An operational supporting tool for assessing wet-snow avalanche danger

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ABSTRACT: Assessing the danger due to wet-snow avalanches is notoriously difficult, in particular, since conditions favouring wet-snow avalanches may persist only for a short period of time. The processes leading to wet-snow instability are complex and the response to them is complicated by fast, concurrently occurring changes in snow stratigraphy. In addition, liquid water does not penetrate snow uniformly. Already small changes in liquid water content will affect wet-snow stability. Previous studies have shown that knowledge of energy input combined with the cold content of the snowpack is important and useful to forecast wet-snow avalanches. Based on these studies we suggest an index defined as the average liquid water content of the entire snowpack, normalised by the starting value of the transition from the pendular to the funicular regime, i.e. 3% by volume. With the 1-D snow cover model SNOWPACK we calculated the index for virtual 38° steep south-facing slopes using meteorological data from 105 Automated Weather Stations (AWS) covering the Swiss Alps. We subsequently compared the index with wet-snow avalanche activity and regional danger estimates. During the 2011-12 and 2012-13 winters the index agreed well with observed wet-snow avalanche activity. It indicated spatial, i.e. elevation bands, and temporal patterns of wet-snow avalanche activity. Only for rain-on-snow induced wet-snow avalanches the forecast performance was poor since the AWS do not reliably measure liquid precipitation during wintertime and therefore we lack information on the transition from solid to liquid precipitation. Consequently, the snow cover model was not able to correctly simulate the transition from rain to snowfall (and vice versa). The results are promising and should improve the reliability of wet-snow avalanche forecasts. In addition, our approach allows a real forecast if output data of Numerical Weather Prediction models is used as input for the snow cover model.

KEYWORDS: Wet-snow avalanches, forecast, energy balance, avalanche danger assessment

1 INTRODUCTION

The mechanics of wet-snow avalanches are still not very well understood and therefore wet-snow avalanche activity is difficult to forecast. In order to assess the difficulties of forecasting this type of avalanches, Techel and Pielmeier (2009) presented results of a questionnaire on wet-snow avalanches, which was previously handed out to several avalanche professionals world-wide. The results showed that many avalanche professionals stated in particular the problem of predicting the correct timing of the onset of a period with high release probability and its peak activity.

These problems are obviously linked to limited field observations during periods of wet-snow avalanche activity and to the lack of adequate proxy data provided by meteorological forecasting models or Automated Weather Stations (AWS). Air temperature (T_A) is commonly related to days with wet-snow instability (Kattelmann, 1985), but is not suitable for forecasting wet-snow avalanches since many false-alarms are produced (Mitterer and Schweizer, 2013; Trautman, 2008). Already by introducing a combination of air and snow surface temperature (T_{SS}) predictive performance for days with high wet-snow avalanche activity improved (Mitterer and Schweizer, 2013). By doing so, days when high air temperatures hint to conditions when energy input is only used to warm up the still cold snowpack, but no snow is melted and no water produced, i.e. $T_{SS} < 0°C$, are not classified as avalanche days. In addition, Mitterer and Schweizer (2013) showed that when modelling the entire energy balance for virtual slopes, avalanche and non-avalanche days could be classified with a fairly high accuracy.

However, modelling and interpreting the energy balance in terms of wet-snow avalanche release probability is still complex and sometimes not feasible for operational avalanche forecasting. Therefore we introduced an easily interpretable liquid water content index (LWC_{index}) indicating changing liquid water content in the snowpack and thus periods with high wet-snow avalanche activity. The index is based on modelled energy and mass balance calculated with the 1-D snow cover model SNOWPACK at a 3-hours interval for 105

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Automated Weather Stations (AWS) covering the Swiss Alps. We compared the results of this index to wet-snow avalanche activity and will in the following qualitatively present its predictive performance for the two winter seasons 2011-2012 and 2012-2013.

2 DATA

2.1 Meteorological input data for SNOWPACK

In order to obtain mass and energy balance values, we run the 1-D snow cover model SNOWPACK (Lehning and Fierz, 2008) for 105 Automated Weather Stations (AWS) on virtual 38° steep slopes for the main aspects, i.e. 0° (N), 90° (E), 180° (S) and 270° (W). We grouped the stations into three elevation classes: below 2000 m a.s.l., between 2000 m a.s.l. and 2500 m a.s.l., and above 2500 m a.s.l. The stations cover most of the Swiss Alps and range between elevations of 1600 m a.s.l. to 2970 m a.s.l., with more than half of the stations ($N = 64$) between 2000 and 2500 m a.s.l. (Fig. 1). The stations provided air temperature (T_A), snow surface temperature (T_{SS}), wind speed (V_W) and direction (D_W), snow height (H_S), and reflected shortwave radiation (S_R) as input data for the model runs.

