PREDICTIONS

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ABSTRACT: Machine learning (ML) models are revolutionizing avalanche forecasting, providing increasingly reliable predictions. At present, however, such model output can hardly be integrated into the traditional operational forecast workflow. To close this gap, the Swiss Avalanche Warning Service has developed the Snow Avalanche Forecast Editor (SAFE), allowing a flexible integration of both human forecasts and model predictions. In SAFE, each hazard source (e.g., an avalanche problem) is assessed and described as a separate layer. This allows an entirely independent characterization of the severity of avalanche problems including their spatial extent, in line with the European Avalanche Warning Services standards. Once the assessment has been completed, all existing layers are automatically combined and published as regional avalanche forecasts. Forecast accuracy can be increased by minimizing noise. Decision theory advises to calculate an expected value from multiple independent assessments. For this reason, each of the two or three forecasters on duty assesses the regional avalanche danger in the forecast domain independently of each other. Another estimate comes from the danger-level model. To combine these, forecasters and models must assess the same hazard source using the same target variable. SAFE merges these independent assessments to expected values of the danger level including sub-levels, and the particularly affected elevations and aspects. This includes clustering into a limited number of danger regions, characterized by similar expected avalanche conditions. Following the discussion between forecasters, clusters can be refined. Lastly, the avalanche danger of each cluster is manually described. SAFE is conceived as open-source platform and a first version has been operational within the Swiss avalanche warning since winter 2023/24.

KEYWORDS: Avalanche Forecast, Bulletin Editor, Numerical Models, Decision Support, Hazard Assessment

1. INTRODUCTION

Traditionally, public avalanche forecasts have relied on professional forecasters analyzing and interpreting data sources such as measurements, observations, weather, and - in some cases, snow-cover models (e.g., Morin et al., 2019). More recently, the coupling of snow-cover models with statistical or machine learning (ML) models has made snow-cover simulations more accessible to avalanche forecasters by extracting and predicting parameters relevant to the forecasting process. These models provide predictions of parameters like potential snow-cover instability (e.g., Mayer et al., 2022), the likelihood of natural avalanches (Viallon-Galinier et al., 2022; Hendrick et al., 2023; Mayer et al., 2023), or the presence of specific avalanche problems (e.g., Reuter et al., 2022). They also allow clustering of spatially distributed snow-cover simulations (e.g. Herla et al., 2021) or the predictions of danger levels (Fromm and Schönberger, 2022; Pérez-Guillén et al., 2022; Maissen et al., 2024), including sub-levels - as used in the Swiss avalanche forecast (e.g., Techel et al., 2022, Peréz-Guillén et al., 2024). Increasingly, these models become available to avalanche forecasters in operational use, for instance in Canada (Horton et al., 2023), France (Morin et al., 2019), or Switzerland (van Herwijnen et al., 2023). However, optimally integrating them into the daily forecasting process is challenging and not yet defined.

Expanding on the approach of Maissen et al. (2024), we developed and tested a model pipeline providing regional predictions for the danger level, sub-level, as well as aspects and elevations, where the danger level applies. This pipeline is described in Section 4. The predictions from this pipeline agreed well with the published forecast for the winter of 2023/24 (Section 4.5). Given the reliability of the model predictions, which are expected to increase even further in the coming years, it's time to move beyond visualizing these models as supplementary information and to start integrating them directly into the forecasting process in the form of a '*virtual forecaster*'. However, until now, no software known to us for creating avalanche forecasts permit the integration of model predictions. With a possible (semi-)automated integration of model predictions in mind, we have therefore developed the Snow Avalanche Forecast Editor (SAFE). The most important requirements were:

- **Consistent Integration:** Ensure that model predictions can be seamlessly and uniformly incorporated into the forecasting process.

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- **Adaptive Framework:** Maintain a flexible structure to allow responding to advancements in model developments.
- **EAWS[1] Workflow Compliance:** Implement forecasting workflow in line with EAWS standards (EAWS, 2024b).

