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Evaluating and improving the stability predictions of 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}. Since the index depends on snow layer characteristics those were first compared to manual observations. Some significant differences between model results and observations existed. A new parameterisation for the snow hardness index was introduced. The skier stability index SK_{38} performed poorly in terms of identifying potential weak layers. However, if the potentially critical weak layers were found, the SK_{38} was significantly correlated with observed stability. By introducing a new stability formulation that combines the SK_{38} with differences of hardness and grain size across layer interfaces — known indicators of structural instability — the model performance was substantially improved. Simulated snow stratigraphy could successfully be classified into three stability classes. With these improvements the snow cover model SNOWPACK will become useful as supporting tool for stability evaluation as done by avalanche warning services.

Keywords: Avalanche forecasting; Snow cover modeling; Snow stability evaluation; Numerical simulation

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1. Introduction

The type and location of weak layers or interfaces found in a snowpack and how the snowpack is consolidated in general are some of the crucial questions for avalanche forecasters. Therefore, besides information on snow and weather conditions, snow cover stratigraphy is considered as the key contributing factor in avalanche forecasting (Schweizer et al., 2003a). Today, forecasting services almost exclusively use manually observed snow profiles combined with stability tests to assess snowpack instability — at least in areas with predominantly continental or transitional snow climates. Manual observations are relatively time-consuming — and sometimes dangerous — point observations so that the spatial and temporal resolution of snowpack data is usually poor. Important information on the snowpack variability is missing. Numerical modeling of snow cover stratigraphy and thereof derived stability information is considered as the method of choice to augment snowpack data and hence might be a valuable supporting tool for forecasting services.

The French model chain SAFRAN-Crocus-MEPRA (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). Input for the snow cover model Crocus is provided by the meteorological

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model SAFRAN. The expert system MEPRA derives the avalanche danger from the modelled snow stratigraphy. It calculates snow ram hardness and various stability indices and in combination with expert rules predicts the release probability for natural and skier triggered avalanches (Giraud and Navarre, 1995).

The snow cover model SNOWPACK calculates snow stratigraphy for the locations of automatic weather stations. Based on shear frame measurements by Jamieson and Johnston (2001) snow strength is estimated per layer depending on snow density and grain type. Comparing the strength to the overlaying load two static stability indices are calculated. A third index depends on the rate of deformation (Lehning et al., 2004). Two case studies showed that there is in general fair agreement between model results and observations (Nishimura et al., 2005). However, so far no systematic verification has been done.

Whereas the skier stability index as introduced by Föhn (1987) and refined by Jamieson and Johnston (1998) is closely related to avalanche activity, the natural stability index is a poor predictor for spontaneous releases. Recently, it has been pointed out that in addition to mechanical stability, there are snowpack layer properties that are clearly related to snowpack instability (McCammon and Schweizer, 2002). These indicators of structural instability are mainly grain size and hardness and their differences across layer interfaces (Schweizer and Jamieson, 2003, 2006).

The aim of the present study is to verify the stability prediction and possibly improve it by introducing structural instability information. As grain size, snow hardness and density are crucial input data for the stability assessment they are verified first with the help of detailed manual snowpack observations. Predicted snowpack stability is compared with the results of stability tests and observed snowpack stability data collected during specific verification periods.

2. Methods

The one-dimensional snow cover model SNOWPACK numerically solves the 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,b). The finite elements building up the snow cover are typically at most a few centimeters thick, i.e. usually thinner than manually observed layers. To speed up the numerical calculation, thinner elements may be merged with adjacent elements, provided the properties of both elements are close enough. Furthermore, several elements may be grouped together into layers for visualisation purposes, if their snow type is very similar. However, both procedures do not smooth out the discontinuities that are crucial for slab avalanche formation. For the Swiss avalanche forecasting service, the snow cover model SNOWPACK operationally assesses the new snow amount, snow accumulation by wind and snow stratigraphy at about 85 automatic weather stations (Lehning et al., 1999).

