# APPLICATION OF PHYSICAL SNOWPACK MODELS IN SUPPORT OF OPERATIONAL AVALANCHE HAZARD FORECASTING: A STATUS REPORT ON CURRENT IMPLEMENTATIONS AND PROSPECTS FOR THE FUTURE

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ABSTRACT: The application of physically-based numerical modeling of the snowpack in support of avalanche hazard prediction is increasing. Modeling, in complement to direct observations and weather forecasting, provides information otherwise unavailable on the present and future state of the snowpack and its mechanical stability. However, there is a significant mismatch between the capabilities of modeling tools developed by research organizations and implemented by some operational services, and the actual operational use of those by avalanche forecasters, thereby causing frustration on both sides. By summarizing currently implemented modeling tools specifically designed for avalanche forecasting, we intend to diminish and contribute to bridge this gap. We highlight specific features and potential added value, as well as challenges preventing a more widespread use of these modeling tools. Lessons learned from currently used methods are explored and provided, as well as prospects for the future, including a list of the most critical issues to be addressed.

KEYWORDS: avalanche forecast, numerical modeling, snowpack modeling, meteorological forecast

## 1. INTRODUCTION

Avalanche hazard forecasting requires information about the past, current and future state of the snowpack, including the vertical profile of its key microstructural and mechanical properties (density, temperature and liquid water content, snow type, shear and penetration resistance, etc.) for as many as possible avalanche-prone slopes within the region addressed by the avalanche bulletin. Despite the significant spatial variability of snow conditions and the potential non-representativeness of point observations, avalanche forecasters have traditionally focused on field observations of snow conditions. These are based on automated observation networks (often only addressing meteorological conditions and basic snow properties such as snow depth) and field reports from registered observers at established observation stations, outing reports on mountaineering and ski-touring community websites and their own observations. The extrapolation in space (for locations not covered by observations) and time (future snow conditions one or two days ahead) is typically based on the forecaster's ability to assimilate the broad diversity of snow and meteorological observations and forecasts, together with knowledge relevant to snow evolution processes. Because of the complexity of the many interrelated processes involved in post-depositional snow processes (most notably wind-driven redistribution of snow and snow metamorphism) and their connection to the spatially variable meteorological conditions, physically-based snowpack modeling has been developed since the 1980s. They were initially designed to provide avalanche forecasters with information complementary to field observations and meteorological forecasts (either as text bulletins for meteorological forecasters or output of numerical weather prediction models). Snowpack model-

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ing driven by observed or forecast meteorological conditions was primarily designed to assist them in their operational duties, namely the production of regular avalanche hazard assessments and bulletins throughout the course of the winter season.

Several physically-based snowpack models initially dedicated to avalanche forecasting purposes have been developed for the last decades, such as Crocus originally in France (Brun et al., 1989, 1992, Vionnet et al., 2012, Lafaysse et al., 2013) and SNOWPACK originally in Switzerland (Lehning et al., 1999, Bartelt and Lehning 2002, Lehning et al., 2002a, 2002b). The physical principles upon which they are based are rather close. They however differ in the way they have been implemented for operational activities in their host and collaborating organizations, in terms of nature and use of meteorological driving data (e.g. balance between point-scale meteorological observations and output of numerical weather prediction models). Additionally, substantial differences emerged with post-processing of model output for operational avalanche forecastering.

In recent years, it has become apparent that an increased number of avalanche forecasting services are considering using physically-based snowpack models in support of their operational activities (Vikhamar-Schuler et al., 2001, Floyer et al., 2016). However, there has been no comprehensive assessment on the successes and lessons learned regarding the use of such models for operational applications. Indeed, scientific publications tend to focus on the description of newly developed model chains, and mostly address quantitative assessments of their predictive performances against meteorological or snow observations, and not necessarily regarding their added-value for avalanche forecasting itself. Conceptual or statistically-based avalanche forecasting models (e.g. Buser et al., 1989) were developed either independently or complementary to physically-based snowpack models. However, their description and critical assessment in operational context is beyond the scope of this article, which addresses physically-based approaches only.

