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Automatic classification of manual snow profiles by snow structure

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Automatic classification of manual snow profiles

F. Techel and C. Pielmeier

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 representative 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.

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 (e.g. van Herwijnen and Jamieson, 2007; Sigrist and Schweizer, 2007).

1.1 Unfavorable snowpack structure

Several studies compared stable and unstable snowpack conditions – generally profiles in slopes which were not triggered by skiers vs. those which 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, snow structure 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).

Slab properties also play a fundamental role in crack propagation leading to avalanche release (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).

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 grain types are those considered following temperature-gradient metamorphism as facets and depth hoar (Jamieson and Johnston, 1998) and also surface hoar

- a combination of snowpack and avalanche observations, where a persistent weakness is one which was still active 10 days after its formation (resulting in avalanche activity on this layer) (Haegeli and McClung, 2007)

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1.2 Snowpack observations and classification scheme currently used in Switzerland

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

These profiles are manually classified according to the stability classification scheme introduced by Schweizer and Wiesinger (2001), called hereafter stab_{01}. The stab_{01}-classification approach combines information on snow stability (e.g. Rutschblock score) and snowpack structure. Some of the key parameters defining the stability class 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. Profiles are classified from 1 (very poor) to 5 (very good). A more detailed overview is given in Schweizer and Wiesinger (2001). The stab_{01}-classification scheme is primarily a stability classification: Rutschblock information generally has a higher weight and overrules profile type or weak layer information (Schweizer and Wiesinger, 2001).

Profiles not containing a stability test, as those in flat study plots (which are about 30 % of all profiles), are therefore not classified. The classification scheme allows considerable room for a subjective interpretation of snow stability.
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 storm snow but also in persistent weak layers deep in the snowpack

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  - snowpack structure is of interest particularly in the long-term (base for new snow, structure before wetting), here the focus is on persistent weaknesses
- to 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
- to increase the number of profiles available for analysis by including profiles without stability information
- to reduce the workload necessary for manual classification of snow profiles

In this paper we investigate methods to automatically classify snowpack structure for manual snow profiles based on slab and weak layer properties.

2 Data and methods

Snow profile observations in Switzerland follow the international recording standard for snow profile observations (Fierz et al., 2009). 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 classification of snow structure, we randomly selected 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 based solely on layering information by excluding information on location and snow stability and removing any additional text information describing snow and avalanche conditions. Snowpack structure was classified from 1 (unfavorable) to 5 (favorable). 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 related to unstable snow conditions and dry-snow slab avalanche release were calculated from the layering information (Table 2). Calculated parameters included simple means or sums over the full profile, but of particular interest were properties providing weak layer and slab information. 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. A value of 15 cm was chosen as a minimum threshold for a relevant slab depth and corresponds closely to the TSA approach (Table 1). Grain shape was classified as persistent and non-persistent (Jamieson and Johnston, 1998) or melt form.

In a first step, we compared the existing classification ($stab_{01}$) with the manually classified snow structure ($SNPK_{manual}$) and stability information (Rutschblock test). For the latter, the Rutschblock result was classified in five classes by Rutschblock score and release type (RB_{stab}, Table 3).

To investigate the relevance of the snowpack parameters for the manual snow structure assessment, we used the non-parametric Spearman rank order correlation testing for a monotonic relationship (Crawley, 2007) and conditional inference trees (*ctree*, 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 $\alpha \leq 0.05$.

Based on the outcome of the uni-variate and multi-variate analysis, we developed a snow structure index incorporating some of the most relevant variables describing slab, weak layer and layer interfaces.

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3 Results and discussion

As both the Rutschblock test and snowpack criteria are important components of the existing $stab_{01}$-classification, it is not surprising that they are both correlated to $stab_{01}$ (RB_{stab} : $\rho = 0.65$, $SNPK_{manual}$: $\rho = 0.50$). The correlation between stability information (RB_{stab}) and manual snow structure classification ($SNPK_{manual}$), however, is significant but much weaker ($\rho = 0.33$).

