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On forecasting large and infrequent snow avalanches

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ABSTRACT

Snow avalanches that threaten a highway or a residential area are often large avalanches that have a return period >1 year. Danger assessment strongly relies on precipitation data since these avalanches are typically triggered by major snow storms. Given the extensive protection work that is in place in the European Alps, the avalanche control service (also called avalanche commission) responsible for danger assessment will usually monitor the avalanche situation throughout the winter, but only become active in case of a major snow fall. Related safety concepts describing the procedures and measures to be taken in a given danger situation are therefore often based on threshold values for new snow. By analysing the avalanche occurrence of a major avalanche path, we show that forecasting based on new snow amounts involves high uncertainty. Whereas the return period of an avalanche to, for example, the road was about 5 years, the return period for the corresponding new snow depth was substantially smaller, in our case slightly less than 2 years. Similar proportions were found for a number of other avalanche paths with different snow climate. The return period of the critical new snow depth was about 2–5 times smaller than the return period of the avalanche. This proportion is expected to increase with increasing return period. Hence, based on the return period of an avalanche path a first estimate for the critical new snow depth can be made. With a return period of the critical new snow depth of 1–2 years, avalanche prediction for individual avalanche path becomes very challenging since the false alarm ratio is expected to be high.

1. Introduction

In the European Alps most of the severe avalanche problems have been mitigated in the past decades by permanent protection measures such as supporting structures in the starting zone, or dams and sheds in the run-out zone. Still, there remain very many avalanche paths that threaten a highway or road section, or a residential area, without permanent protection work in place. They either produce infrequent events or permanent protection works are technically difficult to implement and/or too costly (poor cost-to-benefit ratio). In particular for economic reasons, avalanche forecasting (i.e. preventive closures) — often combined with artificial avalanche release is now frequently favoured over permanent protection works (e.g. Bründl et al., 2006; Wilhelm, 1998).

Avalanche control by temporary preventive measures (based on avalanche forecasting) requires a well organized local avalanche control service. As critical situations are infrequent and the avalanche service has to assess the situation and take action only occasionally during the winter there is no full-time professional forecaster on duty. Instead the personnel consists of some part time contracted forecasters and observers. Although it is recommended that they closely follow the avalanche situation during the winter, it is common that a service only starts working when a major snow storm is pre-announced (Stoffel and Schweizer, 2008). Ideally, the avalanche service has established a concept that connects a given avalanche situation to some temporary protection measures. The avalanche situation in such a safety concept is often characterized by the amount of snow loading. Threshold values are commonly determined based on past events. Often the non-events are not considered in this type of analysis. These critical values should be considered as a first guess and always be adapted to the actual situation. After an unexpected avalanche event that e.g. hit an open road, the snow accumulation before the release is often considered as relatively minor compared to the large extent of the unexpected avalanche. In other words, people are surprised by the discrepancy between the amount of snow accumulation and the extent of the avalanche event.

Snow avalanches — a type of fast-moving mass movement — can be considered as a weather-related natural hazard. In the context of risk assessment, avalanche events are characterised by their frequency of occurrence and their extent or magnitude. The event frequency expressed as return period is central to avalanche hazard mapping (e.g. Ancey et al., 2004; Burkard and Salm, 1992; McClung, 1999). In their pioneering work Föhn and Meister (1982) made a first attempt to combine this approach with local avalanche prediction.

Avalanche forecasting tools for one or more individual avalanche path do not exist to our knowledge. Statistical forecasting of large and infrequent avalanche events in a single avalanche path seems particularly difficult since the events are rare and it is not quite clear which variables are best related to the release probability. In principal, the probability of release, for example for a given amount of new snow,

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Table 1
Contingency table (total of cases: $n = a + b + c + d$).

		Observed	
		non-event	event
Forecasted	non-event	*a*: correct non-events	*b*: misses
	event	*c*: false alarms	*d*: hits

can simply be determined with a logistic regression analysis (Ancey et al., 2003). They found that the 3-day sum of new snow was the best explanatory variable. Avalanche activity around Zuoz (Engadine valley, Switzerland) has been related to snow and snowpack parameters (Stoffel et al., 1998). They found that new snow depth alone was insufficient for forecasting, but that snowpack stratigraphy and temperature evolution were essential contributing factors even for large catastrophic avalanches. A similar analysis for various regions was performed by Schneebeli et al. (1998). Several numerical avalanche prediction models for highway corridors were developed (e.g. Floyer and McClung, 2003; Hendrikx et al., 2005) that usually predict whether one or more avalanches (from a large number of paths) will occur on a given day, i.e. forecasting is done at the regional level. Blattenberger and Fowles (1995) developed a statistical model that improves road closure

