Analysis of temporal and spatial snow depth changes in a steep rock face

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ABSTRACT: To understand snow distribution in steep rock walls a high resolution terrestrial laser scanner (TLS) was used to achieve precise snow height digital surface models. We collected surface data without snow, before and after significant snowfall or wind drift events and during the ablation period. We then generated digital surface models (DSM) for each observation period. The summer scan under the total absence of snow allowed us to provide a digital elevation model (DEM) and to calculate absolute snow depth. Relative snow depth changes can be extracted by the comparison of different winter scans. In addition to the laser scans, orthophotos were taken with a digital camera. In a first step we could show that with TLS reliable information on surface data of a steep rocky surface can be achieved. In comparison to a flat field point measurement the mean snow depth in the rock face was smaller during the entire winter, but trends of snow depth changes were similar. We observed repeating accumulation and ablation patterns in the rock face, while maximum snow depth loss occurred always at those places with maximum snow depth gain. Furthermore, increasing snow depth resulted in a decrease of high slope angles. Further analyses should involve the statistical relation of spatial and temporal distribution of snow depth to (i) terrain features e.g. slope angle, aspect or curvature and (ii) resulting surface processes derived from spatial distributed model outputs e.g. radiation, wind fields or blowing and drifting snow.

KEYWORDS: Terrestrial laser scanning, snow depth changes, rock face, snow distribution.

1 INTRODUCTION

A good knowledge on spatial and temporal variability of snow depths in steep alpine terrain is of high importance, because snow plays an important role on many alpine processes, e.g. water management, snow avalanches or permafrost distribution. Inaccessibility and alpine dangers in very steep terrain are the main reasons for lack of such studies. In Switzerland more than 20% of the area above timberline consists of rock faces with slope angles steeper than 40°. In high alpine regions, precipitation is stored as snow during the cold months. Snow cover thus determines the important runoff during the melting period in spring (Luce et al., 1998; Lehning, 2006; DeBeer and Pomeroy, 2009). The existence of alpine permafrost strongly depends on the spatial and temporal variability of snow depth (Haeberli, 1996; Keller and Gruber, 1994; Lütschg et al., 2008). Given the present lack of knowledge on snow distribution in steep rock walls, better investigations and field studies are needed and further analysis of processes involved are necessary.

In the last few years terrestrial laser scanning (TLS), a method to measure snow depth changes in alpine environment, came up (Bauer and Paar, 2004; Prokop et al., 2008; Schaffhauser et al., 2008). This new observation technique allows detecting snow depth changes with high spatial resolution in inaccessible terrain. Thus far, TLS has never been applied to look at the temporal and spatial variability of snow depth in rock faces.

This is the first study, to present an analysis of snow depth data in an inaccessible rock face. It discusses the amount and variability of the snow cover and the factors contributing to it.

2 METHODS

2.1 Data acquisition

A terrestrial laser scanner (Riegl, LPM-321) was used during the winter 2009 to collect snow depth data and orthophotos in a steep rock face (Chüpfenflue, in the region of Davos, Eastern Swiss Alps).

The study site is a rough, southwest-facing slope between 2200 and 2658 m a.s.l.. The mean slope angle is 42° and varies from flat to nearly vertical parts (max. 86°). The surrounding area is equipped with seven automatic weather stations.

The TLS measures distances with a near infrared signal (900 nm). The beam divergence of the TLS is 8 cm per 100 m. The density of the point cloud depends on the predefined resolution. We used 0.036° for the *fine scans*, which

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would result in a vertical density of about 9 points per m^2 at a distance of 300 m. The distance from the rock face to the TLS varied between 350 and 750 m. For precise measurements, the scanner, installed on a tripod, should not move during a scan. Therefore the duration of one single scan was restricted to one hour. Gaps in the measured surface occurred due to blind areas.

In addition to the distance measurements, a digital camera (Canon EOS 350D) installed on the platform of the scanner was used to take photos of the area on every field day. The software of the scanners allowed generating orthophotos from these photos. They provided important supplementary information on the surface conditions.