The profile type classification (based on the ram hardness profile, Schweizer and Wiesinger, 2001), showed few associations to $SNPK_{manual}$. The two exceptions were: a profile which was very soft throughout was rated mostly as unfavorable and a profile which was very hard throughout was rated mostly favorable.

3.1 Snowpack variables related to manual snowpack structure classification

3.1.1 Univariate analysis

The calculated snowpack parameters were tested for their relevance to $SNPK_{manual}$ (Table 4).

Slab properties ($slab_{strength}$, $slab_{bridging}$, $slab_{thick}$) showed moderate to strong correlation ($\rho = [0.69, 0.72]$). Layer interface information (TSA_{max}) and weak layer information (wL_{prop}, TSA_{layer}) showed moderate correlation to $SNPK_{manual}$.

Many of the snowpack variables describing slab properties, weak layers or weak layer interfaces are moderately or strongly correlated to $SNPK_{manual}$. However, they all have some short-comings: for instance, slab properties are particularly suitable for discrimination of intermediate to favorable snowpack structure, while parameters related to weak layers and weak layer interfaces are most useful to distinguish between intermediate and unfavorable snowpack classes. Therefore, a combination of different parameters seems most plausible and is also consistent with previous research.

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3.1.2 Classification tree approach

Additionally to the correlation analysis, we used classification tree analysis to investigate which properties are most relevant to classify snowpack structure. A combination of slab properties ($slab_{strength}$, $slab_{bridging}$, $slab_{thick}$) and weak layer criteria (TSA_{layer}, p_{wL}), as well as the overall mean grain size, was most suitable for the classification of the snowpack structure. The classification accuracy of this classification tree was: 64 % of profiles classified correctly, 31 % ±1 class and 4 % ±2 classes.

3.1.3 Snowpack structure index

Further, we developed a continuous index variable for 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:

1. preferably, a strong correlation to the manual snowpack structure classification and

2. 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. For instance, the slab variables $slab_{strength}$ and $slab_{bridging}$ showed a marginally better correlation to $SNPK_{manual}$ than $slab_{thick}$ and were also selected by the classification tree analysis, but they showed a much stronger correlation to weak layer interfaces (TSA_{max}) and layer properties (TSA_{layer}) than $slab_{thick}$.

Also, for the presented index, hereafter called $SNPK_{index}$, we selected relatively basic criteria, which are easy to calculate (e.g. slab thickness) and/or are based on existing snowpack assessment procedures (in particular the threshold sum approach TSA, Ta-

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ble 1). Boxplots for the three selected parameters TSA_{layer}, TSA_{max} and $slab_{thick}$ are shown in Fig. 1.

To combine several parameters with different units or ranges of values, the parameters had to be standardized. About one dozen combinations of three different parameters were tested. Most of these combinations performed with similar quality and only marginally better than using only one or two parameters. However, using three parameters reduced the bias in the classification error with a similar number of profiles classified better or worse than the manual classification.

The calculation of the $SNPK_{index}$ consists of three separate calculations, each standardizing one parameter to values from 0 (favorable) and 1 (unfavorable):

1. The first part of the index describes the mean of the proportion of the snowpack which is very soft ($hard_{prop}$) and the proportion which is coarse-grained ($size_{prop}$) and the proportion which consists of persistent grain type (PG_{prop}) (see Tables 1 and 2), standardized by the number of the three components.

$$TSA_{layer_{index}} = \frac{TSA_{layer}}{3} \tag{1}$$

2. The second part of the index uses the maximum score of the threshold sum approach for layer interfaces, standardized by the maximum possible score.

$$TSA_{max_{index}} = \frac{TSA_{max}}{6} \tag{2}$$

3. The third part of the index incorporates a slab parameter, the standardized slab thickness.

$$slab_{depth_{index}} = \left| \frac{slab_{thick} - 30}{170} - 1 \right| \tag{3}$$

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, see also Fig. 1, right). $depth_{slab}$ which is less than 30 cm (or greater than 200 cm) are accordingly assigned a $slab_{depth_{index}}$ of 1 (or 0).

