Forecasting forest avalanches: A review of winter 2011/12

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ABSTRACT: Mountain forests play a crucial role in avalanche mitigation by hindering avalanche formation. Nevertheless, due to the complex interactions between ecological conditions, terrain, snowpack and meteorological parameters the protective effect of forests may be reduced. Therefore, so-called 'forest avalanches' do occur and may be a threat to roads, railways and ski-runs below the forest. Due to their sporadic occurrence, gaining experience in forecasting forest avalanches is challenging for local avalanche forecasters. We describe a period of widespread high activity of forest avalanches which occurred in late February 2012. The weather situation was characterized by a sudden increase in air temperature which led to a high activity of wet and glide snow avalanches in general; however, the high number of avalanche releases in forests was surprising and challenging for safety authorities since they buried roads, railways and ski-runs. We tested an approach for forest avalanche forecasting which is relatively easy to apply by practitioners. The method is based on the combination of the five meteorological parameters mean air temperature, air temperature difference, new snow height, snow depth and sunshine duration measured by automatic snow and weather stations within a period of five days in the respective area. Two meteorological patterns which increase the probability of forest avalanche releases are distinguished: (1) 'new snow forest avalanches' (Type I) and (2) 'other forest avalanches' (Type II) which include old, wet and glide snow avalanches. The events in February 2012 were correctly detected by the model as Type II forest avalanches.

KEYWORDS: forest avalanches; forecasting; road, railway and ski-run safety

1 INTRODUCTION

Mountain forests play a crucial role in avalanche mitigation by hindering avalanche formation (Schneebeli and Bebi, 2004). Forests modify the snow cover and its properties compared to the open field; in particular the formation of continuous weak layers is disturbed (e.g. Bebi et al., 2001; Schweizer et al., 2003; Bebi et al., 2009; Viglietti et al., 2010). The relevant processes are:

- *The interception of falling snow by tree crowns:* In contrast to open unforested terrain, snow depth in forests is lower since interception by tree crowns reduces the amount of snow reaching the ground by 10 to 50% (McClung and Schaerer, 2006). Moreover, the intercepted snow falls out irregularly and creates a more heterogeneous snowpack around the stems within a typical distance of about 1.5 times the crown projection (Imbeck, 1983).
- *The reduction of near-surface wind speeds:* Wind speeds in forests are reduced which prevents extreme snow accumulation in gullies and depressions as they tend to occur in open areas (Schneebeli and Bebi, 2004). Maximum snow accumulation usually occurs in forest gaps with widths of 1 to 2 times the height of the surrounding trees (Imbeck and Ott, 1987).
- *The modification of the radiation and temperature regimes:* Due to shielding effects of the canopy, fluctuations in snowpack surface temperatures are more moderate than outside forested areas (Höller, 1998). Forests reduce the incoming shortwave and outgoing longwave radiation, and enhance the incoming longwave radiation. The modified radiation and temperature regimes affect snow stability positively and reduce weak layer formation at the snow surface (Shea and Jamieson, 2010).
- *The direct support of the snowpack:* Stems, remnant stumps and dead wood disturb and support the snowpack especially in dense forests (Schneebeli and Bebi, 2004).

Nevertheless, due to the complex interactions between ecological conditions, terrain, snowpack and meteorological parameters the

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protective effect of forests may be reduced and, therefore, snow avalanches do occur in forests. These so-called ‘forest avalanches’ are usually small, but may be a threat to roads, railways and ski-runs below forested slopes (Techel et al., 2013). Forest avalanches are often not recognized or documented and, therefore, observation data on avalanches in forested areas are rare (Teich et al., 2012a). Due to their sporadic occurrence, gaining experience in forecasting forest avalanches is challenging for local avalanche forecasters. Thus, developing methods to predict situations during which the probability of forest avalanche release is increased would be highly valuable for road, railway and ski-run safety.

In this contribution, we describe a period of widespread activity of forest avalanches which occurred in late February 2012 in Switzerland (Fig. 1). About 30 avalanches which started in forested terrain were reported to the SLF since they buried roads, railways and ski-runs (Fig. 2). In order to better predict and manage such situations, we test an approach for forest avalanche forecasting which is relatively easy to apply by practitioners since it is based on the combination of only five meteorological parameters measured by automatic snow and weather stations (SWS) within a period of five days in the respective area.

