Measurements of small scale spatial and temporal variability of snow depth and SWE in a small mountain catchment

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ABSTRACT: Using a new type of terrestrial laser scanner (TLS), which is particularly suited for measurements of snow covered surfaces, we monitored snow depth, snow water equivalent (SWE) and melt rates in a high alpine catchment during the Winter 2007/08 ablation period. For the first time the spatial variability of these quantities and its temporal development could be studied with a high spatial resolution (cell size 2.5 m). A very high variability of snow depths ranging between 0 - 9 m at the end of the accumulation season was found. This variability decreased during the ablation phase. Average daily melt rates were between 15 mm SWE at the beginning of the ablation period and 30 mm SWE at the end. The spatial variability of the melt rates increased during the ablation season and could not be explained in a simple manner by geographical or meteorological parameters.
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KEYWORDS: spatial variability, snow water equivalent, snow depth, terrestrial laser scanner, melt rates

1 INTRODUCTION

The snow cover in mountains is characterised by high spatial and temporal variability in snow depth and snow water equivalent (SWE). The spatial distribution and the total volume of snow stored in an area and its evolution during the hydrological year, are questions of high importance: The total amount of snow and the timing of snow melt strongly affect tasks such as flood control, drinking water supply, agriculture or vegetation growth (e.g. Elder et al., 1998; Armstrong and Brown, 2008; Deems et al., 2006;, Jones et al., 2001; Keller et al., 2000).

In recent years investigations on spatial snow cover characteristics were mainly carried out by extrapolating limited numbers of manually sampled snow depth and density data using statistical models (e.g. López-Moreno and Nogués-Bravo, 2006; Marchland and Killingtveit, 2003; Chang and Li, 2000; Luce et al., 1999;, Erickson et al., 2005). Terrestrial laser scanning (TLS) provides a new method to collect snow depth data in a very high spatial resolution with limited time effort. Prokop et al., 2008 and Schaffhauser et al., 2008 proofed TLS to be an accurate technique for snow depth investigation and also present detailed information on accuracy and applications of TLS in snow sciences.

In this study we present an assessment of area wide snow depth data from an high alpine catchment for a complete ablation period. This high spatial resolution available at regular time intervals offers for the first time the possibility to analyse spatial patterns and temporal development of snow distribution and ablation.

2 METHODS AND DATA

Four TLS measurement campaigns were performed in the Albertibach catchment in about two week intervals between the time of peak SWE (26 April) and the disappearance of most of the snow (10 June). The catchment is a small (1.3 km^2) high alpine basin located above the valley of Davos (Switzerland).

To monitor the snow surface data we used a Riegl LPM 321 terrestrial long range laser scanner, which, due to its wavelength (904nm) and long range (> 1500 m), is an instrument particularly suited for applications on snow (Riegl, 2008).

From point clouds obtained by the TLS we produced raster maps with a 2.5 m - grid resolution. As TLS just measures distances to the observed surface and therefore creates digital surface models, a digital elevation model was used to transfer the data to real snow depth.

Furthermore nine snow density measurements were made at well selected spots during each of the field campaigns. Using average values of the measured snow density together with the snow depth maps obtained by the TLS, we were able to calculate SWE maps of the area. The difference between consecutive time steps gave information on the temporal change of SWE and average melt rates could be calculated for the time intervals.

We performed an analysis of snow depth, SWE and melt rates by visual interpretation of the maps and by using basic statistics such as mean values (μ) and standard deviation (σ). Furthermore, we investigated whether there were

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statistical dependencies on geographical and meteorological parameters such as aspect, elevation, slope, incoming solar radiation and wind speed using simple linear regression. Solar radiation was calculated using the ArcGIS solar radiation tool and wind speed was derived from small scale atmospheric modelling with the Advanced Regional Prediction System, ARPS (Xue et al., 2000; Mott et al., 2008; Raderschall et al., 2008).

3 RESULTS AND DISCUSSION

In Fig. 1 the snow depth distribution is shown at the end of the accumulation season. Apart from very small patches, which are mainly located in steep rock walls, the whole area was snow covered. The average snow depth was 2 m (σ = 1.3 m) which corresponds to an average SWE of 697 mm. The high spatial variability of snow depth is obvious from the map with values ranging from 0 to 9 m of snow. In general most snow seemed to be located in the steep north facing slopes of Wannengrat and in the Vordere Latschüel whereas the Chilcher Berg area showed snow depths below average. Most striking were the features characterised by outstanding high snow depth located in the north eastern slope of Wannengrat (arrows in Fig. 1). These features could be identified as cross slope accumulation zones due to wind drift (Mott et al., this issue) and preferential deposition (Lehning et al., 2008). The same processes might account for the snow filled ditches in the Chilcher Berg area (arrows in Fig. 1).

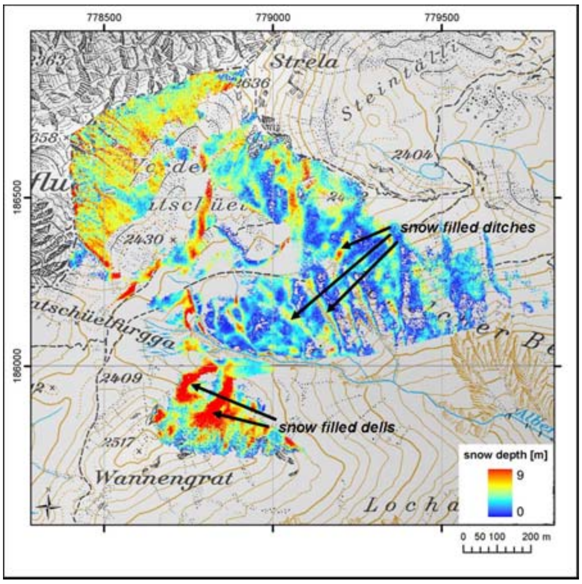

Figure 1. Snow depth map showing the Albertibach catchment at end of the accumulation season (26 April).

