Validation of the SNOWPACK model in the Dolomites

Fabiano Monti[1,*], Anselmo Cagnati[1], Charles Fierz[2], Michael Lehning[2], Mauro Valt[1], Andrea Pozzi[3]
[1] ARPA Veneto – DRST Centro Valanghe di Arabba, Arabba (Italy)
[2] WSL, Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[3] Dipartimento di Scienze Chimiche e Ambientali, Università degli Studi dell'Insubria, Via Valleggio 11, 22100 COMO ITALY

ABSTRACT: Starting from the 2004 winter season, the SNOWPACK snow cover model has been operational at the Avalanche Forecasting Centre in Arabba (Dolomites, Italy). Snowpack characteristics, such as snow depth, temperature, hardness, density, wetness but also snow microstructure, layering and stability, are modelled using data from automatic weather stations. Until now there has been no statistical validation of the SNOWPACK model for the Dolomites climate area. Throughout the 2007-2008 winter, snow pit observations were performed weekly in a study plot close to the automatic weather station in "Monti Alti di Ornella". Snow profiles were compared to simulation results in both a qualitative and a quantitative way.
Early in the season, the agreement between measured and simulated snowpack characteristics is good (74%). The quality of the simulations decreases with the start of the melt season. Snow depth is generally well simulated, although the model tends to underestimate the snow depth early in the season and to overestimate it late in the season.
Analyzing the effects of wind on the snow cover, the SNOWPACK model proves unable to simulate the densification of the surface layers under strong wind conditions (wind crusts). We introduce and describe an empirical "wind effect" function providing additional densification under strong winds. This results into improved simulations of snow density and other parameters, especially in the second half of the season.

KEYWORDS: SNOWPACK model; Snow metamorphism; Model validation; Wind effects

1 INTRODUCTION

Between 1967 and 2008, avalanches caused an average of 19 victims per year in Italy (Valt, 2008). Most victims were engaged in recreational activities (97%); these data underscore the importance, for those in charge of predicting avalanches, of having information on the snow pack with ever-more-detailed spatial and temporal details.

Snow profiles and stability tests for avalanche forecasting are usually taken manually. This praxis leads to some disadvantages: it takes relative a long time; temporal resolution is scarce and above all no observations are carried out in the most dangerous days. The SNOWPACK snow cover model is well suited to such a context. The Swiss model solves the one-dimensional equations governing heat and mass transfer, deformation and phase changes within the snow cover. SNOWPACK calculates snow metamorphisms taking into account the contributions and losses of mass due to fresh snow, wind drift and snow ablation. Snow is modelled as a three-phase porous element, composed of ice, air and water in constant transformation. The Lagrangian Gauss-Seidel finite-element method allows the model to assume a stratified snow cover (Lehning et al., 1999; Bartelt and Lehning, 2002; Lehning et al., 2002a, b).

The model uses snow and weather data from a network of automatic weather stations (AWS) that are located in the most representative and remote sites. Data collected from AWS are then processed by the model and supplemented with important parameters such as new snow amount, settling rates, surface hoar, temperature profiles and layers microstructure (Lehning et al. 1999).

In the Dolomites, the only study published regarding SNOWPACK was focused on the snow water equivalent of the snowpack (Valt et al., 2006). This study showed that the discrepancies between data from the model and data acquired in the field amount to less than 15 %, thus confirming that the model can be used under normal operating circumstances. In the south eastern Alps, an analysis of the correspondence between the micro-structure of the modeled snow pack and the real snow pack has not yet been performed.

This paper aims to perform an objective evaluation of SNOWPACK simulations in the Dolomites to provide useful indications for im-

Corresponding author address:
Fabiano Monti
ARPAV- Centro Valanghe di Arabba .
Via Pradat, Arabba 32020 BL
email: fmonti@arpa.veneto.it

proving the model and evaluate its possible use under everyday operating conditions.

2 METHODS

2.1 Description of the study site

Out of several available automatic AWS, we chose the station named “Monti Alti di Ornella” as our study site because of its vicinity to the Arabba Avalanche Centre, its easy access during the winter season, and the stability of its data flow. The AWS is located on the northern slopes of the Padon range at an altitude of 2250 m. This area lies immediately north of the Marmolada range, and on the right bank of the Cordevole stream (Piave basin). The topsoil is siliceous, and until about 35/40 years ago it was subject to regular mowing and grazing. It can thus be considered a “high altitude alpine meadow”, free from any tree or shrub species.

The Monti Alti di Ornella AWS is representative of the general evolution of the snowpack on the northern slopes of the Dolomites. In winter, the station is only reachable on skis (it is about 400 meters far from a ski run), and in summer by off-road vehicles. There are no habitations in the vicinity.