Snow metamorphism is described in terms of changes in dendricity, sphericity (Brun et al., 1992; Fierz and Baunach, 2000), grain size and bond size (Baunach et al., 2001), and then classified for the graphical output into the grain types as described in Colbeck et al. (1990). Snow density follows from snow settlement which depends on compactive viscosity which is affected by the metamorphic processes. The initial new snow density was estimated statistically from measurements at the experimental site Weissfluhjoch (2540 m a.s.l.) (Lehning et al., 2002b).

Snow hardness was determined from snow density and grain type (Geldsetzer and Jamieson, 2001). Hardness was analyzed using the hand hardness index R from 1 to 6 for Fist (F), Four-finger (4F), One-finger (1F), Pencil (P), Knife (K) and Ice (I), respectively.

Lehning et al. (2004) introduced a stability estimation providing three stability indices for a model profile at a flat location. In the following, we will only consider the skier stability index since it is well related to human triggered avalanche activity which causes most fatalities.

Following Jamieson and Johnston (1998) the skier stability index SK_{38} is extrapolated on a 38° slope from measurements — and in our case from simulations — in a flat study plot. It is defined for a given depth h (measured vertically from the snow surface) as

$$SK_{38} = \frac{\tau_{\mathrm{I,II}}}{\tau_{\mathrm{xz}} + \Delta\tau_{\mathrm{xz}}} \tag{1}$$

where τ_{I} and τ_{II} are the shear strength for non-persistent and persistent grain types, respectively (Jamieson and Johnston, 1998), τ_{xz} is the shear stress due to weight of the overlaying slab layers $\tau_{\mathrm{xz}} = \rho\, g\, h \sin\psi \cos\psi$ (with ρ : average slab density, ψ slope angle, and g : acceleration due to gravity) and $\Delta\tau_{\mathrm{xz}}$ is the additional shear stress due to a skier modelled as a line load (Föhn, 1987). For a skier on a 38° slope, and considering ski penetration, P_{K}, the additional shear stress $\Delta\tau_{\mathrm{xz}}$ (in Pa) simplifies to $155/(h - P_{\mathrm{K}})$ where h and P_{K} are in meters. We use the microstructure-dependent normal load adjusted shear strength as described by Jamieson and Johnston (1998). Recently, Zeidler and Jamieson (2006) have proposed a microstructure-independent normal load adjustment. For the not normal load adjusted shear strength $\sum_{\mathrm{I}}$, $\sum_{\mathrm{II}}$ (in Pa), Jamieson and Johnston (2001) found for the non-persistent grain types (precipitation particles, decomposing and fragmented precipitation particles, and rounded grains):

$$\Sigma_{\mathrm{I}} = 14.5 \times 10^3 \left(\frac{\rho}{\rho_{\mathrm{ice}}} \right)^{1.73} \tag{2}$$

and for the persistent grain types (faceted crystals and depth hoar):

$$\Sigma_{\mathrm{II}} = 18.5 \times 10^3 \left(\frac{\rho}{\rho_{\mathrm{ice}}} \right)^{2.11}. \tag{3}$$

Jamieson and Johnston (1998) estimated ski penetration P_{K} from slab density ρ_{30} at $h=0.3$ m, $P_{\mathrm{K}}=42.4/\rho_{30}$. In the primarily transitional snow climate (McClung and Schaerer, 1993) of the Swiss Alps ski penetration is about 10–20 cm. Therefore, we estimated ski penetration from the mean slab density of the upper 30 cm of the snow cover $\overline{\rho}_{30}$, $P_{\mathrm{K}}=34.6/\overline{\rho}_{30}$. For layers of buried surface hoar, the shear strength was estimated with a statistical relation (Lehning et al., 2004) based on an analysis by Chalmers and Jamieson (2001).

Accordingly, the skier stability index can be calculated for any depth h in the snow cover. If this is done from the snow surface to the bottom layer, the minimum value should indicate the most critical instability where a skier might trigger a slab avalanche. Therefore, the model provides a critical depth and an accompanying stability value. For the critical depth, values up to 1 m below the penetration depth were considered. For layers deeper than about 1.2 m triggering is assumed to be not probable (Schweizer and Jamieson, 2001).

