TOWARDS A BETTER UNDERSTANDING OF GLIDE-SNOW AVALANCHE FORMATION

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ABSTRACT: Full-depth avalanches (i.e. glide-snow avalanches) often release due to either a failure in the basal layer (e.g. depth hoar) or a failure at the snow-soil interface. The latter one typically occurs when the snow-soil interface is moist or wet so that the basal friction is reduced. In that case, snow gliding and the formation of a glide crack precedes avalanche release. Furthermore, observations indicate that the soil surface has little roughness and the slope angle exceeds 15°. The occurrence, however, of glide cracks and their evolution to glide-snow avalanches are still poorly understood. As a consequence, glides are difficult to predict as (*i*) not all cracks terminate in an avalanche event, and (*ii*) for those who do, the timing between crack opening and avalanche event might vary from hours to weeks or even months. It seems that the processes producing liquid water at the bottom of the snowpack can be divided into a warm temperature and cold temperature event: Cold temperature events include warm and dry autumns followed by heavy snowfalls favoring the storage of heat in the ground. The stored energy might be sufficient to melt snow at the bottom of the snowpack that consequently will reduce the friction. With a simple simulation we demonstrate that if a dry snowpack overlies a wet porous medium, resulting large hydraulic pressure gradients will lead to an upward flux of soil water content. Apart from the snow-soil interface the entire snowpack is dry and cold, and the formation of glide cracks and avalanches seems poorly correlated to air temperature. Warm temperature events are characterized by rain-on-snow events or high radiation combined with warm air temperature producing melt water which then is percolating through the entire snowpack. Ponding of that water on the snow-soil interface will reduce friction and strength of the snowpack.

1. INTRODUCTION

During the winter season 2011-2012 the Swiss Alps experienced strong snow gliding with repeated cycles of large glide-snow avalanches (Fig. 1). Deep open glide cracks posed difficulties to local authorities, as their evolution into glide avalanches was hardly predictable. Some cracks immediately developed into glide avalanches others stood open for weeks before producing an avalanche. Numerous approaches have been proposed to forecast the release probability of glide-snow avalanches, but the success was limited (Simenhois and Birkeland, 2010). The forecasting of glide-snow avalanches is particularly difficult as the occurrence of glide-cracks and their evolution to an avalanche is still poorly understood. Liquid water is thought to play a vital role for the triggering mechanism of glide-snow avalanches. Observations (Clarke and McClung, 1999; in der Gand and Zupančič, 1966) suggest that in many cases a thin wet or moist basal layer or percolating water reduced the friction at the snow-soil interface. Glide avalanches may therefore be classified as wet-snow avalanches (McClung and Schaerer, 2006). Weather events, snow cover and soil properties influence the conditions at the snow-soil interface, but so far no direct relation between snow gliding and these factors have been established. Based on meteorological data Clarke and McClung, (1999) classified glide-snow avalanches into cold and warm events. While avalanches during warm events could be explained with increasing air temperature, it was impossible to predict the cold events, where most of the snowpack is dry and sub-zero temperatures prevail.

The released volume tends to be large as the entire snowpack fails. Therefore avalanches are often long running and destructive (Fig. 1). Glide snow avalanches often release from specific or well known starting zones and their location is highly dependent on topography (Lackinger, 1987; Leitinger et al., 2008). Once friction is reduced and a glide crack has opened the peripheral strength, in particular of the stauchwall, seems to be crucial for stability (Bartelt et al., 2012).

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Figure 1: (a) Release zone with fracture line of a glide-snow avalanche above Davos, Switzerland (10 January 2012). (b) Run-out of the same avalanche which damaged a hut in Davos Dorf.

Jones (2004) reviewed glide processes with special emphasis on glide-avalanche release, predictability and possible control work. Despite important progress, he concluded that methods for artificial release and forecasting of glide-snow avalanches were still relatively limited. Our aim is to update the review by Jones (2004) andsummarize and discuss previous studies in order to present an overview of the current state of knowledge on processes favoring glide-snow avalanches. In addition, we present a first simple approach towards modeling the processes at the interface snow-soil (1-D) that favor the formation of a wet basal layer.

2. TRIGGERING PROCESSES AND PATTERNS

As presently understood (in der Gand and Zupančič, 1966), the prerequisites for snow gliding are:

- A snow temperature of 0°C at the snow-soil interface allowing the presence of liquid water.
- A smooth snow-soil interface with little roughness (e.g. bare rock or grass).
- A slope angle steeper than 15°.
- A deep overlaying snowpack without any prominent weak layer.

