ANALYZING THE ATMOSPHERE-SNOW ENERGY BALANCE FOR WET-SNOW AVALANCHE PREDICTION

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ABSTRACT: Melt water is the major driver of wet-snow instability. Its percolation and interaction with snow is complex, poorly understood and hence not well depicted in today's snow cover models. As snow melt depends on the energy input into to the snow cover, we computed the energy balance and studied whether it is a good proxy for predicting periods with high wet-snow avalanche activity. The energy balance was calculated for virtual slopes at different elevations for the aspects south and north using the 1-D snow cover model SNOWPACK. In addition to the computed energy balance and its components, we used recorded meteorological variables to compare wet-snow avalanche days to non-avalanche days for four consecutive winter seasons in the surroundings of Davos, Switzerland. Air temperature, the net shortwave radiation and the energy input integrated over 3 or 5 days discriminated best between event and non-event days. Multivariate statistics, however, revealed that for better predicting avalanche days, information on the cold content of the snowpack (i.e. snow temperature) or the snow surface temperature is needed. This additional information indicates whether the energy input was used for warming the snowpack or directly for melting. Prediction accuracy with measured meteorological variables was as good as with computed energy balance parameters, but simulated energy balance variables accounted better for different aspects, slopes and elevations than meteorological data.

1. INTRODUCTION

Wet-snow avalanches are particularly difficult to forecast, but often threaten communication lines in snow-covered mountain areas. Once the snowpack becomes wet the release probability obviously increases, but determining the peak and end of a period of high wet-snow avalanche activity is particularly difficult (Techel and Pielmeier, 2010). While for large new snow avalanches the 3-day sum of precipitation is the strongest forecasting parameter (Schweizer et al., 2009) and closely related to avalanche danger (Schweizer et al., 2003a), air temperature is often used as a critical parameter for predicting wet-snow avalanche activity (McClung and Schaerer, 2006). It is included in statistical prediction tools, which were designed for a defined climatic region (Romig et al., 2005; Zischg et al., 2005). However, there are many examples which show that air temperature is in many cases not a good predictor and causes a high number of false alarms (Romig et al., 2005). Nevertheless, it appears to be a variable clearly related to wet-snow instability (Baggi and Schweizer, 2009; Peitzsch et al., 2012).

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Processes leading to wet-snow avalanches are complex and the conditions of the snowpack may change from stable to unstable in the range of hours (Trautman, 2008). The presence of liquid water within the snowpack in the starting zone is a prerequisite and several field campaigns (Bhutiyani, 1996; Brun and Rey, 1987) and experiments under laboratory conditions (Yamanoi and Endo, 2002) found decreasing shear strength with increasing liquid water content. However, quantifying the amount of liquid water within the snowpack in the field is a difficult task, as even experienced observers tend to overestimate the amount of liquid water (Fierz and Föhn, 1995; Martinec, 1991). Only objective methods such as permittivity measurements (Denoth, 1994) or calorimetric methods (Boyne and Fisk, 1990) provide reliable results. As those methods are experimental, often costly and time consuming, they are mainly restricted to research investigations and hardly used among practitioners. In-situ stability tests commonly used to assess dry-snow instability showed ambiguous results when performed in moist or wet snow covers (Techel and Pielmeier, 2010).

In order to detect the meteorological boundary conditions favoring the triggering of wet-snow avalanches, we analyzed four winter seasons (from 2007-2008 to 2010-2011) with different distinct wet-snow avalanche events in the surroundings of Davos, Switzerland. As suggested by Trautman (2008) we computed the entire energy balance in order to reveal the dominant energy sources during wet-snow instabilities. In addition, we studied whether the energy balance or its terms have a better predictive power than commonly measured meteorological parameters

2. METHODS AND DATA

2.1 Avalanche occurrence

Avalanche occurrence data were recorded for the winters 2007-2008 to 2010-2011 for the surroundings of Davos, Switzerland. Data consisted of avalanche size (Canadian avalanche size class, McClung and Schaerer, 2006) and included only events which were classified as wet-snow avalanches. We calculated a daily avalanche activity index (AAI) using a weighted sum of recorded avalanches per day with weights of 0.01, 0.1, 1 and 10 for size classes 1 to 4, respectively (Schweizer et al., 2003b). For the statistical analyses (see below) only days with an AAI > 2 were considered as wet-snow avalanche days. In addition, we calculated the median elevation of the release zones. Due to the recording system used in Switzerland it was not possible to clearly relate avalanches and their size to a given aspect. Therefore we introduced an aspect index, which is the ratio of the frequency and size of avalanches recorded in southern aspects to the one recorded in northern aspects. If the ratio was > 1 we assumed that the avalanche cycle took place in southern aspects and vice versa for < 1. Following this approach we obtained 66 wet-snow avalanche days and 663 non-avalanche days for the four winters.