To take into account structural instability, the threshold sum approach introduced by McCammon and Schweizer (2002) and refined by Schweizer and Jamieson (2006) was combined with the skier stability index SK_{38}. For each layer boundary, the resulting stability index SSI was defined as:

$$\mathrm{SSI} = \mathrm{SK}_{38} + D \tag{4}$$

with

$$D = \begin{cases} 0 \text{ if } \Delta R \geq 1.5 \text{ and } \Delta E \geq 0.5\text{mm} \\ 1 \text{ if } \Delta R < 1.5 \text{ or } \Delta E < 0.5\text{mm} \\ 2 \text{ if } \Delta R < 1.5 \text{ and } \Delta E < 0.5\text{mm} \end{cases} \tag{5}$$

where ΔR is the hardness difference (in absolute value) and ΔE is the grain size difference (in absolute value) between the two adjacent layers. The threshold values were estimated based on the threshold values found by Schweizer and Jamieson (2003) and on characteristics of the model SNOWPACK. To calculate the skier stability index SK_{38} at each layer boundary, the shear strength, which is a layer property, was estimated from the properties (density, grain type) of either the layer above or below the interface, depending on which layer had the lower shear strength.

An overall assessment — a profile-by-profile comparison — as previously used (Lundy et al., 2001) was not sufficient for our purpose, since by applying this procedure various discrepancies might balance each other and thus remain undetected. On the other hand, a direct, layer-by-layer comparison between observed and modelled profiles was not feasible since this requires an almost full agreement between simulated and observed layer depth and thickness. Instead, we compared the distributions of the snow layer characteristics and used the non-parametric Mann–Whitney U-test to decide whether there was a difference between model and observation. To compare several samples the H-Test was used. Differences between the samples were judged to be statistically significant where the level of significance is $p<0.05$ (Spiegel and Stephens, 1999).

3. Data

For verification two data sets were used. The first included 141 manual snow profiles, about half observed at the experimental site Weissfluhjoch during the winters of 1995–1996 to 2003–2004 (69 profiles) and the other half in the surroundings of Davos during the winters of 1996–1997 to 2003–2004 (72 profiles). These profiles were used to compare modelled snow layer characteristics (grain type, grain size, snow density and hardness) with observed ones. Overall, about 1680 observed layer characteristics were available. These observations were compared with a dataset of 280 simulated profiles with in total about 10,000 layers. The simulated profiles covered about the same winter times and area as the observed ones.

To assess the stability performance the modelled stability information for 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.) was compared to the regional snowpack stability as verified on 10 days during the winters of 2001–2002 and 2002–2003. At these dates several teams collected snowpack data to verify the regional avalanche danger in the surroundings of the four weather stations (Schweizer et al., 2003b). The manual snow profiles were classified into five stability classes (Schweizer and Wiesinger, 2001) and the regional mean was compared to the stability output of SNOWPACK. In total, the second data set included 33 regional stability ratings for 10 days. In other words, a stability rating was not available for each day and for all four regions surrounding one of the four automatic stations where the snow stratigraphy was modelled. For analysis, the originally five stability classes were condensed into three classes (poor, fair, good) by grouping very poor and poor, and good and very good.

4. Results

4.1. Snow density

Snow densities were compared per grain type. Only the primary grain type was considered and the analysis confined to 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). Fig. 1 shows that the modelled density was substantially higher than the observed density for the rounded grains, and slightly lower for the persistent grain types. All three differences were found to be statistically significant (*U*-test).

4.2. Grain size

Observations show the well known trend of decreasing average grain size (greatest extension of particle) with conditions of equilibrium metamorphism — with a minimum for rounded grains — and increasing grain size with conditions of kinetic growth metamorphism (Fig. 2). Observed grain size is the lower bound of the range traditionally given by Swiss observers which coincides with the average grain size (Baunach et al., 2001). Modelled grain sizes show a quite different behaviour. Due to the initial size assigned to precipitation particles (0.3 mm), the modelled grain sizes continuously increased from one grain type to the other. For none of the grain types there was agreement between observation and modelling (*U*-test).