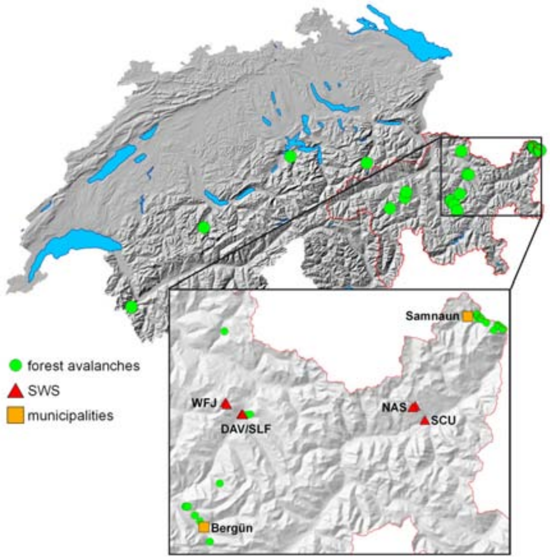

Figure 1: Recorded avalanches which started in forest or forest openings on the 24th and 25th of February 2012. The highest number of avalanches was recorded in the south-eastern part of Switzerland (red line: Canton Grisons) close to Samnaun and Bergün. However, some avalanches were also recorded in other regions.

Figure 2: Numerous forest avalanches buried the Samnaunerstrasse (Grisons, Switzerland) on the 24th and 25th of February 2012 (photo: P. Caviezel).

2 CASE STUDY

2.1 Snow and weather situation

The winter 2011/12 was characterized by several large snowfall events in December and January which resulted in a well-above average snow depth, i.e. about 1.5 to 2 times the normal snow depth in most parts of the Swiss Alps. In mid-February, the snowpack structure in open unforested terrain generally consisted of a well consolidated middle and lower part without significant weak layers. The upper part of the snowpack was faceted and rather unconsolidated after a cold period in early February (Fig. 3). Unfortunately, we have no snowpack observations within forested areas.

At the end of February, the freezing level rose towards 2500 m asl in the Eastern and to about 3000 m asl in the Western Swiss Alps (Fig. 4). The sudden increase in air temperature led to a destabilization of the snowpack and resulted in a high activity of wet and glide snow avalanches in general.

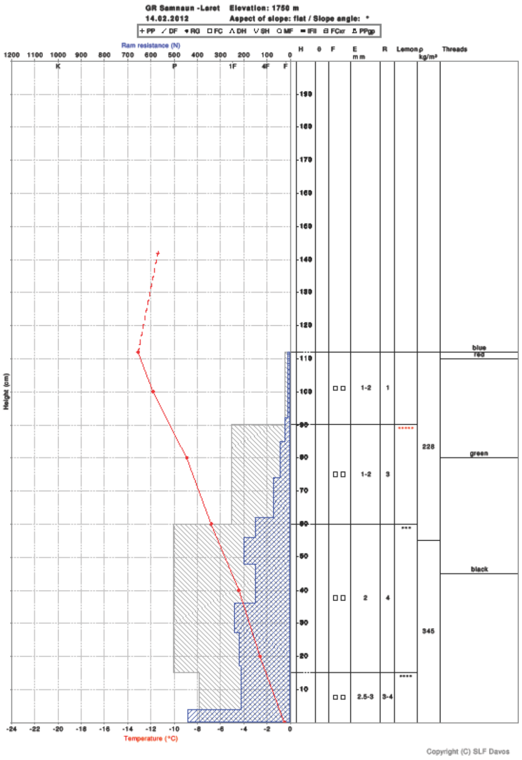

Figure 3: Snow profile from February 14th recorded in Samnaun, Switzerland at 1750 m asl.

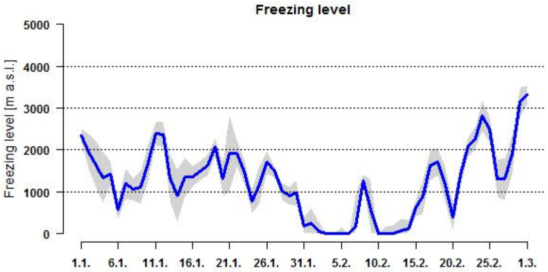

Figure 4: Freezing level development in January and February 2012. Note that the freezing level increased significantly on the 24th and 25th of February to 2400-3200 m asl after almost two months of cold conditions (blue line: mean air temperature of 11 SWS evenly spread over the Swiss Alps; grey areas: ± 1 standard deviation).

