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Snow as a driving factor of rock surface temperatures in steep rough rock walls

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ABSTRACT

Observations show that considerable amounts of snow can accumulate in steep, rough rock walls. The heterogeneously distributed snow cover significantly affects the surface energy balance and hence the thermal regime of the rock walls.

To assess the small-scale variability of snow depth and rock temperatures in steep north and south facing rock walls, a spatially distributed multi-method approach is applied at Gemsstock, Switzerland, combining 35 continuous near-surface rock temperature measurements, high resolution snow depth observations using terrestrial laser scanning, as well as in-situ snow pit investigations.

The thermal regime of the rock surface is highly dependent on short- and longwave radiation, albedo, surface roughness, snow depth and on snow distribution in time and space. Around 2 m of snow can accumulate on slopes with angles up to 75°, due to micro-topographic structures like ledges. Hence, contrasts in mean annual rock surface temperature between the north and the south facing slopes are less than 4 °C. However, significant small-scale variability of up to 10 °C in mean daily rock surface temperature occurs within a few metres over the rock walls due to the variable snow distribution, revealing the heterogeneity and complexity of the thermal regime at a very local scale. In addition, multiple linear regression could explain up to 77% of near-surface rock temperature variability, which underlines the importance of radiation and snow depth and thus also of the topography.

In the rock faces the thermal insulation of the ground starts with snow depths exceeding 0.2 m. This is due to the high thermal resistance of a less densely packed snow cover, especially in the north facing slope. Additionally, aspect induced differences of snow cover characteristics and consequently thermal conductivities are observed in the rock walls.

1. Introduction

Pronounced rock fall activity has been observed in Alpine permafrost regions over the last decades (Deline et al., 2012; Gruber and Haeberli, 2007; Gruber et al., 2004a; Ravanel and Deline, 2010). Rock slopes containing ice are sensitive to ongoing climate change (IPCC, 2013). Rising air and rock temperatures can reduce the effective thermal stress in ice filled rock joints (Haeberli et al., 1997), enhancing destabilization and possibly leading to rock slope failure (Krautblatter et al., 2013). Rock temperature data are therefore essential for a detailed understanding of thermo-mechanical processes in rock walls, and to model and predict permafrost related hazards (Krautblatter et al., 2011), which may threaten human lives and infrastructure in the densely populated Alps.

Snow has a thermal influence on the ground due to its low thermal conductivity (Fierz and Lehning, 2001), high surface albedo and the consumption of energy during snow melt (Sturm et al., 1997; Zhang, 2005). The snow cover either has a warming or cooling effect on ground temperatures, depending mainly on the snow depth (Luetschg et al., 2008; Phillips and Schweizer, 2007), as well as on its initial timing and duration (Hoelzle et al., 2003; Zhang et al., 2001). A thick snow cover (>0.6 m) decouples the rock surface from the air temperature due to increasing thermal insulation with increasing snow depth (Keller and Gubler, 1993), resulting in an increased MAGST (Keller and Gubler, 1993; Luetschg et al., 2003; Matsuoka and Sakai, 1999; Zhang et al., 2001). In contrast, a thin (<0.15 m) and patchy snow cover leads to ground cooling due to an increase in longwave emissivity and albedo at the surface, in combination with a low thermal resistance of the

Abbreviations: AWS, automatic weather station; BH, borehole; DTM, digital terrain model; HS, snow depth; MAAT, mean annual air temperature; MAGST, mean annual ground surface temperature; N, north-west slope; NSRT, near-surface rock temperature; p, level of significance; PISR, potential incoming solar radiation; R, ridge; R^2, coefficient of determination; S, south-east slope; SO, surface offset; STD, standard deviation; TA, air temperature; TLS, terrestrial laser scanning.

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thin snow cover (Keller and Gubler, 1993; Luetschg et al., 2008). Snow depth and its distribution therefore influence the existence of permafrost in both gently inclined slopes and in steep rock faces. The occurrence of snow in steep rock walls has been confirmed by Wirz et al. (2011), a possible influence of snow on spatially distributed rock surface temperatures is discussed by Magnin et al. (2015), as well as Hasler et al. (2011). Haberkorn et al. (2015) provide a first quantitative (measured and modelled) investigation of the effects of snow on rock thermal processes.

To account for the complexity of rock walls and their thermal conditions, spatially distributed rock temperature measurements in various types of rock walls covering different aspects are necessary. Measurements in compact, near-vertical and also snow free rock (Gruber et al., 2003), as well as distributed surface energy balance modelling (Gruber et al., 2004b; Mittaz et al., 2000; Noetzli et al., 2007) to extrapolate rock thermal conditions in space and time underline the dominance of topography on permafrost distribution in steep bedrock. These authors found 7–8 °C warmer MAGST in Alpine rock faces exposed to solar radiation than in shaded ones. The assumption of a lack of snow in rock walls exceeding 50° due to gravitational processes such as avalanching and sloughing (Blöschl and Kirnbauer, 1992; Seligman, 1936; Winstral et al., 2002) is not applicable for rough rock walls with a complex micro-structure (Haberkorn et al., 2015). This implies that the thermal regimes observed and modelled in the idealized case of vertical compact rock are different. Hasler et al. (2011) reported a likely reduction of MAGST of 2–3 °C in moderate to steep (45°–70°), fractured rock faces exposed to solar radiation. This is assumed to be due to the accumulation of snow persisting during the months with most intense solar radiation. The thermo-insulating effect of snow accumulating locally in steep rock is also addressed by Magnin et al. (2015). For a thick snow cover (>0.6–0.8 m) the latter observed a MAGST increase in shaded areas comparable to that in gentle mountain slopes — and in contrast, a MAGST decrease in sun-exposed faces due to the higher surface albedo of snow, thus reversing the thermo-insulating effect of thick snow.