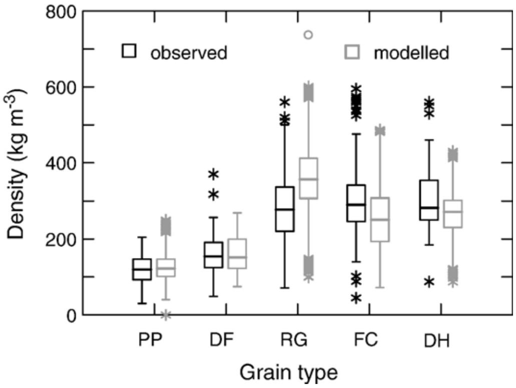

Fig. 1. Observed (left) vs. modelled (right) density distributions per grain type (PP: precipitation particles, DF: decomposing and fragmented precipitation particles, RG: rounded grains, FC: faceted crystals, DH: depth hoar). Boxes span the interquartile range from 1st to 3rd quartile with a horizontal line showing the median. Whiskers show the range of observed values that fall within 1.5 times the interquartile range above and below the interquartile range. Asterisks show outliers, open dots show far outside values.

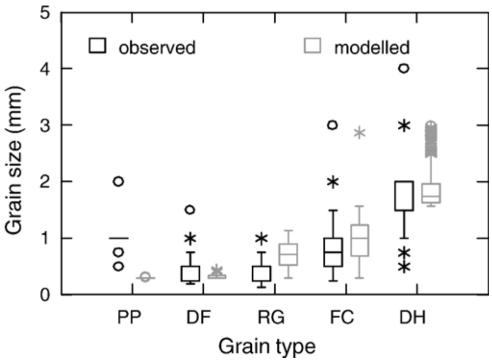

Fig. 2. Observed (left) and modelled (right) grain size distributions per grain type (grain types and box plots as in Fig. 1).

4.3. Hardness

Snow hardness as manually estimated from penetration resistance is a fairly subjective measure. Observed hardness increased from precipitation particles to small rounds in accordance with the ongoing settlement process. The more coarse grained layers of faceted crystals and depth hoar had lower hardness than the fine grained

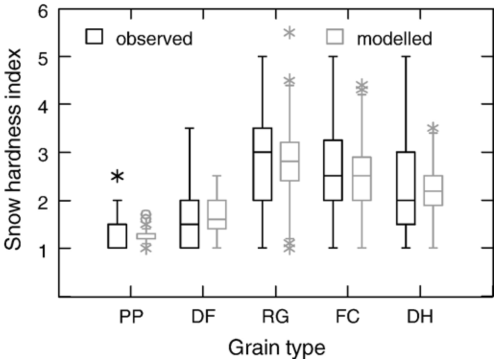

Fig. 3. Observed (left) vs. simulated (right) snow hardness index distributions per grain type (grain types and box plots as in Fig. 1). Hardness is given as hand hardness index from 1 to 6 for Fist (F), Four-finger (4F), One-finger (1F), Pencil (P), Knife (K) and Ice (I), respectively.

Table 1
Linear regression results for the snow hardness index R on density ρ per grain type using the Swiss observations ($R=A+B\rho$, $N=1679$, r^2 is the coefficient of determination). For each grain type the range of density is given (central 90% of the values). Grain types are PP: precipitation particles, PPgp: graupel, DF: decomposing and fragmented precipitation particles, RG: rounded grains, FC: faceted crystals, FCmx: mixed forms, DH: depth hoar

Grain type	Density (kg m^{-3})	A	B	N	r^2
PP	30 – 205	0.79	0.0036	29	0.17
PPgp	85 – 315	0.0078	0.011	10	0.67
DF	82 – 227	0.50	0.0074	144	0.32
RG	146 – 400	0.20	0.0072	467	0.58
FC	188 – 425	0.39	0.0083	460	0.38
FCmx (4c)	250 – 445	−0.52	0.010	488	0.43
DH	190 – 449	−0.025	0.0072	81	0.35

layers of small rounded grains (Fig. 3). With the hardness parameterisation derived from Canadian data (Geldsetzer and Jamieson, 2001) the modelled hardness index was strongly overestimated for all grain types compared to the observations. This discrepancy is not surprising as it has been previously reported (McClung and Schaerer, 1993) that the pushing force typically applied for hand hardness in North America is less than 50 N which is the force given in the ICSSG (Colbeck et al., 1990).

