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Relating meteorological parameters to glide-snow avalanche activity

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ABSTRACT

Glide-snow avalanches are notoriously difficult to predict, in part because we still do not fully understand the physical processes governing their release. Previous research has highlighted the presence of a wet basal layer as a prerequisite for glide-snow avalanche release. Different processes are believed to contribute to the formation of this basal layer in winter and in spring, since in winter the snowpack is usually cold and dry, while in spring it is warm and wet. We compared glide-snow avalanche activity to meteorological parameters of nearby weather stations for two winter seasons, the winter of 2008–2009 and the winter of 2011–2012. During both these winters, glide-snow avalanche activity was high in the Swiss Alps, posing a particular challenge to avalanche forecasting services. We used univariate and multivariate statistical methods to analyse the data for *cold temperature events* in winter and *warm temperature events* in spring, separately. For *cold temperature events* the minimum air temperature and the amount of new snow prior to avalanche release were the most significant variables, while for *warm temperature events* the most significant variables were air temperature, snow surface temperature derived from outgoing longwave radiation and decrease in snow height. Our results support the hypothesis that different processes result in the formation of glide-snow avalanches in winter and in spring. While the limited data set does not allow us to draw general conclusions, our results clearly indicate that treating *cold* and *warm temperature events* separately is of paramount importance to develop a widely applicable glide-snow avalanche forecasting model.

1. Introduction

Glide-snow avalanches can endanger exposed infrastructure and communication lines, they are difficult to forecast and hard to control. They occur when the entire snowpack glides on the ground and a slab releases in full depth. When glide-snow avalanches occur with a deep snow cover, large masses of snow are released resulting in long running avalanches with considerable destructive power (Ancey and Bain, 2015; Bartelt et al., 2012b; Jones, 2004). Prior to the release of a glide-snow avalanche, a tensile crack can open in the snow cover (Fig. 1). Predicting the exact timing when a glide crack evolves into a glide-snow avalanche poses a challenge to avalanche forecasting services. Reliably forecasting glide-snow avalanche release is difficult since the gliding slab may be triggered instantly or, in some cases, cracks may stay open for weeks before evolving into an avalanche, if at all (Akitaya and Shimizu, 1988; Lackinger, 1987; van Herwijnen et al., 2013). Indeed, Feick (2013) found that most glide-snow avalanches released within the first 3 days after the glide crack had opened. Nevertheless, while after 4 days glide-snow avalanche release probability decreased substantially, release was still possible (Feick, 2013).

The formation of glide-snow avalanches has been investigated in the past (e.g. In der Gand and Zupančič, 1966). If glide rates of the snowpack along a slope differ too much, a glide crack might develop across the slope. Most research proposed three prerequisites for snow gliding: (*i*) A smooth snow–soil interface with little roughness as grass or bare rock, (*ii*) a snow temperature of 0 °C at the snow–soil interface which allows the presence of liquid water, and (*iii*) a slope angle greater than 15° (e.g. McClung and Clarke, 1987; Mitterer and Schweizer, 2012). A deep snowpack without a weak layer is assumed as additional prerequisite by e.g. Lackinger (1987) or Höller (2013). According to McClung and Clarke (1987), liquid water at the base of the snowpack may form due to three different processes: (*i*) heat, stored in the ground during a warm and dry autumn, melts the lowermost snow layer after the first significant snowfall; (*ii*) meltwater or rain percolates from the snow surface to the snow–soil interface, and (*iii*) water – produced by melting due to solar radiation (e.g. bare rocks) or originating from natural springs – runs downwards along the snow–soil interface. Meteorology, snowpack, soil properties, and terrain characteristics therefore influence the evolution of the moist snow layer at the snow–soil interface. Still, no clear relationship between these influencing factors and snow gliding has thus far been established.

Glide-snow avalanche activity varies every year (Höller, 2013; Lackinger, 1987) and is favoured by a warm autumn prior to substantial snowfall early in the winter (Frutiger and Kuster, 1967). Several

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Fig. 1. A tensile crack opens in the snow cover (left) prior to the release of a glide-snow avalanche (right).

observations showed high glide-snow avalanche occurrence after warm periods (i.e. melt) and rain-on-snow events (Clarke and McClung, 1999; Höller, 2013; Stimberis and Rubin, 2011). Clarke and McClung (1999) called glide-snow avalanches during these periods *warm temperature events* since snowpack conditions were 0 °C-isothermal and wet. They concluded that high air temperatures prevailing for 24 h or longer were indicative of increased glide-snow avalanche activity. Concurrently, Clarke and McClung (1999) found glide-snow avalanche events during periods when the snowpack had sub-zero temperatures and thus was dry, so-called *cold temperature events*. In contrast to *warm temperature events*, they could not explain *cold temperature events* with any meteorological parameter with reasonable accuracy.