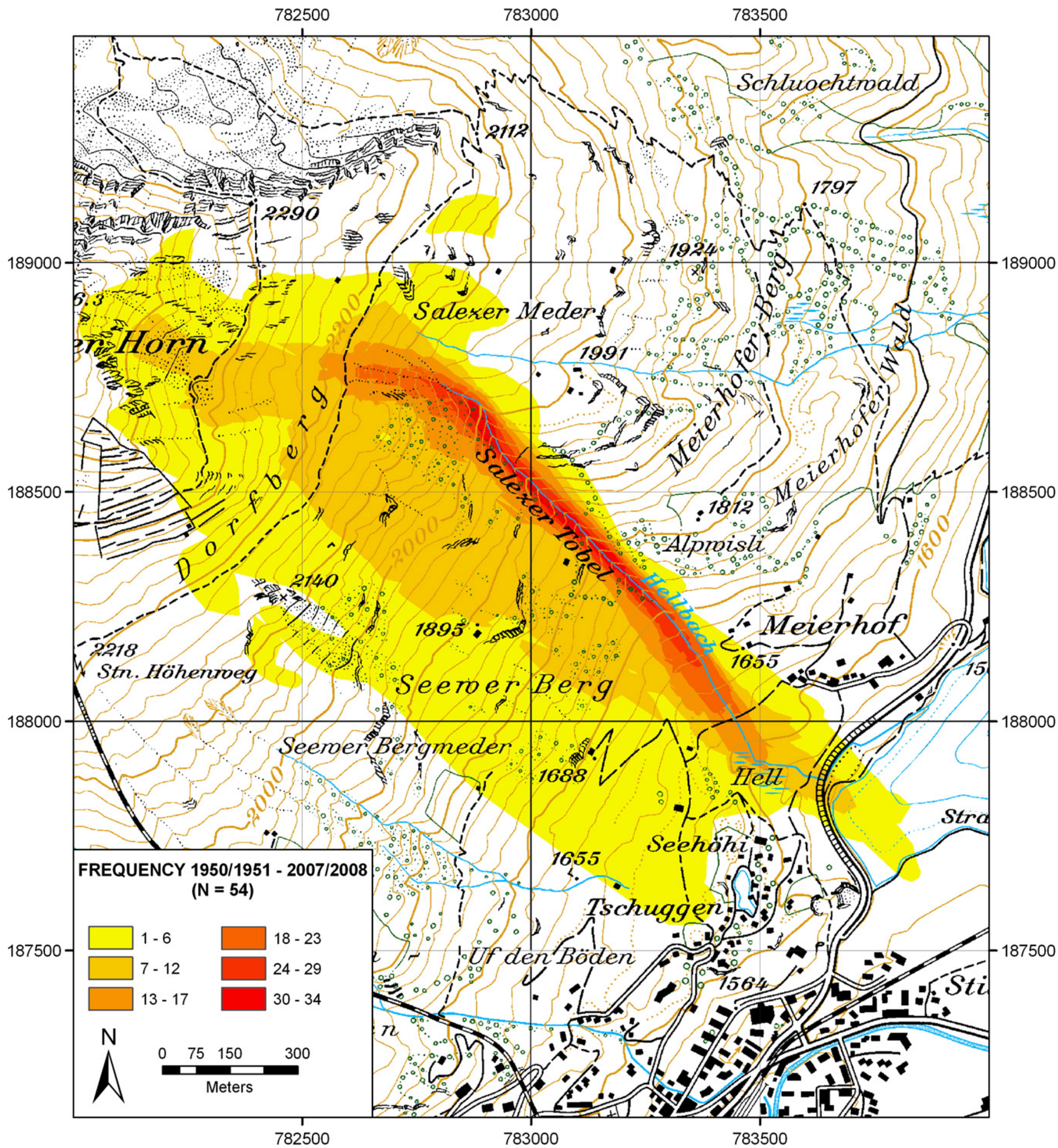

Fig. 1. Avalanche frequency in the Salezertobel path (Davos, Switzerland). During a period of 58 years (1950–1951 to 2007–2008) 54 avalanche events were mapped (Map source: PK25©2006 Swisstopo (JA082256)).

Table 2
Summary statistics for avalanches that reached the road level ($N=12$) vs. other large avalanches ($N=22$) for snow and weather data from Weissfluhjoch and Davos.

Variable	Weissfluhjoch				Davos			
	Median		Threshold (or cut value)	p	Median		Threshold (or cut value)	p
	To road	Not to road			To road	Not to road		
HN	43 cm	16 cm	≥49 cm	**0.008**	39 cm	11 cm	≥33 cm	**0.015**
*HN*3d	72 cm	42 cm	≥57 cm	**<0.001**	67 cm	34 cm	≥59 cm	**0.013**
*HN*5d	88 cm	50 cm	≥59 cm	**0.009**	67 cm	44 cm	≥29 cm	0.052
*HN*10d	94 cm	85 cm	≥64 cm	0.101	81 cm	61 cm	≥33 cm	0.188
Δ*HS*3d	53 cm	22 cm	≥36 cm	**0.008**	49 cm	14 cm	≥19 cm	**0.007**
HS	211 cm	219 cm	≥242 cm	0.279	115 cm	99 cm	≥115 cm	0.296
*HS*3d	147 cm	191 cm	≥140 cm	**0.035**	73 cm	80 cm	≥45 cm	0.279
ΔT_a	+3.1 °C	−0.7 °C	≥2.1 °C	**0.022**	−0.8 °C	−0.9 °C	≥−3.7 °C	0.256
SPBase (0/1)	8/4	7/15	N/A	0.111	12/0	13/8	>0	**0.042**

For each variable, distributions were contrasted (*U*-test, cross-tabulated), and the level of significance p is given. Variables with $p<0.05$ are given in bold. For the variable that describes the snowpack classification (SPBase) the number of weak (0)/strong (1) cases is given.

decision making by merging statistical analysis and expert opinion and takes into account the costs of misclassification.