The records of the SWS Naluns (NAS) and Scuol (SCU), which are located in the region where most forest avalanches occurred (see Fig. 1), show, that the freezing level rose on the 23rd of February to about 2000 m asl, peaked on February 24th at about 2800 m asl, and dropped rapidly in the evening of the 25th (Fig. 5a). The rapid warming caused an increase in snow surface temperature, which was certainly higher at elevations of the forest avalanche starting zones (mainly below 1800 m asl) compared to the location of the SWS NAS at 2350 m asl (Fig. 5a). The 24th of February was rather sunny (Fig. 5b). The night of the 25th was partly overcast and, therefore, the snowpack could not refreeze and remained unstable. Both, the 25th and the 26th of February were partly overcast. During the night of the 26th the air temperature got significantly colder with very little snowfall. Very few additional forest avalanches were observed on the 26th of February.

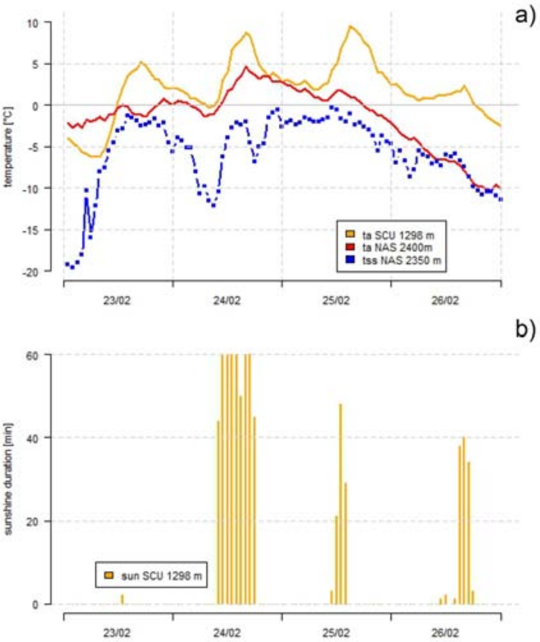

Figure 5: a) Air temperature recorded at the SWS Scuol (SCU, 1298 m asl, orange line) and Naluns (NAS, 2400 m asl, red line) and snow surface temperature measured at NAS (2350 m asl, blue line); b) sunshine duration at SCU.

2.2 Consequences for road and railroad safety

The forest avalanche activity was highest during the day on the 24th until the late afternoon of the 25th. These avalanches were small and released mainly as surface avalanches (Fig. 6).

However, the unexpected high activity of forest avalanches challenged the responsible safety authorities in Grisons, Switzerland. The highest activity was recorded in the Unterengadin in south-eastern Switzerland close to the Austrian border (Fig. 1): On February 24th around 10 am, the first small avalanche released from a forest and buried a main road followed by a second avalanche immediately after. Until noon, multiple forest avalanches were observed in the area leading to road closures and substantial snow removals (Fig. 7); before some threatened road sections could be closed, several cars got trapped in between avalanches released from forests. In the area of Bergün (see Fig. 1), an avalanche which started in less dense forest buried an important railway connection (Fig. 8).

Figure 6: Forest avalanche starting zone located directly next to defense structures (photo: P. Caviezel).

Figure 7: Road buried by an avalanche released from forest (photo: P. Caviezel).

Figure 8: A forest avalanche buried an important railway connection. The starting zone was located in less dense forest on a very steep slope (photo: U. Fliri).

In the morning of the 26th of February, the responsible authorities controlled the area and noticed many more avalanches which had released late on the 25th. After the rapid cooling on the 26th, no significant further forest avalanche activity was observed. After extensive snow clearing the roads could be opened for public traffic.

3 METHODS AND DATA

3.1 Forest avalanche forecasting

In contrast to avalanche releases in open unforested terrain, much less is known about contributory factors of forest avalanche occurrence. In order to identify critical meteorological situations with a high probability of avalanche release in forested terrain, Teich et al. (2012b) analyzed 21 snow and weather variables of 189 naturally released forest avalanches in order to support forest avalanche forecasting. By applying a hierarchical clustering method, they distinguished two forest avalanche types: (1) 'new snow forest avalanches' (further referred to as Type I) which release in periods of heavy snowfall and under stormy and permanently cold conditions and (2) 'other forest avalanches' including wet, old and glide snow avalanches (Type II) which release after periods of high insolation and an increase in air temperature. The snow and weather variables characterizing Type I and Type II forest avalanches and corresponding thresholds are defined in Table 1.