The snow cover influences the rock surface energy balance, due to changes in both the radiation budget and the turbulent fluxes of sensible and latent heat at the rock surface (Armstrong and Brun, 2008). Although Hasler et al. (2011) and Magnin et al. (2015) assume reduced MAGST differences between north and south facing rock walls due to the accumulation of snow on micro-reliefs, HS are only estimated in these studies and are described qualitatively in terms of 'thin' or 'thick' snow accumulations rather than quantitatively. High quality snow depth and snow characteristic data in combination with rock temperature measurements are therefore required to better quantify the impact of the snow on the rock thermal regime.

High resolution TLS is suitable to measure snow depths accurately and to determine the spatial distribution of snow, both in gently inclined slopes (Deems et al., 2013; Grünewald et al., 2010; Prokop, 2008) and in steep, rough rock walls (Haberkorn et al., 2015; Wirz et al., 2011). The accumulation of considerable amounts of snow (2–3 m) in slopes between 70° to even 90° due to local micro-topographic asperities was observed by Haberkorn et al. (2015). The heterogeneous spatial distribution of the mountain snow cover (e.g. Pomeroy and Gray, 1995; Seligman, 1936) is mainly attributed to the deposition and redistribution of snow due to wind (Lehning et al., 2008; Schweizer et al., 2008; Trujillo et al., 2007; Wirz et al., 2011), to micro-topographic properties such as terrain roughness, terrain concavity and distance to underlying ledges (Haberkorn et al., 2015; Magnin et al., 2015) and to spatially varying ablation processes due to local radiation (Mott et al., 2011) and shading from surrounding terrain.

To assess the impact of the heterogeneously distributed snow cover on the strong small-scale variability of NSRT, steep north and south facing rock walls were investigated over a period of 2 years at Gemsstock, Swiss Alps. The sectors of the rock walls where snow can or cannot accumulate are characterized and the thermal response of the rock is analysed. To do this, we applied a spatially distributed multi-method approach with a high temporal and spatial resolution. This involved combining 35 continuous NSRT measurements, remote observations of the snow depth and its distribution using TLS and in-situ snow cover observations (snow pits) at different stages over two consecutive winters.

The dependence of the surface offset and consequently of NSRT on air temperature, snow depth, terrain roughness and PISR is investigated using multiple linear regression and is discussed in the context of the heterogeneous and complex processes occurring in steep mountain rock walls.

2. Study site

The study site is part of the Gemsstock mountain ridge (46° 36′ 7.74″ N; 8° 36′ 41.98″ E; 2961 m a.s.l.), located above Andermatt, central Swiss Alps (Fig. 1). The rocky flanks of the ridge investigated face north-west and south-east and are subsequently simply referred to as the N and S slopes. The 40 m high slopes are 40° to 70° steep, with vertical to overhanging (>90°) sections and extend from an elevation of 2890 m a.s.l. to 2930 m a.s.l. The ridge has a width of 40 m at its base, and tapers off towards the top. The whole N facing scarp slope and the upper part of the S facing dip slope consist of bare Gotthard paragneiss and granodiorite, with quartz veins, whereas the lower half of the southern slope is partly covered by patches of grass and moss. On the local rock wall scale micro-topographic contrasts dominate the N face with a series of practically horizontal ledges intersecting the rock wall, which correspond to joints striking southwards at 70° and alternating with steep to vertical parts. In contrast, the S facing dip slope is rather smooth and homogeneous (Fig. 2).

Gemsstock is located directly on the main divide of the Western Alps, and is thus affected both by northerly and southerly airflows. Meteorological data are obtained from an on-site AWS located at the northern foot of the rock wall (Fig. 1). Meteorological differences to surrounding AWS at lower elevations (Gütsch, 2287 m a.s.l., 6 km north of Gemsstock; Urseren, 2170 m a.s.l., 8 km west of Gemsstock; Bedretto, 2450 m a.s.l., 11 km south-west of Gemsstock) are clearly reflected in the enhanced orographic precipitation from the north and the south at Gemsstock. Maximum snow depths are 4.5 m at the AWS Gemsstock compared with 3.5 m at the close by AWS Gütsch (Haberkorn et al., 2015). Prevailing wind directions are from north-east to north-west, but also from the south during föhn storms. The MAAT measured at the AWS Gemsstock was −2.6 °C during the study period between 1 August 2012 and 31 July 2014. The year 2012–2013 was 1 °C warmer than 2013–2014 (Table 1), although the mean winter temperature (December to February) in 2012–2013 was 3.6 °C colder. Nevertheless, both years were warmer (1.0 to 1.5 °C) than the MAAT in the reference period 1981–2010 measured at the MeteoSwiss AWS Gütsch. The snow cover development during the two particularly long and snow rich winters was relatively similar at Gemsstock (Fig. 3), although most snowfalls in the year 2012–2013 were dominated by northerly airflow, in contrast to 2013–2014, when snowfalls were dominated by southerly airflow, as shown by data from neighbouring AWS. However, initial and maximum snow depths were lower in winter 2013–2014 and hence the timing of snow disappearance differed between the two winters.

Borehole temperatures measured continuously since 2005 in a horizontal borehole through the Gemsstock ridge (Figs. 1c, 2) indicate that there is no permafrost here (PERMOS, 2013). However, ice has been observed in rock fall scars at nearby locations on the N facing slope. Near-surface freeze–thaw cycles take place in autumn and late spring and seasonal frost occurs down to a depth of 8 m on the N side. Gemsstock is located at the lower fringe of permafrost and is additionally affected by ongoing retreat of the Gurschen glacier on the northern side, which makes it susceptible to rock slope failure (Kenner et al., 2011).