Automatic classification of manual snow profiles by snow structure

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ABSTRACT: Manual snowpack observations are an important component of avalanche hazard assessment for the Swiss avalanche forecasting service. Approximately 900 snow profiles are observed each winter, in flat study plots or on potential avalanche slopes. So far, these profiles are manually classified combining both information on snow stability (e.g. Rutschblock test) and snowpack structure (e.g. layering, hardness). To separate the classification of snowpack stability and structure, and also to reduce inconsistencies in ratings between forecasters, we developed and tested an automatic approach to classify profiles by snowpack structure during two winters. The automatic classification is based on a calculated index, which consists of three components: properties of (1) the slab (thickness), (2) weakest layer interface and (3) the percentage of the snowpack which is soft, coarse-grained and consists of persistent grain types. The latter two indices are strongly based on criteria described in the threshold sum approach. The new snowpack structure index allows a consistent comparison of snowpack structure to detect regional patterns, seasonal or inter-annual differences but may also supplement snow-climate classifications.

KEYWORDS: Snowpack structure, avalanche forecasting, snow profile analysis

1 INTRODUCTION

Snowpack information is, among other data, one important source for assessing the avalanche danger. Snowpack observations ideally incorporate observations on snow stratigraphy, failure initiation and crack propagation (McCammon and Sharaf, 2005). Characteristics of the snowpack layering are crucial to the failure initiation (strength, e.g. observed with the Rutschblock score; Föhn, 1987) and the crack propagation process (toughness, e.g. observed with the Rutschblock release type; Schweizer et. al., 2008). Both, properties of weak layer or layer interfaces and the slab overlying a weak layer, play a role in the fracture process necessary for dry-snow slab avalanches (van Herwijnen and Jamieson, 2007; Sigrist and Schweizer, 2007).

1.1 Snowpack observations and classification scheme currently in use in Switzerland

In Switzerland, snowpack structure is regularly being investigated in the extensive observation program. Manual snow profiles are observed by SLF observers twice a month on level study plots (mostly below treeline) and on potential avalanche slopes (mostly above treeline). This information provides an invaluable source for the avalanche forecasters to assess snowpack structure (e.g. presence and regional distribution of weak layers) and of snow stability (slope profiles only).

These profiles are manually classified according to the classification scheme introduced by Schweizer and Wiesinger (2001). This scheme, called hereafter $stab_{01}$, allows considerable room for a subjective interpretation of snow stability. Some of the key parameters defining the stability class (1 – very poor to 5 – very good) assigned to a profile are the Rutschblock score and release type (e.g. Föhn, 1987; Schweizer, 2002), presence of weak layers and layer interfaces, presence and hardness of slab or weak layers and the profile type.

This $stab_{01}$-classification approach combines information on snow stability (e.g. Rutschblock score) and snowpack structure, although Rutschblock information generally has a much higher weight and overrules profile type (Schweizer and Wiesinger, 2001). Profiles not containing a stability test, as those in flat study plots (which are about 30% of all profiles), are not classified.

However, from the warning service perspective it was felt necessary to

- differentiate between snowpack structure and snow stability information
    - snow stability is relevant in the short term and is described twice daily in the avalanche bulletin, snowpack weaknesses may be found within the new snow or

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storm snow but also in persistent weak layers deep in the snowpack
- snowpack structure is of interest particularly in the long-term (base for new snow, structure before wetting), here the focus is on persistent weaknesses

- have a systematic, consistent and objective index of snowpack structure relevant to avalanche forecasting facilitating the spatial and temporal analysis of snowpack observations and reducing discrepancies between different forecasters' subjective snow profile rating
- increasing the number of profiles available for analysis by including profiles without stability information
- reduce the workload necessary for manual classification of snow profiles

In this paper we introduce an automatic snowpack structure classification for manual snow profiles based on slab and weak layer properties.