The $SNPK_{index}$ is then calculated as:

$$SNPK_{index} = TSA_{layer_{index}} + TSA_{max_{index}} + slab_{depth_{index}} \quad (4)$$

The continuous $SNPK_{index}$ has a range from 0 (very favorable) to 3 (very unfavorable).

The $SNPK_{index}$ is strongly correlated to the manual snow structure classification $SNPK_{manual}$ ($\rho = 0.79$, $p < 10^{-16}$, Fig. 2).

Applying the classification tree method to the $SNPK_{index}$, results in significant splitting thresholds for all five $SNPK_{manual}$ classes (Table 5). Using these thresholds to classify the 258 profiles, results in 64 % of profiles being classified correctly, 32 % ±1 class and 4 % ±2 classes.

3.2 Examples

The application of the $SNPK_{index}$ to a typical selection of (simplified) profiles (Fig. 3) is shown in Table 6.

The simplified profiles show:

- 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: two rather soft profiles, both have a melt-freeze-crust in the middle of the profile. While B1 has a faceted base (DH), the base of B2 is composed of small round grains.
- C1 and C2 contain a prominent persistent weakness below a slab of varying thickness.

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– Profiles D1 (dry) to D2 and D3 (wet) are examples of typical spring snowpack type evolution.

The $SNPK_{index}$ was calculated with a snow depth of 2 m for profiles A4 and C2, otherwise with 1 m. To compare the index (Table 6, row 1) and the automatically calculated classes from the index (row 2) with the manual classification, 4 forecasters classified these simplified profiles as before (Table 6, row 3). Again, the classification accuracy was similar to before: 64 % of profiles being classified correctly or within $\pm\frac{1}{2}$ class, 27 % ± 1 class and 9 % ± 2 classes.

4 Conclusions

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 misclassified by 2 classes. 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

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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 apply a similar approach to modeled snow profiles such as the snowpack simulation SNOWPACK. This could increase the information density regarding snowpack structure information for avalanche forecasting services.

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Table 1. Relevant snowpack criteria described in the threshold sum approach TSA (Schweizer and Jamieson, 2007).

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

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Table 2. Selection of some of the most important, investigated snowpack parameters.

	variable		definition
full profile	snow depth	hs	[cm]
	grain type	FC_{prop} NP_{prop} MF_{prop}	proportion of snowpack which is either classified as persistent (FC, DH, SH), non-persistent (PP, DF, RG) or melt-form (MF, IF)
	grain size	size	mean [mm]
	hand hardness	hardness	mean [index]
	ram hardness	ram	mean [N]
	temperature	ts	mean [°C]
	wetness	wetness	mean [index]
	profile type		Categorical classification, 10 types (Schweizer and Wiesinger, 2001)
	Rutschblock stability	RB_{stab}	Ordinal classification by RB score and RB release type (Table 3)
	stability classification	$stab_{01}$	Ordinal classification according to Schweizer and Wiesinger (2001)
	proportion coarse grained, soft layers	$size_{prop}$	proportion of snowpack which is coarse-grained (grain size $\geq$ 1.25) AND has a hand hardness $\leq$ 3, relative to hs
	proportion persistent, soft layers	PG_{prop}	proportion of snowpack which consists of persistent grain type AND has a hand hardness $\leq$ 3, relative to hs
	proportion very soft layers	$hard_{prop}$	proportion of snowpack which is very soft (hand hardness $\leq$ 1.3), relative to hs
	layer threshold sum	TSA_{layer}	$size_{prop} + PG_{prop} + hard_{prop}$
weak layer	persistent weak layer	p_{wL}	1 if the three TSA layer criteria (grain type, grain size, hardness) are fulfilled in same layer (Table 1); else 0
	non-persistent weak layer	np_{wL}	1 if criteria grain type (PP, DF) AND hardness $\leq$ 1.5 AND size $\geq$ 1 mm are fulfilled in same layer; else 0
	weak layer proportion	wL_{prop}	proportion of thickness of layers where p_{wL} = 1, relative to hs
layer interface	layer interface threshold sum	TSA_{max}	threshold sum for layer interface with maximum score (Table 1)
slab	thickness	$slab_{thick}$	all layers above the persistent weak layer closest to the snow surface (where p_{wL} = 1), but at least 15 cm below the snow surface, if no persistent weak layer than $slab_{thick}$ = hs
	hardness	$slab_{hard}$	weighted mean of the hand hardness of the slab $\frac{\sum_{p_{wL}=1}^{snow\_surface}(h_i \cdot H_i)}{slab_{thick}}$, where h_i is the thickness and H_i the hand hardness of each layer within the slab
	strength	$slab_{strength}$	a slab strength index, as in Winkler and Schweizer (2009): $\sum_{p_{wL}=1}^{snow\_surface}(h_i \cdot H_i^2)$, where h_i is the thickness and H_i the hand hardness of each layer within the slab
	bridging	$slab_{bridging}$	$slab_{hard} \cdot slab_{thick}$ as in Schweizer and Jamieson (2003)
	texture	$slab_{texture}$	$\frac{\sum_{p_{wL}=1}^{snow\_surface}(h_i \cdot \frac{size_i}{H_i})}{slab_{thick}}$, where h_i is the thickness, $size_i$ the grain size and H_i the hand hardness of each layer within the slab