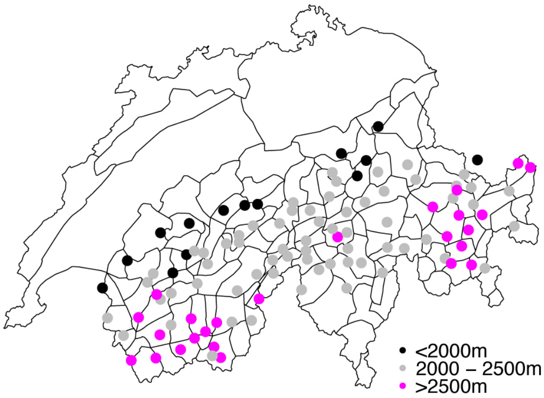

Figure 1: Spatial distribution of Automated Weather Stations (AWS) in the Swiss Alps. Black dots show stations below 2000 m a.s.l., grey dots stations between 2000 m a.s.l. and 2500 m a.s.l. and magenta dots indicate stations above 2500 m a.s.l.

2.2 Avalanche occurrence

We used an avalanche activity index to be related to the newly introduced liquid water content index (LWC_{index}). For calculating the avalanche activity index (AAI) we considered wet-snow avalanches only. Avalanches were weighted according to their size (Schweizer et al., 2003). The weights were 0.01, 0.1, 1, 10 and 100 for the sizes 1 to 5, respectively (Canadian avalanche size class; McClung and Schaerer, 2006). Since aspect was not always unambiguously reported, we used an aspect index which represented the ratio of the frequency and size of avalanches recorded in southern aspects to the one recorded in northern aspects, i.e. if the ratio was > 1 we assumed that the avalanche cycle mainly occurred in southern aspects and vice versa for < 1. As we were interested in forecasting wet-snow avalanches on a regional to national scale we judged days with an AAI > 20 as a day with high activity, i.e. that at least 20 mid-sized or 2 large wet-snow avalanches had to occur within Switzerland.

3 LIQUID WATER CONTENT INDEX

The way water moves through the snowpack highly depends on the amount of water. At low liquid water content (θ_w), capillary forces dominate and water is kept between grains (pendular regime). If θ_w increases, water will start to flow due to gravity (funicular regime). The transition from the pendular to the funicular regime is grain type dependent (Denoth, 1980) and was experimentally observed in the saturation range of 7-15% of the pore volume. Depending on density, this corresponds to a volumetric liquid water content ($\theta_{w,v}$) of 3-8%. Accordingly, as soon as a value for $\theta_{w,v}$ is larger than 3%, it is likely that gravitational flow is dominating (funicular regime) and water will drain. Conway and Raymond (1993) found that from the moment when water starts infiltrating the snowpack to the beginning of basal outflow wet stability is significantly decreasing. Recently, Mitterer et al. (2011) showed that it is important to know the arrival time of water at the bottom of the snowpack in order to predict the correct onset of wet-snow avalanche activity.

Based on the above findings, we defined the index by the average liquid water content of the entire snowpack, normalised by the starting value of the transition from the pendular to the funicular regime, i.e. 3% by volume. Accordingly, the LWC_{index} is given by

$$\mathrm{LWC}_{index} = \frac{\bar{\theta}_{w,v}}{0.03}, \qquad (1)$$

where $\bar{\theta}_{w,v}$ is the modelled, average volumetric liquid water content within the entire snowpack. The values to calculate the LWC_{index} were exported from the SNOWPACK simulations for the virtual slopes. In general we wanted that the index hints to the three important periods for wet-snow instability, pointed out by Conway and Raymond (1993): (i) decrease of stability (= increase of the index towards 1), timing of maximum instability (index indicates completely wetted snowpack, i.e. $\mathrm{LWC}_{index} = 1$) and return to stability due to ongoing wet-snow metamorphism (index above 1 for extended period of time). These three scenarios are paramount for an appropriate assessment of wet-snow avalanche danger.

4 RESULTS AND DISCUSSION

The winter 2011-2012 was characterised by above average snow height in the Swiss Alps. Throughout the season the snowpack was well consolidated and did not show any prominent weak layers. Due to these conditions, many large glide-snow avalanches occurred until mid January. Most glide-snow avalanches were cold temperature events (Clarke and McClung, 1999).