2.1 *The role of liquid water*

Many studies revealed (Clarke and McClung, 1999; in der Gand and Zupančič, 1966; McClung and Clarke, 1987) that glide avalanche activity is always connected to the presence of liquid water within the snowpack. This seems obvious as presence of water reduces the friction at the snow-soil interface (McClung and Clarke, 1987). Preliminary results of shear measurements on different substrates indicate that the relation of shear strength to liquid water content behaves highly non-linear, but generally decreases with increasing water content (Kamiishi, pers. Comm.). Beside snow temperature, the liquid water content determines the viscosity of the snowpack, which again has an effect on gliding behavior over a rough surface. Quantitative observations on the influence of liquid water on snow viscosity are not available at present, but estimates on the relation between snow hand hardness and liquid water content exist. Izumi and Akitaya (1985) reported that snow hardness decreases significantly with increasing water content. Based on this knowledge McClung and Clarke (1987) introduced a mechanical model providing a relation between basal shear stress σ_b, glide velocity U_0 and liquid water:

$$\sigma_b = \frac{\mu U_0}{2(1-\upsilon)D^*}.$$

D* is a geometrical parameter (stagnation depth), μ is the shear viscosity and ν the viscous analogue of the Poisson's ratio of the snow above the ground. Both, μ and ν are functions of snow density and liquid water content. Increasing water content means a decreasing value of μ, and thus an increase in glide velocity.

2.2 Triggering events

As the presence of water seems so decisive for the formation of glide-snow avalanches it is paramount to know the processes that are responsible for the presence of water at the snow-soil interface.

Three different processes may deliver liquid water to the snow-soil interface (McClung and Clarke, 1987): (*i*) Water – produced due to surface melting or rain – percolates through the entire snowpack, (*ii*) heat released from the still warm ground melts snow after the first major snowfall. (*iii*) Finally water might be produced at terrain features with strong energy release (e.g. bare rocks) and is running downwards along the snow-soil interface or may originate from springs (ground water outflow).

The triggering case (*i*) is very similar to the triggering process related to wet-snow avalanches: The less permeable substrate below the snowpack often acts as a barrier for infiltrating water. Backed up water lowers the strength of the basal layer and thus determining the arrival time of the water is crucial for predicting avalanche events (Mitterer et al., 2011). The main processes associated with producing the water are due to melting at the snow surface and rain-on-snow events. Clarke and McClung (1999) related most avalanches to either snowmelt or rain-on-snow events using air temperature as proxy. However, so-called cold temperature events could not be explained with air temperature. They suggested that the third process (*iii*) was responsible for those very few events. Lackinger (1987) observed more glide avalanches after warm spells and rain events and in about 85% of all recorded events an isothermal snowpack. His dataset does not include cold temperature events. In der Gand and Zupančič (1966) stated that the existence of a lowermost moist snow layer is especially important as a dry boundary layer would not cause glide motion on a grass surface. Moreover, they suggest that liquid water is produced due to warm ground temperatures. Snow layers with low temperatures (below 0°C) may exist above the wet layer. These observations have been confirmed by several later studies (Höller, 2001; Newesely et al., 2000). However, to our knowledge none of the studies analyzed why the water can be preserved over several days or even weeks at the boundary and why no drainage occurs.

In addition to the presence of water, Lackinger (1987) proposed that glide activity is high when early in the season a heavy snowfall covers the bare soil. It is, however, not always evident that additional snowfall will increase the release probability. While in der Gand and Zupančič (1966) and Höller (2001) see a clear dependency, Lackinger(1987) reported only one such loading event that was decisive for triggering a glide-snow avalanche.

2.3 Terrain characteristics of glide-snow avalanches

Glide snow avalanches occur mostly on steep terrain, i.e. 30°-40° steep slopes (Leitinger et al., 2008; Newesely et al., 2000), covered with smooth rock (e.g. Stimberis and Rubin, 2011), grass (in der Gand and Zupančič, 1966), but also tipped-over bamboo bushes (Endo, 1984). Newesely et al. (2000) observed increased snow gliding on abandoned pastures compared to slopes with short grass. Leitinger et al. (2008) and Höller (2001) observed that the lack of dense forest stands causes glide-snow activity, in particular if the distance to surrounding anchor points is longer than 20 m. Observations suggest that most glide avalanches release on convex roles (e.g. in der Gand and Zupančič, 1966). Research results on prevailing aspects and elevations are inconclusive, as in most studies observations do not cover all aspects.

2.4 Seasonal and diurnal variations

Glide rates may vary throughout the entire winter season and from year to year. According to the observations by Clarke and McClung (1999), Höller (2001), McClung et al. (1994) and above suggested formation processes, high glide activity can be expected in either early winter or spring.