One of the snow loading variables, the increase in snow depth during 3 days (Δ*HS*3d) is also used in the context of modelling the dynamics of large catastrophic avalanches for hazard mapping to assess the fracture depth. This approach has been questioned (e.g. Barbolini et al., 2002).

We focus on avalanche forecasting at the local scale and try to provide insight into some aspects of predicting large and infrequent avalanches. To that purpose, we analyse the avalanche activity in an active avalanche path (Salezertobel, Davos, Switzerland), derive values for the critical new snow depth and relate the return period of the critical new snow depth to the avalanche return period. We will then describe the ratio of return periods for a number of other avalanche paths in order to provide some rough guidance on how to establish preliminary threshold values for an avalanche path where little information is available apart from avalanche occurrence data.

2. Methods and data

The analysis was made for an avalanche path that runs towards the main road that enters the city of Davos (1560 m a.s.l., Eastern Swiss Alps) from the north: the Salzertobel path. The Salezertobel avalanche path has already been analysed by Föhn and Meister (1982). The starting zone reaches up to 2500 m a.s.l., is about 33–37° steep and has mainly easterly to south-easterly aspect. The distance to the road is about 1800 m. Avalanche records go back to the 15th century. For the last about 60 years the occurrence was consistently recorded. However, the avalanche extent is not always known and there were many small events. We will consider the winter periods from 1950–1951 to 2007–2008 (58 years). About 70 avalanches were recorded. We will only consider the 55 avalanche events that were mostly well documented. Except for one event, the avalanches were mapped and available for GIS analysis. From the 55 avalanches considered, 34 were large events that had a runout below 1700 m a.s.l., i.e. on the alluvial fan above the road. From these large events 12 reached (±20 m) the road or the shed (since 1984 the road is protected by a snow shed; construction started in 1981). In five winters two (and once even three) large events were recorded, still we consider all large avalanches as independent events since they resulted from individual storms.

The snow and weather data used for the analysis were recorded at the study plots of Weissfluhjoch (2540 m a.s.l.) above Davos and of Davos Dorf (1560/1590 m a.s.l.) where two plots exist. At both locations new snow depth was recorded daily on a snow board. Other meteorological parameters included air temperature, wind speed, and radiation. However, many of the meteorological variables were not available for the whole observation period, because they were either not measured, not accessible in digital form, or in the case of wind, no daily averages were available for the early years. For the analysis, we used daily values of the 58 winters from 1 November to 30 April, in total 10,513 daily records. To simplify the analysis we reduced the dataset and only considered days with a new snow depth $HN \geq 10$ cm measured at Weissfluhjoch ($N=1564$). Furthermore, for days immediately after an event, the 3-, 5- or 10-day sum of new snow depth was set to −999 so that these values could be excluded from the analysis (i.e. we assumed a second major release during a snowfall period as

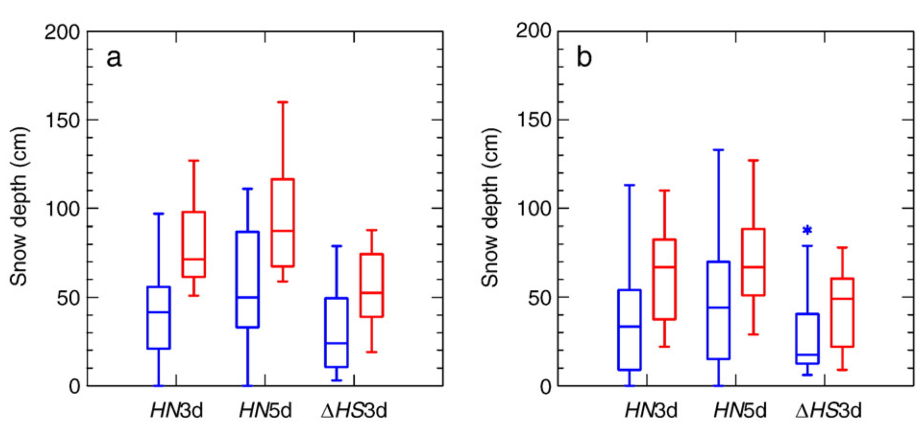

Fig. 2. Sum of new snow depth for 3 and 5 days (*HN*3d, *HN*5d), and 3-day increase in snow depth (Δ*HS*3d) measured at (a) the Weissfluhjoch and (b) Davos for large avalanches that stopped above the road (left, in blue; $N=22$) and avalanches that hit the road (right, in red; $N=12$).

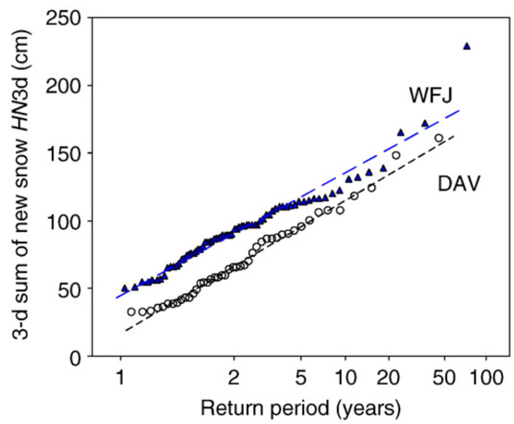

Fig. 3. Extreme value statistics (Gumbel distribution) for 3-day sum of new snow depth *HN*3d for Weissfluhjoch ($N=72$) and Davos Dorf ($N=45$).

