GLIDE-SNOW AVALANCHES: INSIGHTS FROM SPATIO-TEMPORAL SOIL AND SNOW MONITORING

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ABSTRACT: Glide-snow avalanche release at the ground-snow interface and are currently considered unpredictable due to a lack of process understanding. It is generally accepted that the release of glide-snow avalanches is due to a loss of friction at the ground-snow interface, which is suspected to be linked to interfacial water. However, the source, quantity, and spatial distribution of the interfacial water are currently unknown. We installed a grid of sensors for spatio-temporal measurements within a slope with frequent glide-snow avalanche activity. The 24 grid sensors measured the temperature and liquid water content of the soil across the slope during seasons 2021/22 to 2023/24. During this time period, seven glide-snow avalanches released over the sensor grid. Investigation of three events showed that: (i) the interfacial water originated from geothermal heat, rain, and meltwater percolation, (ii) the liquid water content of the snow was lower for glide-snow avalanches that released in early winter than in spring, (iii) if the interfacial water originated from geothermal heat, we observed (locally) higher soil temperatures below the release area, (iv) if interfacial water originated from rain/melt, we observed (locally) higher soil LWC below the release area. In the future, with continued monitoring, the spatio-temporal investigation of the soil will help to quantify the drivers of glide-snow avalanche release which likely depend on the source of interfacial water.

KEYWORDS: glide-snow avalanche, spatio-temporal monitoring, soil temperature, liquid water content

1 INTRODUCTION

Glide-snow avalanches release at the ground-snow interface and endanger infrastructure in mountain regions (e.g. Clarke and McClung, 1999; Mitterer and Schweizer, 2012a). There have been numerous phenomenological observations of snow-gliding and glide-snow avalanche release (e.g. McClung et al., 1994; Reardon et al., 2006; Höller, 2001). Nevertheless, we still lack sound process understanding and consequently, glide-snow avalanche forecasting remains difficult (Simenhois and Birkeland, 2010; Jones, 2004) and mitigation measures are mostly unreliable (Sharaf et al., 2008; Jones, 2004). Review papers on snow gliding and glide-snow avalanches (Ancey and Bain, 2015; Höller, 2014; Jones, 2004) agree that the challenge is the investigation of processes occurring at the interface between the snowpack and the ground, which lead to the formation of interfacial water (Ancey and Bain, 2015). In more recent years, the number of in-situ observations of soil liquid water content (LWC), soil temperature (Ceaglio et al., 2017; Maggioni et al., 2019; Mitterer and Schweizer, 2012b), and snow liquid water content (Fromm et al., 2018) have increased. Findings include increasing glide rates with increasing soil LWC (Ceaglio et al., 2017) and a significant influence of soil LWC and soil temperature on snow gliding (Fromm et al., 2018). While the temporal resolution of these point observations is high, sensors are rarely below a glide-crack or avalanche.

Our aim was to investigate the source, quantity, and spatial distribution of interfacial water leading to glide-snow avalanche release. We monitored soil LWC and temperature across an avalanche-prone slope with a grid of sensors. A total of seven glide-snow avalanches released over the sensor grid during the seasons 2022 (refers to winter season 2021/22) to 2024. Here, we focus on the measurements associated with one early winter event (2 Dec 2023), one rain-on-snow event (27 Jan 2023), and one event due to meltwater percolation (16 Mar 2022).

2 FIELD SITE: SEEWER BERG

The Seewer Berg slope (about 1800 m a.s.l.) is located on the mostly southeast-facing hillslope of the Salezer Horn (called Dorfberg, Davos, Switzerland, Figure 1). The frequent glide-snow avalanche activity in the Seewer Berg slope is well-documented through time-lapse photography since the 2009 season (Fees et al., 2023). The slope is mostly covered in long grass with interspersed shrubs and small rocky areas (Feistl et al., 2014). A shallow and protected slope approximately 100 meters northwest of the Seewer Berg was used as a reference site for (bi)weekly manual snow profiles (Figure 1).

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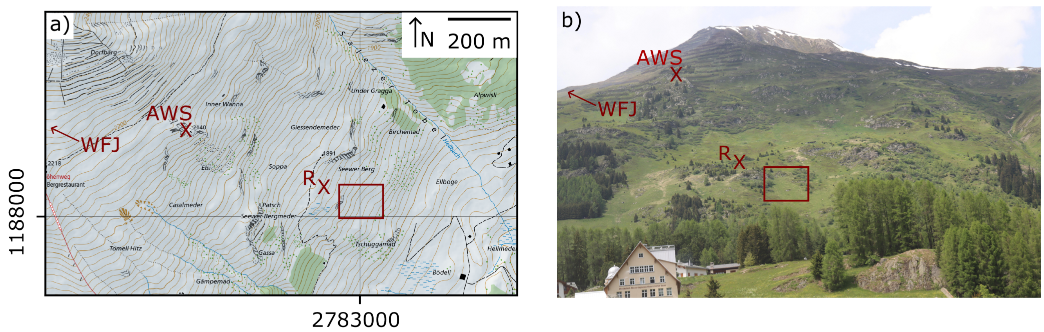

Figure 1: a) Map and b) picture of Dorfberg indicating the location of the weather station (AWS), the reference location (R), the Seewer Berg slope with the spatio-temporal monitoring setup (square), and the direction towards the Weissfluhjoch measurement site (WFJ). Map: Federal Office of Topography, CH1903+.

