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Snowpack characteristics on steep frozen rock slopes

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ABSTRACT

Data from 27 snow profiles taken in frozen rock walls at two sites in the Swiss Alps reveal that steep slopes have distinctive snowpack characteristics. Snow pits were dug in 50–65° slopes at elevations between 2900 and 3600 m asl on north- and south-facing slopes at Gemsstock and Jungfraujoch Sphinx in the winters 2012–2013 and 2013–2014. There were marked contrasts in snow characteristics between the two aspects, yet strong inter-site similarities. Under the influence of intense solar radiation, basal ice layers and multiple hard melt-freeze crusts formed on the south-facing slopes. Soft layers of facets and depth hoar developed between the crusts. On the shady north-facing slopes, thick basal melt-freeze crusts formed when snow persisted during stable weather periods in autumn. The dominant snow grain types in winter were facets and depth hoar. When solar elevation exceeded slope angle from mid-April onwards, gravity-driven percolation of melt water flowing parallel to the frozen rock surface from areas with warm protruding rocks led to the formation of thick basal ice layers in the north-facing slopes. Windward slopes were covered with rime and glaze during storms, regardless of aspect and season. Despite widespread snowpack instability, the formation of large slab avalanches was hindered by the pronounced roughness of the rock surfaces. The main drivers contributing to the distinctive character of snow covers in frozen rock walls are the negative rock surface temperatures, enhanced/minimized solar radiation and multidirectional fluxes of water, vapour and heat induced by the steepness of the rock slopes.

1. Introduction

Snow accumulates in rock walls with slope angles reaching approximately 75° (Haberkorn et al., 2015a), yet slopes around 50–55° are often regarded to be the threshold angle for snow deposition (Warscher et al., 2013; Winstral et al., 2002). Snow and rime can adhere to rock slopes steeper than 75° during storms but tend to rapidly sluff off or melt. The spatial distribution of snow in rock walls has been described using terrestrial laser scanning (Haberkorn et al., 2015b; Sommer et al., 2015; Wirz et al., 2011) and its effects on rock temperature in permafrost regions have recently been investigated using snow gauge poles (Magnin et al., 2015) and time-lapse photography, combined with rock temperature measurements (Haberkorn et al., 2015a). Whilst laser scanning allows to determine snow depth and distribution during winter (Deems et al., 2013), neither this method nor other remote sensing techniques allow insight to snowpack properties and their evolution in the course of a winter.

Realistic simulations of the constitution of the snow cover can be obtained using 1D snow cover models such as SNOWPACK (Lehning et al., 2002) or CROCUS (Vionnet et al., 2012), but with the exception of the simulations of snow depth carried out by Haberkorn et al. (2015a) using the former model, there are no examples of snowpack characteristics being modelled in very steep terrain. Although vertical fluxes such as melt water runoff can be modelled in the snow cover using SNOWPACK (Wever et al., 2014), lateral gravity-induced effects (e.g. water fluxes beneath the snowpack, parallel to the rock surface) or lateral heat transfer caused by terrain microstructure, as modelled by Arons et al. (1998) are not taken into account by 1D snow cover models. Ground based information from steep slopes is essential to verify such point scale models and improve spatially distributed energy balance models like ALPINE3D (Lehning et al., 2006), which can realistically simulate snow cover duration in very steep terrain but less convincingly reproduce snow cover distribution and snow characteristics (Haberkorn et al., 2016). This problem is aggravated by a complete lack of meteorological data measured directly in steep slopes.

To our knowledge, there are no examples of in-situ snow cover investigations in rock walls exceeding 50° in the literature. In addition, the SLF snow profile data base (which currently contains almost 31,000 snow profiles), does not contain any snow pit observations from rock slopes over 50°, other than those presented in this paper. The lack of snow pit data from very steep terrain can probably be explained by the challenge of access and by the fact that this type of terrain is not

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particularly relevant for avalanche formation. However, information on snowpack characteristics is essential to determine the thermal influence of snow on rock walls. This is of particular interest with regard to the stability of frozen rock walls containing ice in pores and fractures, and where rock and fracture dynamics can be strongly linked to the thermal regime (Draebing et al., 2016; Hasler et al., 2012; Krautblatter et al., 2013). The influence of winter conditions and of snow on rock slope failures is unclear and currently being investigated, as large events exceeding 100,000 m^3 have been observed in mid-winter (Phillips et al., 2016b).

27 snow profiles measured in rock walls at two sites in the Swiss Alps with slope angles at or exceeding 50° are discussed here. The data were obtained in the context of a research project designed to determine the role of snow on rock slope temperature and stability in mountain permafrost (Haberkorn et al., 2015a; Haberkorn et al., 2015b). These two papers focused on the spatial distribution and depth of the snowpack and its effects on rock temperature. Here, we focus on the properties of the snowpack measured directly in rock walls. The number of snow profiles is restricted and their aspect-distribution uneven (17 on north-facing slopes and 10 on south-facing ones), thus preventing a robust statistical analysis. In addition, the snow profiles were taken at different times of winter, yet never simultaneously at the two study sites.

We therefore present a preliminary qualitative characterization of snow in very steep rocky terrain at elevations between 2900 and 3600 m asl in the Swiss Alps to illustrate the potential of such slopes for more detailed field investigations and for improved modelling of particular processes and characteristics. The aims of this paper are to describe the main characteristics of snow in frozen rock walls on the basis of 27 snow profiles and to discuss certain recurring particularities of the snow on steep north- and south-facing rock slopes at high elevations in Alpine environments. In addition to the well known drivers influencing snow layer properties and snow instability (Reuter et al., 2015; Schweizer et al., 2008), we propose that there are additional drivers which are specific to snowpacks on steep frozen rock slopes.

