Wet snow avalanche activity in the Swiss Alps – trend analysis for mid-winter season

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ABSTRACT: During the winter 2011-2012 the Alps experienced repeated periods with high activity of wet snow and full-depth glide avalanches during mid-winter season (December to February). Damage to infrastructure but also fatalities were the consequence. Looking back 5 years, there was at least one intense and widespread wet snow and full-depth glide avalanche period in four out of five mid-winter seasons. To study the long-term trend, changes in wet snow and full-depth glide avalanche activity during mid-winter season were analyzed from 1952 to 2013, based on long-term observation stations. Robust time series analyses showed a positive trend in number and proportion of wet snow and full-depth glide avalanche records. The trend coincides with the trend in increasing air temperature in Switzerland. A break in the data series is shown that originates probably from a major revision of the snow and avalanche recording system in 2002. For the 50 year period before the revision, the proportion of wet snow avalanches increased by 0.4% per year. With the anticipated increasing temperatures in the European Alps, the positive trend in wet snow avalanche activity will most likely continue, which requires adaptations in risk management.

KEYWORDS: Wet snow avalanche, full-depth glide avalanche, snowfall limit, avalanche forecasting, climate change

1 INTRODUCTION

An extensive study in the mid 1990s did not provide evidence for a trend in extreme snowfall and severe avalanching in the Swiss Alps during the period 1500-1990 (Laternser and Pfister, 1997; Schneebeli et al. 1997; Laternser, 2002). More recently, Marty and Blanchet (2012) studied temporal trends of annual maximum snow depth and 3-day snowfall sum during the last 80 winters, where low elevation stations in particular showed a significant decrease in extreme snow depth. This was attributed to the observed decrease in the snow/rain ratio (Serquet et al., 2011) due to increasing air temperatures. But does the increase in air temperature impact the wet snow avalanche activity during mid-winter (December till February)?

Subjectively, wet snow and full-depth glide avalanches became more noticeable during mid-winter in recent years in Switzerland. For example, the snowy winter 2012 (i.e. the season 2011-2012) lead to high avalanche activity with damage to infrastructure and forest, mostly due to full-depth glide avalanches during December and January (Techel et al., 2013). And last winter on 23 December 2012, it rained to above 2000 m which lead to the highest activity during the whole winter with 90% wet and partially wet avalanches (Darms, 2013). From these and other observations it is our hypothesis that the proportion of wet snow and full-depth glide avalanches has increased significantly during the mid-winter season.

The aim of this study is to quantify correlations and trends in avalanche activity using robust time series analysis. It is based on the snow and avalanche records of long-term SLF observation stations. These records distinguish between dry and wet or partially wet snow avalanches from the winters 1951-1952 to 2012-2013. The trends are discussed in the realm of snow climate change in Switzerland. Adaptations in local and regional avalanche forecasting are shown and future challenges are discussed.

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2 DATA AND METHODS

2.1 Avalanche records 1952-2013

Avalanche activity in the Swiss Alps is recorded today by more than 150 observers of the Swiss avalanche warning service. Since the winter 1952, the observed avalanche data is stored in the SLF snow and avalanche database. Laternser (2002) rated the long-term observation stations according to avalanche observation quality. In our study, we use 24 long-term stations (Table 1) which are well spread over the seven regions of the Swiss Alps, are all located at medium elevation (1195 to 1800 m a.s.l.), have the most complete datasets, are still reporting today and have medium to high avalanche observation quality ratings according to Laternser (2002).

Table 1: Details of the 24 long-term SLF snow and avalanche observation stations. In brackets is the number of years, the data are missing for the whole year.