The present article initiates a conversation, hopefully contributing to bridging the gap between the research community, which has devoted significant efforts to the development of snowpack modeling chains and proposed visualization of their raw or post-processed output data, and operational avalanche forecasting centers, which have gathered experience and expressed challenges about the use of such models. It aims at providing a synthesis of the current and future status of snowpack modeling in support of operational avalanche forecasting, which may provide a platform for informing future discussions and decisions in this area.

## 2. ONE-DIMENSIONAL PHYSICALLY-BASED SNOWPACK MODELS USED OPERATIONALLY

Snow on the ground evolves constantly due to exchange processes at its boundary with the overlying atmosphere and underlying ground, and under the action of internal transformation processes referred to as snow metamorphism (Armstrong and Brun, 2008). Interfacial energy and mass balance and internal processes are strongly coupled. Seasonal snow on the ground can remain there for several months, so that its state at a point in time may depend on the seasonal history of meteorological conditions and their interaction with snow processes.

To adequately represent the main energy and mass fluxes at the snowpack interfaces in a numerical model (assuming planar layering geometry) requires several physical ingredients such as those able to capture the variations of snow density and albedo, and account for the internal energy storage associated with phase change processes in snow. Given the significant vertical variations of physical snow properties in most observed snowpacks, and the space-time coupling of snow processes such as heat conduction driven by diurnally variable atmospheric boundary conditions, a multi-layer approach is generally considered necessary to represent snow in a physically-based numerical model (e.g., Armstrong and Brun, 2008).

Furthermore, the mechanical stability of the snowpack depends strongly depends on snow stratigraphy, and in particular the existence of weak layers within the snowpack (e.g. Schweizer et al., 2003). Using a physically-based snowpack model for avalanche hazard forecasting thus requires that it can appropriately handle the most significant processes responsible for the formation of such weak layers and that their mechanical stability can correctly be described.

Lateral snow redistribution processes, driven by wind erosion and re-deposition, exert a significant influence on snow conditions (e.g., Mott et al., 2010, Vionnet et al., 2014). They induce significant deviations from planar layering geometry. Local topography and interactions with the vegetation also induce such deviations. Physically-based models have been developed to explicitly account for such processes. However, to the best of our knowledge, none are currently in operational use. Only one-dimensional models assuming layering parallel to the local slope, such as Crocus (Vionnet et al., 2002, Lafaysse et al., 2017), SNOWPACK (Bartelt and Lehning, 2002, Lehning et al., 2002a, 2002b), SNOWGRID (Olefs et al., 2013) and seNorge (Saloranta et al., 2012) are used operationally. Here we do not describe their internal functioning, but rather focus on the ways they are operated and how their output is used in the forecasting process.

## 3. CURRENTLY OPERATIONALLY IMPLEMENTED METEOROLOGICAL FORCING CONFIGURATIONS AND ASSOCIATED GEOMETRY

Physically-based snowpack models operate intrinsically at the point scale, i.e. they are driven by a number of individual time series of meteorological variables at the sub-diurnal time resolution. The time evolution of the vertical profile of the physical snow properties are predicted based on these time series. Several approaches were developed to generate such meteorological driving data. Snowpack modeling for avalanche hazard prediction can be considered a demanding subclass of hydrological modeling in mountain regions. As such, it shares most of the challenges involved in mountain hydrological modeling (with the notable exception, in most cases, of snow/vegetation interactions), which are all related to scaling issues of hydrometeorological conditions in complex topography (Klemes, 1990). The geometrical configuration is in most case intricately linked to the model design to whom it was initialy made for, which is why this component is introduced first.

In terms of data sources, for past and present meteorological conditions ("nowcast"), in-situ observations can directly be used to drive the models. Configurations where numerical weather prediction model forecasts for past conditions are optimally blended with in-situ observations are referred to as "analysis", consistent with the terminology used in numerical weather prediction. For future conditions ("forecast"), outputs from numerical weather prediction models need to be employed and can be adapted in various ways to the geographical model configuration.

In terms of geographical configurations, some model configurations focus on numerical simulations performed "at" observation stations, which are referred to as "station-based" approaches in the following. The alternative is to operate the models on a topography independent of the location of the observation stations, either on a structured grid ("grid-based" approaches, which typically corresponds to the operating mesh of mesoscale numerical weather prediction models) or on the basis of a geometric decomposition of relief ("topographic class-based" approach using mostly altitude, slope angle and aspect descriptors). Figure 1 summarizes these different approaches.