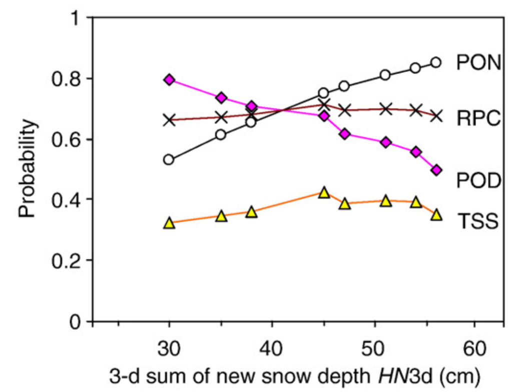

Fig. 4. Optimization of threshold to predict large avalanches ($N=34$) based on 3-day sum of new snow *HN*3d measured at Weissfluhjoch. PON: Probability of non-events; RPC: unweighted average accuracy; POD: probability of detection (events); TSS: True skill score.

unlikely). Avalanches that were recorded on a given day were compared to the meteorological variables measured at that morning. Therefore, the new snow depth might have been some lower for avalanches that occurred before 0700 in the morning, and higher for avalanches that occurred later during the day.

Snow stratigraphy was included based on the bi-weekly snow profiles taken at the Weissfluhjoch, Büschalp (1960 m a.s.l.) and Davos Dorf study plots. Profiles were classified according to Schweizer and Wiesinger (2001) into those with weak basal layers (profile types 1–5) and those with well consolidated (rather hard) basal layers (profile types 6–10). This snow stratigraphy classification was only available for analysis for days with large avalanche events as it would have been too time consuming to establish these data for all days.

To contrast variables from days with no avalanche events to avalanche days the non-parametric Mann–Whitney *U*-Test was used. Categorical data such as snowpack classification were cross-tabulated and a Yates' corrected Pearson χ^2 statistic was calculated (Spiegel and Stephens, 1999). A level of significance $p=0.05$ was chosen to decide whether the observed differences were statistically significant. Split (or threshold) values between two categories were determined with the classification tree method (Breiman et al., 1998). An ordinary least square loss function was used to optimize the splits. The minimum proportion reduction in error for the tree allowed at any split was set to 0.05. The same value was used as minimum split index value allowed at any node. To characterise the return period of a given new snow amount (e.g. new snow depth of 24 h: *HN*, or 3-day sum of new snow depth: *HN*3d), we used the Gumbel extreme value statistics. We also had explored other models such as the generalized extreme value distribution (GEV) but found differences were relatively minor and not sufficiently relevant when relating return periods of snowfall and avalanche events. For low return periods a thresholds model based on the Pareto distribution might be better suited.

To describe the performance of the prediction models, we used the unweighted average accuracy (RPC), the true skill score (TSS), the false alarm ratio (FAR), and the probabilities of detection of events (POD) and non-events (PON). With the definitions used in contingency tables (Table 1) the measures are defined as follows (Wilks, 1995; Doswell et al., 1990):

Unweighted average accuracy: $$\mathrm{RPC} = 0.5\left(\frac{a}{a+c} + \frac{d}{b+d}\right) \quad (1)$$

Probability of detection: $$\mathrm{POD} = \frac{d}{b+d} \quad (2)$$

Probability of non−events: $$\mathrm{PON} = \frac{a}{a+c} \quad (3)$$

Probability of false detection $$\mathrm{POFD} = \frac{c}{a+c} \quad (4)$$

False alarm ratio: $$\mathrm{FAR} = \frac{c}{c+d} \quad (5)$$

True skill score: $$\mathrm{TSS} = \frac{d}{b+d} - \frac{c}{a+c}. \quad (6)$$

The probability of detection POD is also called sensitivity and the probability of non-events PON ($=1-\mathrm{POFD}$) is called specificity. A model that discriminates well has a high sensitivity as well as a high specificity, i.e. predicts events and non-events equally well.

The performance for various thresholds can be shown with a receiver operating characteristics (ROC) graph, a technique originally used in signal detection theory. ROC graphs can be used to visualize the performance of classifiers, in particular to show the tradeoff between hit rate and false alarm rate. A classifier is only useful if the

Table 3
Summary statistics for non-event days ($N=1541$) vs. days when a large avalanche was observed ($N=34$) for snow and weather data from Weissfluhjoch and Davos.

Variable	Weissfluhjoch			Davos		
	Median		*p*	Median		*p*
	Non-events	Avalanche events		Non-events	Avalanche events	
HN	17 cm	25 cm	0.251	10 cm	19 cm	**0.010**
*HN*3d	29 cm	55 cm	**<0.001**	16 cm	43 cm	**<0.001**
*HN*5d	38 cm	68 cm	**<0.001**	21 cm	57 cm	**<0.001**
*HN*10d	59 cm	92 cm	**<0.001**	32 cm	64 cm	**<0.001**
Δ*HS*3d	18 cm	35 cm	**0.002**	9 cm	19 cm	**<0.001**
HS	166 cm	213 cm	**<0.001**	64 cm	107 cm	**<0.001**
*HS*3d	146 cm	169 cm	**0.019**	50 cm	79 cm	**<0.001**
ΔT_a	−1.6 °C	+0.8 °C	0.058	−1.1 °C	−0.75 °C	0.369

For each variable, distributions were contrasted (*U*-test, cross-tabulated), and the level of significance *p* is given. Variables with $p<0.05$ are given in bold.