Code	*Station name*	*Elevation (m a.s.l.)*	*Observation since*
1MR	Mürren	1660	1951
1MN	Moleson	1520	1965
1AD	Adelboden	1350	1954
1WE	Wengen	1310	1969
1GS	Gsteig	1195	1954
2AN	Andermatt	1440	1952
2ME	Meien	1320	1954
2ST	Stoos	1280	1952
3BR	Braunwald	1340	1954
3SW	Schwägalp	1290	1967(11)
4BP	Bourg-St-Pierre	1610	1952
4GR	Grimentz	1570	1954
4UL	Ulrichen	1350	1953(1)
5AR	Arosa	1820	1954(3)
5BI	Bivio	1770	1953(2)
5SA	St. Antönien	1510	1952
5SP	Splügen	1460	1952
5SE	Sedrun	1420	1952(1)
6SB	San Bernardino	1640	1952
6BG	Bosco Gurin	1490	1952
7MA	Maloja	1800	1952
7SN	Samnaun	1750	1952
7LD	La Drossa	1710	1968
7ZU	Zuoz	1710	1952

For the winters 1952-2001, avalanche data are available according to the coding system shown in Table 2. In the early years, the observers transmitted their coded snow and avalanche observations by telegram, telephone, telex or telefax to the SLF where it was eventually entered into the database. In the late 1980's digital transmission took over. In 1987, the coding system for avalanche observations was slightly altered. The old codes were converted into L2 and L5 codes (Table 2) as far as possible.

A yet larger change of the coding system happened after the avalanche winter 1999 after which the Intercantonal Early Warning and Crisis Information System - IFKIS (Bründl et al., 2004) was launched in Switzerland. This implied that the observation guidelines as well as the codes for snow and avalanche observations were completely revised at the start of the winter 2002. The platform became internet based and the templates became much more detailed. Because the detail of avalanche records in the new coding system is greater than it is in the old system, we manually regrouped the avalanche records from 2002-2013 into the previous coding scheme. Nevertheless, the change of the observation and coding system does coincide with a marked decrease (Figure 1) in number of avalanche records from the 24 long-term observer stations, which will be discussed in Chapter 4.

The type and number of avalanches was taken from the SLF database according to the codes L2 (type of avalanche) and L5 (number, size and impact of avalanche) for 1952-2001. According to the observation guidelines (SLF, 1987) the avalanche codes L2 and L5 were determined by the observer by going through the coding tables from top to bottom and choosing the first applicable code according to Table 2.

Since L5 contains data of mixed ordered-categorical scale we cannot count each individual avalanche. However, it is possible to group and count avalanche records according to snow wetness and magnitude of activity, where:

- Dry snow avalanches of small magnitude correspond to L2 = 2, 4, 7, 9 and L5 = 1, 2, 7, 8, 9;
- Dry snow avalanches of large magnitude correspond to L2 = 2, 4, 7, 9 and L5 = 3, 4, 5, 6;
- Wet snow/mixed avalanches of small magnitude correspond to L2 = 1, 3, 5, 6, 8 and L5 = 1, 2, 7, 8, 9;
- Wet snow/mixed avalanches of large magnitude correspond to L2 = 1, 3, 5, 6, 8 and L5 = 3, 4, 5, 6.

By definition, avalanches with unknown type are considered as dry snow avalanche records. Mixed avalanches (dry and wet) and full-depth glide avalanches are considered as wet snow avalanche records. For 2002-2013, all avalanche records in the database were manually regrouped accordingly.

Avalanches causing damage are stored separately from the above mentioned snow and avalanche data-base. In this data-base 4340 avalanches from all regions of Switzerland, which caused damage to buildings, infrastructure or forest during mid-winter season (1952-2013) are recorded. However, 75% of these recordings contain no information on wetness of the avalanche. Therefore, these data cannot be used to supplement the long-term analysis of wet and dry snow avalanche records.

Tab. 2: SLF code system for avalanche observations from 1952-2001 (SLF, 1987).