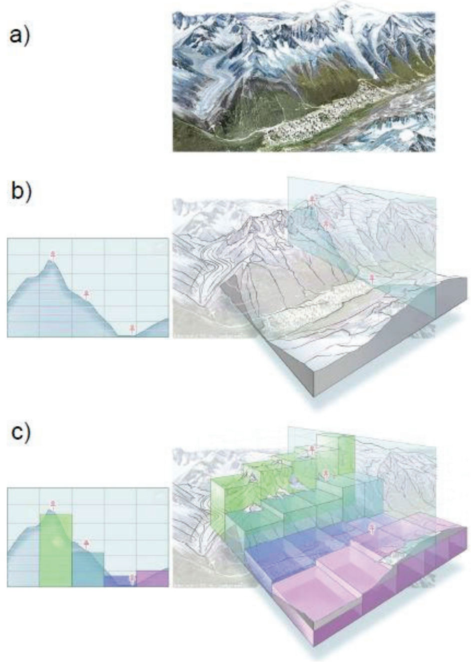


Figure 1: Schematic representation of the various geographical configurations used for snowpack modeling. a) Sketch of a typical mountainous environment. b) Illustration of station locations and elevation bands. c) Illustration of the typical resolution of a mesoscale numerical weather prediction model, from which meteorological information is extracted.

In practice, station-based approaches are mostly used at the geographical location of in-situ measurement stations. While they allow rather direct comparison to in-situ measurements, their main limit is the fact that model results are only available for a limited set of geographical conditions, thereby hampering extrapolation in space (altitude ranges, slopes etc.). Topographic class-based approaches mitigate this extrapolation issue, but the more conceptual design makes it more difficult to combine model output with other data sources, including in-situ measurements and field reports.

Gridded approaches are increasingly considered, although either using simpler models (seNorge, SNOWGRID) or using a subset of the data output from the more complex ones, because of the very large data volume, which can be generated on a km-scale grid over large mountainous areas.

## 4. POST-PROCESSING OF SNOWPACK MODEL OUTPUTS AND VISUALIZATION

Raw 1D model output consists of the vertical profile of simulated snow stratigraphy along with diagnostics of the energy and mass fluxes at the interfaces. Post-processing is required to provide process-relevant information which can be used for avalanche forecasting. Below we introduce a general overview of such diagnostics, along with examples of visualization.

### *4.1 Basic diagnostics*

Total snow depth and snow water equivalent (SWE) are a typical diagnostic of physically-based snowpack models. Snow surface temperature and bottom liquid water flux also inform on the thermal state of the snowpack. Snowpack models can be used to derive the total thickness and mass (in terms of SWE) of snow deposited for the past one or several days. This allows computing the new snow amount and height of new snow from the model output, accounting for settling, and thus can be compared to snow board measurements (Fierz et al., 2009). In addition, muti-layers models make it possible to compute the near surface wet snow thickness (sum of the thicknesses of contiguous layers with a non-zero liquid water content, starting from the top if the uppermost layer is also wet), as well as near surface refrozen thickness (sum of the thicknesses of contiguous layers with a null liquid water content, starting from the top if the uppermost layer is also dry).

### *4.2 Mechanical stability diagnostic*

Simulated vertical profiles from Crocus and SNOWPACK (e.g., MEPRA, Giraud et al., 1992) can be post-processed to compute the penetration resistance and shear strength of each layer depending on density, snow type descriptors and thermal state. Furthermore, depending on the vertical profile of physical properties, such tools assess the location of potential weak layers and compute stability criteria for natural releases and skier triggered avalanches for each simulated profile. Recently, Mitterer et al. (2013) introduced a new index related to wet-snow instabilities, based on the liquid water content of each layer of the snowpack. Figure 2 shows such an example of a wet-snow diagnostic in a station-based approach for Austria (see details in Gobiet et al., 2016).