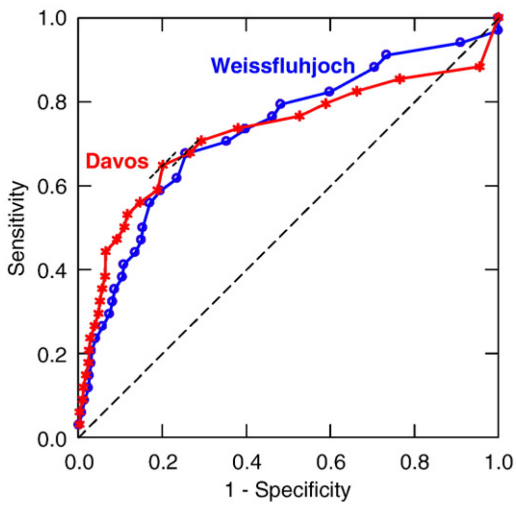

Fig. 5. Receiver operating characteristics (ROC) graph for *HN*3d measured at Davos (*) and Weissfluhjoch (○) for varying discriminating thresholds (the threshold decreases with increasing sensitivity). The optimal threshold values are 33 cm and 45 cm for *HN*3d Davos and Weissfluhjoch, respectively. These points on the ROC graphs are those where the tangent with slope 1 meets the ROC curve.

probability of detection is always larger than the probability of false detection, i.e. the classifier has to appear in the upper left triangle above the 1:1 line in the ROC graph (e.g. Fawcett 2006; Kantz et al., 2006).

3. Results

Fig. 1 shows the avalanche frequency in the Salezertobel path for the 54 avalanches mapped from 1950–1951 to 2007–2008. During the 58 years considered, 12 avalanches reached the road (±20 m) so that the return period for an avalanche to the road is about 5 years.

We will first consider the meteorological situation for the 12 avalanches that reached the road. The new snow amount prior to the release varied widely. For example, the 3-day sum of new snow depth at Weissfluhjoch varied between 51 cm and 127 cm, with a median value of 68 cm. For nine out of 12 avalanches *HN*3d measured at Weissfluhjoch was at least 64 cm (1st quartile). Considering the new snow measurements at the valley bottom showed that the median *HN*3d was 67 cm with a range of 22 cm to 110 cm. For nine out of 12 avalanches *HN*3d measured at Davos was at least 41 cm. The air temperature change to the previous day ΔT_a was in most cases positive at Weissfluhjoch, i.e. about +3 °C. There was no comparable trend for the temperature measured at Davos. Analysing the snow stratigraphy showed that the profiles taken prior to the release at the lower elevation study plots (Davos and Büschalp) had almost exclusively weak basal snowpack layers; at the elevation of the Weissfluhjoch eight out of twelve profiles had a weak base.

In the following, we compare the above described conditions for the avalanches that hit the road to those of the other 22 rather large events (Table 2). All variables related to snow loading (*HN*, *HN*3d, *HN*5d, Δ*HS*3d) showed larger median values for the avalanches that hit the road compared to the other large events (either measured at Weissfluhjoch or at Davos) (Fig. 2); the differences were statistically significant (Mann–Whitney *U*-test; $p \leq 0.015$) except for *HN*5d measured at Davos ($p = 0.052$). The level of significance *p* was in general lower for the values measured at Davos. Based on univariate tree statistics, a threshold value for an avalanche to the road of ≥57 cm and ≥59 cm for *HN*3d was found, measured at Weissfluhjoch and Davos, respectively. Also significant variables were ΔT_a at Weissfluhjoch (≥2.1 °C, $p = 0.022$) and the snow depth 3 days before the event (*HS*3d) at Weissfluhjoch (≥140 cm, $p = 0.035$). The proportion of profiles (taken at either Büschalp or Davos) with weak base was significantly larger for days with avalanches that hit the road. Whereas a strong base suggests that an avalanche will not reach the road, a weak base has no discriminating power. Though, for almost all avalanches that reached the road a snowpack with a weak base existed — but weak snowpack basal layers existed also when many of the large avalanches stopped above the road.

Based on the analysis of the events only, a new snow amount of about 55–60 cm (measured either on the level of the starting zone at the Weissfluhjoch or in the valley bottom at Davos) seems to indicate that an avalanche might reach the road. The return period of a new snow depth of about 55–60 cm in 3 days at Davos is about 1.5–2 years, at Weissfluhjoch it is about 1 year (Fig. 3).