1.2 Unfavourable snowpack structure

Many skier-triggered and fatal avalanches release in so-called persistent weak layers (e.g. Schweizer and Lütschg, 2001). The distinction between persistent and non-persistent weak layers is based on grain type (persistent weak layers: grain types following temperature-gradient metamorphism as surface hoar, facet, depth hoar, Jamieson and Johnston, 1998) or a combination of snowpack and avalanche observations (Haegeli and McClung, 2007) where a persistent weakness is one which was still active 10 days after its formation (avalanche activity).

Several studies compared stable and unstable snowpack conditions - generally profiles in slopes which were not triggered by skiers vs. those who were triggered or where signs of instability like whumpfs, shooting cracks and recent avalanching were observed (e.g. Simenhois and Birkeland, 2006; Winkler and Schweizer, 2009). The focus in these studies was generally on snow stability (stability tests). However, snowpack information was also investigated. One important result was the threshold sum approach (TSA, e.g. Schweizer and Jamieson, 2007), which describes typical ranges of snowpack parameters associated with snow instability (Table 1).

Tab. 1: Relevant snowpack criteria described in the threshold sum approach (Schweizer and Jamieson, 2007, in North America often called 'lemons'*).*

Variable		**Critical range**
Layer	hardness	≤ 1.3
	grain size	≥ 1.25
	grain type	persistent
Layer interface	difference in grain size (mm)	≥ 0.75
	difference in hardness	≥ 1.7
	slab thickness or failure layer depth (cm)	18…94

Slab properties also play a fundamental role in crack propagation (van Herwijnen and Jamieson, 2007). The slab is generally defined as the layer which slides in an avalanche or a stability test above a weak layer. Slab properties related to skier-triggering of dry-snow slab avalanches include layering within the slab, grain type, thickness, density and hardness, but also the differences between slab and weak layer (e.g. Schweizer and Lütschg, 2001; van Herwijnen and Jamieson, 2007; Habermann et al., 2008).

2 DATA AND METHODS

Snow profile observations in Switzerland incorporate the recording of location, slope aspect and angle. The investigated snow layering information consists of: snow depth; thickness, hardness, grain shape, grain size and wetness of each layer. Snow temperatures are measured in 10 cm increments. Often, a ram profile accompanies the snow profiles. Snow water equivalent is measured in flat study plots, while on potential avalanche slopes a stability test, generally the Rutschblock test (Föhn, 1987) complements the snow profile observations.

To develop an objective snow structure index, we randomly selected in a first step 258 profiles from the SLF snow-profile data-base (profiles with poor recording quality were rejected) and asked 9 experienced (current and previous) SLF avalanche forecasters to rate the snowpack structure solely based on layering information (excluding information on location and snow stability, also removing any text). Snowpack structure was classified from 1 (unfavorable snowpack) to 5 (favorable snowpack). Each profile was assessed by at least 2 and up to 4 forecasters. For further analysis, we used the mean snowpack structure rating for each profile, hereafter called $SNPK_{manual}$. Snowpack parameters were compared to $SNPK_{manual}$, but also to snowpack characteristics related to unstable snow conditions and dry-snow slab avalanche release. As the $SNPK_{manual}$ was based on layering information only – no stability test identified the slab and the relevant weak layer – the slab was defined as all layers above the persistent weak layer closest to the surface but with a minimum depth of 15 cm. The value of 15 cm was chosen as a minimum threshold for a relevant slab depth and corresponds closely to the TSA approach (Table 1). An overview of some of the most relevant investigated parameters is shown in Table 2.

In a second step, we used the non-parametric Spearman rank order correlation testing for a monotonic relationship (Crawley, 2007) and conditional inference trees (R package party, Hothorn et al., 2006) to investigate which properties are most relevant for snowpack structure classification. Results were considered significant if the level of significance $\alpha \leq 0.05$.

Finally, we developed a snow structure index incorporating some of the most relevant variables describing slab, weak layer and layer interfaces.

In this paper we present the most important variables and the index itself.