Mitterer and Schweizer (2012) assumed that the moist basal snow layer for *warm temperature events* is mainly formed by the infiltration of water through the entire snowpack due to surface melting or rain-on-snow events. For *cold temperature events*, they suggested that the liquid water is produced due to warm ground temperatures melting the lowermost snow layer, water running down the slope (originating from springs or melt) or by the upward flux of water from the soil. Using a simple model simulating the hydraulic processes at the snow–soil interface, they showed that a strong hydraulic pressure gradient causes the water to move from the soil through the grass into the snow layer at the bottom of the snowpack. The presence of brownish coloured saturated basal snow layers, which were often observed by Mitterer and Schweizer (2012) support their finding.

Cold temperature glide-snow avalanches caused many problems during 2008–2009 and 2011–2012 for local and national forecasting services in the European Alps (Etter et al., 2011; Höller, 2014; Techel et al., 2013). Conditions required for *cold temperature events* are more likely to exist during early and mid-winter and may therefore persist for a considerable period of time (Mitterer and Schweizer, 2012). For *cold temperature events*, In der Gand and Zupančič (1966) and Höller (2013) assumed that additional load due to new snow increases glide rates and enhances the formation of glide-snow avalanches. Lackinger (1987) suggested similar behaviour but observed only one glide-snow avalanche due to new snow. Peitzsch et al. (2012) analysed glide-snow activity in spring and found that in addition to high air temperature, the settlement of the snowpack plays an important role in discriminating avalanche and non-avalanche days. In their analysis, it was not possible to distinguish between *warm* and *cold temperature events*.

In addition to meteorological and snowpack parameters, some research focused on monitoring glide rates as a predictor variable (e.g. Akitaya, 1980; Hendrikx et al., 2010; van Herwijnen et al., 2013). Observed glide rates were often higher early and late in the season compared to mid-season, i.e. January and February (Jones, 2004). Observations regarding daily variation in glide-snow avalanche activity are ambiguous. While Lackinger (1987) reported avalanche releases mainly in the evening and at night, Feick (2013) found increased glide-snow avalanche activity around noon and in the afternoon. No differences in glide rates between day and night were reported by Clarke and McClung (1999). Higher glide rates are expected to favour the release of avalanches (Endo, 1985; McClung et al., 1994) and in some cases increasing glide rates prior to avalanche release have been observed (Stimberis and Rubin, 2011; van Herwijnen et al., 2013).

Glide-snow avalanches remain notoriously difficult to forecast. Warning services often expect glide-snow avalanches and issue a warning only to produce false alarms, i.e. no glide-snow avalanches occurred. Simple meteorological indicators related to glide-snow avalanches would therefore be very helpful. We believe that thus far no clear relationship between glide-snow avalanche activity and meteorological parameters has been established because glide-snow avalanches follow two fundamentally different regimes. We therefore hypothesise that different contributing factors relate to glide-snow avalanche release in early to mid-winter, when the snowpack is cold and dry (*cold temperature events*), and in spring when the snowpack is 0 °C-isothermal and moist (*warm temperature events*). In order to identify meteorological parameters related to glide-snow avalanches, we compared meteorological measurements during two winter seasons (2008–2009 and 2011–2012) with daily glide-snow avalanche activity to both types of glide-snow avalanches separately. We monitored an area well-known for glide-snow avalanches with time-lapse photography and used meteorological data recorded throughout the entire winter seasons with high temporal resolution at automatic weather stations in the immediate vicinity of the glide-snow avalanche path. Multivariate statistical methods were applied to identify meteorological parameters related to *cold* and *warm temperature events* separately. The goal is to increase our knowledge of the meteorological conditions promoting glide-snow avalanches to ultimately improve glide-snow avalanche forecasting.

2. Study site and data

2.1. Study site for glide-snow activity

Glide-snow activity was monitored at the Dorfberg field site above Davos, Switzerland, during the winter seasons 2008–2009 and 2011–2012 (Fig. 2). The Dorfberg slopes have a well-documented glide-snow avalanche activity and were already used in the pioneering study by In der Gand and Zupančič (1966). Land cover of the east to southeast-facing slopes at Dorfberg consists mainly of steep and very steep meadows interrupted by open and closed forests, shrubs and some rocky areas (Fig. 3). Feistl et al. (2014) studied vegetation and terrain characteristics of glide-snow avalanche release areas at Dorfberg. They found that low basal friction due to smooth terrain with long grass correlated with flat and short release slopes, whereas high basal friction caused by stepped and rocky terrain covered with shrubs was related to steep and long release areas. The median slope angle of the Dorfberg