From season 2022 to 2024, we monitored the soil in 24 locations across the Seewer Berg slope using a grid of combined soil LWC and temperature sensors (TEROS11, Meter Group). The sensors were installed at a soil depth of -5 cm. The grid spacing between sensors was approximately 8 m by 8 m (Figure 2a). The time interval between measurements was 15 minutes for all sensors. Four soil LWC sensors were excluded from the analysis. They responded slowly to water infiltration after summer rainfalls, indicating that they may not be fully connected to the soil matrix (Figure 2).

The snowpack was monitored with regular manual snow profiles at the reference site (Figure 1). Snow profiles were recorded according to Fierz et al. (2009). Density and relative permittivity were measured every 5 to 10 cm to derive LWC. Snow density was obtained from the average of two measurements with a cylindrical density cutter. The relative permittivity was determined with a capacitive probe (Denoth, 1994). We defined the snow LWC as the liquid water content of the lowermost 20 cm of the snowpack. The snow LWC was calculated as the average of all measurements that exceeded 0% LWC in the lowermost 20 cm of the snowpack. When a glide-snow avalanche released on the Seewer Berg slope, if possible, an additional manual snow profile was recorded close to the fracture line, typically within a few days after release.

3 RESULTS

3.1 Observed avalanches

A total of seven glide-snow avalanches released over the sensor grid which provided data on the source and quantity of interfacial water (Figure 2).

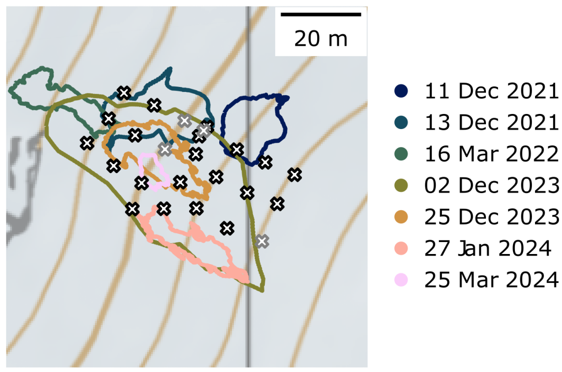

Figure 2: Release areas extracted from time-lapse photographs for glide-snow avalanches on the sensor grid. Grid sensors (x) that were not used for analysis are marked in grey. Map: Federal Office of Topography, north up, contour line spacing: 10 m.

3.2 Comparison in/outside release area

We investigated three glide-snow avalanches (2 Dec 2023, 27 Jan 2024, 16 Mar 2022) in detail. The grid sensors were grouped into sensors within the release area and sensors outside the release area. The sensors were assigned to a group based on the release area detected in the time-lapse photographs. The time-lapse photographs provide a resolution of approximately 0.25 m^2 and are known to underestimate the release area (Fees et al., 2023). We manually added sensors to the release area if we observed them within the release area during the manual snow profile close to the fracture line.

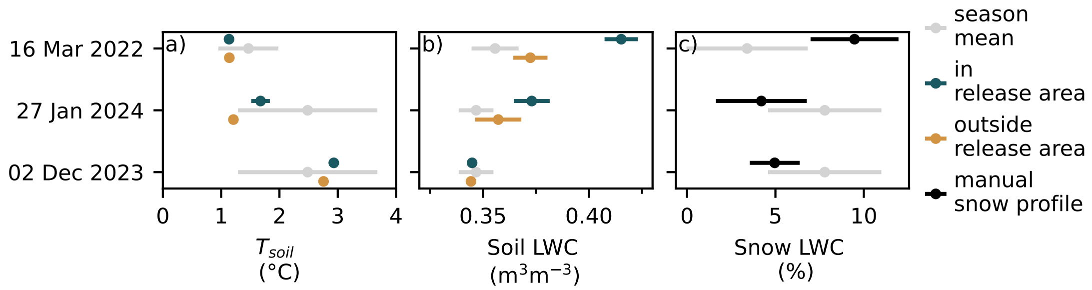

Figure 3: a) Average soil temperature and b) average soil LWC 8 days prior to avalanche release (blue and orange) and the season average (grey). For the rain-on-snow event, the average is calculated from the start of the rain to the time of avalanche release. c) Snow LWC in the lowermost 20 cm of the snowpack observed a few days after avalanche release in a manual snow profile.

