THE FORMATION OF BASAL LIQUID-WATER LAYERS IN EARLY-WINTER ("COLD") GLIDE-SNOW AVALANCHES

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ABSTRACT: A liquid water layer in the basal snowpack is considered one of the critical requirements for glide-snow avalanche release. However, the processes leading to this liquid water formation are not well understood. This is particularly true for so-called "cold" events, which tend to occur in winter without percolation of water from the snow surface. For these cold events, the liquid water is thought to form due to capillary suction from the soil into the snow and/or from melting of the basal snowpack due to the warm ground. Here, we use theoretical calculations and the 1D-model SNOWPACK, to investigate the interplay of capillary and thermal processes during the formation of basal liquid water layers in cold glide-snow avalanche events. Two early-winter glide-snow avalanches observed at the Dorfberg (Davos, Switzerland) field site are analyzed. For these events, melting was responsible for the basal liquid water layers as capillary rise was not expected based on the conditions within the soil. Application of this model to larger glide-snow avalanche datasets will further improve our understanding of this basal liquid-water layer, its formation, and the critical thresholds relevant for predicting cold glide-snow avalanche release.

KEYWORDS: glide-snow avalanche, liquid water content, avalanche formation

1 INTRODUCTION

The formation of liquid water layers in the basal snowpack is thought to be critical for glide-snow avalanche release. Unfortunately, the formation of these layers is not well understood, leading to poor forecasting (Jones, 2004; Reardon et al., 2006; Simenhois and Birkeland, 2010; Höller, 2014) and inefficient mitigation (Clarke and McClung, 1999; Sharaf et al., 2008; Simenhois and Birkeland, 2010). The formation of these liquid water layers at the ground-snow interface is typically assumed to be different for two types of glide-snow avalanches, "warm" and "cold" as defined by Clarke and McClung (1999) or "surface" and "interface" as defined by Fees et al. (2023). For warm (or surface) events, the interfacial water is thought to come from the snow surface through melting or rain (Clarke and McClung, 1999). For cold (or interface) events, the interfacial water comes from the ground-snow interface through melting (Clarke and McClung, 1999) or capillary suction (Mitterer and Schweizer, 2012).

While the presence of liquid water has been correlated with glide-snow avalanches (in der Gand and Zupančič, 1966; Clarke and McClung, 1999), little is known about the dynamics of its formation. For warm or surface events, rain-on-snow has been shown to lead to avalanche release with a delay of 12-30 hours (Clarke and McClung, 1999; Stimberis and Rubin, 2011). For cold events, in der Gand and Zupančič (1966) noted that geothermal melting is generally possible on southern slopes in the Alps up to an elevation of 2400 m. Field studies have correlated soil moisture with glide rates and avalanche release (Ceaglio et al., 2017; Maggioni et al., 2019). Mitterer and Schweizer (2012) performed preliminary calculations demonstrating that capillary forces may cause capillary suction from the soil into the snowpack.

Unfortunately, these studies have not been conclusive. Here, we investigated the interplay of capillary rise and geothermal melting in the formation of interfacial water layers in cold (interface) glide-snow avalanches. The contribution of capillary forces was estimated with theoretical calculations while the contribution of geothermal melting was addressed with modelling. The calculations and simulations considered the hydraulic and thermal properties of the soil, vegetation, and snowpack. The calculations and simulations were performed with field data from the Dorfberg (Davos, Switzerland) field site (Fees et al., 2023). We analyzed the conditions during two observed avalanches at this site in December 2021 to determine the relative contributions of capillary suction and melting to the formation of basal water layers.