2.2 Meteorological data

Meteorological data were obtained from three automatic weather stations: Weissfluhjoch (WFJ, 2540 m a.s.l.), Stillberg (STB, 2150 m) and Dorfberg (DFB, 2145 m). After the first winter season 2007-2008 data from Stillberg were replaced by data from the new Dorfberg weather station which is located in the vicinity of a well-known wet-snow avalanche starting zone. The three stations are located at two distinct elevations: STB and DFB are slightly above the tree-line, near the lower limit of where most wet-slab avalanches are initiated, and WFJ is located higher than most starting zones of all wet-snow avalanche cycles.

For the statistical analyses radiation (all four components), snow depth, relative humidity and air temperature were used as explanatory variables. In addition to mean, maximum and minimum values we derived differences and sums over 1, 3 and 5 days; wind was not considered.

2.3 Simulation of energy balance

In order to obtain energy balance data for slopes of various elevations and aspects we used the 1-D snow cover model SNOWPACK (Lehning et al., 2002a,b; Lehning and Fierz, 2008). Slope angle was fixed to 35° which represents the median slope angle of all recorded wet-snow avalanches. Input data for the model were meteorological values taken from the weather station Weissfluhjoch (WFJ) only; we had to extrapolate or adapt air temperature, snow surface temperature and incoming shortwave radiation for different elevations and aspects. Air temperature was extrapolated using a constant lapse rate of 0.65°C/100 m. Outgoing longwave radiation and consequently snow surface temperature was modeled in SNOWPACK using Neumann boundary conditions (Lehning et al., 2002b). We adapted the input of the shortwave radiation according to the lapse rate suggested by Marty (2001). We did simulations only for slopes of the two main aspects, i.e. 0° (N) and 180° (S). The change in incoming solar radiation on these aspects was taken into account.

2.4 Statistical analyses

The non-parametric Mann-Whitney *U*-test (Spiegel and Stephens, 1999) was used to contrast meteorological or energy flux variables from avalanche and non-avalanche days. Observed differences were judged to be statistically significant where the level of significance was $p < 0.05$, i.e. the null hypothesis that the two groups are from the same population was rejected. In order to match the monthly distribution of avalanche days, we randomly selected the same number of non-avalanche days considering the frequency of wet-snow avalanche days per month for the period December-May. Days with an AAI ≤ 2 were excluded as our focus was on prediction of a regional avalanche activity. Non-avalanche days were selected 10 times and for every run a *p*-value was computed. We averaged the *p*-values and only if the *U*-test indicated a statistically significant difference, variables were passed to a classification tree analysis (Breiman et al., 1998) and its newer derivative the *RandomForest* classification (Breiman, 2001). Classification trees were obtained by optimizing the misclassification costs