Next, we will consider if it is possible to forecast whether a large avalanche has to be expected. We compared the snow and weather situation at days ($N = 34$) when a large avalanche occurred to those days when there was no avalanche (Table 3). All loading parameters were significant variables ($p \leq 0.01$) except for the 24 h new snow depth (*HN*) measured at Weissfluhjoch ($p = 0.251$). Also significant variables were the snow depth variables (*HS*, *HS*3d). The difference in air temperature to the previous day ΔT_a measured at Weissfluhjoch was not a significant variable ($p = 0.058$). Tree statistics with standard parameters did not suggest any split value for any of the snow loading parameters, except for *HN* measured at Davos (≥49 cm). However, as the dataset was very unbalanced it is not surprising that no split values were found, and the one found is questionable (POD ≈ 21%), but even when using priors and giving equal weight to events and non-events tree statistics did not provide useful results. Hence, we optimized the thresholds to reach the highest unweighted average accuracy or the highest true skill score (Fig. 4). Alternatively, the ROC graph can be considered (Fig. 5). This shows that *HN*3d measured at either Davos or the Weissfluhjoch are useful classifiers but yield rather conservative results. Classifying results for the various variables are summarized in Table 4. The unweighted average accuracy can be increased to 75% if in addition to *HN*3d or *HN*5d at Davos also the snow depth HS (≥76 cm) is considered. However, the probability of detection (correct avalanche events) is only about 65%, whereas the false alarm ratio is about 90%. Introducing additional variables such as the ΔT_a or *HN* did not improve the performance of the models that included the 3- or 5-day sum of new depth and the snow depth. Despite the high false alarm ratio that is questioning the applicability

Table 4
Optimal threshold values based on unweighted average accuracy to discriminate between days when a large avalanche occurred and non-event days.

Variable	Threshold value (cm)	Probability of detection (POD) (%)	True skill score (TSS) (%)	Unweighted average accuracy (%)	False alarm ratio (FAR) (%)
Weissfluhjoch					
HN_WFJ	≥25	52.9	29.2	64.6	95.3
HN3d_WFJ	≥45	67.6	42.6	71.3	94.4
HN5d_WFJ	≥54	67.6	38.3	69.1	95.2
Davos					
HN_DAV	≥19	52.9	33.9	66.7	94.4
HN3d_DAV	≥33	64.7	45.0	72.5	93.3
HN5d_DAV	≥38	67.6	45.4	72.7	93.7
Combinations					
HN3d_WFJ	≥45	67.6	47.7	73.9	93.0
and HS_DAV	≥48				
HN3d_WFJ	≥45	64.7	50.4	75.2	90.9
and HS_DAV	≥76				
HN3d_WFJ	≥54	52.9	42.8	71.4	89.7
and HS_DAV	≥76				
HN3d_DAV	≥33	64.7	51.9	75.9	90.0
and HS_DAV	≥76				
HN5d_DAV	≥38	67.6	53.8	76.9	90.3
and HS_DAV	≥76				

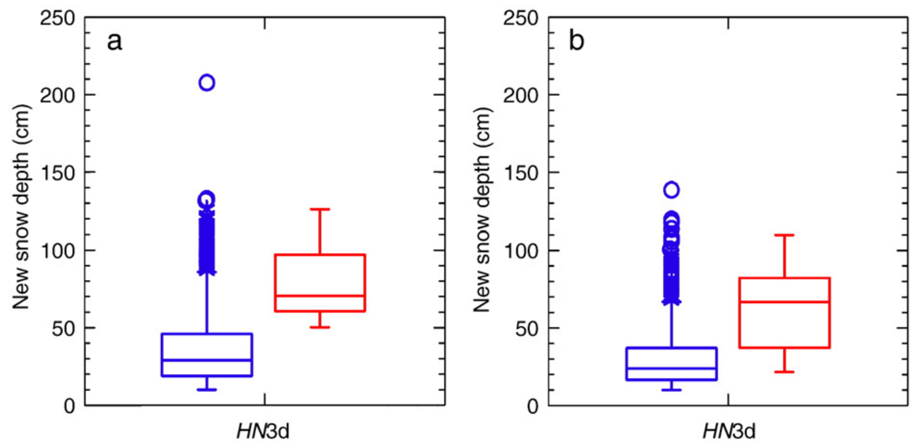

Fig. 6. Sum of new snow depth for 3 days measured at (a) the Weissfluhjoch and (b) Davos for all days (left, in blue; $N=1528$) and avalanches that hit the road (right, in red; $N=12$).

of these models, it is still remarkable how well this very simple models discriminate — indicating the high relevance of the snow loading parameters for these large and infrequent avalanches.

Forecasting the avalanches that reached the road was slightly easier, since the snow and weather situation prior to the release was in general more extreme (Fig. 6). We again primarily considered the loading variables (Table 5). The threshold values were at least about 10 cm higher than those found for predicting all large avalanches. First of all, the results show that the false alarm ratio (FAR) was generally higher than 90%, i.e. only in 1 (or even less) out of 10, for example, road closures an avalanche actually released. Obviously, the false alarm ratio decreased with increasing threshold value (or increasing number of variables), but inevitably more avalanches were missed, i.e. the number of "hits", or the probability of detection (POD) decreased. If we would, for example, request that a classification model has to have a POD ≥ 75% and a FAR < 90%, none of the models in Table 5 would pass the test. Nevertheless, already a remarkable part of the avalanches can be forecasted by only using one or two loading variables. The variables at Davos had slightly more discriminating power as the new snow amounts for the avalanche reaching the road level were more extreme in Davos than at the Weissfluhjoch. In addition, the false alarm ratio was slightly lower if the loading variables measured in the valley bottom were used for similar threshold values.