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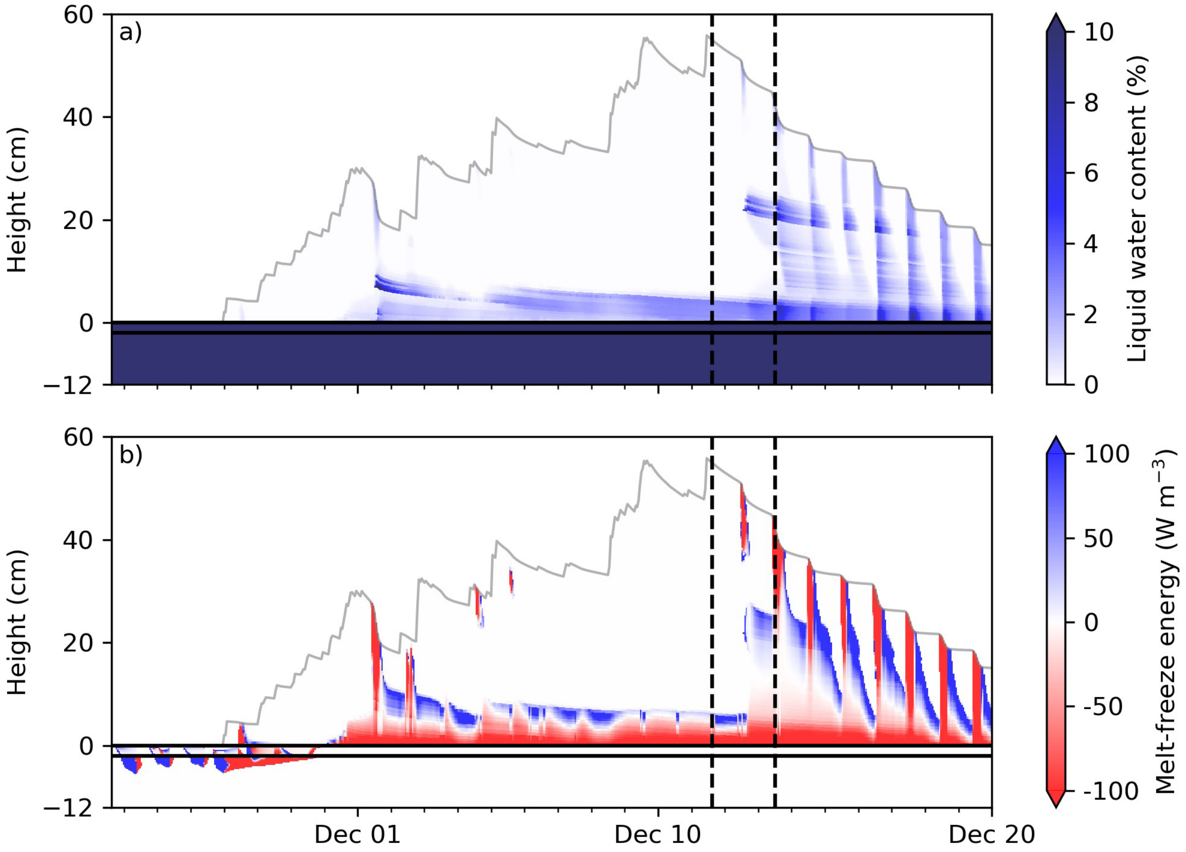

Figure 1: SNOWPACK simulation results at the Dorfberg field site for (a) the LWC and (b) the melt-freeze energy. Black horizontal lines delineate the 2 cm thick grass layer. Vertical dashed lines indicate the two observed glide-snow avalanches. The snow height is shown in gray. Negative values of melt-freeze energy indicate melting while positive values correspond to freezing.

2 SNOWPACK MODELLING

Snowpack modelling was performed using SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a,b) for the Dorfberg field site (Fees et al., 2023) from 23 November 2021 to 20 December 2021. The model was initialized with 10 cm of soil below a 2 cm grass layer. Deeper soil layers were not included. The hydraulic properties of the soil and grass layers were determined as described below and provided to the model. Water fluxes were solved with the Richards equation (Richards, 1931) in both the soil and snow with a free drainage lower boundary condition. Heat fluxes were solved with the standard temperature equation in SNOWPACK with the lower boundary condition set to the measured temperature from Dorfberg at a soil depth of 10 cm. In addition to the standard outputs, the melt-freeze energy was also extracted. The melt-freeze energy (in W m^{-3}) indicates the amount of energy used for phase changes within each layer with negative values representing melting and positive values representing freezing. Meteorological data was taken from Fees et al. (2023).

3 HYDRAULIC PROPERTIES

The hydraulic properties of porous materials such as soil and snow can be described with the so-called water-retention curve (WRC), which relates the capillary pressure to the liquid water content (LWC). Here, we described the WRC with the van Genuchten model (van Genuchten, 1980) as shown in Eq. 1

$$\theta = (\theta_s - \theta_r)\left(\frac{1}{1 + (\alpha h)^n}\right)^m + \theta_r \qquad (1)$$

where θ is the volumetric LWC [m^3 m^{-3}], θ_s is the saturated water content [m^3 m^{-3}], θ_r is the residual water content [m^3 m^{-3}], h is the pressure [Pa], α is a parameter related to the inverse of the air-entry pressure [Pa^{-1}], and n and m are unitless parameters related to the pore-size distribution. Here, we relate m and n via $m = 1 - 1/n$ (van Genuchten, 1980).