2.2 Data and comparison methods

In this work, we compared 20 observed regular full profiles with the corresponding calculated profiles from the SNOWPACK model simulations. The study period runs from 28-11-2007 to 23-4-2008. The profiles are collected once a week from the snowfield located a few meters away from the Monti Alti di Ornella AWS. The terrain is slightly uneven, something that must be taken into account both in the evaluation of the snowpack’s basal layers and in the comparison of snow depths. The surroundings of the AWS and the snowfield do not show any morphological characteristics that may lead to substantially different snowpacks. We can thus exclude significant anomalies due to micro-morphological causes between the two analysis points.

In order to make visual comparisons easier, the profiles generated by the model were represented in the same way as the manual profiles, using the symbols and colors adopted by the new international snow classification (Fierz et al., 2009) (Fig. 1).

Our approach in comparing profiles requires that we consider the observed profiles as a reference rather than the simulated ones (Lehning et al., 2001). We must, however, also take into account possible errors from the observations. These errors can be caused by the operator, erroneous personal interpretations, or weather conditions that hinder correct data collection. Establishing comparison methods between observed and simulated profiles required several considerations. Qualitative comparisons are undoubtedly the most useful approach to understand SNOWPACK’s difficulties in terms of modeling and to determine which physical processes have been poorly interpreted. There is also the need for objective considerations in order to evaluate the actual validity of the simulations, expressed in indexes or concordance percentages. For these reasons, we chose the method proposed by Lehning et al. (2001). This method calls for evaluating the agreement between simulations and reality for five different characteristics of the snow pack: grain type, grain size, temperature, density, hardness, and wetness. For each parameter, a percentage index is calculated which indicates the degree of fit with reality.

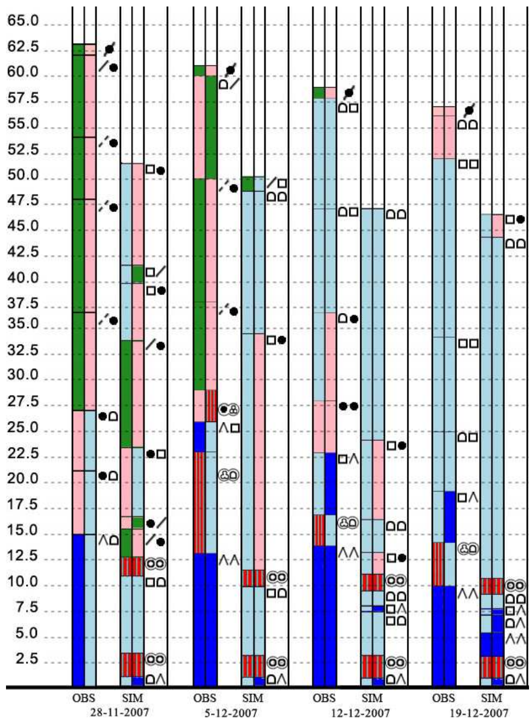

Fig.1. Display used for the qualitative comparison of the observed (obs) and simulated (sim) snow profiles. Each left column represents the dominant grain type. Corresponding snow grain symbols are also shown (Fierz et al., 2009).

2.2 Analysis of the effects of wind

Wind modeling is very important because of the role of wind in avalanche formation (Lehning et al., 2008). In order to evaluate the simulations produced by SNOWPACK, the first step was to observe the snowpack and its modeling qualitatively. Strong wind events were very helpful for understanding problems with simulations: under these conditions, simulation deficiencies were much more evident, and thus easier to analyze. For example, we observed that the model was not able to reproduce the wind induced superficial densification of the snowpack. We therefore implemented a mechanism to mimic this densification process. At wind speeds in excess of 3 m s^{-1}, the topmost 7 cm of snow are additionally compacted proportionally to the excess wind speed. The same enhancement is applied to the rate of change of both dendricity and sphericity. The whole mechanism acts on dry snow only but hardly affects new snow during its deposition.

3 RESULTS

Generally speaking, the 2007-2008 winter season on the southern part of the Alps was average, with greater snowfalls in the central Alps. In the eastern Alps, particularly those of the Veneto region, the winter was characterized by snowfall events early in the season (in October and November) and a dry December (especially at low elevations and in the Prealps). Snow fell abundantly in the first days of January, the first days of February, and in early March, however. In the second and third decades of February there was stable weather.