The major period of wet-snow avalanche activity started at the end of February and lasted with a short break until 4 March 2012 (Fig. 2). The activity peaked at 2 March 2012, which was the day with the highest activity in that season. Most avalanches were observed on south-facing slopes (Figure 2b) and 10 days had a considerable activity on south-facing slopes with an AAI > 20 during that season (boxes in Figure 2a). The median elevation of the starting zones was between 2000 m and 2500 m a.s.l. The median LWC_{index} on south-facing slopes started to rise shortly before the onset of the first days with high activity for the low elevation class (<2000 m) or on the day of highest activity (2000-2500 m and >2500 m). The increase indicated well the onset of avalanche activity. Manual snow profiles (dots in Fig. 2a) indicating when the total snow profile was isothermal agreed fairly well with the index. Once the LWC_{index} was close to 1, it followed a diurnal cycle, staying always slightly above 1. From that moment on, no distinct rise was observable which complicated the detection of days with avalanche activity. In fact, activity with AAI > 20 for 28 March 2012 was not detectable since during the previous days the LWC_{index} was similarly high as on that particular day. For north-facing slopes the index performed worse than for south-facing slopes (not shown here). During the first two periods with high activity the index for all elevation classes still indicated a dry snowpack. However, activity for the beginning and mid of May were again well detected.

Figure 3 displays a view, which was provided to the forecasters of the Swiss avalanche warning service during spring 2013. The graphic shows the current value of the LWC_{index} for all 105 AWS, the elevation distribution of the LWC_{index} including the 24-hours difference, and median values for the three elevation classes over the course of the preceding two weeks (similar as in Fig. 2a).

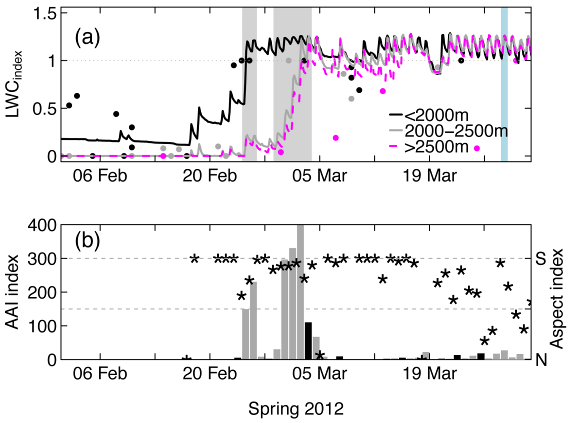

Figure 2: (a) Liquid water content index (LWC_{index}) for three elevation classes calculated for virtual, 38° steep south-facing slopes during spring 2012. The black linee represents the median values based on the stations below 2000 m a.s.l., grey line represents the stations between 2000 m and 2500 m and magenta line shows values for stations above 2500 m. Grey boxes show days with an AAI > 20 which coincide with an significant increase in LWC_{index}, lightblue boxes show days with an AAI > 20, but no coincidence with the LWC_{index}. Dots show the isothermal state (1= completely isothermal) of manual snow profiles in the respective elevation class. (b) Wet-snow avalanche activity for the three elevation classes. Asterisks indicate whether the avalanche activity occurred rather on south-facing or north-facing slopes.

The winter 2012-2013 had about average snow heights, however, due to an early season snowfall, basal layers were characterised by large facets and depth hoar. Towards spring 2013 the first period of wet-snow avalanche activity started again at the end of February, was shortly interrupted and lasted until the first days of March (not shown here). For the major period in that season (around mid April) the index performed very well for south-facing slopes. The onset and the peak activity were well depicted (Fig. 3). The graph shows nicely that the activity started in the north and west of Switzerland at low (i.e. <2000 m) and mid (2000 m to 2500 m) elevations (Fig. 3a) and reached its peak in the entire country at almost all elevation two days later (Fig. 3b). Accordingly, the onset and the peak activity of that period were well described within the avalanche bulletin. It was a bit more difficult to determine the end of avalanche activity since the LWC_{index} remained constant around 1 with diurnal changes only. Nevertheless, it gave an important hint to when the snowpack was completely wetted and underwent considerable melt-freeze cycles or wet-snow metamorphism, which favoured the return to stability (Conway and Raymond, 1993).

