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PREDICTING SNOW COVER STABILITY WITH THE SNOW COVER MODEL SNOWPACK

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ABSTRACT: The snow cover model SNOWPACK simulates snow stratigraphy for the locations of automatic snow and weather stations. Based on the stratigraphy, snow stability is predicted by calculating three stability indices. We verified the performance of the skier stability index SK_{38} in order to develop a supporting tool for avalanche warning services. Since stability depends on snow stratigraphy, modelled grain type, grain size, hardness and density were first validated. The skier stability index SK_{38} performed poorly in terms of identifying potential weak layers. By introducing a new stability formulation (*SSI*) that combined the SK_{38} with differences of hardness and grain size across layer interfaces – known indicators of structural instability – the model performance was substantially improved. For manually observed flat field profiles, the *SSI* was significantly related with stability test results. At the regional scale, a statistically significant relation between predicted and verified stability was found. Stability patterns at the mountain range scale were reproduced. With these improvements the snow cover model SNOWPACK will develop into a valuable supporting tool for stability evaluation as done by avalanche warning services.

KEYWORDS: avalanche forecasting, snow cover modelling, snow stability evaluation, numerical simulation

1. INTRODUCTION

Evaluating of snow cover stability and its development is the key to avalanche forecasting. Therefore snow cover information in terms of snow profiles manually observed by experts is required. This procedure is time consuming and sometimes dangerous.

Furthermore, the amount of manually observed profiles is limited. Snow cover models could provide high resolution – in time and space – snow cover stability information, which would assist avalanche warning services in predicting snow cover stability. Snow cover models have been developed for that purpose. The French model chain SAFRAN-Crocus-MÉPRA (SCM) predicts the regional avalanche danger (so-called massif scale: 500 km^2) for virtual slopes of a given elevation and aspect (Durand et al., 1999). The Swiss model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b) is used operationally by the Swiss avalanche warning service.

We will briefly summarize recent verification results of the snow cover model SNOWPACK (for details see Schweizer et al., 2006), and present a comparison of observed and predicted snow cover stability for two dates in winter 2005-2006 at the mountain range scale.

2. METHODS

The one dimensional snow cover model SNOWPACK simulates snow stratigraphy for the location of automatic weather stations. It numerically solves partial differential equations governing the mass, energy and momentum conservation within the snowpack using the finite-element method (Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b). Stratigraphy includes the grain type, grain size, density and hardness for each layer. Snow density follows from settlement which depends on snow viscosity and is affected by the metamorphic processes. The snow hardness parameterisation was originally based on Canadian data (Geldsetzer and Jamieson, 2001). Three types of stability information are derived (Lehning et al., 2004), among those the skier stability index SK_{38} (Jamieson and Johnston, 1998). The skier stability index in a given depth h (measured vertically from snow surface) is defined as:

$$SK_{38} = \frac{\tau}{\tau_{xz} + \Delta\tau_{xz}} \qquad (1)$$

where τ is the shear strength per grain type (Jamieson and Johnston, 2001), τ_{xz} is the shear stress due to the weight of the overlaying slab

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layers $\tau_{xz} = \rho\, g\, h\, \sin\psi\, \cos\psi$ (with ρ : average slab density, ψ : slope angle, and g : acceleration due to gravity) and $\Delta\tau_{xz}$ is the additional shear stress due to a skier modelled as a line load (Föhn, 1987). The SK_{38} is calculated with layer properties from flat field observations or simulations and extrapolated to a 38° slope.

It has been pointed out by McCammon and Schweizer (2002), that snowpack properties are related to snowpack instability. This indicators of structural instability are mainly grain size and hardness and their differences across layer interfaces (Schweizer and Jamieson, 2003; Schweizer and Jamieson, 2007). Combining mechanical and structural instability a new stability formulation (*SSI*) was suggested (Schweizer et al., 2006):

$$SSI = SK_{38} + \Delta R^{*} + \Delta E^{*} \qquad (2)$$

where ΔR^{*} is the hardness difference and ΔE^{*} is the grain size difference across a layer boundary in a given depth. The differences ΔR^{*} and ΔE^{*} take the values 0 or 1 depending on whether the threshold value is reached:

$$\Delta R^{*} = \begin{cases} 0 & if \quad \Delta R \geq 1.5 \\ 1 & if \quad \Delta R < 1.5 \end{cases} \qquad (3)$$

$$\Delta E^{*} = \begin{cases} 0 & if \quad \Delta E \geq 0.5 \\ 1 & if \quad \Delta E < 0.5 \end{cases} \qquad (4)$$

The threshold values were estimated based on the threshold values found by Schweizer and Jamieson (2003) and on characteristics of the model SNOWPACK.