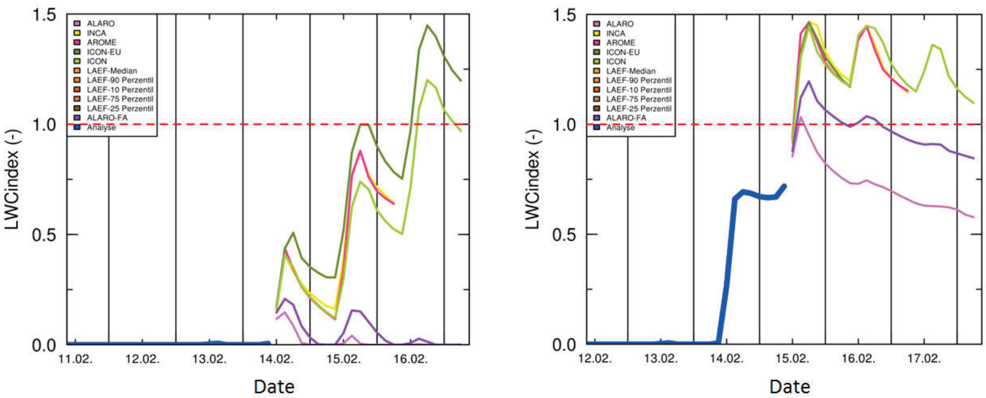


Fig. 2: Liquid water content index ensemble forecasts for south-facing slopes in the Eastern Alps (Hochschwab, Sonnschienalm, 1520m). Left: 14.2.2017, 11:00 MEZ; Right: 15.2.2017, 11 MEZ. Blue: Nowcast; Coloured: Forecasts based on different NWP models.

### *4.3 Surface hoar diagnostic*

Horton et al. (2015) proposed a method to predict surface hoar formation. It is based on a simplified surface energy balance model, which feeds the surface hoar formation routine in SNOWPACK. This allows computing surface hoar size at the time of burial. The accumulated precipitation since the time of burial is also calculated at each simulation point to estimate the load on buried surface hoar layers. Figure 3 shows an example of a surface hoar diagnostic, generated using a grid-based approach and displayed on a map.

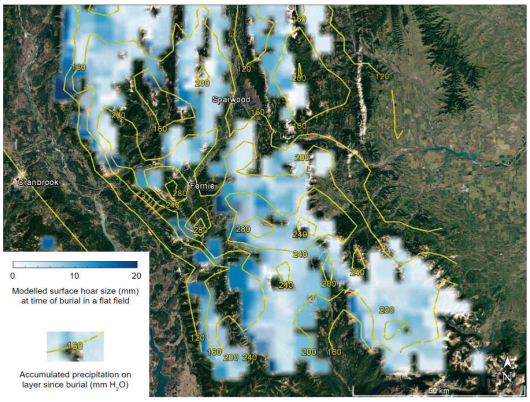


Fig. 3: Example of surface hoar diagnostic using the Horton et al. (2015) approach. See section 4.3 for details.

### 4.4 *Blowing snow diagnostic*

SYTRON (Durand et al., 2001, Vionnet et al., 2017) and the blowing snow module of SNOWPACK (Lehning et al., 2008) provide indices of blowing snow (occurrence and intensity) at the point scale (station-based SNOWPACK with virtual slopes) or by altitude bands within each massif (SAFRAN configuration). These diagnostics are complementary to the scarce network of automatic stations measuring blowing snow fluxes. For example, SYTRON provide blowing snow information over a wide range of areas and elevations, including regions without AWS, nor human observations. Figure 4 shows an example of this diagnostic, using a topographic class-based approach.