2. PUBLIC AVALANCHE WARNING IN SWITZERLAND

2.1 Avalanche Forecast

In Switzerland, the forecasting domain is split into 149 *micro regions*. When preparing a forecast, these micro regions are flexibly aggregated to *danger regions*, which reflect regional patterns of expected avalanche conditions (Fig. 1). For each of these regions, avalanche danger is characterized by a danger level, sub-level, critical elevation and aspects, and one or more avalanche problems (SLF, 2023). In addition, avalanche danger is described using sentences from a predefined catalogue of phrases. If the chance of wet-snow avalanches increases during the course of the day, two separate danger maps are created for the morning and the afternoon.

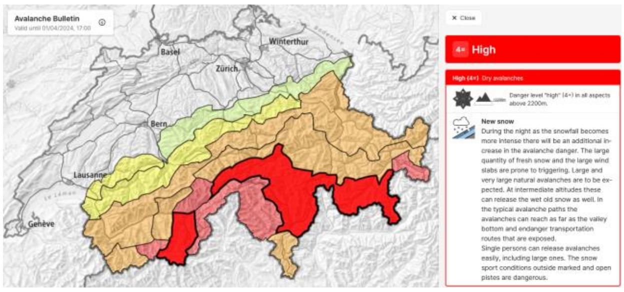

Figure 1: Swiss avalanche forecast with selected danger region. Example shows forecast for 1 April 2024.

2.2 Snow-cover and machine-learning models

In 2024, snow-cover simulations were available at the location of 142 automated weather stations (AWS) in the Swiss Alps. At these locations, the snow cover is calculated with SNOWPACK, using measurements up to the current time, and driven with downscaled data from numerical weather prediction models for the following 27 hours (Mott et al., 2023). ML models calculate various avalanche-relevant parameters from these snow-cover simulations and weather parameters (Fig. 2). The calculations are not only carried out for the flat fields of the stations, but also for four virtual slopes (N, E, S, W) inclined 38°. Currently, three models relating to dry avalanches are operationally available to avalanche forecasters: the *danger-level model* (Pérez-Guillén et al., 2022),

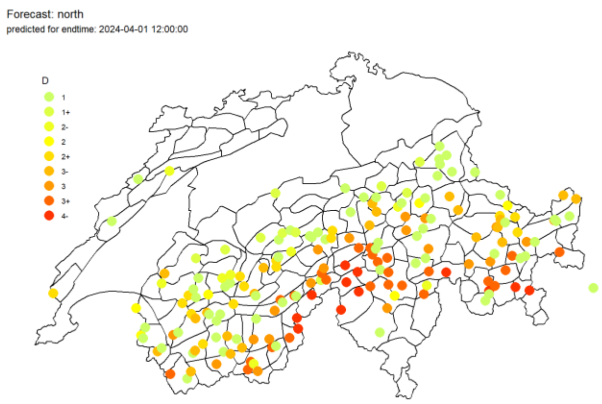

Figure 2: Danger level (sub-level) predictions, as obtained with the danger-level model at the location of the AWS for the following day. The example shows the predictions for North aspects for 1 April 2024

the *instability model* (Mayer et al., 2022), and the *natural-avalanche model* (Mayer et al., 2023).

3. SAFE - THE CONCEPT

SAFE offers all functions required for creating and publishing public avalanche forecasts. These include:

- Each forecaster on duty can create his/her individual forecast draft (*suggestion*) for the entire forecasting domain, independent of their colleague's drafts.
- Each hazard source (i.e., an avalanche problem) can be assessed and described as a separate *layer* (Fig. 3). This allows an independent assessment of the severity and spatial extent of each hazard source across multiple micro regions, ensuring alignment with EAWS standards (EAWS, 2024b).
- Each layer can be described using a catalogue of predefined, flexible sentences, including a fully automated translation (Winkler et al., 2017).
- Model predictions – providing parts of the forecast – can directly be integrated as suggestion (Section 4).
- All suggestions can be automatically combined, providing the most likely value for the forecast (Section 5), which serves as the starting point for the subsequent forecaster discussion.
- After defining consolidated versions for each layer, layers are automatically merged and published as avalanche forecasts.
- Further functions as the triggering of push notifications or the option to enter free text.
- Forecasts are produced in European CAAML V6 format.

