The influence of weather on glide-snow avalanches

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ABSTRACT: During the winter 2011-2012 the Swiss Alps experienced high glide-snow activity. The danger of glide-snow avalanches combined with large snow depths posed a challenge to the local authorities. Glide-snow avalanches are difficult to predict and hard to control. Weather, snowpack, soil and terrain are known to influence snow gliding. So far, however, no clear relationship between these variables and glide-snow activity could be established. Many research results report that a wet basal layer is paramount for the formation of glide-snow avalanches. Based on observations, the assumption is made that different processes favor the production of this basal layer and thus the triggering of snow gliding in winter and in spring. In winter the snowpack is usually cold and dry, in spring it's warm and wet. Thus, there are different processes causing water at the snow-soil boundary. In order to shed some light into these two different periods, glide-snow activity was monitored at a well-known glide-snow avalanche site, the Dorfberg above Davos, Switzerland during the winter seasons 2008-2009 and 2011-2012 using time-lapse photography. Glide-snow avalanche activity was compared to weather parameters of a nearby weather station. We used univariate and multivariate statistical methods to explore the data. Results verify different processes in winter and spring. Most important weather parameters in winter are maximal air temperature, the 5-day sum of new snow and incoming shortwave radiation. In spring, the parameters snow surface temperature, minimal air temperature, difference in air temperature to the day before and relative humidity seem most important. The difference in important parameters for winter and spring periods indicate different sources of the thin water layer at the snow-soil interface and therefore different underlying processes that lead to snow gliding.

KEYWORDS: snow gliding, weather influence, glide-snow avalanche, multivariate statistic.

1 INTRODUCTION

In winter 2011-2012, there was above-average glide-snow activity in the Swiss Alps. In combination with high snow depths the hardly predictable and controllable glide-snow avalanche activity posed a major challenge to local authorities.

It's known that a thin water layer at the snow-soil interface is crucial for snow gliding (Clarke and McClung, 1999; Mitterer and Schweizer, 2012). The liquid water at the snow-soil interface is produced either through i) melting of the basal snow layer on warm ground, ii) rain or melt water percolating from the surface through the whole snowpack or iii) snow melting at high energy spots (e.g. exposed and heated rocks) and running down along the snow-soil boundary (McClung and Clarke, 1987; Mitterer and Schweizer, 2012). The conditions at the snow-soil interface are influenced by weather, snowpack, soil and terrain characteristics. So far, however, no clear relationship between these variables and glide-snow activity could be established.

The influence of weather on glide-snow activity has been investigated in several works. Observations showed increased occurrence of glide-snow avalanches after rain and warm periods (Clarke and McClung, 1995; Lackinger, 1987; Stimberis and Rubin, 2005; Stimberis and Rubin, 2011). Höller (2001) reported frequent releases of glide-snow avalanches in spring when snow temperatures rise. Peitzsch et al. (2012) investigated glide-snow avalanches and wet-snow avalanches in spring. They pointed out air temperature and settlement of snowpack as two important parameters to classify avalanche days and non-avalanche days. In der Gand and Zupančič (1966) and Höller (2001) found rising glide rates and frequent formation of glide cracks to be coupled with higher snow load.

Snow gliding probably underlies different processes in winter when the snowpack is cold and dry and in spring when the snowpack is warm and moist. Clarke and McClung (1999) described glide-snow avalanches in winter as *cold temperature events* which, in contrary to *warm temperature events* in spring, could not be connected with warm periods.

In this work we investigated the influence of weather on glide-snow avalanches to shed

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Figure 1: Monitored slopes (autumn and winter) at Dorfberg above Davos (Switzerland).

some light into the processes underlying snow gliding in winter (*cold temperature events*) when the snowpack is cold and dry and in spring (*warm temperature events*) when the snowpack is isothermal and moist. Our goal was to strengthen the knowledge of snow gliding processes and to contribute to the improvement of the predictability of glide-snow avalanches.