Combining a layer property (shear strength) with interface properties (ΔR^{*}, ΔE^{*}) meant that for the calculation of the SK_{38} at each interface the layer (above or below) was selected that had the lower shear strength. The skier stability index *SSI* identifies the location of a potential weak layer in a snow cover, combining mechanical and structural instability.

3. DATA

For stratigraphy verification a data set including 141 manual snow profiles observed in the surroundings of Davos during the winters of 1996-1997 to 2003-2004 was used. For each profile the layer characteristics grain type, grain size, hardness and density were known. Overall, about 1680 observed layers were compared to a dataset of about 10,000 simulated layers from 280 profiles covering the same winter times and areas as the observed ones.

Stability verification was based on two data sets, one for the verification at the regional (< 100 km^2) and the other for the verification at the mountain range scale (> 100 km^2). The regional stability was modelled for the location of four sites with an automatic weather station in the surroundings of Davos (Weissfluhjoch 2540 m a.s.l., Gatschiefer 2310 m a.s.l., Hanengretji 2450 m a.s.l. and Bärentälli 2560 m a.s.l.) and was compared to the observed stability as verified during 10 days of the winters 2001–2002 and 2002–2003. At these days several teams collected information about the snowpack to verify the regional avalanche danger in the surroundings of the four automatic weather stations (Schweizer et al., 2003). The manual profiles were classified into five classes of stability (Schweizer and Wiesinger, 2001) and the regional mean was compared to the modelled stability output of the snow cover model SNOWPACK. These 10 days included 33 stability estimations. Furthermore the original five classes were condensed into three classes (Poor, Fair, Good) by grouping very poor and poor, and good and very good, resulting in a well balanced data set of 12 poor, 10 fair and 11 good cases.

The second data set, to verify the stability at the mountain range scale, consisted of fortnightly taken snow profiles from the whole area of the Swiss Alps and their analysis by the Swiss avalanche warning service. These profiles observed by experienced observers were classified by the avalanche warning service, according to Schweizer and Wiesinger (2001). The resulting stability patterns were described. To compare the observed stability across the whole area of the Swiss Alps to the stability output from the snow cover model SNOWPACK, two periods when stability differences between different areas of the Swiss Alps existed, were considered. Model output included the stability prediction by SNOWPACK for the location of about 85 automatic weather stations covering the whole area of the Swiss Alps.

4. RESULTS

4.1 Stratigraphy verification

Verification of stratigraphy described by Schweizer et al. (2006) included grain size, density and snow hardness. The comparison was done for the five principal grain types in a dry snow cover: precipitation particles (PP), decomposing and fragmented precipitation particles (DF), rounded grains (RG), faceted crystals (FC) and depth hoar (DH). Comparing the absolute values of observed and modelled grain size showed some systematic deviations. In particular, the modelled grain sizes were larger for RG and smaller for PP and DF. These problems might be due to unknown initial conditions for the new snow, and the ongoing metamorphic process described by rates of change in sphericity and dendricity. The model reproduced the grain growth from RG to FC to DH.

Modelled density was larger than the observed density for the rounded grains and slightly lower for the persistent grain types. Poor agreement between modelled and observed snow hardness index was found with the implemented hardness parameterisation, based on a Canadian dataset of grain size and density (Geldsetzer and Jamieson, 2001). Since including grain size did not improve the agreement, a linear regression of hardness on density as independent variable has been carried out with a Swiss dataset. The new parameterisation substantially improved the relation between modelled and observed hardness.