[1] EAWS: European Avalanche Warning Services

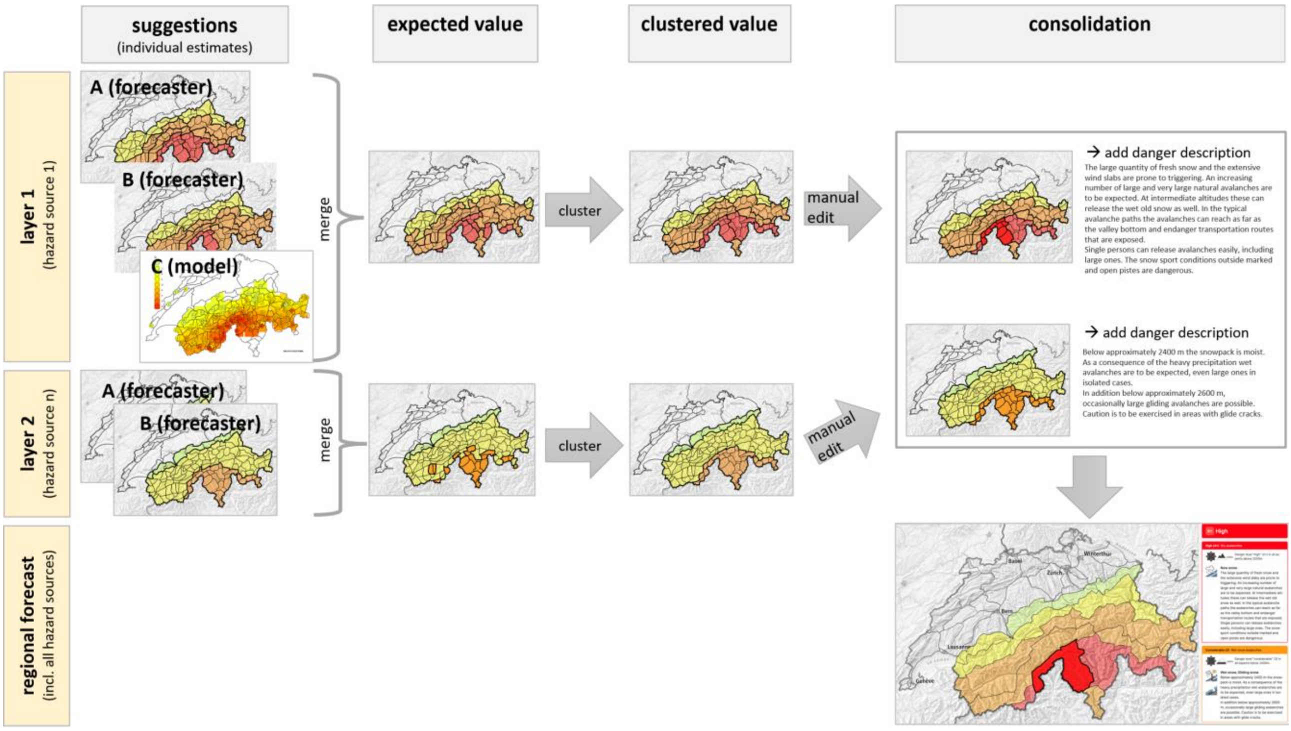

Figure 3: Scheme of SAFE

4. VIRTUAL FORECASTER

The *virtual forecaster* is an additional module, currently located outside of SAFE. It integrates the outputs of machine-learning models (currently only the danger-level model, see Section 7). Model predictions and suggestions of avalanche forecasters can only be combined if they assess the same target variable in the same format and resolution as the suggestions of the avalanche forecasters. This is done in four steps:

4.1 Time resolution and forecast time

As long as the avalanche forecasters create the avalanche forecast (or at least parts of it) manually, the spatial and temporal resolution of the forecast is severely limited. In the setup of the Swiss avalanche forecast, this limits the forecast to two editions per day (8 am and 5 pm). According to the interpretation aid for the avalanche bulletin (SLF, 2023), the avalanche situation is estimated for the forenoon. We therefore use the model predictions for 9 UTC, which corresponds to 10 am (standard time) or 11 am (summertime). In addition, in case of higher avalanche danger and a strong decrease in avalanche danger during the night, the situation at 21 UTC is used for the 5 pm edition.