2 DATA AND METHODS

2.1 Monitoring of glide-snow events

We used time-lapse photography (15 min intervals) to monitor glide-snow avalanches at the test-site Dorfberg above Davos (Eastern Swiss Alps) which is known for glide-snow events. The monitoring camera was installed on a building in Davos and covers most of the east-southeast-facing Dorfberg slopes (Figure 1) which range from 1700 m to 2400 m above sea level (main peak: Salezer Horn, 2536 m a.s.l.). Land cover mainly consists of steep and very steep meadows, but also some rocky areas, bushes and closed and open forest stands can be found. Standard photo cameras record pictures in the visible light spectrum and depend on good visibility. In periods with low visibility due to bad weather conditions or at night no or incomplete information could be recorded. The analyzed periods last from 9 December 2008 to 2 April 2009 and from 8 December 2011 to 9 March 2012 since both years produced an above-average amount of glide-snow avalanche events. Every picture was analyzed manually and date and time of the first sighting of every glide-snow avalanche were recorded (Feick et al., 2012).

2.2 Meteorological data

Weather parameters (Table 1) recorded at the weather station of the experimental test site Weissfluhjoch (2540 m a.s.l.) which is situated northwest of the Dorfberg were used for our analysis. We calculated minimum, maximum and average values per day and the corresponding differences to several days before to account for potential lag influences of these parameters on glide-snow activity. New snow height was measured every morning at Davos (1560 m a.s.l.) and Weissfluhjoch (2540 m a.s.l.) by local observers. The average of both values was considered as representative for Dorfberg. Since we believed that loading due to new snow plays a major role on glide-snow avalanche activity, we computed the sum of new snow over five days (current day plus four days before) and added it to the weather parameter data set. The data set used for the statistical analysis consisted of 26 weather parameters.

Table 1: Weather parameters recorded at the experimental field site Weissfluhjoch (2540 m a.s.l.).

Parameter	Unit
Air temperature	°C
Relative humidity	%
Incoming shortwave radiation	W/m^2
Reflected shortwave radiation	W/m^2
Incoming longwave radiation	W/m^2
Outgoing longwave radiation	W/m^2
Snow height	cm

Clarke and McClung (1999) distinguished between *cold temperature events* and *warm temperature events*. We assumed that different processes lead to gliding of a dry, cold snowpack (mostly in winter) and a wet and warm snowpack in spring. To shed some light on these processes we split the two winter seasons 2008-2009 and 2011-2012 in winter and spring periods. The beginning of spring period in winter 2008-2009 was set to 16 February 2009 and to 11 February 2012 in winter 2011-2012 respectively. Spring and winter periods of both winter seasons were analyzed together.

2.3 *Univariate and multivariate statistical analysis*

Glide-snow activity was considered as a binary variable: either glide-snow avalanches were observed on a given day or not (avalanche/non-avalanche day). We used boxplots to describe the distribution of weather parameters on avalanche and non-avalanche days. The Wilcoxon rank-sum test was performed to test the consistency of the distribution of a given weather parameter on avalanche and non-avalanche days (significant: p-value < 0.05, highly significant: p-value < 0.01).

Multivariate statistical methods included classification trees and random forests (Breiman, 2001; Hothorn et al., 2006; Liaw and Wiener, 2002) and were applied to analyze the influence of combinations of several weather parameters on glide-snow avalanche activity. Binary classification trees give an insight into the effect of the input parameters (Hothorn et al., 2006). This established method was applied in several works regarding avalanche prediction for data exploration as well as forecasting (Peitzsch et al., 2012). Binary classification trees divide the data set into two classes, in this case avalanche days and non-avalanche days. The tree splits the data set recursively by the input parameter which has the strongest connection to the response variable and a p-value < 0.05. If no significant input parameter may be found the tree stops growing.