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Table 3. Classification of profile stability based on the Rutschblock (RB) test result in five classes (RB_{stab}) based on RB score and RB release type. The classification is based on the stability classification scheme by Schweizer and Wiesinger (2001). RB release type: wBl – whole block, pBr – partial break, Edg – edge only.

RB_{stab}	score, release type		
1	RB1 all	RB2 wBl	
2	RB2 pBr OR Edg	RB3 wBl	
3	RB3 pBr OR Edg	RB4 all	RB5 wBl
4	RB5 pBr OR Edg	RB6 wBl	
5	RB6 pBr OR Edg	RB7	

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Table 4. Relevance/contribution of snow stability and snowpack structure observations for stability assessment according to Schweizer and Wiesinger (2001, $stab_{01}$, right part of table). Parameters were subjectively ranked by 9 experienced forecasters (score between 0 – not important and 1 – very important). The left part of the table shows the approximately corresponding parameters for the presented study. For these variables, the Spearman correlation ρ to the manually classified snowpack structure ($SNPK_{manual}$) is given. The correlation is not for all investigated parameters shown. *Profile type (nominal variable) – no correlation calculated.

Snowpack variable current study	ρ	sign of correlation	Snowpack variable (Schweizer and Wiesinger, 2001)	Subjective relevance
wL_{prop}	0.59	–	weak layers	1
profile type	*		profile type	1
RB_{stab}	0.33	+	Rutschblock	0.9
$slab_{thick}$	0.69	+	slab thickness	0.9
size	0.43	–	grain size	0.7
FC_{prop}	0.39	–	grain type	0.7
hs	0.47	+	snow depth	0.6
ts	0.01	+	snow temperature	0.5
hardness	0.59	+	hand hardness	0.4
$slab_{bridging}$	0.72	+	slab hardness	0.4
wetness	0.02	+	liquid water content	0.1
TSA_{max}	0.60	–		
TSA_{layer}	0.70	–		
$stab_{01}$	0.50	+		

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Table 5. Best-splitting $SNPK_{index}$-thresholds to classify profiles in five classes.

threshold between classes	$SNPK_{index}$ threshold
1 and 2	2.462
2 and 3	1.687
3 and 4	1.254
4 and 5	0.788

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Table 6. Comparison of eleven simplified, typical profile types by manual snowpack structure classification $SNPK_{manual}$, the calculated $SNPK_{index}$ and the classes derived from $SNPK_{index}$ for profiles shown in Fig. 3.