4.2 Spatial interpolation and zonal statistics

The danger-level model predictions (Fig. 2) for the AWS stations are spatially interpolated for each of the four virtual slopes individually for the entire territory of Switzerland (Fig. 4). This spatial interpolation is conducted using the kriging function from the *GSTools* package (Müller et al., 2022), with a digital elevation model (DEM) at a 1 km resolution incorporated as an external drift. The model is a super-spherical covariance model, with its parameters fitted explicitly to the data for each interpolation. Additionally, we log transform the stations elevations and the DEM and clip them to a maximal elevation of 2600 m a.s.l. to prevent unrealistically high danger levels in the high alpine regions.

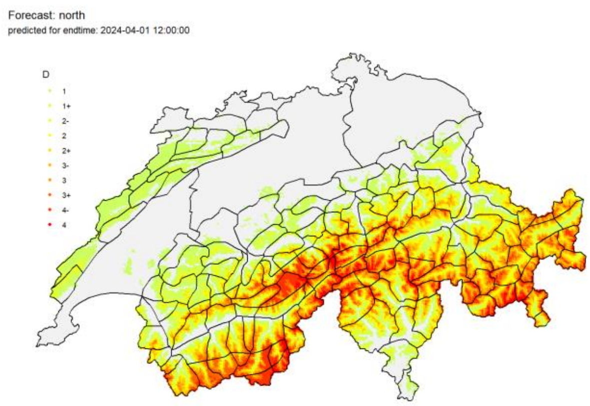

Figure 4: Spatially continuous interpolated avalanche danger (sub-levels). The example shows the predictions for North aspects for 1 Apr 2024 (image of the test system in winter 2023/24).

Subsequently, we apply elevation-band masks to the interpolated grid and compute the median value for each micro region within each elevation band (Fig. 5a). This computation is carried out using the zonal statistics functionality of the *rasterstats* Python package (Perry, 2013).

To exclude micro regions with no significant avalanche danger, we assess the maximum snow height per micro region using the snow depth map from the previous day (provided by SLF) and exclude all regions where the maximum snow height is less than 50 cm.

4.3 Avalanche danger per micro region

In addition to the four aspects (N, E, S, W), the values for the four intermediate aspects (NE, SE, SW, NW) are obtained using the mean of the respective neighboring elevation bands (i.e., mean of N and E for NE; Fig. 5b). Subsequently, the continuous danger-level predictions are converted into danger levels and sub-levels (Fig. 5c).

4.4 Danger level, critical elevation and aspects

The avalanche danger is reduced to the format in which the forecasters make their assessment (Fig. 5d):

- Danger level and sub-level: the highest value
- Critical elevation: the lowest altitude at which the maximum danger level is reached. The sub-level is not considered. Thus, e.g. for danger level 3+, the transition from level 2 to 3 is indicated (and not the transition from 3= to 3+).
- Particularly affected aspects: all aspects at which the maximum danger level is reached, also without taking the sub-level into account.

4.5 Agreement between model prediction and human forecast

Last winter, the virtual forecaster was only available as a test version and was not yet integrated into SAFE. We compared all model predictions from the danger-level model with the public avalanche forecast for all micro regions for which both estimates were available, from 1 Nov 2023 to 30 Apr 2024. The deviation between human forecast and model-predicted sub-level was within one sub-level in 88% of cases. This is undoubtedly a good value, even if it is lower than the 95% for which the forecasts of two avalanche forecasters differ by a maximum of one intermediate level (Techel et al, 2024b).