The 2 Dec 2023 avalanche occurred 8 days after a snowfall on bare ground on the Seewer Berg slope. In the 8 days preceding the avalanche, the soil sensors recorded constant and above average soil temperatures across the sensor grid (compare blue/orange and grey in Figure 3a). The soil temperatures below the release area were generally higher than in the remaining sensor grid (Figure 3a). The snow LWC observed in the manual snow profile (release area) was (5 ± 1)% (Figure 3c). This inidicates that the interfacial water at the soil-snow interface likely originated from snow melt due to geothermal heat. Another potential source of interfacial water that has been suggested for early winter avalanches is capillary suction of water from the ground into the snow (Mitterer and Schweizer, 2012a). However, we observed that the soil LWC during 8 days before avalanche release was constant and its quantity was comparable between the release area, the remaining sensor grid, and the season mean (Figure 3 b). As the soil LWC was close to the season mean and capillary suction was unlikely (Lombardo et al., 2024) we exclude capillary suction as a contributing source of interfacial water for this avalanche.

The 27 Jan 2024 avalanche released two days after the rain event. However, we already observed water percolation into the soil 12 hours after the rainfall. This indicates that liquid water was available at the soil-snow interface for around one and a half days before the avalanche released. The soil LWC was significantly higher below the release area compared to the rest of the grid (Figure 3b), suggesting that higher quantities of interfacial water were available locally below the release area.

For the 16 Mar 2022 avalanche, we observed diurnal peaks of meltwater infiltration into the soil in the 7 days preceding avalanche release. These peaks occurred around 13:00 local time (LT), coinciding with the expected time for diurnal meltwater percolation across the soil-snow interface. The diurnal observation of water infiltration in the soil indicates that liquid water was available at the soil-snow interface several days before the avalanche released. The soil LWC across the entire slope was substantially above the season mean and the soil LWC in the release area was significantly higher than outside the release area ($p<0.01$, Mann-Whitney U test, Figure 3b).

For both the rain-on-snow event and the meltwater percolation event, we can exclude considerable contributions from geothermal heat as soil temperatures for both events were below the season mean (Figure 3a). For the rain event, the sensors indicated soil LWC close to soil saturation, which would technically allow for capillary suction from the soil into the snow (Lombardo et al., 2023). However, the high saturation is only reached when the water from the soil-snow interface percolates into the soil, so the water is already present at the soil-snow interface.

For all events, we observed available interfacial water (snow LWC) and time periods without snow LWC were indicative for no or low glide-snow avalanche activity on all of Dorfberg (data not shown). The snow LWC for the meltwater event (16 Mar 2022) was substantially higher than for the early winter avalanche or the rain event (2 Dec 2023 and 27 Jan 2024, Figure 3c). These findings may suggest that different quantities of snow LWC are needed for early winter and spring avalanches.

4 DISCUSSION AND OUTLOOK

We used spatio-temporal soil monitoring and regular manual snow profiles to investigate the source and quantity of water for three out of seven recorded glide-snow avalanches. We found that the interfacial water leading to avalanche release originated from geothermal heat, meltwater percolation from the surface, or rain. For the early winter event driven by geothermal heat (2 Dec 2023), we observed higher soil temperatures in the release area than in the remaining slope. Soil temperatures of at least 2 °C seem to be a prerequisite for glide-snow avalanches that release due to geothermal heat at our field site.

For the rain- and meltwater-driven events, the soil LWC was a good proxy for the available interfacial water and locally higher values were observed below the release area. We also found that in the rain- and meltwater-driven events, interfacial water and its percolation into the soil occurred one to seven days prior to release. In the snow, we observed lower LWC during the early winter avalanche than in the spring avalanches, which is in line with observations by Maggioni et al. (2019).

Recent pseudo-3D slope scale modelling of glide-snow avalanches (Fees et al., 2024) suggests that spatial variability in basal friction plays an important role in glide-snow avalanche release. In the future, we will use the spatio-temporal data recorded in the grid before and during avalanche release to investigate the role of the spatial distribution of the soil LWC. Preliminary investigations suggest that the soil LWC spatial variability reaches a local minimum at the time of release.

Overall, the spatio-temporal soil monitoring and regular manual snow profiles provided a first insight into soil temperature and LWC leading up to and during glide-snow avalanche release. A more detailed evaluation of all seven observed avalanches as well as additional data from more winters will be needed to confirm our findings. With continued monitoring, the spatio-temporal investigation of the soil will help to quantify the process-related drivers of glide-snow avalanche release and reveal how these drivers depend on the source of interfacial water. Establishing this link will help to more accurately predict the time of avalanche release. In addition to improved process understanding, this will help narrow down length and time scales as well as suitable proxies for glide-snow avalanche monitoring that could be used for forecasting and mitigation.

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