3 RESULTS

3.1 Snowpack structure index

Based on correlation and regression analysis In a second step we developed a continuous descriptive variable describing snowpack structure. One of the requirements for this index was that it incorporates information relevant to dry-snow slab avalanche initiation and propagation. Thus, we forced the index to contain at least one parameter describing the slab, weak layer interfaces and layer properties. Selection criteria to obtain the most suitable three parameters were:

(a) a strong correlation to the manual snowpack structure classification and
(b) preferably, no correlation between the selected variables.

As all variables contributing to snowpack structure were significantly correlated to each other, we selected those with the lowest correlation between each other. To combine several parameters with different units or ranges of values, the parameters had to be standardized.

About one dozen parameter combinations were tested, most of them performing with rather similar quality and only marginally better than using only one or two parameters. However, us-

Table 2: Selection of the most important snowpack parameters, which are used for the snowpack structure index.

variable		**definition**
layer threshold sum	TSA.layer	proportion of the snowpack which fulfills either one of the TSA layer criteria (Table 1), repeated for all 3 criteria and added up; grain size and grain type criteria only counted if hardness ≤ 3. Using just layers with hand hardness < 3 is based on results by van Herwijnen and Jamieson, 2007 which showed that avalanche failure planes were not harder than hand hardness 3.3. $SUM\ (x(IF\ hand\ hardness\ criteria\ =\ YES), x(IF\ grain\ type\ criteria\ =\ YES), x(IF\ grain\ size\ criteria\ =\ YES\ AND\ IF\ hand\_hardness\ < 3))$ where x is layer thickness
layer interface threshold sum	TSA.max	TSA for layer interface with maximum score
Slab thickness	$depth_{slab}$	all layers above the persistent weak layer closest to the surface, but at least 15 cm below surface; if no persistent weak layer than slab = full snow-depth

ing three parameters reduced the bias in the classification error with a similar number of profiles classified better or worse than the manual classification. For the presented index, we chose relatively basic criteria, which are either relatively easy to calculate (e.g. slab thickness) and/or are based on existing snowpack assessment procedures (threshold sum approach, Table 1).

The calculation of the index consists of three parts:

(1) The first part of the index $TSA.layer_{index}$ describes the proportion of the snowpack which is very soft and/or coarse-grained and/or consists of persistent grain type (see Table 1, Table 2).

$$\frac{\mathrm{TSA.layer}}{3 * \mathrm{hs}}$$

(2) The second part of the index uses the maximum value of the threshold sum approach for layer interfaces $TSA.max_{index}$ (Table 1)

$$\frac{\mathrm{TSA.max}}{6}$$

(3) The third part of the index $slab.depth_{index}$ incorporates a slab parameter, the standardized slab depth.

$$-\left(\left\lceil\frac{\mathrm{slab_{thick}} - 30}{170}\right\rceil - 1\right)$$

The slab thickness is standardized to values between 1 (thickness 30 cm which corresponds roughly to the median of slab thickness (32.5 cm) for $SNPK_{manual}$ class 1 and is similar to slab thickness values described in van Herwijnen and Jamieson (2007) and 0 (thickness 200 cm which corresponds to median of slab thickness for $SNPK_{manual}$ class 5). $Depth_{slab}$ which is less than 30 cm (or greater than 200 cm) are accordingly assigned $slab.depth_{index}$ of 1 (or 0). The $SNPK_{index}$ is then calculated as (Fig. 1):

$$SNPK_{index} = TSA.layer_{index} + TSA.max_{index} + slab.depth_{index}$$

The $SNPK_{index}$ is strongly correlated to $SNPK_{manual}$ (ρ=0.79, $p<10^{-16}$, Fig. 2). Using the classification tree method results in significant splitting thresholds for all five $SNPK_{manual}$ classes (Tab. 3).

Applying the obtained splitting thresholds to the data, 64% of profiles are correctly classified, 32% ±1 class and 4% ±2 classes. An almost equal number of profiles are classified higher or lower than $SNPK_{manual}$.

