Glide Snow Avalanches **Revisited**

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DURING THE 2011-12 WINTER SEASON, the Swiss Alps experienced strong snow gliding with repeated cycles of large glide-snow avalanches (Fig.1). Local avalanche services were challenged by deep open glide cracks, as their evolution into glide avalanches was hardly predictable. Some cracks immediately developed into glide avalanches, while others stood open for weeks before producing an avalanche.

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 reduces the friction at the snow-soil interface. Glide avalanches may therefore be classified as wet-snow avalanches (McClung and Schaerer, 2006).

Weather, 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 has been established. 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. We will update Jones' review and 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 snow-soil interface (1-D) that favor the formation of a wet basal layer.

TRIGGERING PROCESSES AND PATTERNS

The role of liquid water

The four following points are still considered as prerequisites for snow gliding (in der Gand and Zupančič, 1966):

- 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°C.
- A deep overlaying snowpack without any prominent weak layer.

Many studies (Clarke and McClung, 1999; in der Gand and Zupančič, 1966; McClung and Clarke, 1987) revealed 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). 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.

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):

- Water—produced by surface melting or rainfall—percolates through the entire snowpack.
- Heat released from the still-warm ground melts snow after the first major snowfall.
- 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 first triggering scenario 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). In fact, 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 (water produced at terrain features) 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 suggested that liquid water is produced due to warm ground temperatures. Snow layers with low temperatures (below 0°C) may exist above the wet basal layer. 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.

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), or 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 20m. Research results on prevailing aspects and elevations are inconclusive, as in most studies observations do not cover all aspects.

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 the above suggested formation processes, high glide activity can be expected in either early winter or spring. Observations of diurnal variations and patterns are conflicting. 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.

FORECASTING OF GLIDE SNOW AVALANCHES

Many studies 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

FIG. 1: RELEASE ZONE WITH FRACTURE LINE OF A GLIDE-SNOW AVALANCHE ABOVE DAVOS, SWITZERLAND, JANUARY 10 2012.

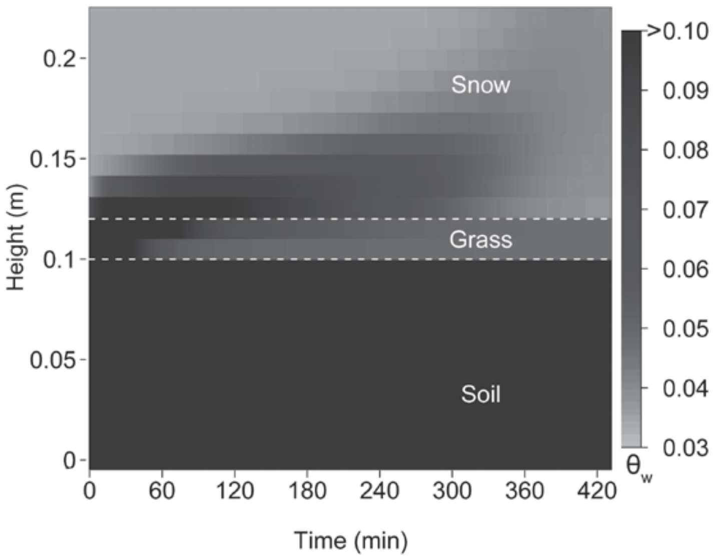

FIG. 2: SIMULATED VOLUMETRIC LIQUID WATER CONTENT (Θ_W) FOR A 1-D SOIL-GRASS-SNOW COLUMN. WHITE DASHED LINES SHOW THE INTERFACES BETWEEN THE DIFFERENT MEDIA.

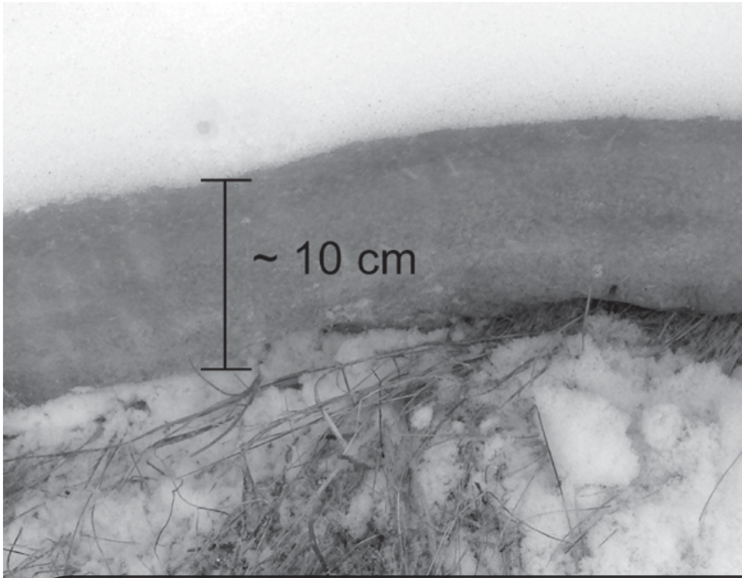

FIG. 3: PHOTO TAKEN AT THE BASE OF AN OPEN GLIDE CRACK. BASAL SNOW LAYERS SHOW HIGH WATER SATURATION. BROWNISH COLOR HINTS TO SOIL SOLUTES TRANSPORTED INTO THE SNOWPACK THROUGH WATER FLOW.

relationship is complex as it influences indirectly several processes related to glide. Rising air temperatures 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; 1985), much research focused on automatically detecting glide cracks and follow them over time. Basically two different approaches were chosen:

- 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).
- 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 are taken throughout the entire season.

The approach of van Herwijnen and Simenhois (2012) seems especially promising for monitoring important glide-snow avalanche paths as instrumentation is fairly cheap. 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.

MODELLING THE WET BASAL LAYER

In the following, we will focus on the processes associated with the hydraulic properties at the snow-soil interface. In order to do so we implemented the governing equations into a numerical model.

We assumed a soil (0.1m), grass (0.02m) and a snow layer (0.1m) to represent the natural conditions within our model. The grass layer was simulated as a porous medium with very large pores. A fine-textured snow layer (grain size of 1mm) covered the grass. For the sake of simplicity, snow was modeled as a non-changing isothermal porous medium. Results show that due to capillary effects, liquid water rises until 0.2m 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 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. The difference in water content is an effective driver in transporting liquid water into the basal layer of the 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. Our interpretations of the simulation are only valid for snowpacks overlaying a porous medium (e.g. grass, soil). The situation will be different for smooth impermeable rock substrates, on which stored heat will be the major source of water. In the future, we will incorporate the presented model into more complex models to better identify which of the two processes dominates.

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 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 rock.

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