4.2 <u>Stability verification</u>

The skier stability index SK_{38} did perform poorly in terms of identifying the location of weak layers in a simulated snow cover (Schweizer et al., 2006). So far the skier stability index SK_{38} has usually been applied to a known weak layer, in particular to monitor its temporal evolution. The SK_{38} cannot be used to identify potential weak layers since it generally increases with increasing depth since density (and hence strength) increases with increasing depth. To solve the problem of identifying weak layers, a new stability formulation (*SSI*, Eq. 2), combining structural (Eqs. 3 and 4) as well as mechanical properties (Eq. 1) was suggested.

To relate Compression Test results (Jamieson, 1999) to the *SSI*, the *SSI* was calculated for 11 manually observed flat field profiles taken during 2005-2006, and compared to the Compression Test results in the corresponding height. The values were scaled by the depth of the potential weak layer since Compression Test results tend to increase with increasing depth (Jamieson, 1999). The *SSI* also increases with increasing depth, but less continuous and can reach smaller values due to structural instabilities located deeper in the snow cover. The scaled Skier Stability Index *SSI* was significantly correlated with the scaled Compression Test score (correlation coefficient $R^2 = 0.61$, $p < 0.001$).

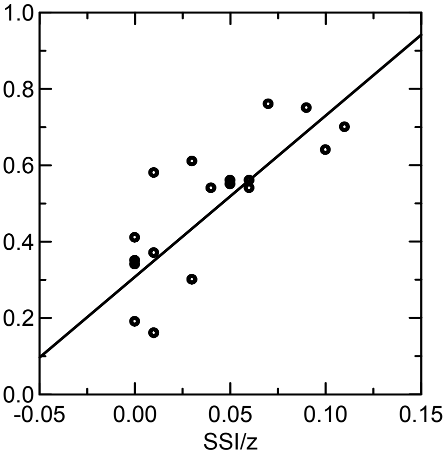

Figure 1: Compression Test results (CT/z) vs. Skier Stability Index (SSI/z). Both values were scaled to depth z. *SSI* was calculated for 11 manually observed flat field profiles taken during winter 2005-2006 in the surroundings of Davos. Only CT-results for layers of persistent grain types deeper than 15 cm from the snow surface were considered for regression ($N = 20$, $p < 0.001$ and $R^2 = 0.61$).

To verify the performance of the Skier Stability Index (*SSI*) on a regional scale, we compared the stability output of the snow cover model SNOWPACK to observed regional stability. Both, the *SSI* and the SK_{38}, for the depth of the potential weak layer as identified by the *SSI*, were compared to the observed regional stability (Fig. 2).

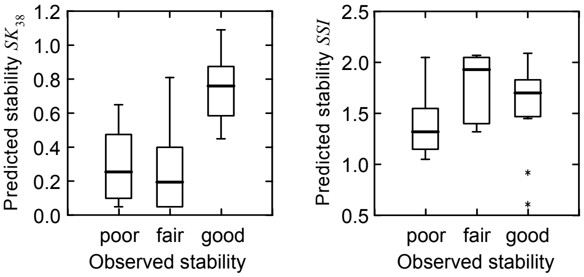

Figure 2: Comparing predicted to observed regional stability for 10 days during the winters of 2001-2002 and 2002-2003. Predicted stability indices are the SK_{38} (left) and the *SSI* (right) calculated for the locations of four weather stations in the surroundings of Davos (Switzerland). Observed stability is based on assessing manual snow profiles from slopes in the vicinity of the stations ($N = 33$).

Spearman rank-order correlation coefficients (0.57 for SK_{38} and 0.30 for SSI) between simulated and observed stability suggested a significant relation for SK_{38}, but not for SSI. Furthermore, the SK_{38} differentiated well between Good and the group of Fair and Poor stability. The SSI showed a significant difference between Poor and the group of Fair and Good stability. Therefore, both the SK_{38} and the SSI were used to classify the simulated profiles into Poor, Fair and Good. Split values were:

Poor Stability if $SK_{38} < 0.45$ and $SSI < 1.32$,
Fair Stability if $SK_{38} < 0.45$ and $SSI \geq 1.32$,
Good Stability if $SK_{38} \geq 0.45$.