3.1 Qualitative comparison

By visually comparing all profiles – both observed and simulated – we can make some general remarks: 1) during the parts of the season when snow fell, the simulation of the snow pack appears satisfactory; 2) transformations in the snow caused by physical processes within the snow pack are simulated correctly, and correspondence is excellent; 3) during the mildest part of the season, and in spring, the quality of the simulation drops and it poorly fits reality. By examining both the observed and the modeled stratigraphy of the snowpack, we notice that, at the intuitive level, the snowpack can be divided in three parts: the part closest to the surface, characterized by recently fallen snow; a central layer, subject to metamorphism; and a basal layer that responds much less dynamically to transformation processes. At first sight, the basal layer shows significant differences between observed and simulated profiles. Before formulating hypotheses, we must consider the following:

- observed profiles are always made in a slightly different site, and thus micro-variations in the terrain can impact the layers closest to the ground;
- prior to 25-11-2007, the date of the first significant snowfall (when snow depth reached 61 cm), there were several minor snow falls that may have partially melted away. This dynamics leads us to hypothesize that prior to the heavy snowfall in November, the snow field was covered with a very variable amount of snow, distributed irregularly in patches. This hypothesis perfectly explains the results obtained in the profiles, which show that, depending on the week, melt-freeze crusts alternating with basal depth hoar layers may or may not be observed while the model stratigraphy persists over the season. The differences between profiles are thus not due to metamorphism during the week, but rather to different initial conditions. In light of the above, the simulation of the basal layer of the snow pack can be considered satisfactory.

SNOWPACK leads to a profile of the snow pack characterized by layers of a few centimeters in thickness, which are generally thinner than those observed. Although the model tends to unite layers with very similar characteristics, there are more of them than in reality. This result was also obtained by Schweizer et al. (2006). This characteristic can be seen in a positive light, with simulations being able to achieve better resolution than observations. Qualitative comparison provides the opportunity to deduce ongoing transformations in the snowpack and determine the processes causing them. By observing the profiles we can deduce that:

- throughout the season, the model shows a certain tendency to transform precipitated snow particles too rapidly into rounded grains or faceted crystals.
- during the mildest part of the season, SNOWPACK is late in identifying snow melting processes, and never predicts the formation of melt-freeze crusts.
- during the spring thaw, the melting of the basal layer of the snow pack is completely absent from the model.
- manual profiles describe a more variable and dynamic snow pack. This greater variability can be explained by the fact that the profiles can never be replicated at exactly the same spot, and that a certain degree of subjectivity of the observer can affect his observations. Apparently in real life, the snowpack is characterized by rather rapid shifts from kinetic growth to equilibrium growth metamorphism than in simulated situations. These shifts are not recognized by the model.

If we instead look at snow depth as measured manually and from simulations, we note that:

- the model tends to underestimate the depth of the snow pack during the coldest part of the winter, and to overestimate it during the mildest part. The dividing date between the two behaviors of the model falls between 19-2-2008 and

28-02-2008. The underestimation of snow depth during the coldest part of the season can be explained by the fact that SNOWPACK tends to transform fresh snow too rapidly, and consequently the subsequent settling process (a phenomenon that leads to the reduction of total volume) as well. Overestimates during the mildest period are due to the delay with which the model reproduces the humidification of snow (Fig. 3).

- SNOWPACK's difficulties with simulations carried out in the spring coincide with the shift to the phase in which the model overestimates snow depth.

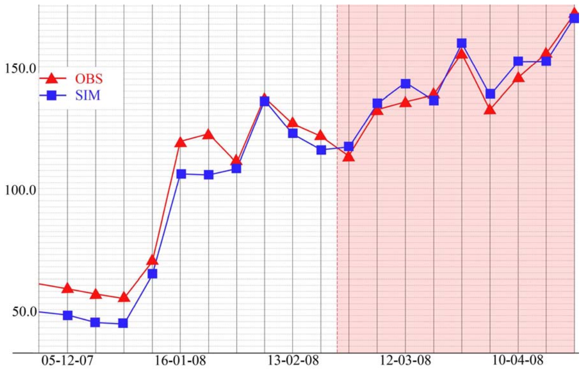

Fig. 3. Snow depth graph for simulated and observed profiles. We can see that SNOWPACK underestimates the snow depth in the first part of the winter and overestimates its in the mildest part.

With specific regards to the simulation of surface hoar crystals, the model shows itself to be capable of correctly identifying the conditions for their formation, although the model also eliminates surface hoar faster than in direct observations. Overall, this simulation can nevertheless be considered positive.

3.2 Quantitative comparison

The impression given by the qualitative comparison of simulations getting worse as winter wears on, that is, with the warming of the snow pack, is confirmed by the quantitative comparison. In particular, we notice simulations starting to get worse after 05-03-2008. For this reason, we decided to evaluate index trends both throughout the period (from 28-11-2007 to 23-04-2008) and for the first 13 profiles only (from 28-11-2007 to 5-3-2008), which correspond with the coldest part of the season.

