Observations and analysis of two wet-snow avalanche cycles

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ABSTRACT: Wet-snow avalanches threaten mountain communities and communication lines. Their formation as well as the snowpack processes leading to wet-snow instability are poorly understood. Forecasting wet-snow avalanches is a great challenge and poses great difficulties for local authorities. Better knowledge about the processes leading to wet-snow instabilities is therefore very important. During the winters of 2007-2008 and 2008-2009 two distinct wet-snow avalanche cycles occurred in the surroundings of Davos, Switzerland. We analyzed meteorological data, in-situ snowpack information and mapped avalanche extent. In addition, the snow cover model SNOWPACK was used to fill the gap where snowpack data, such as volumetric water or snow temperature, were not available. The analysis focused on the causes of instability: loading and/or weakening due to water infiltration. The full energy balance was calculated using meteorological data and extrapolated to the investigation area using the model ALPINE3D. Both avalanche cycles occurred in a short period of time. Precipitation amounts and the type of precipitation, i.e. rain or snow, played an important role during the first avalanche cycle, while terrain parameters such as aspect and slope angle combined with liquid water infiltration patterns were crucial during the second wet-snow avalanche cycle. Although different meteorological conditions prevailed during these two avalanche cycles, it appears that wet-snow instabilities were mostly influenced by snow stratigraphy, rapid increase in air temperature and water infiltration patterns.

KEYWORDS: snow avalanche, wet snow, liquid water content, avalanche release

1 INTRODUCTION

Due to their destructive power wet-snow avalanches often threaten mountain communities and communication lines. The prediction of these avalanches remains difficult. Air temperature is often used as a critical parameter for predicting wet-snow instabilities (McClung and Schaerer, 2006), however, there are many examples which show that air temperature is not a good predictor (e.g. Kattelmann 1985, Trautmann, 2008). During the last decades, most research has focussed on dry-snow slab avalanches since these are responsible for most avalanche victims (e.g. Schweizer and Lütschg, 2001). Comparatively, little research exists on wet-snow avalanches.

Processes leading to wet-snow avalanches are complex and poorly understood. The presence of liquid water within the snowpack in the start zone is a prerequisite. Processes that favour wet-snow instabilities can quickly change snowpack properties, since the snow is very close to its melting point (Schneebeli, 2004). Wet-snow metamorphism, for instance, leads to rapid increase in grain size (Brun, 1989). This influences the porosity of the snowpack and hence the infiltration patterns of water, resulting in a complex feedback system which is sensitive to small perturbations in a highly non-linear manner. This makes it very difficult to observe, measure and quantify the characteristics leading to wet-snow avalanches.

The aim of the present work is to shed some light on triggering mechanisms of wet-snow avalanches by examining two wet-snow avalanche cycles. Meteorological data, snowpack information obtained from the 1-D SNOWPACK model (e.g. Lehning et al., 2002) and spatial distribution of liquid water content obtained from the ALPINE3D model (Lehning et al., 2006) are compared with avalanche activity.

2 DATA

2.1 Avalanche data

Avalanche occurrence data, consisting of avalanche perimeter and approximate occurrence time, were gathered for two wet-snow avalanche cycles in the vicinity of Davos, Switzerland. The first wet-snow avalanche cycle occurred on 22-23 April 2008 and 251 avalanches were registered. The second avalanche cycle took place in the first week of April 2009 and 249 avalanches were recorded (Figure 1).

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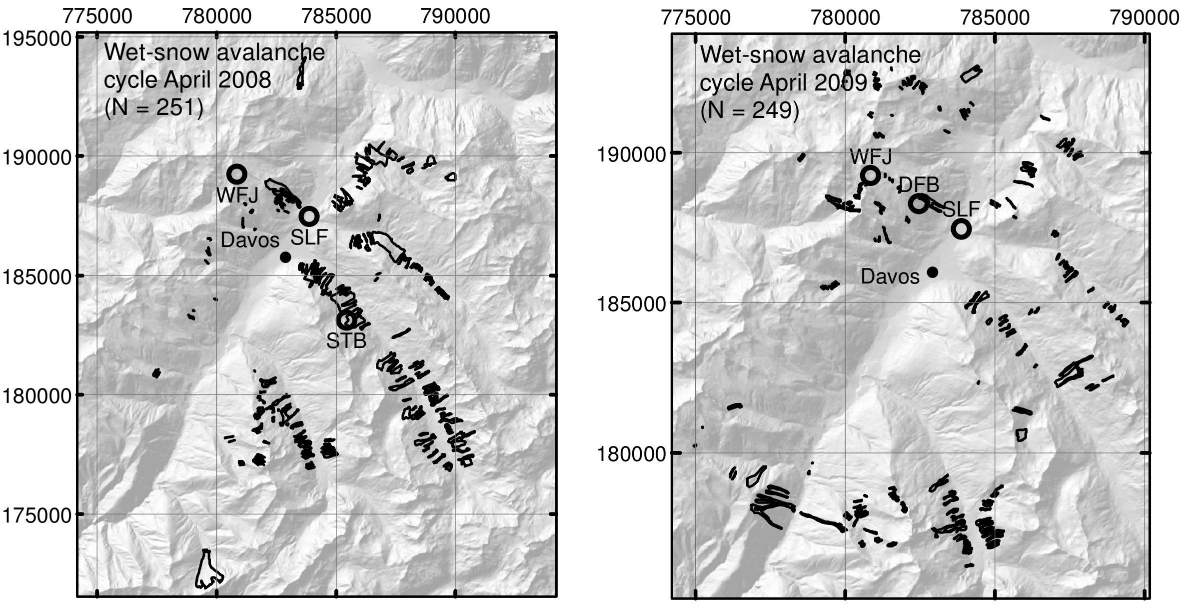