The 11-fold cross-validated classification accuracy was about 76%. However, three cases with poor observed stability were classified as Good. A manual adjustment of the split values led to a general underestimation of stability, and a not cross validated accuracy of about 70%.

To verify the performance of the new stability formulation at the scale of the whole Swiss Alps, fortnightly stability observations done by experienced observers were compared to the model output. Figure 3 shows two periods of stability observations in February and March 2006. At the end of the first period, 3-15 February 2006, the avalanche warning service described a difference in snow cover stability between the northern parts (rather stable), and the southern parts (rather unstable) of the Swiss Alps (Fig. 3a). At the end of the second period, 10-18 March 2006, the avalanche warning services estimated the stability to be fairly good in the central Alps, and rather poor in the western and eastern inneralpine parts (Fig. 3b).

The number of observed profiles was much smaller than the number of simulations for the location of automatic weather stations (Fig. 3c to 3f). Observed profiles were typically not done in the near vicinity of the stations, so that a direct quantitative comparison of snow cover stability was not feasible. However a qualitative comparison at regional scale where small scale spatial variability is negligible, seems reasonable.

The pattern of period one, a difference between more northerly and southerly parts of the Alps is shown in Figure 3a. Simulations were done for the first and last day of the observation period. Conditions in the more southerly parts were reproduced by the model. A comparison of the two simulations (Figs. 3c and 3e) suggested that the snowpack stabilised during the observation period in the northern parts of the Swiss Alps. This was in fact described by the avalanche warning service.

In the second period, two inner alpine regions of rather unstable snow cover, and rather stable conditions in the central parts of the Swiss Alps (Fig. 3b) were reproduced by the snow cover model SNOWPACK (Fig. 3d). The stabilisation, again described by the avalanche warning service, is visible by comparing Figures 3d and 3f.

In general, the observed patterns of snow cover stability were reproduced by the model SNOWPACK. Deviations between observations and simulations might be due to flat field stations not being representative for regional slope stability, or to a general overestimation of simulated snow cover stability as mentioned above.

5. CONCLUSIONS

We analyzed the stability prediction of the snow cover model SNOWPACK. Since stability depends on snow stratigraphy, grain size, density and hardness were verified. Some significant differences between the model and observations existed. The deviations in grain size were probably caused by the unknown initial conditions and grain type classification derived from sphericity and dendricity. Layer density is well modelled for layers of precipitation particles and of partly decomposing and fragmented particles. For layers of small rounded grains snow density was overestimated, for layers of faceted crystals and depth hoar underestimated. A new hardness parameterisation based on Swiss data, which resulted in a better agreement between observed and modelled hardness was introduced.

The skier stability index SK_{38} performed poorly in terms of identifying potential weak layers in a simulated snow cover. The minimum value of the SK_{38} was often found next to the surface, persistent layers deeper in the snowpack were not recognized. To identify potential weak layers in a snow cover, structural properties (Eqs. 3 and 4) of the snow cover were combined with the SK_{38} to a new stability formulation. The new Skier Stability Index (SSI) was significantly correlated with Compression Test results.

Predicted stability, calculated for the location of automatic weather stations (flat fields), was significantly related to verified regional stability as assessed from manual profiles on slopes in the vicinity of the weather stations. To classify simulated snow stratigraphy into three stability classes, both the SK_{38} and the SSI were used. The 11-fold cross-validated classification