2.2 Data post-processing

During the post-processing, we used the two software tools RiProfile (Riegl, version,1.4.3) and ArcGIS (ESRI, version 9.3). The raw data were filtered and transformed to a global coordinate system. A filter (*octree*) helps to achieve a more balanced point density. The measured point cloud was transformed into a global coordinate system by a transformation-matrix, which was calculated using several permanently installed reflectors with known global coordinates, located in the view of the scanner. The point clouds were triangulated (*Delauny triangulation*) and converted into a regular grid. For most of the analysis we used a cell size of one meter. The differences in the z-values between retrievals gave us the snow depth changes, or the absolute snow depth. Mean snow depths were calculated for the entire base area of the rock face.

The final dataset consisted of 14 surface data measurements with snow, collected during the winter 2009 between 16 January and 25 May and one scan without snow, serving as the digital elevation model.

2.3 Data quality analysis

Prokop et al. (2008) quantified the error of snow height measurements achieved with a terrestrial laser scanning system in alpine terrain and compared it to other methods. Since these results cannot be transferred to our rough surface, this section gives a short overview of the errors and quality estimations of the dataset described above.

Every field day the entire area was scanned with a coarser resolution (lasting less than 10 min) in addition to the fine scans. The comparison between these coarser scans and the fine scans should indicate if a single scan had an offset or if the tripod moved during one scan.

On several occasions during a scanning day, at least one part of the scan was repeated (to test the *repeatability*). We assumed that during this short time period the surface remained unchanged. The differences in z-values of the double scans gave us an idea about the uncertainties of the measurement method. We also tested the influence of a new position and orientation of the scanner on the *reproducibility* of the measurements: the same area was scanned twice with changed position and orientation of the scanner within a short period of time.

The influence of different cell sizes, increasing slope angle and increasing edge length of the triangles on errors were analysed.

3 RESULTS

The first test during the quality analysis, a comparison of the *fine scans* with the *coarse scan* showed that generally no offset or movement of the tripod occurred during measurements even on windy days.

All repeatability tests of the fine scans showed similar results. We therefore present here the results of one representative day (17 March). A mean error of 8.7 cm (absolute mean) together with a standard deviation of 20.3 cm was observed. The offset was negligible (mean is -2.9 cm). If we changed the orientation and position of the tripod (*reproducibility*) the size of the error was comparable to those values. The main differences between scans of the same surface occurred in steep, rough areas. Analysing the errors with respect to the edge lengths of the triangles, it turned out that triangles with an edge length up to 5 m were useful: areas with lower point density were closed in the triangulation process without increasing errors and standard deviations, while obvious measuring shadows were not interpolated.

To formulate hypotheses and detect important factors influencing the snow depth variability in steep and rocky terrain, we analysed the dataset visually. We concluded that the main snow accumulation occurred on less steep parts or at the base of steep rock parts (Figure 1). Repeating accumulation and ablation patterns could be observed. In particular minimal and maximal snow depth changes seemed to occur always at the same spots: where mass gain was highest during accumulation, mass loss was highest during ablation (Figure 1 and 2).

Of further interest was the comparison of the total amount of snow in a steep rock face to the amount of snow in flat areas. Therefore we compared the mean snow depth (mean difference of z-values of the entire base area of the rock face) and changes thereof for different periods to the data from a nearby flat field point

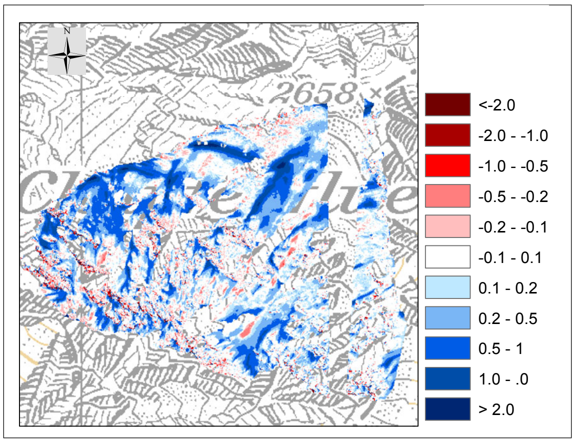

Figure 1: Snow depth change between 2 March and 4 April in the southwest face of the Chüfenflue.