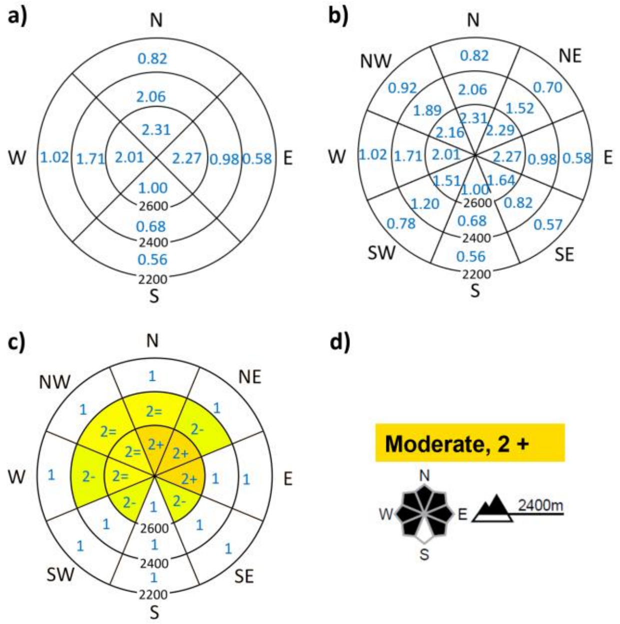

Figure 5: For each micro region, first a) the continuous danger per aspect and elevation band is calculated, then b) these predictions are interpolated to in-between aspects, and c) converted into danger levels and sub-levels. From these grids, d) the danger level incl. sub-level and core zone are determined. In the effective calculation, there are more elevation bands than shown in this example.

5. CONSOLIDATION

Forecast errors can be divided into a systematic error (bias) and a random error (noise), whereby the noise is often greater than the bias (e.g., Kahneman, 2021). To reduce noise, in Switzerland each of the two or three avalanche forecasters on duty makes their independent assessment (*suggestion*). According to decision theory, the mean of all suggestions forms the most probable value. To calculate the mean value, we assign the corresponding numerical value to each danger level. To accommodate the sub-level concept, we subtract 0.33 for sub-level minus (i.e., 3- → 2.67) and add 0.33 for sub-level plus (i.e., 3+ → 3.33). Outside the specified elevations and aspects, the danger is assumed to be 1 level lower ('one-level rule', e.g., SLF, 2023, Winkler et al., 2021). Further contents of the consolidation, which are currently only estimated by avalanche forecasters, are the three factors determining avalanche danger (stability, frequency, avalanche size) and the avalanche problems. The classes and sub-classes characterizing these factors are also assigned numbers representing the underlying rank-order, and mean values are calculated. For the avalanche problem, the majority opinion is used. In principle, all suggestions are weighted equally, but individual suggestions can be excluded, e.g., for an avalanche forecaster in training or when model predictions are considered to be wrong, for example, because it rained all the way up to the AWS.