Evidence of diurnal variations and patterns is ambiguous. While Lackinger (1987) observed avalanches often in the evening or at night, McClung et al. (1994) found in one year increased activity during the day, but in the second year no clear variations. Clarke and McClung (1999) reported for the same study site no significant differences in glide rates between daytime and night. On the other hand, Feick et al. (2012) analyzed two large glide-snow avalanche slopes and found a clear tendency towards increased gliding and avalanching around noon or in the afternoon.

3. FORECASTING OF GLIDE-SNOW AVALANCHES

Lackinger (1987) explored the possibility to forecast glide-snow avalanches based on acoustic emission signals (AE). In one case, the AE signal clearly increased (in frequency and amplitude) prior to a small glide avalanche. The signal was similar to those recorded during crack formation. Other studies mainly focused on using air temperature as a proxy variable to forecast avalanche activity. In general, air temperature is linked to snow gliding activity, however, this relationship is complex as it influences indirectly several processes related to glide. Rising air temperature will warm the snowpack thereby decreasing snow viscosity. This results in enhanced creep rates and may promote gliding. In addition, air temperature is a proxy for melt at the snow surface and indicates whether precipitation falls as rain or snow. Clarke and McClung (1999) showed that glide rates corresponded to increased air temperatures with lag times of 12-24 hours for snow gliding activity after snowmelt or rain events

As increasing glide rates are thought to be a useful predictor variable (Endo, 1984; Endo, 1985), much research focused on automatically detecting glide cracks and follow them over time. Basically two different approaches were chosen: (*i*) The glide motion of the snowpack is directly measured with on-site installed so-called glide shoes (e.g. in der Gand and Zupančič, 1966) or accelerometers (e.g. Rice et al., 1996). (*ii*) The second approach includes taking recurring pictures (Akitaya, 1980; Feick et al., 2012; van Herwijnen and Simenhois, 2012) or optical measurements (Hendrikx et al., 2010) of slopes prone to snow gliding. Especially the approach of van Herwijnen and Simenhois (2012) seems promising for monitoring important glide-snow avalanche paths. They automatically related the number of dark pixels (i.e. the open crack) with time to white pixels (i.e. snowy surrounding of the open crack) and could track the widening of the crack. The number of dark pixels increased shortly before failure.

Both methods are suited for monitoring notoriously dangerous avalanche paths, but do not provide sufficient coverage for a regional avalanche forecasting program. In the future, satellite images may fill this gap (Feick et al., 2012).

4. MODELLING THE WET BASAL LAYER

In the following we will focus on the processes associated with the hydraulic properties at the snow-soil interface.

4.1 Model assumption and boundary conditions

We assumed a soil (0.1 m), grass (0.02 m) and a snow layer (0.1 m) to represent the natural conditions within our model. The grass layer was simulated as a porous medium with very large pores. A finer textured snow layer (grain size of 1 mm) was put on top of the grass. For the sake of simplicity snow was modeled as a non-changing isothermal porous medium. Below the grass layer we assumed a sandy loam soil layer. To calculate the water content we solved Richards' equation by using the moving mean slope approach proposed by Moldrup et al. (1989). Within the iterations unsaturated hydraulic conductivity, capillary pressure and water content were updated using the model of van Genuchten (1980). Saturated hydraulic conductivity was calculated according to Shimizu (1970) and van Genuchten values were parameterized according to Yamaguchi et al. (2010) and Daanen and Nieber (2009).

We did two runs assuming that the grass layer was relatively dry with a volumetric liquid water content of 0.1, and a second one with a volumetric liquid water content of 0.2 for the grass layer. The soil layer had an initial liquid water content of 0.35. We neglected heat flow and production of melt water due to stored heat.

4.2 Preliminary results of modeling approach

Result from the simulations with the wet grass layer show that due to capillary effects liquid water rises until 0.2 m into the snow. The water content is in the pendular regime (i.e. <4% by vol.) for the upper parts of the snow layer (Fig. 2). From the

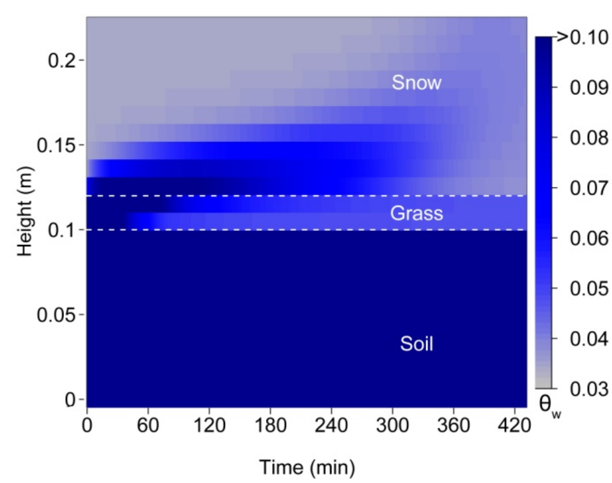

Figure 2: Simulated volumetric liquid water content (θ_w) for a 1-D soil-grass-snow column. White dashed lines show the interfaces between the different medias.

very beginning of the simulation, the amount of liquid water at the interface grass-snow increases, and the grass layer dries out over time. The upward direction of the water is due to a strong hydraulic pressure gradient between the two porous media snow and grass. The gradient results from the large differences in liquid water content when starting the simulation. When running the simulation for dry grass conditions, upward movement of water is less pronounced for the snow layer as the pressure gradient is shifted towards the grass-soil interface. The small difference in liquid water content between grass and snow is still enough to establish an upward flux within the first hours of the simulation.