Random forests consist of numerous binary classification trees (ntree=2500) and were used in this work to obtain the most important weather parameters. Two-thirds of the data set were used to grow the tree. To split the data set a subset of input weather parameters (N=12) was tested. This subset varied for each tree so that numerous different trees were grown. Every observed day was classified as avalanche or non-avalanche day depending on which class prevailed over all trees. The importance of input weather parameters was evaluated with the measures of the mean decrease in accuracy and the Gini importance index. The evaluation follows the steps i) calculation of the specified measure for each tree, ii) permutation of the data of the input parameter used to split the data set and iii) new calculation of the specified measure. The permutation breaks the connection between explanatory variable and response variable. If, for example, the explanatory variable explains the response variable well, the accuracy of the classification decreases after permutation (Breiman, 2001; Strobl et al., 2008). The specified measures were averaged over all trees for each input weather parameter. Differences in the most important weather parameters resulting from different measures were synchronized manually to the five most important parameters.

The language and environment R for statistical computing was used to perform the statistical analysis, including the R packages ‘party’ (Hothorn et al., 2006) and ‘randomForest’ (Liaw and Wiener, 2002).

3 RESULTS AND DISCUSSION

We recorded 73 glide-snow avalanches on 23 days during winter 2008-2009 and 101 events on 26 days during winter 2011-2012. In winter 2008-2009 two periods with high activity were identified in December and some days in March and April. The winter season 2011-2012 showed a continuous activity of snow gliding with five distinct periods of high activity from December to the beginning of March.

Air and snow surface temperatures seem to have an influence on glide-snow activity since in winter and spring periods both the maximum air temperature and maximum snow surface temperature (derived from outgoing longwave

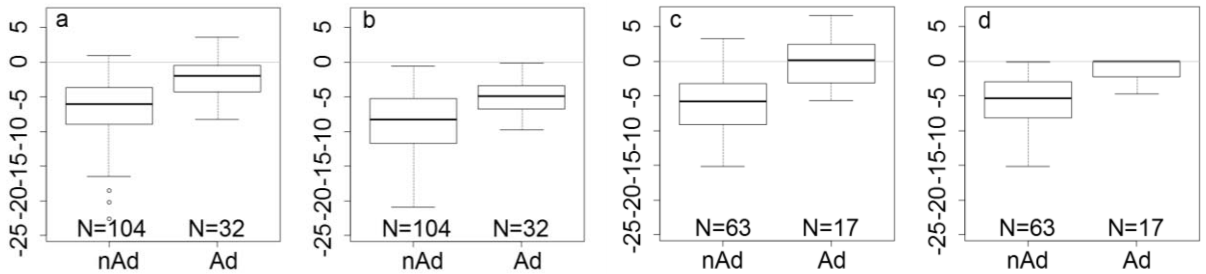

Figure 2: Boxplots of (a) maximum air temperature and (b) maximum snow surface temperature for the specified winter periods on avalanche days (Ad) and non-avalanche days (nAd). Boxplots of (c) maximum air temperature and (d) maximum snow surface temperature for the specified spring periods of both winter seasons 2008-2009 and 2011-2012. The data sets are not balanced since more non-avalanche days than avalanche days were monitored in both winter seasons. The grey horizontal line marks the 0°C level.