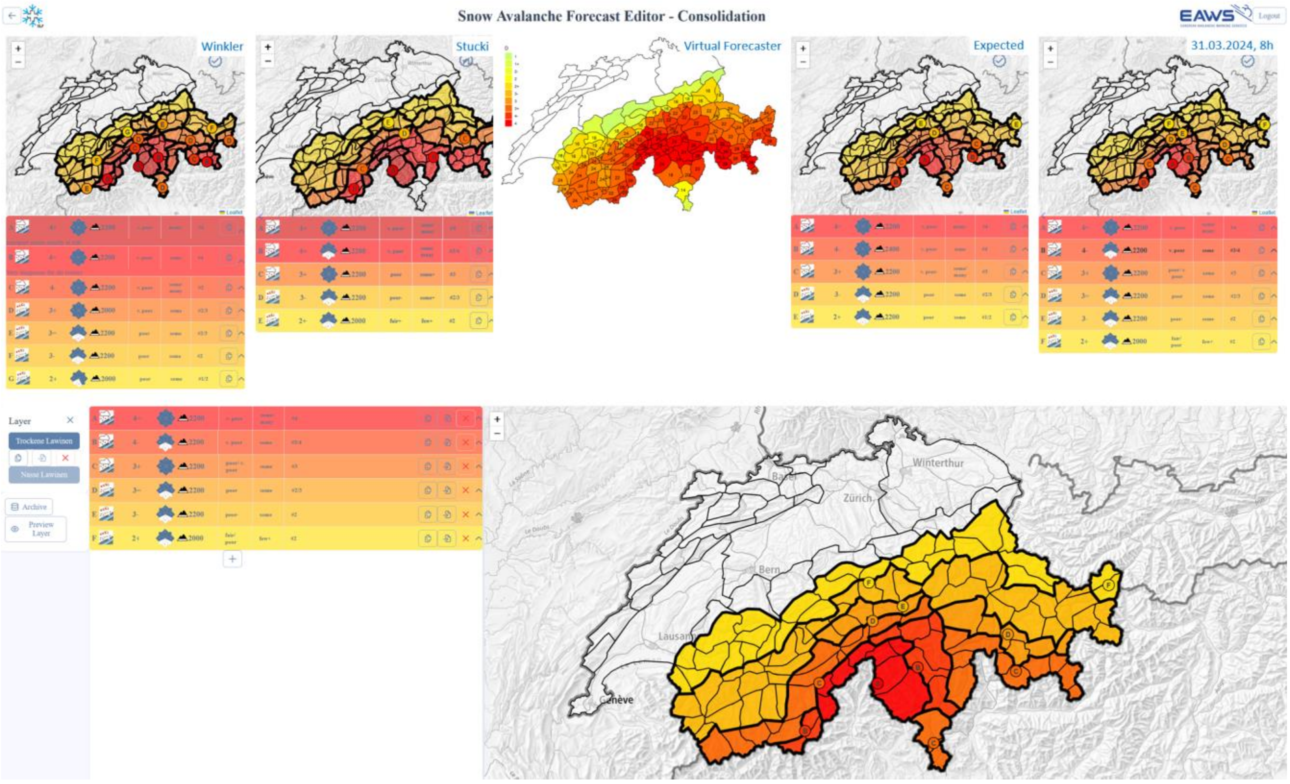

Figure 6: Scheme of the SAFE consolidation page. The upper row shows the various *suggestions* (here: Forecaster 1, Forecaster 2, Virtual Forecaster), the expected value and the currently published avalanche forecast (especially useful for updates in the morning). Any one of these can be imported into the lower area, becoming the consolidation to be finally edited. The virtual forecaster provides the same attributes as the other forecasts, but sometimes many different danger regions. Therefore, its overview page (Middle of the upper row) does not show any danger regions. Instead, the critical elevation is written directly into the corresponding micro region.

Averaging multiple suggestions with numerous parameters frequently leads to differences in at least one parameter between neighboring micro regions. However, since avalanche forecasters can manage a maximum of about ten danger regions, these micro regions must be combined into larger danger regions that capture the most significant spatial patterns. Therefore, a clustering routine is currently being implemented and will be available in winter 2024/25.

The resulting aggregated average forecast is the starting point for the subsequent forecaster discussion, but individual suggestions are also visualized in SAFE (Fig. 6). During deliberation, avalanche forecasters may deliberately deviate from the mean value in justified cases, creating the *consolidation*. This process is repeated for all hazard sources.

Once a consolidated forecast has been determined, avalanche forecasters describe the danger using the catalogue of phrases.

6. SAFE – THE CODE

The code base was designed to create public avalanche forecasts with maximum flexibility. A configuration file allows the specification of parameters to be estimated for each layer. Additionally, micro regions from other areas can be integrated into SAFE via GeoJSON. The various components of SAFE are shown in Fig. 7.

The frontend of the SAFE system includes the *Editor* and *Textcat*. The *Editor*, written in JavaScript using the Vue.js framework, serves as the primary interface for entering forecasts, allowing multiple avalanche forecasters to collaborate on the same forecast, enhancing collaboration and efficiency. *Textcat*, also written in JavaScript, is a web application designed to translate danger descriptions into multiple languages, enhancing accessibility for users from different linguistic backgrounds.

The backend of SAFE consists of the components *Amaretto*, *Mixer*, *Advisor*, and *Waiter*, implemented in either Java, JavaScript or Python. *Amaretto* serves as the backend for the *Editor*, storing forecast data inside a Postgres database and interacting with the *Mixer* to generate bulletins. The *Mixer* combines all

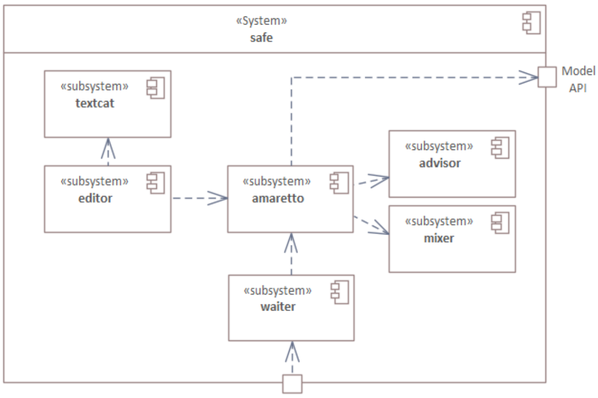

Figure 7: The components of SAFE

estimated layers to produce the final avalanche bulletin. The *Advisor* processes the *suggestions* (including the virtual forecaster) to calculate expected values and cluster them into a manageable amount of danger regions for forecasters (Section 5). Finally, the *Waiter* provides a public interface, outputting the avalanche bulletin in CAAMLv6 format or as GeoJSON, enabling interoperability with other systems.