Table 5
Classification models to discriminate between days when an avalanche reached the road level and non-event days with corresponding skill scores.

Variable	Threshold value (cm)	Probability of detection (POD) (%)	True skill score (TSS) (%)	Unweighted average accuracy (%)	False alarm ratio (FAR) (%)
Weissfluhjoch					
HN_WFJ	≥33	66.7	55.7	77.9	95.5
HN3d_WFJ	≥51	100	78.3	89.2	96.6
HN5d_WFJ	≥59	100	75.3	87.7	97.0
Davos					
HN_DAV	≥36	58.3	54.9	77.3	89.1
HN3d_DAV	≥42	75.0	63.0	81.5	95.4
HN5d_DAV	≥44	83.3	65.5	82.7	96.5
Combinations					
HN3d_WFJ	≥59	83.3	74.6	87.3	93.2
and HS_DAV	≥76				
HN3d_WFJ	≥64	75.0	68.0	84.0	92.4
and HS_DAV	≥76				
HN3d_DAV	≥42	75.0	66.6	83.3	93.6
and HS_DAV	≥76				
HN5d_DAV	≥59	66.7	62.0	81.0	90.1
and HS_DAV	≥76				
HN3d_DAV	≥59	66.7	64.8	82.4	78.4
and HS_DAV	≥76				
and HN_DAV	≥33				

In summary, the analysis suggests that a critical new snow depth ($HN3d_{crit}$) of about 55–60 cm if measured at Davos and about 60 cm if measured at Weissfluhjoch seems appropriate. However, these values imply that about every third avalanche to the road would be missed. Still, most of the times when the road would be closed, no avalanche would release. In fact, a critical new snow depth of 60 cm has a return period at Weissfluhjoch of slightly more than 1 year (Gumbel distribution), but occurs about four times per winter. Given this threshold, the road should be closed (if there would be no shed) at least four times per winter, but an avalanche would reach the road only every 5 years. Due to the high false alarm ratio forecasting based on the threshold value of 60 cm from Weissfluhjoch seems not feasible. Using the snowfall data measured at Davos is somewhat more appropriate. A critical new snow depth of 55–60 cm only occurs slightly less than about twice per winter (1.8 times per winter). In about 30% of these cases the snow depth is less than 80–100 cm at the elevation of the valley bottom so that an avalanche reaching the road level is unlikely. Hence, a critical situation is reached only about 1.3 times per winter.

A similar, though less detailed analysis was performed for other sites where an avalanche path threatens a road or communication line. In these cases the occurrence record was less complete and often only the major events that reached the road were recorded. Consequently, the threshold values cannot be determined statistically by comparing events to the road to events that stopped above the road, nor by comparing conditions of the avalanche events with those of the non-events. The critical new snow depth as measured in a study plot in the valley bottom (usually within a couple kilometres from the starting zone) was determined based on experience and corresponds to about the 10–30% percentile of the new snow depth of all recorded events depending on the observation period and the number of recorded events. Table 6 compiles the results for seven avalanche paths from various region in the Swiss Alps. The snow depth in the valley bottom was usually > 50–60 cm at the beginning of the snowfall period.

The return period of the critical new snow depth was about 2–5 times smaller than the return period of the avalanche event. It is expected that with increasing return period the ratio might increase, i.e. even for the very rare and extreme events the critical new snow depth will often not be extraordinary. This possible trend is reflected in the few examples shown in Table 6. For avalanche paths with a return period of about 5 years the ratio was about 2–3, whereas for the path with a return period of 10–20 years, the ratio was higher, that is about 5.

Table 6
Return periods of avalanche events that threaten a communication line and of corresponding critical new snow depth ($HN3d_{crit}$).

Site	Avalanche return period (years)	Critical new snow depth $HN3d_{crit}$ (cm)	Return period $HN3d_{crit}$ (= potential damage) (years)	Return period ratio
Salezertobel (Davos)	5	55–60	1.5–2	~ 3
Breitzug (Davos)	5	65	2	2.5
Gonda, Lavin (Eastern Swiss Alps)	5	65	2.5	2
Zuoz (Engadine)	5	35–40	1–2	~ 3
Col du Pillon (Les Diablerets, Western Swiss Alps)	10	70–80	~ 2	~ 5
Ravaisch (Samnaun, Eastern Swiss Alps)	12	70	2.5	~ 5
Kreuzbachtobel (Pfäfers-Vättis, (Northern Swiss Alps)	20	80	4	5

Table 6 shows that depending on the snow climate the critical new snow depth can vary substantially. For the avalanche path in Zuoz which is situated in a rather dry inneralpine valley the critical threshold was lower than for the other paths that are situated on the northern slopes of the Alps. However, based on the limited dataset analysed no relation between the return period ratio and the snow climate was found.

In Table 6 only single avalanche paths were considered. If several avalanche paths with similar return period endanger a road the combined return period is lower than the return period in the individual path whereas the return period of the critical new snow depth will be the same so that the ratio will be lower, probably about 1–2.