These two simple model runs reveal that the difference in water content is an effective driver in transporting liquid water into the basal layer of snowpack. The results are supported by observations showing the presence of brownish colored saturated snow layers at the bottom of the snowpack (Fig. 3). The coloring comes probably from soil solutes transported through the upward directed water flux. So far this issue was never taken into account – as far as we know – when presence of liquid water in an otherwise dry snowpack was explained. As we neglected the influence of melt water due to the release of stored heat, it is difficult to conclude which process dominates. Stored heat will obviously melt snow at the bottom of the snowpack; this water will then again obey the hydraulic conditions assumed for our model. Consequently, the water content at the basal snow layer will be higher resulting in a weaker pressure gradient. The heat flow is – similarly to the water flow equation – driven by the gradient, in this case of the temperature. In order to quantify how much water is melted it is necessary to know how long the temperature gradient between soil and snow will prevail. Simulations with more complex snowpack models (e.g. SNOWPACK) suggest that the gradient will diminish within the first three or four days depending on boundary conditions, i.e. temperature, thermal conductivity and densities of soil and snow. In the future, we will incorporate the presented model into more complex models to better identify which of the two processes dominates.

The interpretations of the simulation are only valid for snowpacks overlaying a porous medium (grass, soil). The situation will be different for smooth impermeable rock substrates, on which stored heat will be the major source of water.

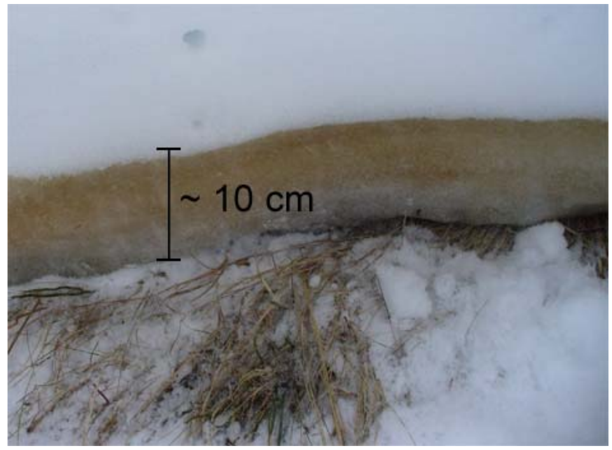

Figure 3: Photo taken at the base of an open glide crack. Basal snow layers show high water saturation. Brownish color hints to soil solutes tranpsorted into the snowpack through water flow.

5. CONCLUSIONS

Based on the review by Jones (2004) we provided an update of research results on glide-snow avalanche formation. We summarized characteristics of glide-snow avalanches and triggering patterns with a special emphasis on the role of liquid water at the snow-soil interface. Prevailing weather conditions and terrain characteristics determine the cause for liquid water at the bottom of the snowpack. Processes producing liquid water include infiltrating water due to either melt at the snow surface or rain, water due to basal melt by heat released from the still warm ground after the first major snowfall, capillary rise due to different hydraulic pressures along the snow-soil interface and water originating from springs (ground water outflow).

We presented first results of a simple model mimicking the hydraulic processes at the snow-soil interface. The model includes three layers: a snow, a grass and a soil layer. It solves the Richards' equation in order to calculate liquid water content, unsaturated hydraulic conductivity and capillary pressure over time in 1-D. The model reveals that a strong pressure gradient at the snow-grass interface causes an upward flux of water. Water moves from the soil towards the snowpack. We showed that capillary forces at the snow-soil interface play a vital role for the formation of a wet basal layer. If the substrate is a wet porous medium, liquid water can be present within the basal snow layer even without basal melting. Results are biased towards our simple model assumptions and the relative importance of the two processes (basal melt and/or capillary rise) will be different for other substrates such as e.g. rock. Future work will include improving the model in order to better depict all relevant processes. In particular, the conduction of heat within soil and snow has to be implemented in order to better assess which of the processes is the dominant driver for the presence of water within the basal layer. In addition, the role of liquid water for snow viscosity and frictional behavior needs to be quantified.

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