The application for forecasting purposes of the two specified meteorological patterns is based on different combinations of the five variables mean air temperature, air temperature difference, new snow height, snow depth and sunshine duration. Thresholds for variables were deduced from the distribution of variables which differ considerably between the two situations. Teich et al. (2012b) applied the lower (Q25) and upper (Q75) quartiles to define minimum or maximum thresholds. Additional information on Type I forest avalanches was derived from a classification tree model (for details see Teich et al., 2012b) and preliminary thresholds were adjusted with expert knowledge. The approach is relatively easy to apply by practitioners by monitoring the five relevant parameters measured by SWS within a period of five days in the respective area (see Tables 1 and 2). Since the analyses of Teich et al. (2012b) are based on measurements outside forested areas, SWS located outside forests can be employed to monitor the development of snow and weather conditions. However, in order to derive thresholds corresponding to the variables to observe, the initial data were interpolated for the starting point positions of the observed 189 forest avalanches. Thus, SWS used for forest avalanche forecasting purposes should be located at eleva-

Table 1: Snow and weather variables and corresponding thresholds useful for forecasting forest avalanches, i.e. two situations with a high probability for forest avalanche releases (according to Teich et al., 2012b).

Variable to observe	Type I ('new snow forest avalanches')	Type II ('other forest avalanches')
Temperature	1-, 3- and 5-day mean air temperature <0°C	-
Temperature difference	-	3- and 5-day temperature difference >0°C
Sunshine duration	1-day sum of sunshine duration <30 min 3-day sum of sunshine duration <60 min 5-day sum of sunshine duration <210 min	1-day sum of sunshine duration >30 min 3-day sum of sunshine duration >90 min 5-day sum of sunshine duration >240 min
New snow height	1-day sum of new snow height >10 cm 3-day sum of new snow height >50 cm	1-day sum of new snow height <10 cm 3-day sum of new snow height <40 cm
Snow depth (open field)	Total snow depth >100 cm	Total snow depth >30 cm

tions where forest avalanches are likely to occur between approx. 1000 and 2400 m asl.[1]

We tested the approach for events in 2012 (see Section 4), i.e. if the forest avalanches which occurred on the 24th and 25th of February could have been predicted by the model.

3.1 Meteorological data

Information on snow and weather conditions are continuously recorded by SWS operated by the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss) and the SLF which are evenly distributed over the Swiss Alps. We used combined data in a daily resolution of selected SWS (i.e. DAV/SLF; WFJ + sunshine duration measured at DAV and NAS/SCU) located at different elevations in the Canton Grisons, Switzerland (Table 2) where most of the forest avalanches from February 2012 occurred between 1100 and 1700 m asl (Fig. 1).

Table 2: Selected automatic SWS operated by MeteoSwiss and the SLF (see Fig. 1). Used variables: mean air temperature (T), new snow height (HN), snow depth (HS) and sunshine duration (S).

SWS (Abbr.)	Station name	Elevation (m asl)	Measured variables
DAV	Davos	1590	T, S
SLF	SLF (Davos)	1560	HN, HS
WFJ	Weissfluhjoch	2540/2693	T, HN, HS
NAS	Naluns	2350/2400	T, HN, HS
SCU	Scuol	1298	S

In order to test the model for its application for forest avalanche forecasting, combinations of meteorological contributory factors and associated thresholds (see Table 1) were used to identify days between December 2011 and May 2012 with a high probability of forest avalanche occurrence.

4 RESULTS AND DISCUSSION

Applying the model thresholds (Table 1) to the period from 1st of December 2011 to 31st of March 2012, no Type I forest avalanche days were predicted at the low elevation SWS DAV/SLF, only one at NAS/SCU and two at WFJ (Table 3). In contrast, conditions increasing the probability of Type II forest avalanche releases occurred more often: on 27 days at DAV/SLF, 44 at NAS/SCU and 47 at WFJ which lies high above the average of 23 Type II forest avalanche days per year calculated by Teich et al. (2012b). This could be due to the well-above average snow depth during this winter which was kind of "extreme" for forest avalanches. Furthermore, especially the high numbers of Type II forest avalanche days predicted at WFJ (average occurrence: 8 days per month) and NAS/SCU (7.5 days per month) in contrast to the low elevation station DAV/SLF[2] (4.5 days per month) indicate that measurements at stations high above the treeline are probably not suitable for forest avalanche forecasting.