SAFE is open source and available on https://gitlab-ext.wsl.ch/safe

7. OPERATIONAL USE IN THE SWISS AVALANCHE FORECAST

SAFE can handle any number of layers, but we, the Swiss avalanche forecasters, cannot. We have therefore decided, to start with just two layers in winter 2023/24. These were: '*dry avalanches*' (combining the avalanche problems *new snow*, *drifting snow,* and *old snow*, and '*wet avalanches*' (combining the avalanche problems *wet snow* and *gliding snow*). The separate description of the different layers was initially somewhat tricky for the avalanche forecasters to get used to. However, with only two layers, the workflow was easy to manage.

The most important parameter in avalanche forecasting is the danger level, both according to the information pyramid (EAWS, 2024a) and in risk calculations for ski tours (Degraeuwe et al., 2024). Therefore, in a first step, we only use the danger-level model, which is the only available model providing the danger level, related to dry snow avalanche conditions. The wet snow layer is assessed separately, currently without automated integration of a model.

SAFE has already performed well in its first winter. It proved to be efficient and stable. The combination of gliding snow and wet avalanches into a single layer posed challenges during the particularly significant gliding snow conditions of the 2023/24 winter. In this case, a separation of these two types of avalanches into distinct layers would likely be beneficial.

8. OUTLOOK

SAFE can be operated with or without models and can handle any number of layers and *suggestions*. This means it can keep up with further developments in avalanche forecasting - until one day forecasting is completely taken over by models.

The division of *wet* and *gliding snow* and the use of a separate *old snow* layer seems interesting. In terms of content, however, such divisions are complex in some cases. For example, how can *old snow* and *new snow* be described separately on a day when the increase in new snow increasingly leads to avalanche releases in the old snow? That is why additional layers should first be thoroughly tested. Other possibilities are the introduction of a *forecasters comment* and a separate layer to describe the snow cover.

More layers, and especially more layers with a danger level, inevitably mean more complexity when compiling the end product as aggregation results in more and smaller danger regions and as the complexity within a danger region also increases with the number of layers. The danger levels assigned to the currently used layers - dry and wet avalanches - are communicated separately. A survey in the field showed that such information can be processed by most forecast consumers. If the dry or wet avalanche danger were further divided into several avalanche problems, these would be assessed individually, but ultimately an aggregated danger level would probably be communicated as not to overwhelm users.

Techel et al. (2024a) show that other models used at SLF – namely the *instability model* and the *natural-avalanche model*, can reliably predict snowpack instability or spontaneous avalanche activity, at a level comparable to human forecasters. Even though further work is needed to make these model predictions compatible with human forecasts, the structure of SAFE permits the (stepwise) integration of such models.

9. CONCLUSIONS

The SLF developed the new Snow Avalanche Forecast Editor (SAFE), allowing a flexible integration of both human estimates and model predictions. Each hazard source (e.g., an avalanche problem) is assessed and described as a separate layer, which allows an independent assessment of avalanche problems by their spatial extent and characteristics. Moreover, SAFE accommodates recent advances in model development allowing the seamless integration of models in the forecast process. To achieve this, model predictions are transformed to the same format and spatial and temporal resolution as the forecasts by human forecasters.

Finally, SAFE applies the principle from decision theory that accuracy improves when independent forecasts, generated by competent forecasters, are combined. Here, this involves merging predictions from both human forecasters and the danger-level model to generate an expected value for the danger level, including sub-levels and the most affected elevations and aspects.

SAFE is conceived as an open-source platform. A first version has been successfully used within the Swiss avalanche warning since winter 2023/24.

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