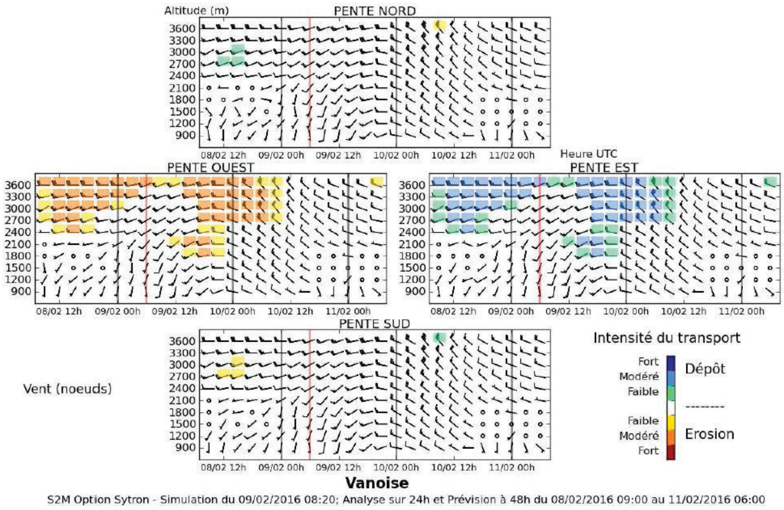


Fig. 4: Example of visualization of data from the blowing snow modeling system SYTRON implemented within the topographic-class geometrical approach of the SAFRAN-based modeling chain in France. The plot represents the diagnosis (time series of blowing snow diagnostic, in color, as a function of elevation and for several slope aspects) for the Vanoise massif for a drifting snow event of February 2016 (8th to 11th).

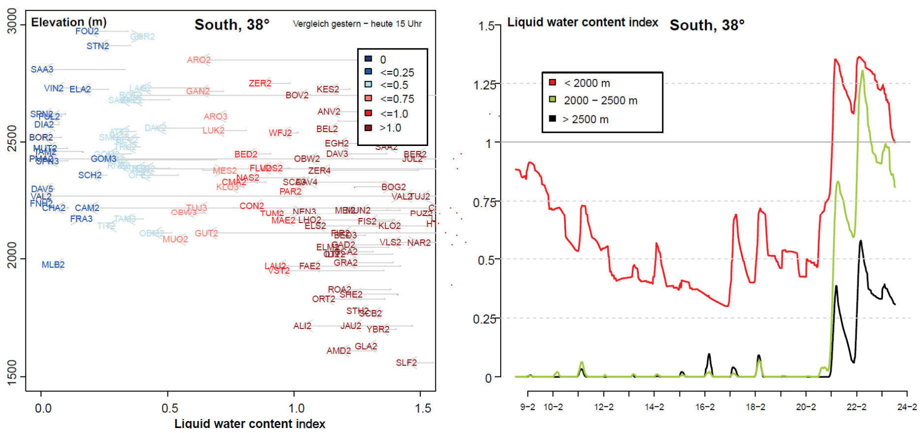


Fig. 5: Example of station-based (left, current conditions) and aggregated (right, three elevation bands, time series) liquid water index for Switzerland for Southerly aspect slopes

### *4.5 Regional-scale diagnostics*

Post-processed information at the point scale can be aggregated at a large scale in order to provide concise, synthetic information relevant to larger areas. For example, in Switzerland the point-scale liquid water content index can be aggregated as a function of elevation bands, thereby providing an ensemble-type wetness index (see Figure 5).

.In France, the mechanical stability indices for natural avalanche release is aggregated at the massif-level, in an attempt to provide a massif-scale natural avalanches level. This index ranges from 0 (lowest level) to 8 (highest level), and is built as a combination of 1D indices at different altitudes from 1500 to 3000 m for 40° slopes and 8 aspects. It was designed to correspond to a massif scale index of observed avalanche activity (Giraud et al., 1987). In theory, such indices, computed at the regional scale, which in the case of France correspond to the avalanche hazard rating zones, bridge the gap to the regional hazard level assessment (see Figure 6).

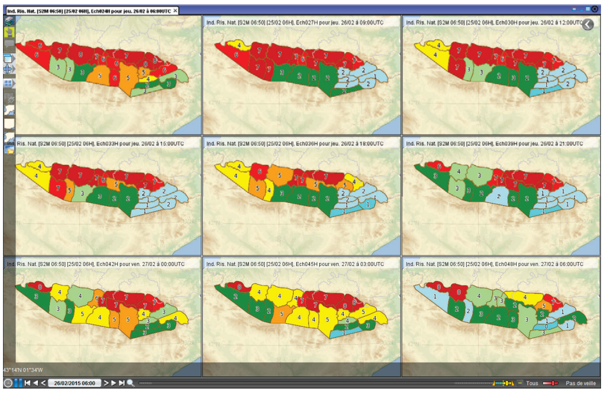

Fig. 6: Example of massif scale (aggregated) snow stability index for the Pyrenees, showing the time evolution (by steps of 3 hours) of the geographical distribution of simulated natural hazard level for all the forecasting areas during a given episode.