Code L2	**Type of Avalanche**	**Code L5**	**Number, size and impact of avalanche**
/	observation impossible	/	observation impossible
0	no avalanches	0	no avalanches
9	type of avalanche unknown	9	extent unknown
8	ground or full-depth glide avalanche	8	avalanche with fatalities
7	slab avalanche dry	7	avalanche with caught or buried persons
6	slab avalanche wet	6	avalanche with property damage (buildings, forest, road, railway)
5	slab avalanche dry and wet	5	several (more than two) big avalanches, without damage
4	slab avalanche and loose snow avalanche dry	4	few (one or two) big avalanches, without damage
3	slab avalanche and loose snow avalanche wet	3	several (more than two) medium avalanches, without damage
2	loose snow avalanche dry	2	few (one or two) medium avalanches, without damage
1	loose snow avalanche wet	1	few or several small avalanches, without damage

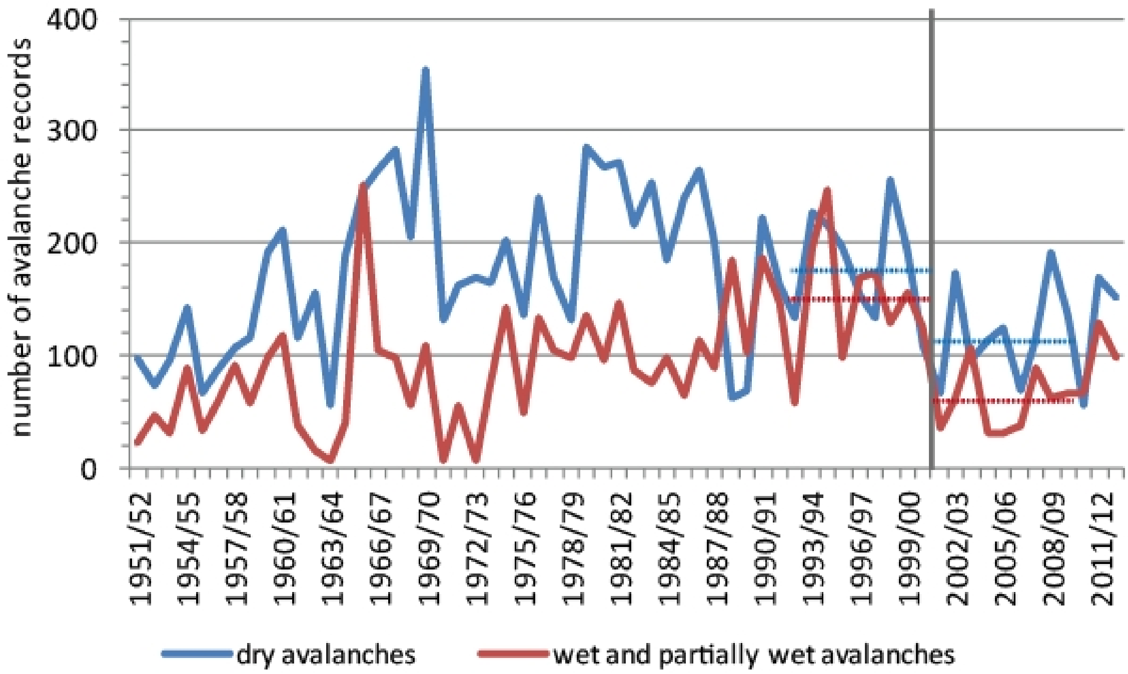

Figure 1: Number of avalanche records for dry snow and wet snow avalanches for the 62 mid-winter seasons from 1952-2013. The grey vertical line marks the winter 2002 where the new observation and database coding system was launched. This coincides with a systematic 'drop' in the amount of data. The dashed, blue and red horizontal lines are the median of 10 mid-winters of the avalanche records until the winter 2001 and afterwards.