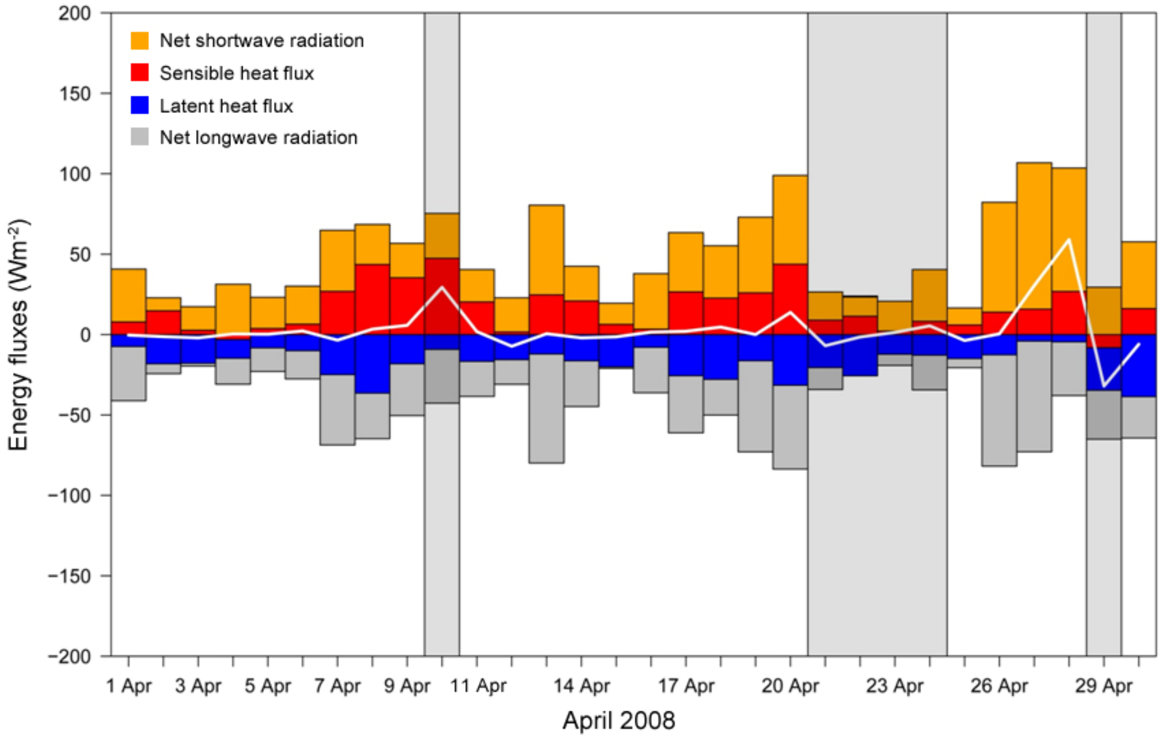

Figure 1: Simulated sum of energy fluxes at the snow surface (white line) for a virtual 35° steep south-facing slope in April 2008. Bars depict the terms of the energy balance. Positive values are energy fluxes towards the snowpack (energy gain); negative values represent energy loss. Grey shaded areas mark days with wet-snow avalanche occurrence on south-facing slopes.

and the complexity (size) of a tree. Tree size was determined through cross-validation (10-fold). To minimize the effect of randomly selecting non-avalanche days we performed the tree analysis 20 times and selected the tree combination, which showed up in most of the cases (in our case about 2/3). To assess the performance of the multivariate analysis we used the true skill statistic (HK), the false alarm ratio (FAR), the probabilities of detection of events (POD), and non-events (PON).

3. RESULTS AND DISCUSSION

Figure 1 shows an example of the simulated terms of the energy balance for a virtual 35° south-facing slope at 2500 m. Periods with avalanche activity (grey shaded areas) had in most cases a peak or a preceding period with high energy input. Latent heat and net longwave radiation were always negative (loss of energy); sensible heat flux and net shortwave radiation determine the energy input. The contribution to the input varies throughout the month. While at the beginning of April the sensible heat flux is the dominating term for energy input, net shortwave radiation gains more and more influence later in the month. The amount of input due to shortwave radiation before the last day with wet-snow avalanche activity exceeds the one of the sensible heat flux by a factor of 3. Nevertheless, on many days the sensible heat flux contributes a considerable amount of energy that needs to be considered when calculating the energy input to the snowpack on a daily basis. It is, however, very difficult to assess the sensible heat flux precisely for large areas – air temperature is still the best proxy for this term of the energy balance.

Even though the net longwave radiation represents always an energy loss, it seems important how negative the value is. For example, net longwave radiation was low during the second period of wet-snow avalanche activity. Low values of net longwave radiation mean that less of the energy input is counterbalanced resulting in an overall positive balance.