Therefore, a new parameterisation was sought using the Swiss data (141 manual profiles). A multivariate statistical regression analysis for snow hardness index per grain type using snow density and grain size as independent variables was performed. Since including grain size did not improve the agreement between simulated and observed hardness, grain size was not considered for further analysis. Though the new parameterisation using the Swiss data performed better than the previously used parameterisation (based on Canadian data), the agreement was still poor. Snow hardness for rounded grains was overestimated, and for faceted crystals and depth hoar was underestimated. This result followed directly from the density differences between observations and model (Fig. 1). To improve the agreement, the linear regression relations were adjusted by scaling the simulated densities to the observed ones (Table 1). Fig. 3 shows good agreement between the median values of observed and modelled hardness. The distributions for the grain types PP and DF were still significantly different ($p<0.001$ and $p=0.03$, respectively). Contrasting the distributions for the grain types RG,

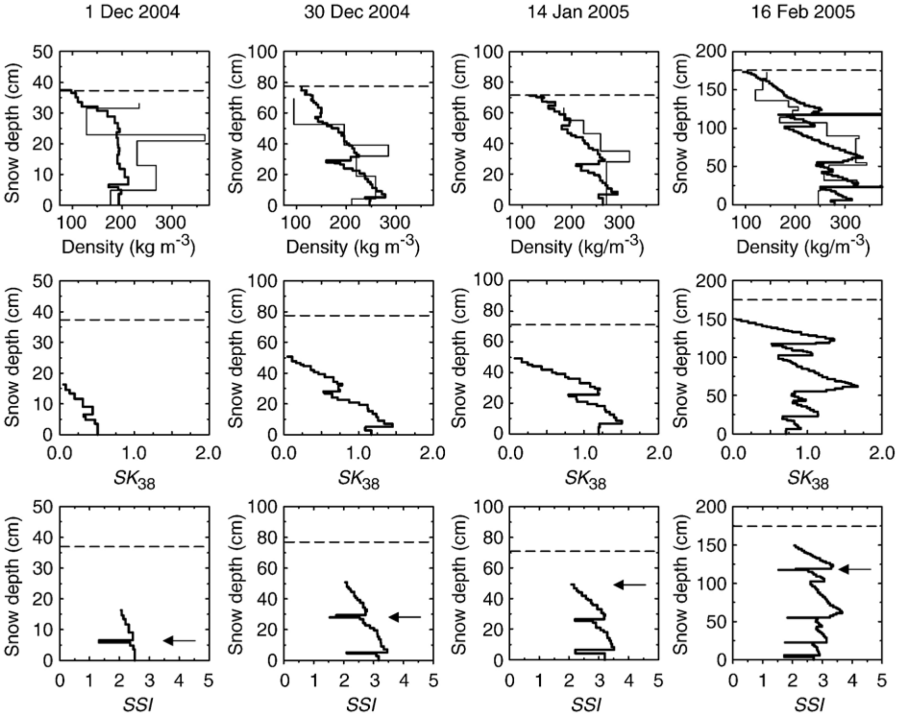

Fig. 4. Development of density (top row), skier stability index SK_{38} (middle row) and stability index SSI with snow depth for four dates in winter 2004–2005 at the experimental site Weissfluhjoch. For snow density, model results (bold) and observations are shown. The modelled snow depth is indicated by a dashed horizontal line. Differences in snow depth between modelled and observed density (top row) are mainly due to a small difference in location between the automatic weather station and the manual pit observation. The difference between the snow depth and the location of the first value of the indices corresponds to the penetration depth. The arrows point to the location of the potentially most critical weak layer.