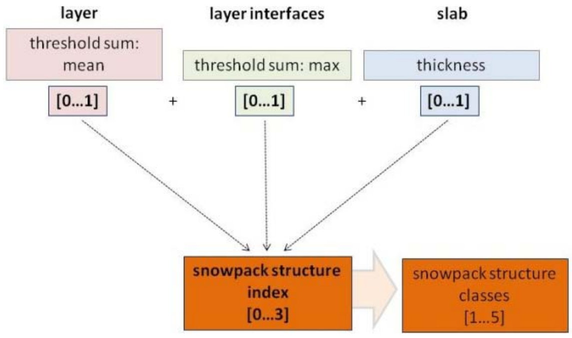

Fig. 1: Components of snowpack structure index and classification in snowpack structure classes using the thresholds shown in Table 5.

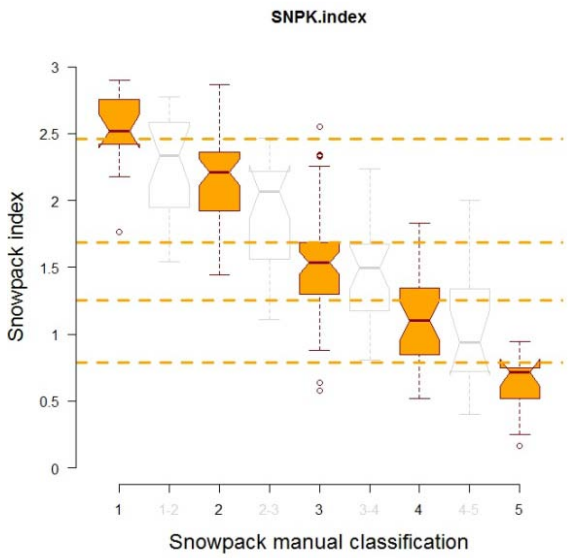

Fig. 2: Boxplot showing the snowpack index and the manually classified snowpack structure (1-unfavorable to 5-favorable). Using the shown splitting thresholds (orange lines) between full classes (orange boxplots) results in 64% of profiles being classified correctly, 32% ±1 class and 4% ±2 classes. The correlation between the index and the manual classification (including intermediately classified profiles) is strong (ρ=0.79, p< 10^{-16}).

Tab. 3: $SNPK_{index}$ thresholds for the snowpack structure classification in five classes (1-unfavorable to 5-favorable).

Between classes	**$SNPK_{index}$ threshold**
1 – 2	2.462
2 – 3	1.687
3 – 4	1.254
4 – 5	0.788

Tab. 4: Manual classification of snowpack structure ($SNPK_{manual}$) and calculated snowpack structure index ($SNPK_{index}$) for the profiles shown in Fig. 3. Additionally the class corresponding to the index thresholds is shown ($SNPK_{index}$ class)

	A1	A2	A3	A4	B1	B2	C1	C2	D1	D2	D3
$SNPK_{manual}$	5	4	2	5	2	3	1-2	3-4	2	3	5
$SNPK_{index}$	1.15	1.65	2.12	0.99	2.18	1.58	2.16	1.34	2.09	1.59	1.45
$SNPK_{index}$ (class)	4	3	2	4	2	3	2	3	2	3	3