Figure 1: Wet-snow avalanches recorded during April 2008 (left) and April 2009 (right) in the vicinity of Davos, Switzerland. Open dots indicate the location of weather stations.

2.2 Meteorological data

Meteorological data for the first avalanche cycle were recorded by three weather stations: Weissfluhjoch (WFJ, 2540 m), Stillberg (STB, 2145 m) and Davos Dorf (SLF, 1560 m). For the second avalanche cycle the STB data were replaced by data from the new Dorfberg weather station (DFB, 2140 m) which is located within a well-known wet-snow avalanche start zone (Figure 1).

2.3 Snowpack data

In order to obtain snowpack information at various elevations and aspects we used the 1-D snow cover model SNOWPACK (Lehning et al., 2002) to simulate the snow stratigraphy. The input data for the model were meteorological values taken from the WFJ station.

The snowpack was simulated at different elevations by calculating the air temperature using a constant lapse rate of 0.65°C/100 m. The snowpack on slopes of different aspect, i.e. 90° (E), 180° (S), 270° (W) and 360° (N), was simulated by taking into account changes in incoming solar radiation. Using the SNOWPACK model data on snow temperature, grain type, grain size and liquid water content were obtained.

For the wet-snow avalanche cycle of April 2008 very few manual snow profiles existed and we only used data from SNOWPACK. For the wet-snow avalanche cycle of April 2009, however, about 20 manual snow profiles were available, including two which where close to a recently released wet-snow avalanche. For the April 2009 avalanche cycle we used both manual and simulated snowpack data.

3 METHODS

3.1 Spatial analysis

The observed avalanches were divided into a start zone and a run-out zone. Slope and aspect of the start zone and run-out zone were obtained from a 25 m digital elevation model (DEM) using the calculation algorithm of ArcGIS. Additionally, the area covered by all avalanches was calculated.

3.2 Analysis of meteorological data

We analyzed the meteorological data in three stages. First, a qualitative comparison was made between avalanche and non-avalanche days. Second, a univariate statistical analysis was performed using the non-parametric Mann-Whitney U-test (e.g. Stahel, 2008) to find variables related to avalanche occurrence. We assumed avalanche and non-avalanche day samples to be significantly different for $p < 0.05$. Third, we applied the two classification splits presented by Baggi and Schweizer (2009) on our data from all weather stations and profiles at different elevations, namely the 3-day sum of positive air temperature at midday and the number of days since isothermal state had been reached. The performance of the separator variables was expressed by using contingency tables and performance measures such as the probability of detection (POD), probability of non-events