FC and DH showed no significant differences ($p = 0.72$, 0.88 and 0.30, respectively).

4.4. Stability

The skier stability index SK_{38} (Eq. (1)) performed poorly in terms of identifying potential critical weaknesses in the simulated snow stratigraphy. Since the density generally increased with increasing snowpack depth, the skier stability index increased as well with increasing depth (Fig. 4). Therefore, the location of the minimum of the skier stability index that should coincide with the location of the most critical potential weakness, was almost always near the snow surface, just below the penetration depth. However, secondary minima indicated potential weaknesses.

4.5. New stability formulation

In order to overcome the above described problem with the skier stability index SK_{38}, the new formulation considering structural information (Eqs. (4) and (5)) was introduced. The location of the minimum of the stability index SSI was in general deeper in the snowpack than the location of the minimum of the stability index SK_{38}. Even deep instabilities were recognised. Fig. 5 shows the critical depth determined as the location where the SSI was minimal during the course of winter 2001–2002 for the Weissfluhjoch experimental site. There was fair agreement with observations indicated in Fig. 5 by the locations of weak layers identified by compression tests. The improvement compared to the SK_{38} is obvious. Also with the new formulation the model identified layer boundaries as weaknesses and minimum stability was no longer found within layers (layers that were condensed for visualisation proposes). Abrupt changes in critical layer depth as can be seen in Fig. 5 occurred in situations when two critical weak layers were present with similar value of the SSI. In that case, small changes of the stability index SSI caused a change in location of the minimum from one layer to the other.

Finally, we compared the stability output of the snow cover model SNOWPACK, SK_{38} and SSI, for the depth of the potentially most critical weakness (as identified by the location of the minimum SSI), to the observed

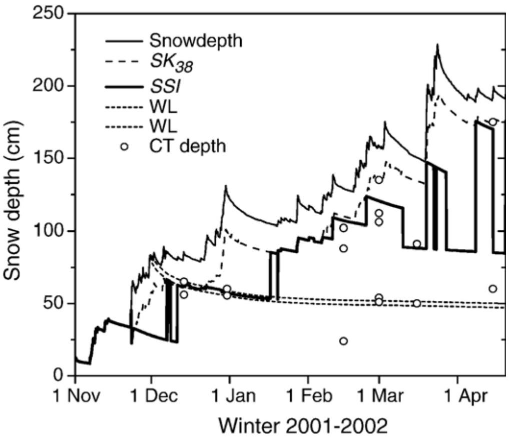

Fig. 5. Development of the location of the critical weakness as identified by the location of the minimum of (a) the skier stability index SK_{38} (dashed line) and (b) the stability index SSI (bold solid line) during the winter 2001–2002 for the Weissfluhjoch experimental site. The thin solid line shows the snow depth. Circles indicate the locations of critical weaknesses as found by compression tests. The dotted lines indicate the locations of two weak layers observed to be critical during the first half of the winter 2001–2002.

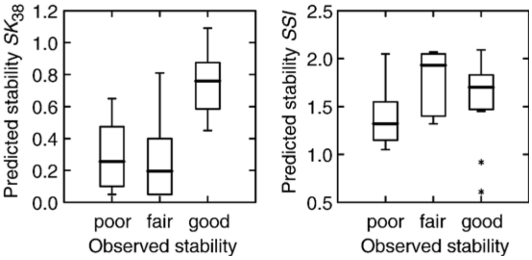

Fig. 6. Comparing predicted to observed regional stability for 10 days during the winters of 2001–2002 and 2002–2003. Predicted stability indices are the SK_{38} (left) and the SSI (right) calculated for the locations of four weather stations in the surroundings of Davos (Switzerland). Observed stability is based on assessing manual snow profiles from slopes in the vicinity of the stations ($N = 33$).