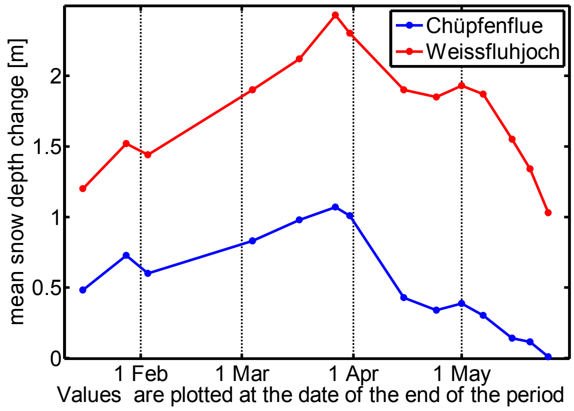

Figure 3: Mean snow depth[1] of the rock face (blue curve) and the snow depth of the measured snow depth at the Versuchsfeld Weissfluhjoch.

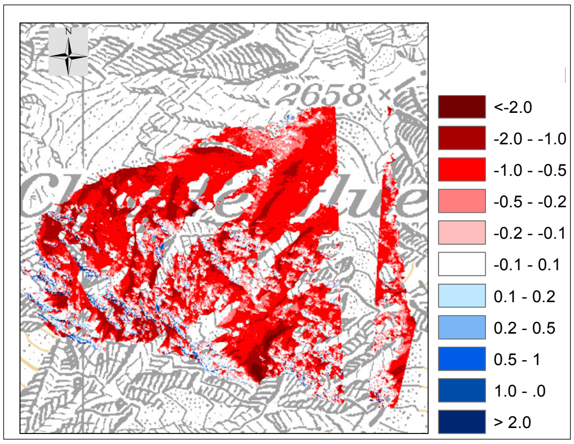

Figure 2: Snow depth change between 31 March and 15 April in the southwest face of the Chüfenflue.

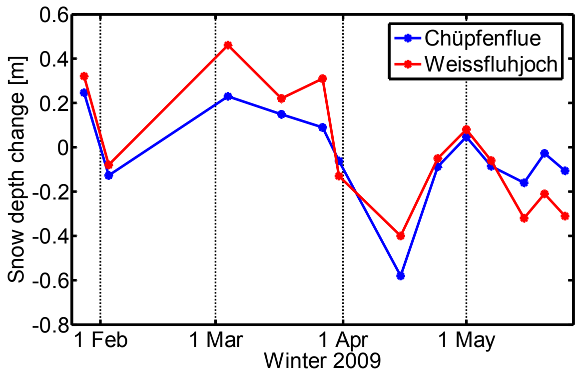

Figure 4: Mean snow depth change[2] of the rock face (blue curve) and the snow depth change of the measured snow depth at the Versuchsfeld Weissfluhjoch. The values are plotted at the date of the end of a period.

measurement with similar altitude (Versuchsfeld Weissfluhjoch, 2540 m a.s.l). During the period analysed the mean snow depth in the rock face was always smaller (Figure 3), with a maximum difference of 1.57 m at the beginning of May. In both study sites the peak of winter accumulation was reached at the end of March. On this day a mean snow depth of 1.07 m was measured in the rock face and 2.43 m at the Versuchsfeld Weissfluhjoch.

The observed snow depth changes of the two sites were similar (Figure 4), especially the trends during the accumulation period. The accumulation of snow during this period was smaller in the rock face. A strong ablation period at the beginning of April followed the peak of winter accumulation. In two weeks the snow depth was reduced by more than half (58 cm) at the Chüpfenflue. During the same time, the loss in snow depth in the flat area was 40 cm. At the end of April a snow fall event caused a break in the ablation process. At the end of the ablation season the rates of mass loss were higher at the Versuchsfeld.

We further investigated if the accumulated snow influenced the slope distribution in the rock face. The comparison of the slope angles of the dataset indicated that the distribution of the slope angles changes, especially the number of the slope angles higher than 50° decreased with increasing snow depth (Figure 5).