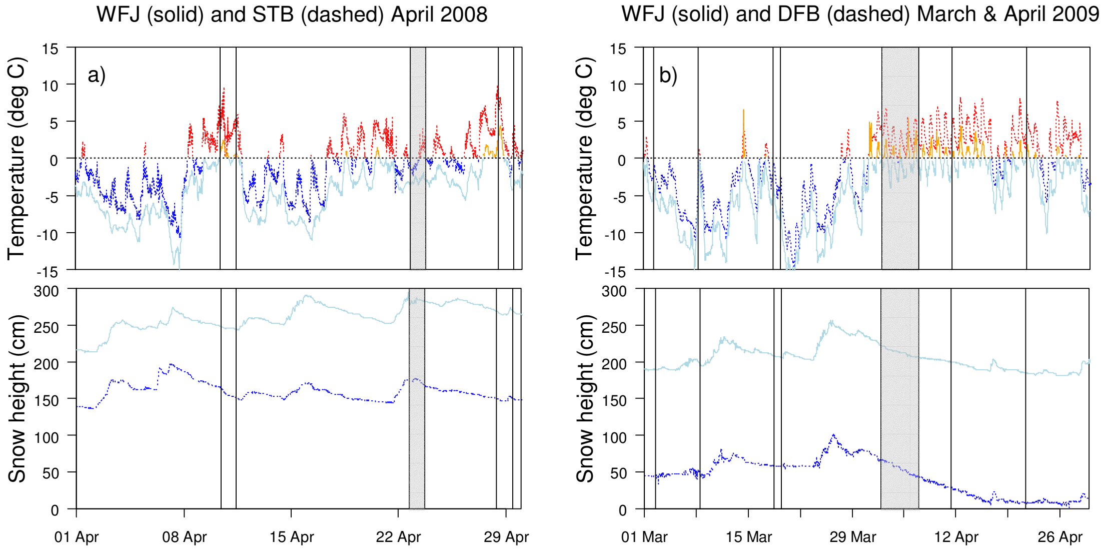

Figure 2: Daily mean air temperature and snow height as measured at the automatic weather stations Weissfluhjoch (WFJ), Stillberg (STB) and Dorfberg (DFB). The black vertical lines indicate single avalanche days, the grey boxes show the periods both avalanche cycles (2008: 7 days, 2009: 11 days). Red and orange colours indicate temperatures above 0 ℃, blue colours stand for temperatures below freezing.

(PON) and the Heidke skill score (HSS), (Wilks 1995, Doswell et al. 1990).

For the wet-snow avalanches cycle of 2008 only data from the month of April were used since the snowpack in the start zones had not reached isothermal state prior to April. For the avalanche cycle of 2009, data from March and April were used as isothermal conditions in southern aspects below 2000 m a.s.l. were reached earlier in this season. We considered a day with a wet-snow avalanche larger than size class 2 (McClung and Schaerer, 2006) as an avalanche day (2008: 23 non-avalanche days, 7 avalanche days; 2009: 50 non-avalanche days, 11 avalanche days).

3.3 Quality check of simulation data

Most quality checks were performed in a qualitative way. When available, simulated profiles were compared to manual snow profiles. For a quality check of ALPINE3D outputs we used several functions of *r.series* implemented in GRASS GIS. The goal of the quality checks was to determine how often spatial patterns of e.g. liquid water content associated with avalanche days were also observed on non-avalanche days.

4 RESULTS AND DISCUSSION

In Figure 2 the meteorological conditions (air temperature and snow height) for both periods are shown. Avalanche days are indicated with vertical lines and the grey boxes indicate the avalanche cycles.

During April 2008 (Figure 2a) warm air temperatures wetted the topmost layers. Prior to the wet-snow avalanche cycle, two distinct warm periods (10 April & 17 April) triggered the first melting. Only very few and small wet-snow avalanches were associated with this warm weather. The simulated snow profiles suggest that parts of the snowpack reached isothermal conditions up to an elevation of 2500 m a.s.l. prior to the avalanche cycle. The cycle was triggered by the onset of rain and snow at higher elevations.

For this avalanche cycle, the statistical analysis showed that minimum air temperature, 3-day sum of positive air temperature at midday and change of snow height were significantly different for avalanche and non-avalanche days. This supports the observation that the interaction of rapid warming and the additional loading due to snow or rain were responsible for triggering the wet-snow avalanches during this cycle.

When testing the performance of the threshold values suggested by Baggi and Schweizer (2009) for the April 2008 avalanche cycle, the 3-day sum performed poorly (POD < 50%). In contrast, the number of days since isothermal state performed very well in discriminating between avalanche and non-avalanche days (POD ~ 85%).

The weather conditions during the second avalanche cycle were different. Again, there