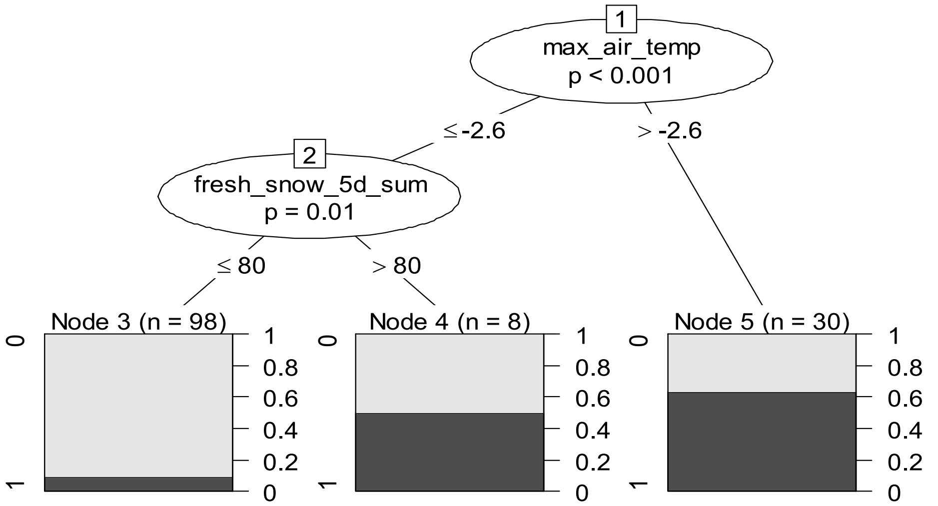

Figure 3: Classification tree for the specified winter periods of both winter seasons 2008-2009 and 2011-2012.

radiation) showed highly significant differences for avalanche and non-avalanche days (Figure 2). In winter, air temperatures on more than 75% of avalanche days stayed below 0°C, whereas air temperatures rose above 0°C on half of the avalanche days in spring. Snow surface temperatures stayed well below 0°C in winter. However, on half of the avalanche days in spring snow surface temperatures reached 0°C. Temperature regimes on avalanche days were considerably different to those on non-avalanche days.

The results obtained with the classification trees underlined the importance of air and snow surface temperatures. For the specified winter periods maximum air temperature was the most important parameter, followed by the 5-day sum of new snow (Figure 3). Maximum air temperature divides the data set with a threshold of -2.6°C in avalanche days (higher) and non-avalanche days (equal or lower temperatures). Non-avalanche days are further classified by the 5-day sum of new snow in avalanche days (more than 80 cm) and non-avalanche days (80 cm or less than 80 cm of new snow in five days). The boxes in Figure 3 show the portion of observed avalanche days (dark grey) and non-avalanche days (light grey) for every end node. High air temperatures and large loading of the snowpack seem to promote the occurrence of glide-snow avalanches in winter. The classification tree for the specified spring periods splits the data set based on mean air temperature into avalanche days (> -0.4°C) and non-avalanche days (≤ -0.4°C). In spring, high mean air temperature seems to promote snow gliding as the only important weather parameter.

Random forests once more pointed to the significance of air and snow surface temperatures as the most important weather parameters in winter and spring (Table 2). Apart from air and snow surface temperatures (derived from outgoing longwave radiation), the amount of new snow, change in snow height, and incoming shortwave radiation were the most important weather parameters regarding glide-snow avalanches in the winter periods. Snow surface and air temperatures as well as change in snow height and relative humidity had a large influence on snow gliding in the spring periods.

3.1 *Discussion of statistically significant weather parameters in winter periods*

In both winter seasons air temperatures and snow surface temperatures were higher on avalanche days than on non-avalanche days (Figure 2). Liquid water was not produced on the surface in winter periods since snow surface temperatures hardly reached 0°C suggesting that no melt water percolated into the snowpack. Presence of water at the snow-soil interface was probably related to the melting of snow in contact with the warm ground or due to rising water from the ground and grass caused by capillary effects (Mitterer and Schweizer, 2012).

Statistical analysis showed that a large amount of new snow highly correlated with avalanche days. New snow increases the load on the snowpack which results in large settlement rates as well as increased gliding and creeping of the snowpack. Downslope forces rise with increased loading of the snowpack (Höller, 2001; In der Gand and Zupančič, 1966). The motion of and within the snowpack might disturb the equilibrium of forces and lead to a collapse of the snow that supports the gliding zone and might consequently release as glide-snow avalanche (Bartelt et al., 2012). Increased air

Table 2: Variable importance according to the random forest analysis. Important weather parameters are in descending order.

Winter	Spring
Maximal air temperature	Outgoing longwave radiation
5-day sum of new snow	Minimal air temperature
24h difference in snow height	24h difference in air temperature
Incoming shortwave radiation	72 h difference in snow height
Outgoing longwave radiation	Mean relative humidity

and snow surface temperatures are connected to days with snowfall therefore it's obvious that these three parameters indicate a high appearance of snow gliding. Very cold days without snowfall indeed showed marginal glide-snow activity.