For snow, the van Genuchten parameters (α, n) were parameterized based on the grain diameter and density (Yamaguchi et al., 2012). For the soil at Dorfberg, the van Genuchten parameters were determined based on the soil texture with the pedotransfer function by Wessolek et al. (2009). The soil texture for the Dorfberg field site was determined from soil samples. For the grass interface layer, the van Genuchten parameters were fit to a WRC of grass samples taken from Dorfberg and measured in the laboratory.

4 RESULTS AND DISCUSSION

Figure 1 shows the results of the SNOWPACK simulation. The glide-snow avalanches released on 11 December 2021 at 15:00 (local time (LT)) and 13 December 13 2021 at 12:00 LT in different areas of the field site (shown as vertical dashed lines in Figure 1). For both avalanches, liquid water was present in the basal snowpack at the time of release (Figure 1a). Melt processes were also ongoing in the basal snowpack (Figure 1b). For the first avalanche (11 December), all of the water came from the ground-snow interface because the LWC within the upper snowpack was 0% and the snowpack was below freezing. For the second avalanche (13 December), the snowpack was isothermal and liquid water was present at all heights. Thus, water could have been formed at the ground-snow interface, the snow surface, or both. The first avalanche should therefore likely be classified as a cold or interface event while the second avalanche should be classified as a warm or surface event.

In order to determine the contribution from capillary suction, we calculated the LWC at the bottom of the snowpack as a function of soil saturation and soil saturation depth (Figure 2). Capillary suction was defined as an increase in LWC of 0.5% or more above the residual water content (θ_r=2%; Yamaguchi et al. (2010)). For both avalanches, the basal snow layers at avalanche release had a density of about 240 kg m^{-3} and a grain diameter of about 0.8 mm. This calculation assumes an equilibrium condition (i.e. the pressure equalizes quickly between the soil, vegetation, and snow), which is likely valid for the hourly resolution in Figure 1, because capillary rise is comparatively fast (order of minutes).

Just prior to both avalanche releases, the soil saturation was around 77% at a depth of 2 cm (red point in Figure 2), which is well below the the saturation necessary at this depth to achieve capillary suction into the snow (about 91%). Thus, we conclude that capillary suction did not cause the formation of liquid water in the basal snowpack for either event. Additional field data are needed to allow for more generalized conclusions, ideally leading to some predictive relationships between the soil conditions and avalanche release.

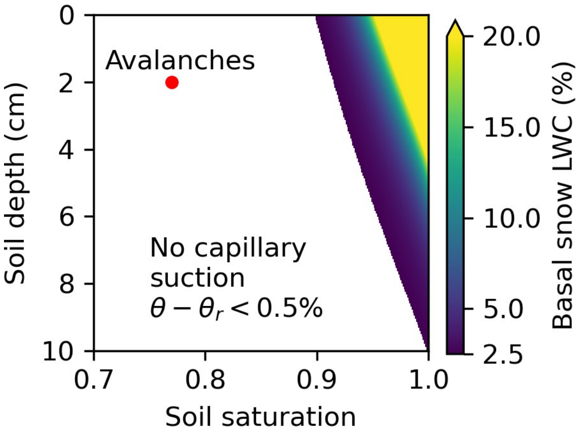

Figure 2: The LWC of snow (density=240 kg m^{-3} and grain diameter=0.8 mm) based on the soil saturation and soil saturation depth of the Dorfberg soil used in the SNOWPACK simulations. The soil saturation depth is the depth below the grass layer (i.e. a soil saturation depth of 2 cm is 4 cm below the bottom of the snowpack). The red point shows the soil conditions at the time of both avalanche releases.

5 CONCLUSIONS AND OUTLOOK

We present a theoretical and modelling analysis of two early-winter glide-snow avalanches on Dorfberg (Davos, Switzerland). The results show that the interfacial water at the ground-snow interface for these events was likely not due to capillary suction. Instead, geothermal melting was solely responsible for the interfacial water in the 11 December avalanche, while a combination of geothermal melting and percolation from the snow surface created the interfacial water in the 13 December avalanche. The analysis presented here could be used to better classify glide-snow avalanches by pinpointing the source of interfacial water. Improved classification based on the formation of liquid water in the basal snowpack should allow for better analysis of the underlying processes leading to glide-snow avalanche release. Application of this analysis to larger datasets should allow for more generalized conclusions, laying the groundwork to better forecasting and mitigation.

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