Grain typology is the most important parameter for evaluating the simulation accuracy of a profile. It is the product of all the metamorphic processes affecting the snowpack, and influences all the physical and mechanical characteristics of a given layer. As expected, the Shape Agreement is the parameter that least matches reality. Over the entire period, the average value of the Shape Agreement is 53%; while if we only take into account the first 13 profiles (from 28-11-2007 to 5-3-2008), the average value of this parameter rises to 60%.

Grain size is another important parameter; it is related to metamorphism too. Its greatest impacts are on the stability, porosity, and hardness of the snow pack. The Grain Size Agreement shows satisfactory simulation on the part of the model, without significant seasonal variations.

The wetness simulation is basically perfect in the initial (winter) part of the season, but it worsens drastically during the advanced thaw phase (the last profile, dated 23-04-2008, shows a correspondence of 51%).

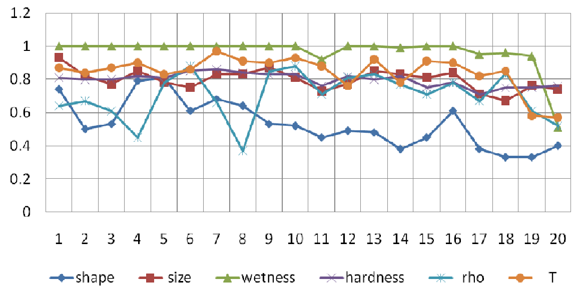

Fig 3. Time series of individual agreement scores between the observed and modeled snow profiles at the Monti Alti di Ornella AWS in the 2007-2008 winter season.

The layer hardness parameter was evaluated on the basis of a hand test for each single layer. Its simulation is satisfactory and does not vary significantly over the season.

The Rho Agreement is the parameter that indicates correspondence between density calculated by the model, and density measured in the field. The density parameter shows a very uneven trend and it is also the only parameter that improves in accuracy over the season. Its average value is 70%.

The T Agreement expresses the degree of agreement between simulated snow pack temperatures and those measured in the field. Over the season, its value was of 84%, and rose to 88% if profiles from the second half of the season are excluded (Fig. 3).

3.3 Quantitative comparison of the SNOWPACK "slab version"

Once again, comparisons were made with regards both to all 20 profiles, and to the first 13 only, in order to make this data comparable with previously obtained data (Table 1).

At first glance, a decreasing performance is once again evident during the final part of the season, although it is not as marked as before. The improvement, which is more marked in spring profiles, can be attributed to the greater density of the simulated snowpack. The change we introduced, which allowed for the densification of surface layers under high wind conditions, produces a snowpack with higher density values. Density impacts on the insulating capabilities of the snowpack, which in turn impact on warming speed later in the season.

	SHAPE	SIZE	WETN	HARD	RHO	T
	Δ	Δ	Δ	Δ	Δ	Δ
SL	0.54	0.80	0.97	0.80	0.74	0.85
O	0.53	0.80	0.96	0.80	0.70	0.84
	Δ13	Δ13	Δ13	Δ13	Δ13	Δ13
SL	0.60	0.82	0.99	0.82	0.75	0.89
O	0.60	0.81	0.99	0.82	0.70	0.88

Table1. Values of the agreement scores obtained with the original version of SNOWPACK (O) and the modified one (SL), both for the winter season (Δ) and for the first 13 profiles (Δ13). The values for which there is an improvement of the simulations are highlighted. The improvement of the density (RHO) score is the only truly significant one (4%).

4 CONCLUSIONS

Comparisons between observed and simulated profiles show that:

- Simulations during the coldest part of the season well fit reality. The general agreement index amounts to 72%. The quality of modeling efforts decreases with rising snow pack temperatures (the last profile has a general agreement index of 51%).

- If we exclude the parameter that measures the wetness of snow layers (which only has a minor impact on the general evaluation of the profiles), the best results come from simulations of temperature, grain size, and layer hardness. The parameter that least fits observations is grain shape.

- In general, snow depth is simulated correctly, although the model tends to underestimate it during the coldest period, and overestimate it once the snow pack begins to warm. These errors are caused by an excessively rapid transformation of precipitated snow and by the delayed simulation of the warming of the snow pack, respectively.

The in-depth analysis of simulations in strong wind conditions highlighted one significant problem: SNOWPACK does not predict the densification process caused by the wind, and therefore the density values given for surface layers are too low. This has led to the implementation of a mechanism mimicking this process.

In summary, the results of the changes made are as following:

- General improvement of the simulations (about 2%); the improvement was more evident during the mildest part of the winter.

- Simulation of the formation of wind crusts showing higher densities.

- The parameter measuring layer density improved by 4% to an agreement of 74%.

Our interventions are a step in the right direction, albeit only the first.

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