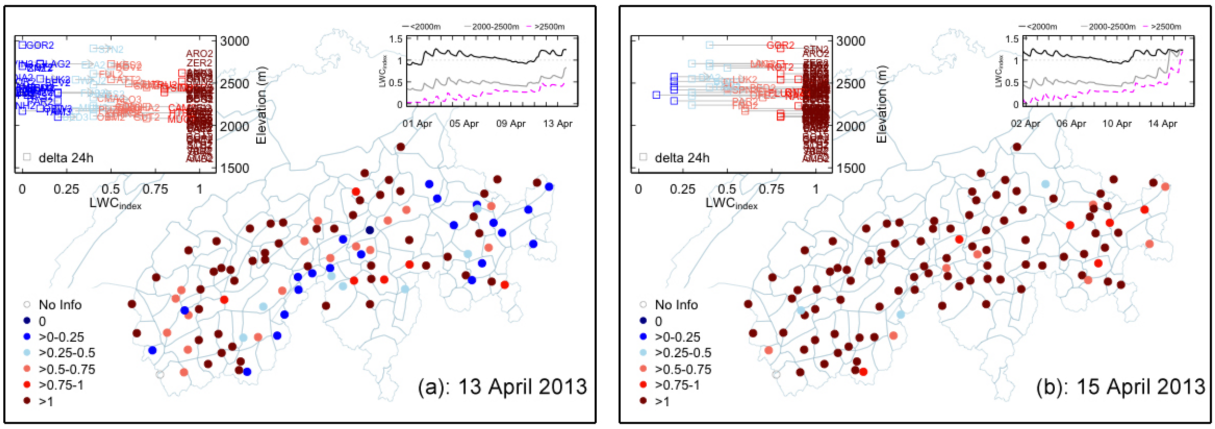

Figure 3: Summary plot showing the liquid water content index (LWC$_{index}$) for all 105 AWS covering the Swiss Alps during (a) the onset and (b) the peak wet-snow activity in mid April 2013. The left insert shows the LWC$_{index}$ for every AWS according to its elevation including the 24-hours difference (squares). The right insert is the same graph as shown in Fig. 2a.

The results show that there were periods when the index worked well (grey boxes in Fig. 2) and periods when it was not really clear that high avalanche activity had to be expected (light blue box in Fig. 2). Analysing the meteorological conditions during these periods in detail, indicated that the index works very well when the meltwater was primarily produced by warm and sunny weather, i.e. during classical spring conditions. In contrast, the index did not perform well during periods when small amounts of rain infiltrated into the snowpack and caused instantaneously instabilities since the snowpack was probably already close to critical or was loaded with new snow. This phenomenon is known to happen fast, i.e. within hours (Conway and Raymond, 1993) and is difficult to forecast. In addition, it was hard to capture the meteorological conditions prevailing during such small rain-on-snow events or snowfalls. The AWS do not reliably measure liquid precipitation during wintertime and therefore we lack information on the transition from solid to liquid precipitation. Consequently, the snow cover model was not able to correctly simulate the transition from rain to snowfall (and vice versa).

One of the largest benefits of the index is that it is readily available compared to direct field observations. During and before the major period in April 2013 only 3 manual snow profiles from high elevation slopes were recorded for the entire area of the Swiss Alps, which is definitely not sufficient to obtain a good overview on wet-snow stability conditions. Figure 3, in contrast, was updated every 3 hours. It took roughly 2 hours to transfer the data from the stations to our servers, run the SNOWPACK simulations and compute the LWC$_{index}$. Simulations for 12:00 noon were available to the forecasters when they prepared the forecast for the next day to be issued at 17:00. Presently, our approach represents a now-cast. However, once the snow cover model is run with output from a high resolution weather model, we will be able to provide a real forecast (e.g. 24-hours) to the avalanche warning service.

5 CONCLUSIONS

Based on previous energy balance studies we presented a liquid water content index (LWC$_{index}$) for better determining periods with high wet-snow avalanche activity. The LWC$_{index}$ was calculated using values obtained with the 1—D snow cover model SNOWPACK. Since the snow cover model is driven by meteorological data, it was possible to calculate the index for 105 Automated Weather Stations covering the Swiss Alps. In this way, forecasters obtained information over a wide variety of elevations and aspects at regular time intervals. We compared the median values of three different elevations classes to wet-snow avalanche activity for two winter seasons. Results show that the index agreed well with observed wet-snow avalanche activity. It indicated spatial and temporal patterns of wet-snow avalanche activity. Onset and peak of wet-snow avalanche activity were mostly well detected, but in particular, when high temperatures and high values of shortwave radiation caused the percolating meltwater. However, it was still not possible to determine the end of a period with wet-snow avalanche activity, since the LWC$_{index}$ showed no pattern for describing the end of such periods. In addition, periods with low activity, i.e. AAI < 20, or which were induced by small rain-on-snow events were not captured with the presented approach. Our approach allows a real forecast if output data of Numerical Weather Prediction (e.g. COSMO2) models is used as input for the snow cover model.

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