## 5. EVALUATIONS, FEEDBACK FROM FORECASTERS, LESSONS LEARNED

### *5.1 Quantitative evaluation, verification strategies and limitations*

Verification of snowpack model output is challenging for a variety of reasons, which can all be traced to the various sources of uncertainty which affect every component of the model chains. Uncertainties are associated to intrinsic observation and forecast errors at the point scale (applicable both for meteorological and snow data), but also the spatial representativeness of data used for the evaluation of model results, be it in-situ (Grünewald et al., 2013) or remotely-sensed. In fact, there has been no systematic undertaking of the verification of the predictive capability of physically-based snowpack models and their associated post-processing routines in terms of avalanche hazard forecast, due to the absence of objective field measurements of avalanche hazard at the regional scale. This also applies to snowpack stability, which has lacked hitherto objective and reproducible field measurements (Reuter et al., 2015). One step less in the model chain, regarding snow stratigraphy, comparisons between observed and simulated stratigraphy data have only been carried out for a few selected cases (e.g. Brun et al. 1992, Lehning et al., 2002b) and generally lacked an objective framework for quantitative comparisons between observed and simulated data in a context with distorsions in layering between observed and simulated data are the norm (Lehning et al., 2001). So far, the evaluation is often limited to comparing simulated and observed snow depth and snow water equivalent.

### *5.2 Feedback from operational forecasters*

General feedback from operational forecasters has been gathered from the organizations wich operate snowpack models in support of avalanche hazard prediction. A detailed, panel-based evaluation of their use of this ressource is beyond the scope of this article, nevertheless recurring topics were identified and are outlined below.

Time. Avalanche hazard forecasters work in a time constrained environment. Information from various sources, spanning sometimes very wide geographical areas, need to be processed, analyzed and used to produce a nowcast or forecast of avalanche hazard level for various rating regions. In many cases, the information from snowpack models is seen as additional, to the more traditional sources of information (observations and weather forecasts), sometimes even superfluous. Using snowpack model output tends to be considered only if time allows. Full integration of model output analysis into an existing workstation helps reducing this trend, but does not fully alleviate it.

Simplicity. Uptake of snowpack model output by operational avalanche hazard forecasters was enhanced in case where a limited number of products, most often directly analogous to conventional observed information (e.g. stratiraphy, heigh of new snow etc.). In France, despite the provision of regional-level integrated avalanche hazard level predictions, and a graphical user interface which favors progressive deepening of the analysis level from the massif scale, to the altitude/aspect scale, finally to the individual stratigraphic profile as the last stage of the complexity level, forecasters' most common feeling with the model output is to be overwhelmed by the quantity of information made available to them.

Training. Appropriate training on the background of the snowpack modeling chains, their strengths, known limitations and uncertainties, and how to best integrate them with other sources of information, is critical for significant uptake of model products in the decision chain of the forecasters.

Obvious errors. Operational use of numerical models has to cope with model errors, in particular the significant misses of the models. These are unfortunately unavoidable, and can greatly reduce the credibility of the models (Pappenberger et al., 2011). The occurrences of significant perceived errors in precipitation amounts, for example, and the resulting snow depth, is a typical case where avalanche hazard forecasters tend to loose trust in the model, even in cases where useful information can still be drawn from model results.

Effective visualization. Good graphic design with colors and easy to read text is critical to gain attention.

## 6. FUTURE CHALLENGES AND PERSPECTIVES

### 6.1 *Re-assessing how model results are made available to the forecasters*

The concerns highlighted above require in-depth assessments on how the model results are made available to the forecasters, and how they are used. This issue is not only challenging for avalanche hazard prediction, but more generally to all decision-making processes involving interactions between human forecasters and predictive models (Pagano et al., 2014). While in some operational forecasting domains, e.g. meteorology, the role of human forecasters is constantly reducing in favor of NWP outputs (Sills et al., 2009), in avalanche hazard forecasting the issue at hand is clearly how to make the most of information used by avalanche forecasters, which in some case rely only marginally, if at all, on numerical simulations in support of their activities. The possibility to automatically produce avalanche warning information remains a long term, possibly elusive challenge (Floyer et al., 2016).