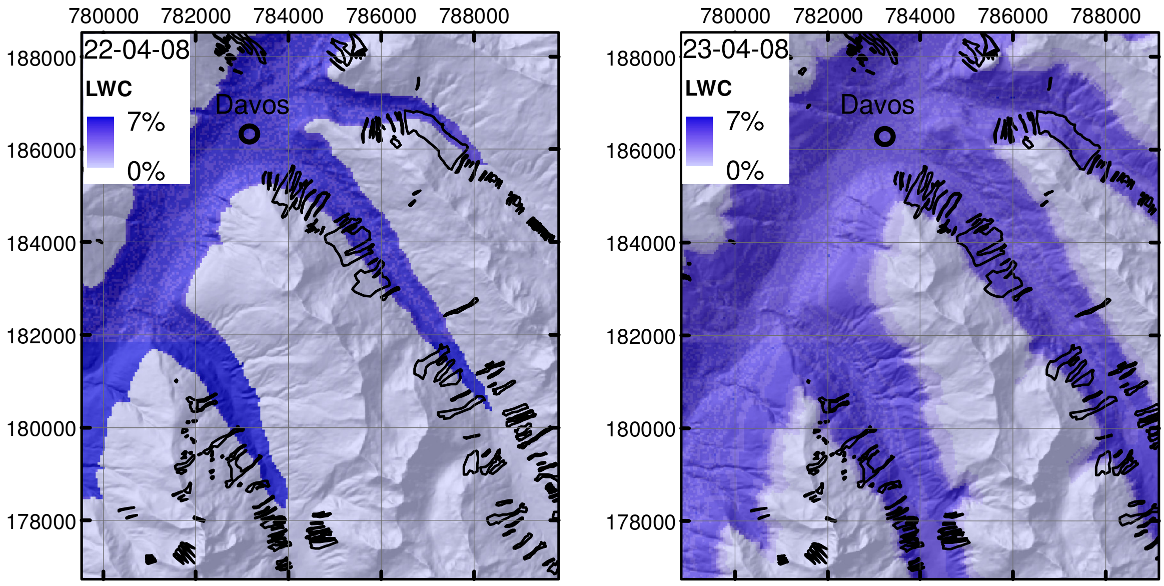

Figure 3: Amount of liquid water content for one day before (left) and during (right) the wet-snow avalanche cycle of April 2008. Avalanche extents are given for orientation; all avalanches released at 22-23 April 2008.

was a distinct warming before the onset of wet-snow avalanche activity (Figure 2b). However, in this case no external loading due to rain or snow was present. In fact, the weather data suggest that melting and subsequent water infiltration triggered this avalanche cycle.

The statistical analysis indicated that the 3-day sum of positive air temperature at midday and the change of snow height were again significantly different for avalanche and non-avalanche days. In contrast to the avalanche cycle of April 2008, this time the 3-day sum of

positive midday air temperatures performed very well (POD = 83%, PON = 79%), whereas the days since isothermal state performed poorly (POD = 26%, PON = 62%).

The spatial distribution of the two avalanche cycles reflected the weather conditions prevailing during the events. During the April 2008 cycle most avalanches (91%) occurred below 2500 m, which is the elevation at which precipitation turned from rain into snow. Furthermore, the simulated snow profiles showed that above 2500 m the entire snowpack had not reached isothermal state before and during the event.

During the second cycle, the start zones had mostly southern and south-easterly aspects and slope angles were slightly higher than in the year before, indicating that solar radiation played a key role. Most avalanches occurred below 2500 m, since air temperatures were below freezing at higher elevations. The avalanches in the April 2008 cycle were larger than the ones recorded in 2009.

Figure 3 shows the amount of liquid water content (LWC) simulated with ALPINE3D for two days in April 2008: one day before and on the day of highest avalanche activity. The avalanches are shown in black again. When cross checking ALPINE3D results with simulated LWC values by SNOWPACK, very similar results for different elevations and aspects were obtained, indicating that the ALPINE3D simulation results were reasonable.

The LWC within the snowpack probably played an important role in the wet-snow avalanche cycles. For the 2008 avalanche cycle the data suggest that thin surface layers with a LWC of about 5% to 7% were subsequently covered by dry snow. It is plausible that at the interface between the wet snow and the dry snow large temperature gradients existed favouring kinetic grain growth (Jamieson and van Herwijnen, 2002). This process might have resulted in widespread weak layer formation, which would explain the large size of the avalanches observed in April 2008. Ongoing loading due to snow and strong winds may have favoured the triggering of the avalanches.

In the April 2009 avalanche cycle, the snowpack was isothermal for all southern and south-easterly aspects up to 2500 m. This might have favoured a more rapid flow of melt water through the snowpack inhibiting the storage at layer boundaries or capillary barriers. The fact that nearly all avalanches failed on the ground supports this assumption.

5 CONCLUSION

We presented and analyzed two distinct wet-snow avalanche cycles which took place in April 2008 and April 2009 in the vicinity of Davos, Switzerland. Analyzing spatial, meteorological and snowpack data revealed different forcings depending on weather and snowpack conditions. The first avalanche cycle was characterized by short periods of warming and additional loading by snowfall and input of melt water due to rain. For the 2009 wet-snow avalanche cycle, on the other hand, distinct warming and solar radiation were probably responsible for a higher production of melt water. Snowpack data suggest that in the first year snow stratigraphy favoured the formation of weak layers, whereas for the second year snow stratigraphy may have favoured a gradual ripening of snowpack leading to a weakening of the basal layers.

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