2.2 Temperature and snow data 1952-2013

The monthly anomalies of the air temperature for the mid-winter seasons in Switzerland are based on homogeneous data series of 13 long-term MeteoSwiss stations. The mid-winter anomaly is the difference between the mean of the monthly anomalies (dTA) for December, January and February for 1952-2013 and the 1961-1990 mean (MeteoSwiss, 2013). For the 24 long-term SLF snow and avalanche observation stations (Table 1) the means of the following snow parameters were calculated for the mid-winter seasons: median snow depth (HS_{median})

and maximum snow depth (HS_{max}). Figure 2 shows the means of dTA and HS_{max} for the 62 mid-winter seasons. Large inter-annual variations exist as well as trends to warmer temperatures and lower snow depth starting in the late 1980s.

2.3 Statistical analysis

The correlations are analyzed with the non-parametric Spearman rank order correlation (ρ) testing for a monotonic relationship (Crawley, 2007). Robust time series analysis is performed by a non-parametric trend test using the statistical software R (R, 2011). The MannKendall trend test (McLeod, 2011) is applied for significance testing and the Theil Sen statistic as slope estimator (Bronaugh and Werner, 2009). The statistical analysis was calculated for the 62 year (1952-2013) and 50 year (1952-2001) series of dry and wet avalanche records in mid-winter, for temperature anomaly and snow parameters. Trends are considered significant if the level of significance $\alpha \leq 0.05$.

3 RESULTS

3.1 Correlation of data series

For the 62-year period, the number of dry avalanche records is correlated with snow depth measurements, most with the mean of HS_{max} ($\rho=0.72$, $p<10^{-7}$). Wet avalanche activity correlates to both, snow depth measurements and temperature anomaly. However, the correlation is weak (HS_{max}: $\rho=0.35$, $p<0.01$, dTA: $\rho=0.45$, $p<10^{-3}$). The proportion of wet to dry avalanches has a moderate correlation to dTA ($\rho=0.61$, $p<10^{-6}$), but no significant correlation to snow depth variables.

3.2 Trends for 62 mid-winter periods (1952-2013) and 50 mid-winter periods (1952-2001)

The absolute numbers of dry and wet snow avalanche records are shown in Figure 1, their relative frequencies in Figure 3. The proportion of dry and wet snow avalanche records is much less influenced by the introduction of the new coding system in 2002 than the absolute numbers of avalanche records. An increase in the proportion of wet avalanches is obvious in the 10-year moving average (Figure 3) and, since the late 1980's it coincides with the increasing temperature anomaly (Figure 2).

The absolute number of wet and dry snow avalanche records as well as their relative frequencies, the temperature anomalies and the snow parameters described above were analyzed with the Mann-Kendall trend test (MK) and the Theil-Sen slope estimator (TS). Table 3 shows the p-values and slope statistics for the significant parameters. In view of the change in the avalanche coding system in the winter 2002, trends were calculated for the whole period of 62 years as well as for the 50 years before the introduction of the new coding system.

The Mann-Kendall trend test showed a highly significant positive trend in the number of wet snow avalanche records, the proportion of wet avalanche records and the temperature anomalies over the 62- and 50-year period. In the 50-year period, wet snow avalanche records increased by 2.2 records per year, the proportion of wet snow avalanche records by 0.4% per year. The trend in the number of dry snow avalanche records was significant only in the 50-year period. The temperature anomaly increased by 0.04 °C per year.

None of the snow parameters showed a significant trend. However, when looking at descriptive statistics for discrete time periods, the median of HS_{max} was lower for the years 2002-2013 (106 cm) than for the 50 years before (117 cm, p=0.06), yet not significantly lower than the 10 years directly before 2002. The dTA also showed no significant differences in these periods.

Tab. 3: Parameters with significant trends from the Mann-Kendall trend test (MK) and the Theil-Sen slope estimator (TS) for the 62 year (62a) and the 50 year (50a) series of mid-winter seasons.