Improvements of the situation may be favored by the following avenues:

- Direct research towards adding value to forecasts, through better design and visualization of the post-processed outputs at the point and regional scale.

- Better communication of the uncertainty. To add value, models need to reduce the forecaster's uncertainty about snow conditions. However snow models have several levels of uncertainty (e.g. meteorological inputs, mechanical models, spatial representativeness) and most products are poor at communicating that.

- Better integration of model output with existing data management platforms. This is a big multifaceted topic which is relevant to data sharing and IT developments.

- Better combination of snowpack models with other models such as statistical models, additional weather products, and risk-based models, such as the conceptual model of avalanche hazard (Statham et al., 2010, Floyer et al., 2016) or the European avalanche warning matrix (Müller et al., 2016)

### 6.2 *Improvements on the physical science side*

Main research items, which are likely to lead to improved snow model chains, can be summarized as follows:

Snow physics and snow modeling. This concerns the improvement of the modeling of intrinsic snow processes, such as liquid water dynamics, snow metamorphism, the impact of light absorbing impurities etc. Advances in snow mechanics could translate into renewed methods to estimate snow stability from simulated snow profiles (Reuter et al., 2015).

Verification. Improved measurements methods, and recently developed method making it possible to pair observations and simulations despite mismatches in layering (Hagenmuller and Pilloix, 2016), open the possibility to more quantitatively evaluate the output of snowpack models and guide most required improvements. Such verifications may also benefit from remote sensing data.

Higher spatial resolution. Numerous snow processes, e.g. blowing snow and preferential deposition, operate at the scale of a few meters and in 3D, and thus require an explicit representation of topography and associated processes. Progress in this area can only benefit from interactions with developments in the field of mountain hydrology (Marsh et al., 2018).

Data assimilation and ensemble forecast. Deviations of model output with in-situ and remotely-sensed observations are a critical issue hampering operational use of the models by the forecasters. Data assimilation is a promising, yet challenging way forward in this respect. Recent developments in data assimilation rely on ensemble-based methods (Lafaysse et al., 2017, Cluzet et al., 2018), which, in addition estimate model errors quantitatively within the assimilation system, open new possibilities for ensemble forecast of avalanche hazard (Vernay et al., 2015).

Post-processing of model output. Model output statistics are routinely used in numerical weather prediction and hydrological prediction, yet seldom used for avalanche hazard forecast, although similar issues need to be addressed. Furthermore, the skyrocketing development of data science and artificial intelligence applied to a broad range of practical issues makes it possible to envision applications to avalanche hazard forecasting, thereby providing added-value products beyond raw snowpack model outputs, with potential for directly feeding the production of avalanche bulletins.

### *6.3 Technical and organizational perspectives*

In contrast to the situation prevailing a few years ago, most snowpack models used by operational services are now open source, community-based software with version control and increasing verification routines. This increases the overall robustness of the models, although the costs associated to their maintenance and development remains high on their host institutions. Moving further into this direction is a clear way forward, following previous examples from the climate, meteorological or hydrological communities.

Beyond developing and maintaining the codes, it may be worth exploring an increased level of pooling of computational resources, especially for organizations operating in neighboring geographical domains. Currently implemented station-based or topographic class-based approaches are generally limited to national or regional boundaries. The development of grid-based approaches based on numerical weather prediction data, remote sensing data and high performance, ensemble based forecast and data assimilation methods, may develop more efficiently in a cross-boundary context, in close association to high performance computing infrastructures, rather than in multiple local implementations. This would facilitate multi-model ensemble approaches (multiple NWP models, multiple snowpack models), analogous to meteorological and hydrological prediction frameworks. Such a long term endeavor remains to the refined, but could benefit from multi-national opportunities such as the Copernicus services, in Europe (e.g., Copernicus Emergency Management Services, or Copernicus Land Monitoring Services), or large scale similar initiatives in North America. Such an approach may even make it possible, in the longer term, to deploy snowpack modeling chains over large geographical areas currently devoid of such systems, such as High Mountains of Asia or South America.

## 7. ACKNOWLEDGEMENTS

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