Snow structure	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
$SNPK_{index} \rightarrow$ classes	4	3	2	4	2	3	2	3	2	3	3

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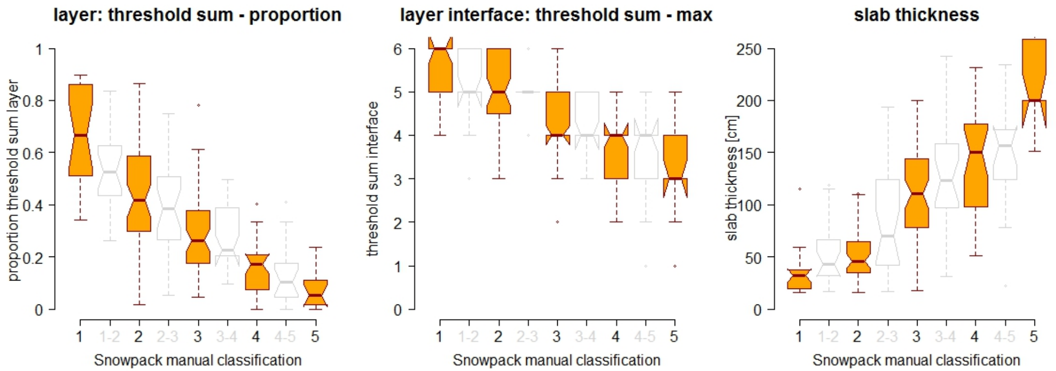

Fig. 1. Boxplots showing variables selected for the snowpack index ($SNPK_{index}$) and their distribution relative to the manually classified snowpack structure ($SNPK_{manual}$): threshold sum approach for layers (left) and layer interfaces (center) and depth of persistent weak layer (right). All three variables are strongly correlated to $SNPK_{manual}$ and moderately correlated to each other.

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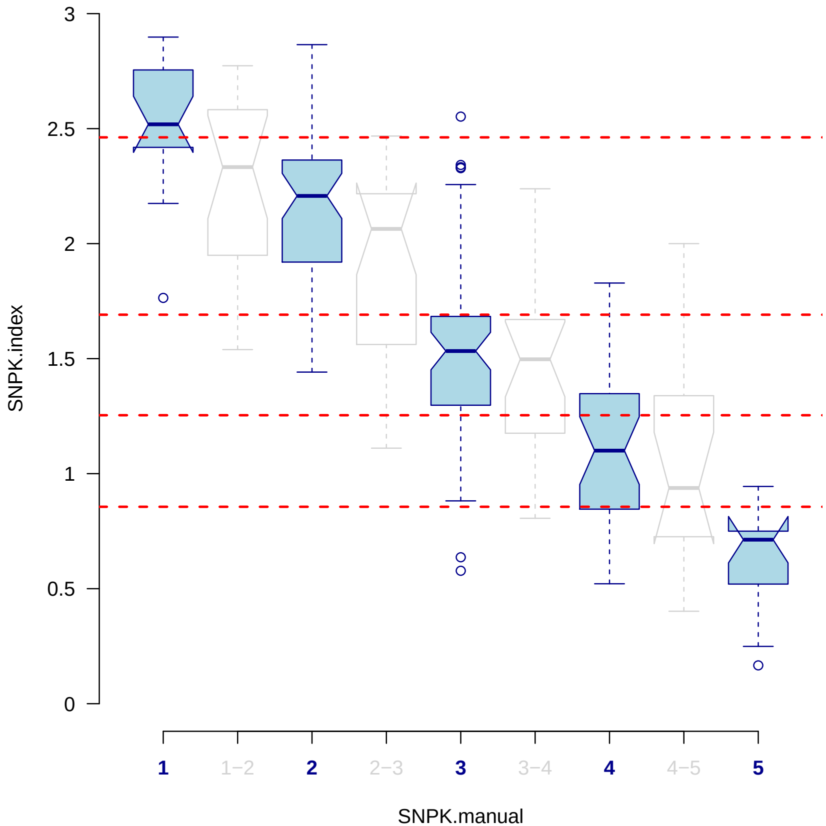

Fig. 2. Boxplot showing the $SNPK_{index}$ and the manually classified snowpack structure ($SNPK_{manual}$, 1-unfavorable to 5-favorable). The red lines represent the $SNPK_{index}$ splitting thresholds between full $SNPK_{manual}$-classes (light-blue boxes), as obtained with the classification tree analysis (Table 5). The correlation between the index and the manual classification (including profiles which were classified with half classes, light boxes) is strong ($\rho = 0.79$, $p < 10^{-16}$).