Parameter	***MK: 62a***	***TS: 62a trend***	***MK: 50a***	***TS: 50a trend***
Wet snow avalanche records	p=0.02	+ 0.8 / a	$p<10^{-4}$	+ 2.2 / a
Proportion wet snow avalanche records	p=0.01	+ 0.2% / a	p<0.01	+ 0.4% / a
Temperature anomalies	p=0.04	+ 0.02°C / a	p<0.01	+ 0.04°C / a
Dry snow avalanche records	p>0.05	- 0.1°C / a	p=0.04	+ 1.5 / a

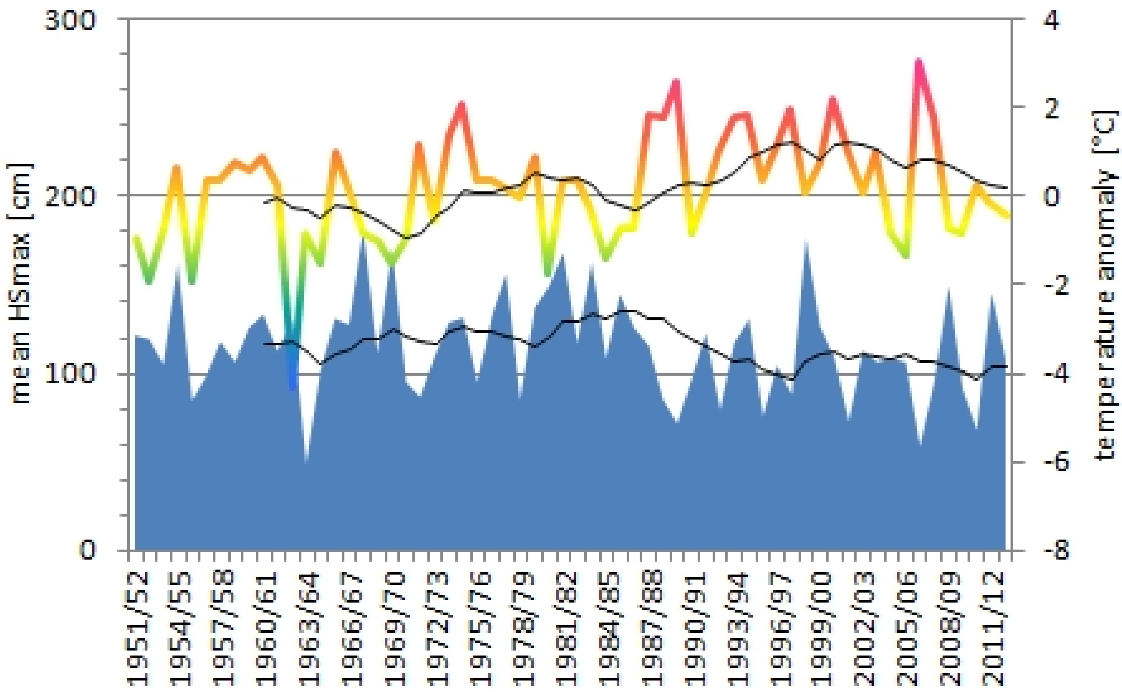

Fig. 2: Means of snow depth maxima and temperature anomaly for the mid-winter seasons of the years 1952-2013. The black curve shows the simple moving average over a 10-year period. An increase in the temperature anomaly and a decrease in maximum snow depth are obvious in the late 1980s.