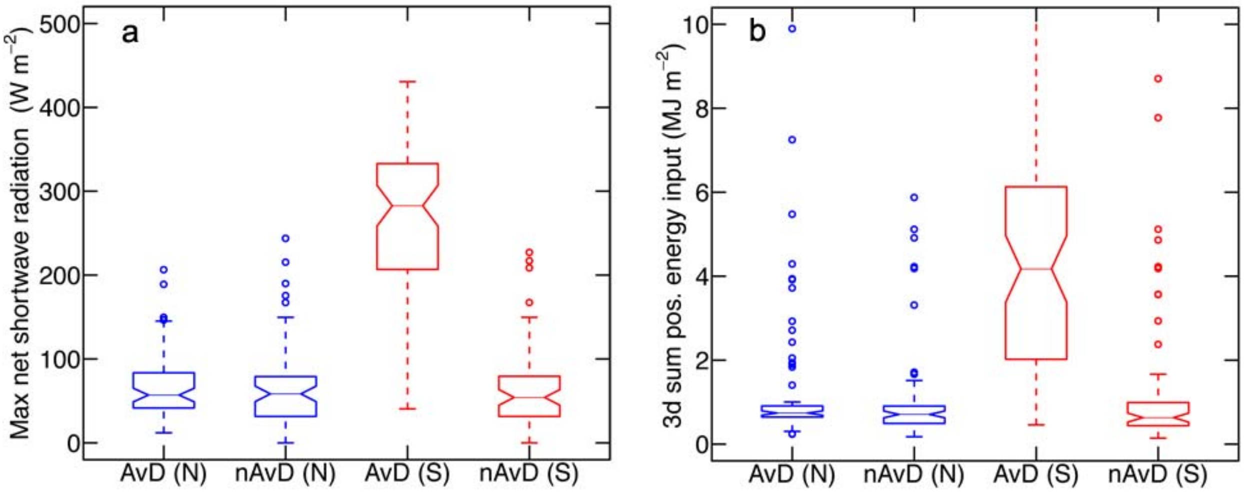

Figure 2: Distribution of (a) max net shortwave radiation and (b) the resulting 3-day sum of positive energy balance values for avalanche days (AvD) and non-avalanche days (nAvD) on south-facing (red) and north-facing (blue) slopes. Values were calculated with SNOWPACK assuming an elevation of 2500 m and a slope angle of 35°. Boxes span the interquartile range; whiskers extend to 1.5 times the interquartile range. Outliers are shown with open circles. Notches are defined by ±1.5 times the interquartile range divided by the square-root of the sample size.

3.1 Univariate analysis

Analyzing the simulations on south-facing slopes for all periods reveals that all variables dealing with net and incoming shortwave radiation discriminated well between avalanche and non-event days if simulated on a slope (Fig. 2a). As most avalanches in the periods we analyzed occurred on slopes of southern aspect, it is not surprising that the net shortwave radiation that provides most energy was closely related to avalanche activity. Median values on avalanche days were about 80 W m^{-2}, however, maximum values may be as high as 200-400 W m^{-2} within 60 minutes (Fig. 2a). These maximum flux values might prevail only for 2-4 hours per day, but contribute about two thirds of the maximum energy input on a single day. In case the snowpack is already at 0°C, this high energy input during a few hours will be directly transformed into about 1.5 mm of water.

Daily minimum and maximum values of the energy balance and the 3-day sum of positive values (Fig. 2b) performed also well in distinguishing between avalanche and non-avalanche days, but for southern slopes only. In addition, distributions of the daily minimum of sensible heat, the mean net longwave, the minimum, mean, maximum value of outgoing longwave radiation, and all sums of outgoing longwave radiation were significantly different for event and non-event days.

The minimum, mean, maximum, and the positive sum of air temperature over 3 days, were statistically different with $p < 0.01$ for the two classes of wet-snow avalanche and non-avalanche days. Furthermore, the distributions of the minimum snow surface temperature were significantly different between the two classes for all stations. The daily mean and maximum of the snow surface temperature, the difference of air temperature in the last 24 h and the difference in snow height for 24 h or 3 days discriminated between the groups only with the data of WFJ. The results agree with previous studies (Baggi and Schweizer, 2009; Peitzsch et al., 2012). Not surprisingly, avalanche days had always higher energy input than non-avalanche days, mostly due to shortwave radiation and high air temperature values. In most cases a preceding period (3 or 5 days) with high energy input and high snow surface temperatures prevailed.

3.2 Multivariate analysis

Figure 3 shows the predictive skills for various statistical models using classification trees and *RandomForests*. In this type of graph, a perfect prediction model appears in the upper right corner with a symbol having the largest size, i.e. the model hits all avalanche days and correctly predicts all non-avalanche days. The classification trees compiled with the meteorological parameters of WFJ, and the energy balance values for a south-facing and a north-facing slope showed the best predictive skill. The tree with data of the weather station WFJ used only terms of the radiation balance to split into the two classes. Air temperature was not chosen by the tree. When omitting radiation terms, the 5-day sum of positive air temperature remained as the only splitting parameter and predictive performance deteriorated (grey circle): the tree missed two thirds of all avalanche events, but correctly predicted most non-event days. When adding the snow surface temperature the predictive power improved, but the prediction accuracy for the non-events went down and consequently the false-alarm ratio increased. Nevertheless, the number of hits (i.e. POD and PON) was in the same range as with the more complex tree data (Meteo WFJ; black circle).