2. Study sites and winter conditions

Snow profiles were measured during the winters 2012–2013 and 2013–2014 at two sites with frozen rock walls in the Swiss Alps: Gemsstock (46°36′7.74″N/8°36′41.98″E, 2961 m asl) in the central Swiss Alps and Jungfraujoch Sphinx (46°32′51.13″N/7°59′07.80″E, 3572 m asl) in the Bernese Alps (Fig. 1). Both sites consist of a mountain ridge with rock walls facing NE to NW in the northern sector and SE to SW in the southern one. For simplicity we henceforth refer to north- (N) and south-facing (S) rock walls. These walls have slope angles ranging from 50° to vertical or overhanging sectors.

The Gemsstock ridge consists of Gotthard paragneiss and granodiorite, containing quartz veins. The S face is a smooth dip slope, whereas the N face is a rough scarp slope characterized by a series of persistent parallel joints dipping steeply south-eastwards at 70°, forming horizontal ledges in the rock wall with a spacing of 3 to 5 m (Phillips et al., 2016a). The rougher rock surface enhances snow accumulation here. Both slopes at Gemsstock are around 50 m high.

At Jungfraujoch Sphinx the top of the ridge consists of gneiss and is underlain by limestone and the basement Gastern granite. In the areas investigated, the rock dips southwards at an angle of 10–15° and is strongly fractured (Keusen and Amiguet, 1987). Both the N and the S face have a rough microtopography (Fig. 2) and are around 100 m high (Figs. 1 and 2).

Whereas Gemsstock is at the lower fringe of Alpine permafrost (Kenner et al., 2011), with patchy occurrences of permafrost in the North face, Jungfraujoch Sphinx has permafrost in both aspects (Hasler et al., 2011), due to its higher elevation. An overview of the permafrost distribution at both sites can be obtained from the Swiss permafrost distribution map (see http://map.geo.admin.ch).

The Gemsstock ridge is on the central Alpine divide and is therefore affected by southerly and northerly airflows. The site has enhanced orographic and convective cloud formation and high precipitation values with measured maximum winter snow depths exceeding 4 m. Mean annual precipitation at the MeteoSwiss automatic weather station (AWS) Gütsch, 6 km North of Gemsstock at 2287 m asl, is around 1500 mm a^{-1}. The mean annual air temperature (MAAT) at the AWS Gemsstock (2869 m asl) is − 3 °C (Phillips et al., 2016a). Jungfraujoch is on the northern Alpine divide, also affected by enhanced orographic cloud formation. Most precipitation falls as snow and MAAT at Jungfraujoch is − 7.3 °C (Hasler et al., 2011).

Winter 2012–2013 was a very snow rich winter, with snow depths deeper than average in the study regions. The snow season started in October 2012 and intense snowfalls in May 2013 prolonged the snow cover duration into the early summer (Techel and Darms, 2014). In contrast, winter 2013–2014 was characterized by having little snow until the end of December 2013. Snow depths in the study areas remained lower than average thereafter (Techel et al., 2015).

3. Flux directions in steep terrain

Heat fluxes, vapour transport and gravity driven processes can occur in different directions on steep slopes, which is relevant for snowpack evolution. Conductive and radiative heat flow mainly occur normal to the rock/snow surface and vapour fluxes occur along temperature gradients (Pinzer et al., 2012) with the same orientation. Heat transfer can also occur laterally/horizontally, for example from warm rock outcrops into the snow (Arons et al., 1998). In contrast, water fluxes (and thus convective heat transfer) occur along preferential flow paths (Marsh, 2006) - i.e. both vertically and parallel to harder snow/ice layers or to the rock surface. Finally, capillary suction occurs upwards (Ceaglio et al., 2017; Mitterer and Schweizer, 2012), both normally and vertically. This combination of flux directions leads to more complex conditions within the snowpack in rock walls than those found in flatter

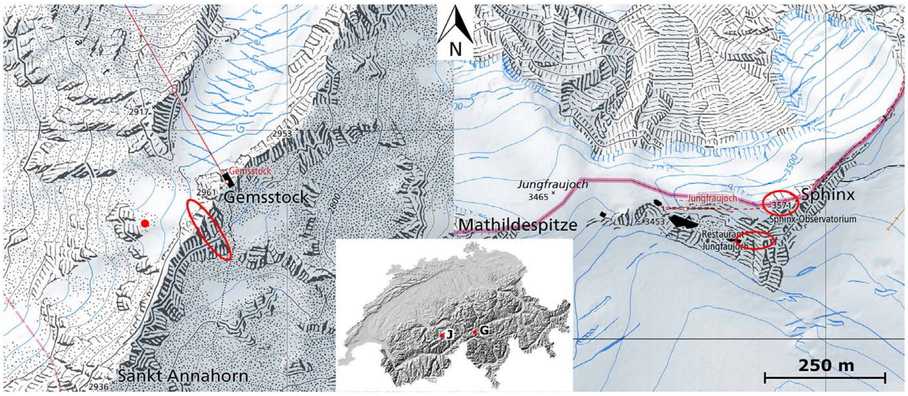

Fig. 1. Map of Switzerland (inset, right) showing the location of the study sites Gemsstock (G) in the central Swiss Alps (topographic map, left) and Jungfraujoch Sphinx (J) in the Bernese Alps (topographic map right). The study areas in the rock walls are circled in red. The automatic weather station at Gemsstock is marked with a red dot. (Swisstopo maps reproduced with permission 5,704,000,000).