Snow accumulation and redistribution in very steep rock faces

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ABSTRACT

We used terrestrial laser scanning to measure snow thickness changes in a rock face. The purpose of the study was the investigation of snow accumulation and redistribution in very steep alpine terrain. The rock face considered was the north-east face of the Chlein Schiahorn in eastern Switzerland. It was scanned before and after a snowfall event.

The flatter, smoother areas of the rock face accumulated most snow. The snow thickness change had a high spatial variability. The total snow thickness exhibited spatial patterns similar to those of the snow thickness change. Snow accumulated at every slope angle. The amount of snow in near-vertical terrain was remarkable. More than 10% of the total amount of snow was contained in areas steeper than 60°. The slope angle as well as the snow thickness were calculated at a resolution of 0.5 m.

Keywords: Snow, rock face, accumulation, snowfall, terrestrial laser scanning

INTRODUCTION

Snow in rock faces affects the occurrence of permafrost (Gruber et al., 2004; Haberkorn et al., 2015; Luetschg et al., 2008), avalanche danger (Schweizer et al., 2003) and it contributes to runoff (Anderton et al., 2002; Lehning et al., 2006).

Many authors found that the amount of snow decreases with increasing slope angle and that above a critical angle no snow accumulates. Blöschl et al. (1991) cited studies with critical angles between 45 and 70°. Wirz et al. (2011) were the first to treat the distribution of snow in a rock face in detail. With terrestrial laser scanning, they measured the snow depth and snow depth changes. The influence of slope angle was unclear. There was only a weak correlation between slope angle and the amount of snow. Snow accumulated in areas up to 80° steep.

The time scale in the study of Wirz et al. (2011) was one to several weeks. We, in contrast, captured a single snowfall event at a time scale of days. Moreover, the precision of the measurements of Wirz et al. (2011) was lower than the precision of TLS data in gentle terrain (Grünewald et al., 2010). This study, therefore, had two aims: first, to reduce errors by improving the postprocessing procedure and second, to gain information on the accumulation and redistribution of snow in steep rock faces.

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DATA ACQUISITION AND PROCESSING

Measurement location
The north-east face of the Schiahorn is extremely steep. On average, the slope angle is 50° but 25% of the area has a slope angle above 60° and 11% is steeper than 70°. Four reflectors were installed on rocks and on fixed structures (Figure 1) to georeference (register) the scans (Revuelto et al., 2014).

![Figure 1. Map of the measurement location. Base map reproduced by permission of swisstopo (JA100118)](image)

Data collection
The data was acquired following the procedure described by Wirz et al. (2011) and Grünewald et al. (2010) and was done with the same terrestrial laser scanner (Riegl LPM-321). Scans were obtained before the snowfall on 21 March 2014 and after the snowfall on the 25, 27, 28 March and 1 April. On 18 August 2014, the bare rock face was scanned.

Postprocessing
Compared to the studies of Wirz et al. (2011) and Grünewald et al. (2010) the postprocessing was modified significantly. The three most important changes were the use of snow thickness instead of snow depth, the consistent application of Multi Station Adjustment (MSA) and a modified view direction. Because snow depth is measured vertically, it is very sensitive to registration errors in near vertical terrain. Snow thickness is measured perpendicularly to the surface and is better suited for steep terrain because the slope angle is taken into account in the calculation. MSA is a software tool and employs an iterative closest points (ICP) algorithm to register (adjust) different scans (Kenner et al., 2011). Triangulated surfaces of the snow-free rock areas were used in addition to the reflectors. The usual vertical view direction is problematic because near-vertical terrain is almost invisible. Such terrain can be better analyzed from the front by rotating the data.

RESULTS

Spatial distribution of the snow thickness and the snow thickness change
Figure 2 presents the spatial distribution of the snow thickness change (ΔDS) between 21 and 25 March. The purple color is an uncertainty zone around zero of ±3 cm. Most snow accumulated in the slope toe, below the actual rock face. The variability was high. Many areas had ΔDS > 60 cm but other areas had a negative snow thickness change. Redistribution of snow by small avalanches could have caused the largest accumulations. Several such avalanches were observed. In the actual
rock face, ΔDS was usually lower than in the slope toe. Only locally did it reach high values, for example in snowfields adjacent to the crest.

Figure 2. Spatial distribution of the snow accumulation during the snowfall.

Figure 3 shows that the spatial patterns of the total snow thickness were similar to those of the snow thickness change. The correlation coefficient between them was \( r = 0.86 \). It appears that the measured snowfall event was representative of most snowfalls in this winter. DS was also highest in the slope toe. In several places, DS exceeded four meters.

Figure 3. Spatial distribution of snow thickness on 25 March.

**Snow in very steep terrain**

Figure 4 shows the snow thickness and snow thickness change as a function of the slope angle. We subdivided the rock face in slope angle classes of two degrees and calculated mean values in these subareas. Below 50°, DS and ΔDS decreased strongly with increasing slope angle. Above 50°, ΔDS and DS began to flatten out and reached values of about 0.1 m and 0.25 m, at which they remained up to 90°.
The amount of snow in very steep terrain is remarkable (Figure 5). The figure shows cumulative distributions of normalized snow volumes as a function of slope angle. The volumes were normalized by the number of cells in each slope angle class. The difference between the two curves indicates that snow was redistributed from extremely steep to moderately steep terrain. Areas steeper than 60° accumulated almost 20% of the snow during the snowfall but these areas “only” contained 10% of the total amount of snow. This terrain could not hold all deposited snow. Nevertheless, the amount of snow in such terrain is considerable.

**DISCUSSION**

It appears that snow can accumulate permanently at all slope angles. Between 70 and 90°, ΔDS and DS were almost constant. It has been assumed by several authors that such terrain cannot retain snow (Gruber Schmid and Sardemann, 2003; Machguth et al., 2006; Winstal et al., 2002). Our results suggest that assuming a constant snow thickness may be more appropriate. In fact, Bernhardt and Schulz (2010) chose this approach. They assumed a constant value of 5 cm at slope angles above 75°. The value of the constant may strongly depend on the roughness. Haberkorn et al. (2015) suggest that step-like (micro-)topography is necessary for snow accumulation in near-vertical terrain. Lehning et al. (2011) observed that less snow is accumulated in rougher terrain than in smoother areas. This may not be valid in near-vertical terrain but depends also on the spatial scale of the analysis.
CONCLUSIONS

The postprocessing has a large influence on the quality of TLS data from rock faces. We propose the use of snow thickness instead of snow depth and the consistent application of MSA. Moreover, the view direction should be perpendicular to the rock face.

Moderately steep terrain accumulates more snow than near-vertical areas. Nevertheless, the amount of snow in such areas is considerable. More than 10% of the total amount of snow lay in areas steeper than 60°. However, only one snowfall event was analyzed and it is unclear how general these results are. Furthermore, the results are also expected to depend on how the extent of the rock face is defined.

REFERENCES