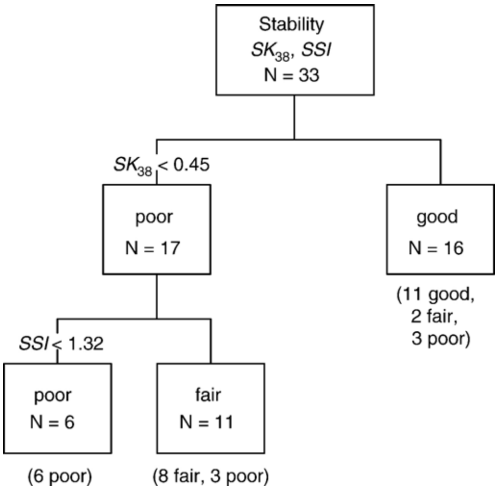

Fig. 7. Classification tree model for stability classification. Simulated snow stratigraphy was classified into three classes of stability (poor, fair, good) using the stability indices SK_{38} and SSI.

(verified) regional stability. The comparison of predicted to observed stability is shown in Fig. 6. The results of a non-parametric *H*-test indicated that the SK_{38} and the SSI can be used to classify simulated snow cover stratifications in regard to stability into three classes of poor, fair and good ($p<0.001$ and $p=0.03$, respectively). However, Spearman rank-order correlation coefficients between predicted and observed stability were 0.57 for SK_{38} and 0.30 for SSI. The latter correlation was statistically not significant. As indicated by the box plots, the SSI seems to discriminate well between poor and the group of fair and good stability. On the other hand, the SK_{38} seems to discriminate well between the group of poor and fair, and good stability. Therefore we tried to use both variables (SK_{38}, SSI) to derive a stability classification. A classification tree analysis revealed the following two split values (Fig. 7):

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. The number of false stable predictions could be substantially reduced by manually adjusting the split values to $SK_{38}<0.66$ and $SSI<1.66$. With these split values the stability was generally underestimated and the overall not cross-validated accuracy decreased to about 70%.

Alternatively, instead of the SSI index, *D* (Eq. (5)) could be used together with the SK_{38} as input variables for the classification tree. With these independent variables the same split values and accuracy would result.

Using either the SK_{38} or the SSI individually, classification into three stability classes was not successful. Major discrepancies between predicted and observed stability were found when no critical differences in grain size and hardness existed in the upper parts of the snowpack, occasionally this was the case after a major snow fall.

5. Conclusions

The performance of the snow cover model SNOWPACK was verified in regard to density, grain size, hardness index and stability. Snow density was 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. Significant differences between modelled and observed grain sizes were found. This result follows partly from largely unknown initial conditions as well as from the classification based on sphericity, dendricity and grain size which needs to be revisited. By using a new Swiss data set for the parameterisation of the snow hardness index a much better agreement between modelled and observed snow hardness could be reached. However, this indicates that there might be substantial differences in estimating the snow hardness index between Canada and Switzerland. Accordingly, if the model would be run in Canada adaptations would be needed.

Since we focussed on human triggered avalanches we only evaluated the skier stability index and did not consider the other two stability indices introduced by Lehning et al. (2004). The skier stability index is usually applied on manually selected weak layers. These layers are identified in mechanical snowpack tests or manually observed snow profiles. If the skier stability index SK_{38} was applied to all SNOWPACK layers, it performed poorly in terms of identifying potentially critical weaknesses. The minimum value was usually found in the surface layer and deeper, persistent weak layers were not recognized.

For this reason, the if–then rules (Eq. (5)) were introduced to assist with the selection of the potentially critical weak layers. In addition, Eq. (4) gives particular weight to layer boundaries where there are differences between adjacent layers in hardness and grain size. With this new stability formulation (SSI) that takes into account structural instability, a better agreement between observation and simulation could be reached. Critical weak layers which were a concern for avalanche forecasting during much of the test winter could be identified. Predicted stability (SK_{38}) calculated for the location of automatic weather stations (flat fields) was significantly related to verified regional stability as assessed from manual profiles from 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 accuracy of the stability classification was about 76%. However, the model overestimated stability. The split values are preliminary and need to be adapted when more verification data will be available. 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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