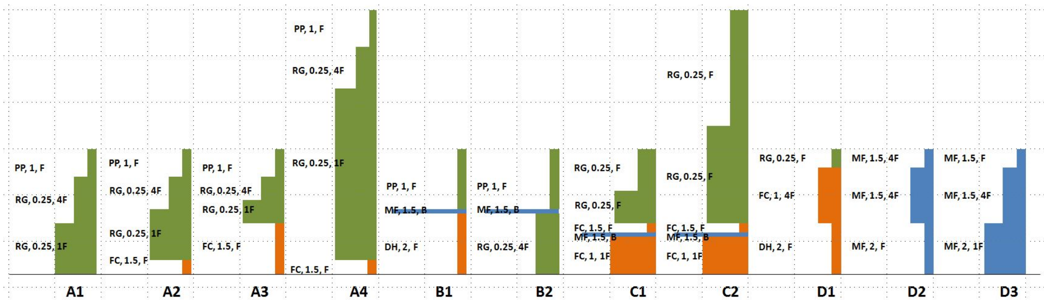

Fig. 3. Simplified snow profiles. The hand hardness profile is shown with the main grain type (color) indicated. Layer properties (text) are given for each layer in the following order: grain type, grain size (mm), hand hardness. Abbreviations are according to Fierz et al. (2009).

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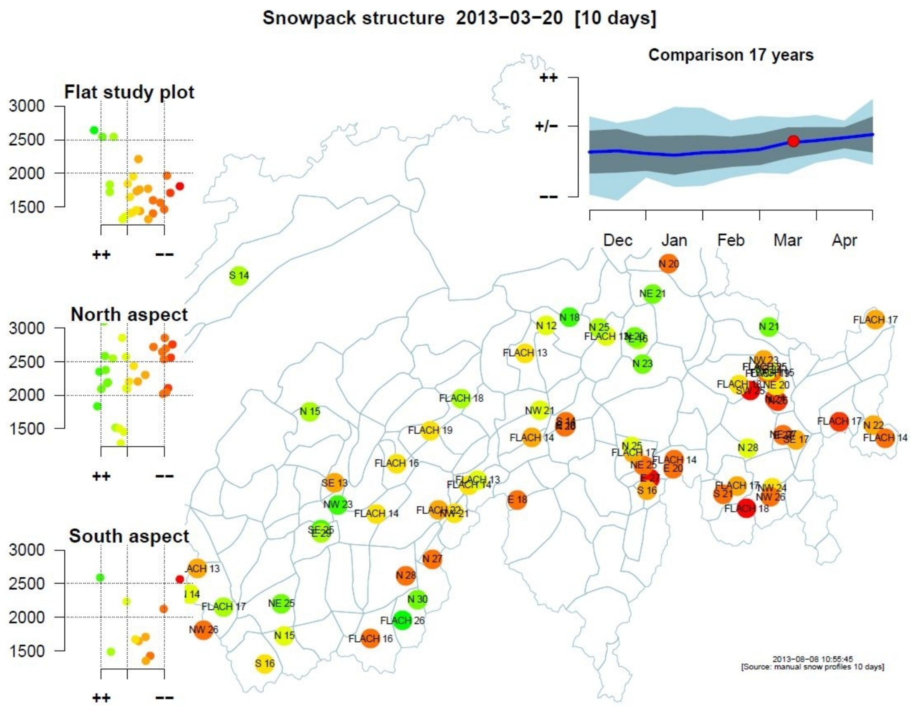

Fig. 4. Map of Switzerland showing the locations, where manual profiles were observed (main graph, colored points). Color coding corresponds to the five classes calculated from $SNPK_{index}$ (red: unfavorable (−−); yellow – medium±; green – favorable (++)). Each point represents one profile with the slope aspect and elevation given (e.g.: N 15 is North aspect at 1500 m). In the background the shape of the 120 forecast regions are shown. The inserts on the left side of the plot show the profiles according to aspect and elevation. The insert in top right corner gives a comparison of the actual conditions (red point) with the previous 17 yr, where the mean is the blue line, the grey-shaded areas are ±1 standard deviations from the mean and the light blue-shaded area show the minima and maxima recorded.

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