The classification trees built with the energy balance data showed reasonable well overall skills. The most important splitting variables included the energy balance summed over 3 days, followed by the mean net shortwave radiation, the internal state of energy of the snowpack (cold content) and the maximum outgoing longwave radiation. Results obtained with *RandomForests* (not shown in the graph) were very similar to those from classification trees, but variable importance differed. Most important variable was the value of

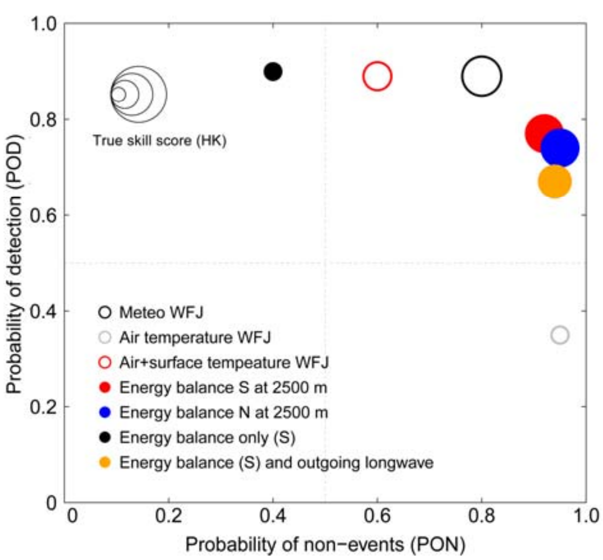

Figure 3: Classification accuracy of different classification tree models for contrasting wet-snow avalanche days to non-avalanche days. Size of the circle corresponds to the true skill score with the largest circle = 1, smallest circle = 0.25.

zero cold content at noon followed by the mean net shortwave radiation for southern aspects and the mean outgoing longwave radiation for northern aspects.

The various statistical models revealed that it is important to know two things in order to better predict periods with a high wet-snow avalanche probability: The occurrence of high energy input and the moment when large parts of the snowpack become isothermal for the first time. Using simply the daily energy balance or air temperature allowed either detecting 90% of the wet-snow avalanche days or hitting most non-event days. The problem, however, is that either many false alarms or false-stable prediction resulted which is not satisfying and lowers the overall predictive skill (Fig. 3). Combining air temperature with snow surface temperature, or energy input with the cold content of the snowpack, improved predictive skills. Having this additional information we can exclude days when the energy input is used for warming the snowpack or determine when surplus of energy is available for melting snow. These findings are linked to previous results by Baggi and Schweizer (2009); some avalanche warning services, e.g. in New Zealand (Conway, 2005), take this fact into account by relating the convergence of snow temperature at different heights towards 0°C to the start of a period with high probability of wet-snow avalanche release.

Our data included only one rain-on-snow event and the above-discussed results may be biased to situations where irradiation and air temperature caused the melting.

4. CONCLUSIONS

We compared 4 years of wet-snow avalanche occurrence in the surroundings of Davos, Switzerland to meteorological data measured by three automated weather stations and to simulated energy balance values. The energy balance was modeled for virtual slopes of southern and northern aspects using the 1-D snow cover model SNOWPACK. Net shortwave radiation and the sensible heat flux were the main energy contributors before days with wet-snow avalanche activity. Univariate analysis revealed that high net shortwave radiation, high energy input values, a high proportion of zero cold content, high snow surface temperature and high air temperature were all closely related to days with avalanche occurrence. Combining various variables in two different multivariate approaches provided satisfactory results in predicting wet-snow avalanche days.

The results obtained with the energy balance did not outperform those obtained with meteorological parameters. Nevertheless, modeling the energy balance for virtual slopes allows simulating the energy input and state of energy of the snowpack (i.e. cold content) for specific slopes and aspects. Results suggest that for cycles when irradiation and air temperature dominate melting, knowing the energy input and the cold content is essential to improve prediction accuracy. Combined with forecasted radiation and air temperature values a model for predicting the probability of wet-snow avalanche release can be developed. Such a supporting tool may help avalanche warning services to narrow down periods with high wet-snow avalanche activity.

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