4. Discussion

If we can estimate the avalanche return period and we assume that the return period of the critical new snow depth is about 2–5 times smaller than the return period of the avalanche event under consideration — as our preliminary analysis suggests, we can estimate the critical new snow depth from nearby snow observations in the same area having the same snow climate. This procedure works in particular, if there is no information about the snow and weather conditions at the times of the avalanche events — as only the year when an avalanche hit the road might be known. Of course, if no records of avalanche events are available, vegetative indicators such as evidence of forest damage or methods such as dendrochronology may be used to estimate the avalanche frequency (e.g. Mears, 1992).

Given this information we can estimate the frequency the road is threatened by a potential avalanche release. We expect this estimate to usually be more specific and hence useful (about ± 10 cm within the observed critical value) than what is indicated in rough guidelines on the relation between new snow depth and avalanche activity (e.g. Salm, 1982). A typical range in these guidelines for the problems listed in Table 5 is 50–80 cm of new snow. If the estimate of the critical new snow depth indicates that the road might be threatened many times per winter this implies that reliable forecasting might be impossible — and permanent avalanche protection works might be better suited to solve the avalanche problem under consideration.

For many of the large, destructive avalanches that occurred in February 1999 in the European Alps the avalanche return periods were on the order of 100 years, but the return period for the 3-day sum of new snow depth was on the order of <10 years. The large ratio is mainly due to the fact that for these avalanches *HN*3d was not the appropriate predictor variable since most avalanches released during the third of three consecutive major storms within about four weeks (e.g. Gruber and Margreth, 2001).

Certainly, the above proposal is preliminary, but the focus on return periods also shows some of the challenging problems inherent to the forecasting of large avalanches in a given avalanche path (Schweizer, 2008).

In particular, it seems that, for example, decisions on preventive road closures based on forecasting involve considerable uncertainty. These preventive measures are considered as cost-effective (costs vs. prevented death) in comparison with permanent protection works. Temporary measures are therefore often preferred to permanent measures — without considering the different levels of uncertainty.

5. Conclusions

We have analysed the avalanche activity for the well documented Salezertobel avalanche path near Davos (Switzerland) for the period 1950–1951 to 2007–2008. The return period for an avalanche to the road level (now protected by a shed) was 5 years. These large avalanche events were all related to substantial snow loading, a snow depth above terrain roughness, a snow stratigraphy which was characterised at the elevation of the track and the run-out zone by weak basal layers and a slightly increasing air temperature trend. However, when including the non-event days in the analysis, forecasting based on the above characteristics becomes difficult due to the high number of false alarms. Simple classification models based on *HN*3d and *HS* measured at Davos showed that the critical new snow depth for an avalanche to the road level is about 55–60 cm.

This value has a return period of less than 2 years that means considerably less than the return period of the corresponding avalanche event (5 years). For return periods of a few years, the Gumbel statistics largely underestimates the actual occurrence. Consequently, there were many days when the critical new snow depth was reached so that the number of false alarms was high suggesting that a model simply based on a critical new snow amount is hardly applicable in practice. The number of false alarms was reduced by considering one or two additional variables such as the snow depth. Still, the probability that an avalanche reaches the road when the model suggests so, was ≤ 0.15. Obviously, in operational avalanche forecasting for roads or residential areas, many other variables are considered by experienced forecasters and the critical new snow depth is adapted so that most avalanche services might perform significantly better than our simple models. Nevertheless, it is still remarkable how well this very simple models discriminated — indicating the high relevance of the snow loading parameters for these large and infrequent avalanches.

For the analysis, we used snow and weather data from two locations: one representative for the starting zone (Weissfluhjoch), the other for the run-out zone (Davos). The data collected at the valley bottom were as useful as the data from the elevation of the starting zone. Forecasting based on data from Weissfluhjoch — though highly correlated with large avalanche events — caused more false alarms than when the data from Davos were used. Though the conditions at the elevation of the starting zone are undoubtedly better captured with automatic stations at this elevation, the data might not be appropriate for forecasting extreme events due to their inherent low predictability (Schweizer, 2008).

The difference in snow depth over the last three days $\Delta HS3d$ was a significant variable to forecast an avalanche to the road, but by far not the best one. However, for avalanches that reached the road level $\Delta HS3d$ was significantly larger than for avalanches that had a shorter run-out, indicating that the run-out distance is related to $\Delta HS3d$ — which is commonly assumed in avalanche dynamics calculations. As mentioned above, for the largest avalanche events that reached the road level, snow stratigraphy at the elevation of the track and run-out zone was characterised by weak basal layers. Thus, we suggest that these snow stratigraphy conditions were favourable for snow entrainment and hence might have contributed to the large run-out (Sovilla et al., 2006).

The ratio of the return period of the critical new snow depth to the avalanche return period was evaluated for six more avalanche paths and values in the range of 2 to 5 were found. This finding might be useful to preliminarily assess the critical new snow depth for an avalanche path for which only the avalanche return period might be known.

Though avalanche control services are in general probably more successful than a simple model based on a critical new snow depth, the generally low predictability makes the prediction of an avalanche event in a specific avalanche path highly uncertain. Therefore, avalanche forecasting (i.e. for example, by preventive road closures) — even when combined with explosive control — might not always be the best option when evaluating the cost effectiveness of potential avalanche protection measures (costs vs. prevented death).

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