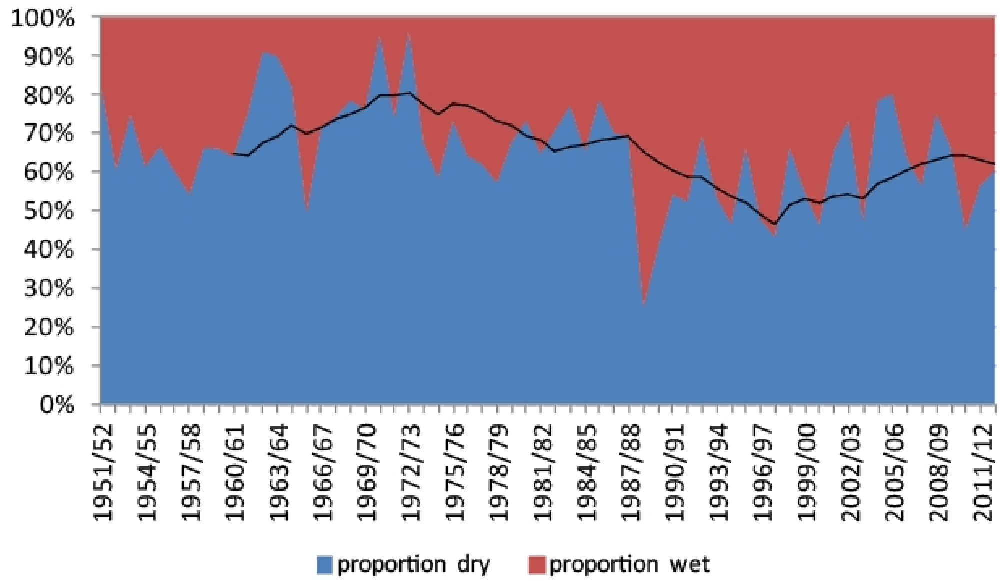

Fig. 3: Proportion of the number of dry snow (blue area) and wet snow (red area) avalanche records for the mid-winter season of 1952-2013. The black curve shows the simple moving average over a 10-year period. An increase in the proportion of wet snow avalanche records (red area) is obvious in the late 1980s.

4 DISCUSSION AND CONCLUSION

We have analyzed a long-term dataset on avalanche observations for detecting trends in dry and wet snow avalanche activity during the mid-winter season (December-February) over 62 years. 24 observer stations were selected according to length and quality of avalanche observations. We found a significant temporal trend in the proportion and absolute number of wet snow avalanche records in the mid-winter season. The trend was more pronounced for the 50-year period from 1952 till 2001 than for the whole 62-year period till 2013. During the 50-year period, the median proportion of wet snow avalanche records increased by 12%, from 35% in the first 10 years to 47% in the last 10 years. Also, the mean temperature anomaly increased significantly, by 0.04 °C per year, which coincides with the proportion and number of wet snow avalanches in the mid-winter seasons, in particular since the late 1980's (Figure 2 and 3). The median and maximum snow depth did not show any significant trends.

The observation and coding system experienced a fundamental revision in 2002. This coincided with a decrease in the number of large avalanches reported by the 24 long-term stations starting in the winter 2002. In addition, also the numbers of avalanche records decreased in 2002. But the proportion of wet to dry snow avalanche records was not as influenced. This 'drop' can possibly be explained with the introduction of an additional group of observers in the same regions who shared the task of avalanche observations with the long-term observers and are not considered in this study. Changes in observation guidelines and recording methods will remain a major challenge when interpreting long-term avalanche data.

Gobiet et al. (2013) and Bavay et al. (2007) predict snow depletion for the European Alps by a decreasing snow/rain ratio due to increasing temperature. Presumably, the trend to increasing wet snow avalanche activity will continue and avalanche forecasters and safety authorities will be more often confronted with periods of high wet snow and full-depth glide avalanche activity during December, January and February. Predicting avalanche release remains difficult, particularly for full-depth glide avalanches. The prediction of wet snow avalanche activity due to rain on snow at high elevation or due to solar radiation strongly depends on precise short-term meteorological predictions, e.g. snowfall line and amount of precipitation (Teich et al., 2012), on monitoring of the energy balance (Mitterer and Schweizer, 2013) and on information on snowpack stability and wetness (Baggi and Schweizer, 2009, Techel et al., 2011). Intensified snowpack and avalanche observations also by remote sensing (Durand, 2012; Lato et al., 2012) as well as process understanding through improved meteorological and snow models can assist local and regional avalanche experts in the challenges present and ahead. Furthermore special products such as the Swiss danger ratings for full-depth glide avalanches, special media communications and new guidelines can assist local safety personnel.

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