Table 3: Number of Type I and Type II forest avalanche days per month detected by the tested forecasting approach at selected SWS (see Table 2).

SWS	DAV/SLF		NAS/SCU		WFJ	
Type	I	II	I	II	I	II
Month						
Dec	0	1	0	5	1	4
Jan	0	2	1	5	1	5
Feb	0	6	0	10	0	8
Mar	0	13	0	12	0	11
Apr	0	5	0	8	0	9
May	0	0	0	4	0	10
Total	0	27	1	44	2	47

Conditions under which Type II forest avalanches are likely to occur are less clearly definable compared to snow and weather conditions associated to Type I forest avalanche releases (Teich et al., 2012b). Type II forest avalanches include various types, i.e. old, wet and glide snow avalanches which allows an only limited distinction between an avalanche day and a non-avalanche day. In contrast, the predictive quality of the proposed snow and weather parameters and corresponding thresholds is much stronger for Type I forest avalanches.

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[1] In the Swiss Alps, the current treeline is located between 1800-2300 m asl (Paulsen and Körner, 2009).

[2] Note that WFJ is located only 3 km distant from DAV/SLF (see Fig. 1).

The events on February 24th and 25th were however correctly detected by the model as Type II forest avalanche days at all three SWS. In addition, several forest avalanches occurred during the winter 2011/2012 in the Swiss Alps; however, due to their sporadic occurrence and a non-continuous monitoring, avalanches in forested terrain are often not recognized and documented as they are not of primary importance compared to large destructive avalanches in open terrain. That is, our record on avalanche releases in forests can be considered incomplete and, therefore, performance and accuracy of the tested forecasting approach could not be evaluated thoroughly.

Based on the presented case study, we assume that snowpack stratigraphy plays a crucial role in forest avalanche formation comparable to avalanche formation in open unforested terrain. Unfortunately, snowpack observations in forested terrain are rare. Therefore, snow profiles recorded outside forested areas might be useful in some cases to estimate snowpack properties in forests (see also Zingg, 1958). Prior to the forest avalanche events in late February 2012, the uppermost snowpack layers were influenced by temperature-gradient induced metamorphism and were rather soft (Fig. 3). No significant periods of snow interception or warming occurred in early February. Interception of falling snow by tree crowns is usually followed by partial unloading in the form of irregular lumps of snow caused by warming and wind resulting in a highly irregular snowpack around trees (Schneebeli and Bebi, 2004). Therefore, we hypothesize that: (1) the main snowpack layering in forests was structured similarly to the open field (soft, faceted upper layers on a relatively strong base), and (2) that this may be one typical snowpack condition critical for forest avalanche release if combined with rapid warming (see also Imbeck and Meyer-Grass, 1988).

The high number of detected Type II forest avalanche days highlights possible improvements of the tested approach for forest avalanche forecasting. To strengthen our assumptions, further investigations of the snowpack in forests and the comparison with its development in open unforested terrain as well as reanalyzing existing snow profiles recorded in forests would be highly valuable (e.g. Fiebiger, 1978; Imbeck, 1983). Based on such investigations, more snow and snowpack parameters (in addition to snow depth and new snow height) could be implemented into the model to increase its applicability for forest avalanche forecasting.

5 CONCLUSIONS AND OUTLOOK

Further developments and improvements of tools for forecasting avalanche release in forested terrain would greatly profit from: (1) comprehensive observations on forest avalanches which allow distinguishing between avalanche days and non-avalanche days, and (2) detailed snowpack information, aiming at establishing a comprehensive database on avalanche observations and related snowpack conditions in forested terrain.

The analyses conducted by Teich et al. (2012b) to gain important snow and weather variables and corresponding thresholds were based on an adequate number of observed avalanches in forested terrain; however, some analyses were still restricted by the amount of available data. More data on forest avalanches and related meteorological and snowpack conditions are necessary to refine the cluster which contains Type II forest avalanches leading to more detailed insights separately for old, wet and glide snow avalanches.

In addition, studying the development of the snowpack in forest gaps over time, i.e. how snow and weather conditions are linked to the growth and development of weaknesses dependent on the distance to the surrounding trees, would strengthen the approach. Therefore, regular field measurements and monitoring of the snow cover stratigraphy in different mountain forest ecosystems could provide stronger evidence for forest avalanche forecasting.

However, the tested approach is a valuable first step for supporting safety authorities in their decision processes.

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