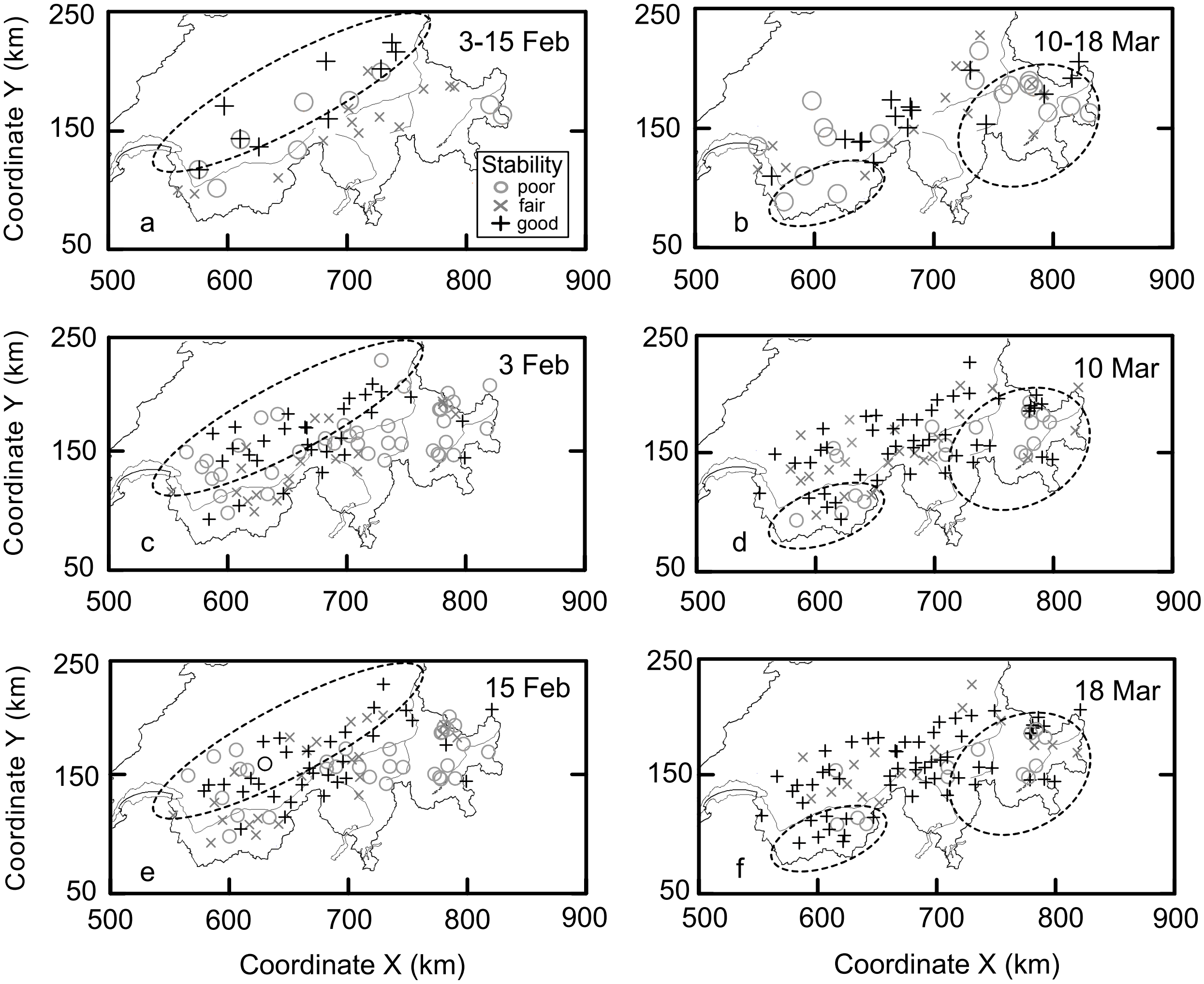

Figure 3: Comparison for two dates in winter 2005-2006 of observed (a) and (b) and modelled (c) to (f) snow cover stability in the Swiss Alps. Snow cover stability is modelled for the location of automatic weather stations covering the whole Swiss alpine region. For comparison the first and last day of the observation period were simulated. Axes show the Swiss-Grid Coordinates in kilometres. Snow cover stability is classified in Poor (○), Fair (✕) and Good (+).

accuracy was about 76%. The split values for classification are preliminary and need to be adapted when more verification data will be available.

Preliminary results for the two periods suggest that observed stability patterns at the mountain range scale can be reproduced by the snow cover model SNOWPACK. With the newly developed stability output the snow cover model SNOWPACK will become more useful for avalanche forecasting services, as it will increase temporal and spatial resolution of snowpack instability information.

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