4 DISCUSSION

The data collection during the winter 2009 confirmed that a terrestrial laser scanner is a useful tool to measure snow depths in inaccessible, steep and rough terrain. Our dataset contains reliable information as shown by the quality

[1, 2] Mean snow depth (change) was calculated for the entire base area of the rock face.

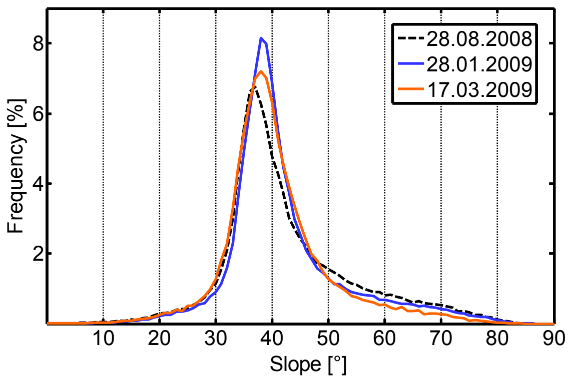

Figure 5. Frequency of the slope angles for different time steps with different snow depths (mean): *28.08.2008*: without snow, *28.01.2009*: 72 cm, *17.03.2009*: 98 cm.

analysis of our data. With a mean absolute error of less than 10 cm, important snow depth variations and changes could be detected, when a maximum edge length of 5 m was allowed in the triangulation process.

We showed that in the steep terrain of the Chüpfenflue, the mean snow depth was smaller compared to flat terrain. Less snow was accumulated during snow fall events due to wind drift and preferential deposition (Lehning et al., 2008). Additionally, snow could not accumulate in very steep terrain and small avalanches due to gravity were observed. We will compare mean snow depths and changes to a very close, but less steep and less rocky area with the same aspect, where we collected surface data with TLS.

The curves of the snow depth changes show similar trends (Figure 5). The mass loss in the face of the Chüpfenflue during the first three days of February (mean loss was 12 cm) happened due to a Föhn storm event, with wind speeds of up to 50 km h^{-1}. At the beginning of the ablation season the change in snow depth was higher in steep terrain. We expected those larger mass losses in the rock face due to a generally larger amount of shortwave radiation (south-west aspect) and also due to smaller albedo values of snow-free rocks. However, after May 5 the loss in snow depth at the Versuchsfeld became larger. For the analysis of the higher mass loss rates of the Versuchsfeld it had to be taken into account, that in the face of the Chüpfenflue most parts were already free of snow in May. But the mean loss in snow depth was calculated and reported for the entire area including the snow free parts. This is probably the reason why at the end of the ablation period the decrease in snow depth in the flat area was higher than in steep terrain (cp. Grünewald, 2009). Thus we will analyse the changes in snow depth only for snow covered areas of the rock face. This information will be improved with the orthophotos obtained by each measurement.

Analysing the slope angle distribution, steep slope angles were less frequently measured when snow depth increased during the accumulation period. We assume that accumulated snow was able to level the surface which resulted in less steep parts of the rock face.

During the first qualitative analysis of our data it turned out that minimal and maximal snow depth changes always occurred at the same places. The reason for this could be increased settling, sublimation and finally melt with increasing snow depth.

We will verify these qualitative results with a statistically analysis of the relation between the daily rate of snow accumulation and factors such as slope angle, curvature as well as modelled solar radiation or wind speed.

5 CONCLUSIONS

In steep and rough terrain a terrestrial laser scanner is a useful tool to measure snow covered surfaces. This method was used to measure snow depth changes during the winter 2009 in a rock face.

We compared our measurements to a point measurement of snow depth in a flat area. The trend of the curves of snow depth and changes thereof was similar. The mean snow depth in the rock face in comparison to the flat area was smaller during the entire period. The slope angle seems to be an important factor influencing the amount of the snow deposition during snow fall events. Slope angles over 50° decrease with increasing snow depth. A statistical analyse of the slope angle, curvature, long wave radiation, air temperature and mean wind fields related to snow depth changes will be done. Another interesting feature, which we will analyse, is the growth of cornice-like deposition maxima starting above vertical rock outcrops in the steep wall

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