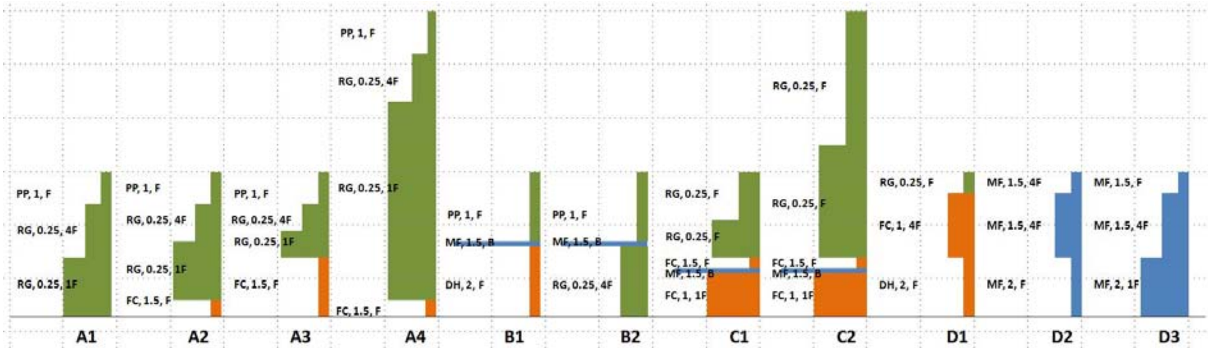

Fig. 3: Simplified snow profiles. The hand hardness profile is shown with the main grain type (color) indicated. Profile A1 has no persistent weaknesses, while profiles A2 to A4 have similar slab layering but with a persistent weak layer and slab combination. Profiles B1 and B2 contain melt-freeze-crusts in a otherwise rather soft snowpack. C1 and C2 contain a prominent persistent weakness below a slab of varying thickness. Profiles D1 (dry) to D2 and D3 (wet) are examples of typical spring snowpack type evolution. The index was calculated with a snow depth of 2 m for profiles A4 and C2, otherwise with 1 m. Layer properties (text) are given for each layer in the following order: grain type, grain size (mm), hand hardness. Abbreviations are according to Fierz et al. (2009).

3.2 Examples

Using some examples of different simplified snow profiles, we demonstrate how the index compares to the forecasters rating of snowpack structure (Tab. 4, Fig. 3).

4 CONCLUSIONS AND OUTLOOK

We have developed an automatic snowpack classification algorithm, which considers slab, weak layer and weak layer interface properties as observed in manual snow profiles. The main advantage of the index is the automatic, objective classification of snowpack structure in regard to dry-snow slab avalanche release. Like any statistical approach, the index has its limitations: about two thirds of the profiles were classified in the same class as the manual snowpack structure assessment. However, only very few profiles were totally misclassified. Also, the index has no bias towards a better or worse classification. While the index is an objective approach to classify snowpack structure, it must be kept in mind that it relies on subjective observations (particularly hand hardness, grain type and size are observer dependent).

Currently, the classification is used operationally by the Swiss avalanche forecasting center in the following way:

- class thresholds are used for color coding and interpretation of the index (Fig. 4)
- index values are used for inter-annual comparison (Fig. 4, insert upper right corner)

The snowpack structure index provides a simple method to include snowpack information relevant to dry-snow slab avalanche release to gain a spatial overview of current snowpack structure and to illustrate the temporal development. It may also be used for historical analysis of avalanche events or for snow-climatological investigations. Using the adjusted threshold sum approach for a simulated snowpack (Monti et. al. 2012), it might be possible to use a similar index on modeled snow profiles such as the snowpack simulation SNOWPACK. This could increase the information density regarding snowpack structure information for avalanche forecasting services.

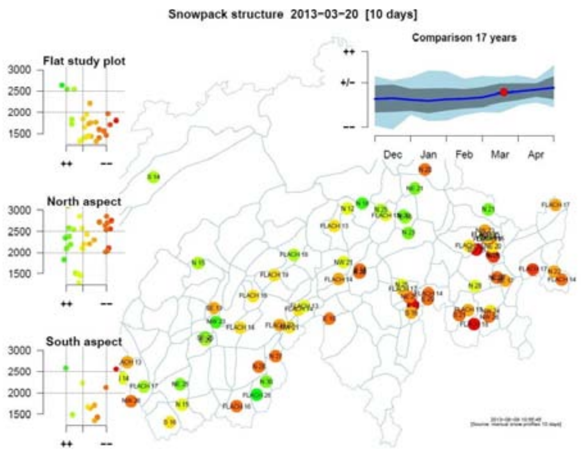

Fig. 4: Bi-weekly map of Switzerland showing snowpack structure (main graph), according to aspect and elevation (inserts on left side of plot) and pluri-annual comparison (insert on top right corner). Each point represents one profile. Color coding corresponds to the five classes calculated from SNPK$_{index}$. (Red: unfavorable; yellow – medium; green - favorable).

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