The strong influence of incoming shortwave radiation indicated that glide-snow avalanches occur frequently on clear sunny days in winter. Clarke and McClung (1999) assumed that shortwave radiation heats rocks below the snowpack which melt the basal snow layer. Water at the snow-soil interface reduces the friction of the snowpack on the ground and leads to higher glide rates (McClung and Clarke, 1987). The assumptions made by Clarke and McClung (1999) match several areas of the Dorfberg (Figure 1). This result is strongly dependent on the local topography of the study area and might not be generalized.

3.2 *Discussion of statistically significant weather parameters in spring periods*

Air and snow surface temperatures (derived from outgoing longwave radiation) played a major role for glide-snow activity in spring periods (Figure 2). Temperatures indicate a snowpack with 0°C or close to 0°C snow surface on avalanche days. Surface melting might have occurred and subsequently the produced water infiltrated the snowpack (Mitterer and Schweizer, 2012). This result is in line with the observations of Clarke and McClung (1999), who attributed periods of high air temperatures to days with high glide rates.

Peitzsch et al. (2012) identified the settlement of the snowpack as an additional important parameter. In this work the multivariate approach of random forests pointed out the importance of change in snow height (Table 2). Since the direction of snow height change does not result unambiguously from random forests it's hard to discuss. A change in snow height on the one hand might result from new snow which, as discussed above, means more load und thus motion within the snowpack that may affect the balance of forces between the gliding zone and the supporting stauchwall (Bartelt et al., 2012). On the other hand the settlement of the snowpack might be responsible for a change in snow height. Settlement often goes along with snow melting, the resulting water may percolate through the snowpack and reduce friction at the snow-soil interface (Peitzsch et al., 2012). In spring, periods with an enhanced settlement of the snowpack seem to be more probable.

3.3 *Separation of winter and spring periods*

The difference in important parameters for winter and spring periods indicated different underlying processes that lead to snow gliding. Clarke and McClung (1999) and Mitterer and Schweizer (2012) share this view. Clarke and McClung divided their observed glide-snow avalanches in *cold temperature events* and *warm temperature events*. In the present work glide-snow avalanches were classified accordingly by splitting the winter seasons in winter and spring periods. In winter (*cold temperature events*), water did not percolate through the snowpack due to an always cold (snow surface ≤ 0°C) and dry snowpack. Water at the snow-soil interface originated from other sources (Mitterer and Schweizer, 2012). In spring (*warm temperature events*), melt water infiltrated the snowpack. Melt water probably percolated through the snowpack and built a thin water layer at the snow-soil interface that reduced the friction of the gliding zone on the ground (Clarke and McClung, 1999).

4 CONCLUSION

We analyzed the glide-snow avalanche activity at Dorfberg above Davos (Eastern Swiss Alps). The influence of weather parameters was examined with univariate and multivariate statistical methods including classification trees and random forests. Analyses were performed for the two periods winter and spring based on the assumption that in both periods different processes lead to snow gliding (Clarke and

McClung, 1999). Results confirm the made assumptions since different weather parameters seem to be important in the two periods. In winter, the most important parameters were air temperature, sum of new snow and solar radiation (shortwave). In spring, snow surface temperature, air temperature and change in snow height played a major role. The crucial thin water layer (In der Gand and Zupančič, 1966) at the snow-soil interface originated from different sources in both periods. In winter (*cold temperature events*), the water film developed at the basal snow layer of the cold and dry snowpack due to melting of the basal snow layer on the warm ground or rising water from the ground into the snowpack as a result of capillary effects (Mitterer and Schweizer, 2012). In spring (*warm temperature events*), melting water infiltrated and percolated through the snowpack down to the snow-soil interface (Clarke and McClung, 1999). The different sources of the water clearly indicate different processes leading to snow gliding in both periods.

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