The following measurement dates were characterized by decreasing mean snow depth due to melting of snow. σ values decreased from 1.3 m to 0.9 m (Table 1). Together with the snow depth maps (not shown) this showed that the spatial variability was slightly decreasing in time during the ablation phase. An interesting observation is that the basic distribution pattern of snow remains unchanged during the ablation period (maps not shown).

Snow depth				
date	*26 Apr*	*13 Mai*	*2 Jun*	*10 Jun*
μ [m]	2.0	1.5	1.2	1.1
σ [m]	1.3	1.1	1.0	0.9
CV	0.6	0.7	0.8	0.8

Table 1: Snow depth statistics: mean (μ), standard deviation (σ) and coefficient of correlation (CV)

Daily melt rates showed high spatial variability and characteristic spatial patterns with melt rates being highest in the south facing slopes of the Vordere Latschüel and lowest in the north face of Wannengrat (map not shown). At the first part of the ablation period, mean melt rates were only slightly increasing from 15 mm/d to 16 mm/d but a dramatic increase to 30 mm/d occured towards the end of the ablation season (Table 2). These high melt rates might be explained with the higher total amounts of energy available for melting later in the ablation season and by lateral advection of energy from snow-free patches. Like for snow depth, the spatial pattern of melt rates remained similar for the whole ablation period. By contrast, increasing σ values suggest that the spatial variability of the melt rates strongly increased at the end of the ablation season (Table 2). The lateral transport of energy may also explain the increasing heterogeneity (Essery and Pomeroy, 2004): The later in season, the more snow free patches are present. These snow free patches increase melt rates in their surroundings. Big differences in melting between small and larger snow patches might therefore occur. Comparison of the coefficient of variations (μ/σ) of snow depth and melt rates showed that spatial variability of the melt rate was still much lower than that of snow depth and SWE.

The spatial patterns in melt rates could not be explained by simple linear regression models. Correlations between melt rates and aspect, elevation, slope, incoming solar radiation and wind speed were weak. The best result with an r^2 of 0.19 for the first rate and decreasing to near zero for the last rate was obtained for elevation. Non-linear and non-local models as well as interactions between the factors have not been investigated.

Melt rate			
period	*26 Apr - 13 Mai*	*13 Mai – 2 Jun*	*2 Jun – 10 Jun*
μ [mm/d]	15.4	15.7	30.0
σ [mm/d]	6.9	6.5	12.0
CV	0.4	0.4	0.4

Table 2: Melt rate statistics: mean (μ), standard deviation (σ) and coefficient of correlation (CV)

4 CONCLUSIONS

We found that snow depth and melt rates were characterised by a high spatial variability. The variability of snow depth was higher and decreased in time. Melt rates were strongly increasing towards the end of the ablation period and their spatial variability was increasing as well. This spatial heterogeneity could not be explained by simple regression analysis.

The measurements are now used to validate models of spatial snow distribution with a particular focus on the spatial variability of turbulent and radiative fluxes. In addition, the question of a representative snow depth or SWE measurement will be addressed with the aim to give recommendations on estimating total available snow in mountain catchments at different phases of the ablation period. Measurments of peak accumulation 2007/2008 and the accumulation season 2008/09 are currently used for modelling wind drift (see Mott et al. this issue).

With additional measurements in the accumulation period to be performed in the coming winters, we expect to gain an improved understanding of the time-space dynamics of the mountain snow cover.

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6 REFERENCES

Armstrong, R.L. and Brown, R., 2008. Introduction, In Armstrong, R. L. and Brun, E. (Editors.): Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling. Cambridge, pp. 1–11.

Balk, B. and Elder, K., 2000. Combining binary decision tree and geostatistical methods to estimate snow distribution in a mountain watershed. Water Resources Research, 36, pp. 13–26.

Chang, K.T. and Li, Z., 2000. Modelling snow accumulation with a geographic information system. Int. J. Geographical Information Science, 14(7), pp. 693–707.

Deems, J.S., Fassnacht, S.R. & Elder, K.J., 2006. Fractal distribution of snow depth from Lidar data. Journal of Hydrometeorology 7(2), pp. 285–297.

Elder, K., Rosenthal, W. and Davis, R.E., 1998. Estimating the spatial distribution of snow water equivalence in a montane watershed. Hydrological Processes, 12, 1793–1808.

Erickson, T.A., Williams, M.W. and Winstral, A., 2005. Persistence of topographic controls on the spatial distribution of snow in rugged mountain terrain, Colorado, United States. Water Resources Research, 41, W10409, oi:10.1029/2004WR003761.

Essery, R. and Pomeroy, J., 2004. Implications of spatial distributions of snow mass and melt rate for snow-cover depletion: theoretical considerations. Annals of Glaciology, 38, pp. 261-265.

Jones, H.G., Pomeroy, J.W., Walker, D.A. and Hoham, R.W., 2001. Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems: Cambridge University Press. 378 pp.

Keller, F., Kinast, F. and Beniston, M., 2000. Evidence of the response of vegetation to environmental change at high elevation sites in the Swiss Alps. Regional Env. Change, 1(2), pp. 70–77.

Lehning, M., Löwe, H., Ryser, M. and Radschall, N., 2008. Inhomogeneous precipitation distribution and snow transport in steep terrain. Water Resources Research, 44, pp. 1–19.

López-Moreno, J.I. and Nogués-Bravo, D., 2006. Interpolating local snow depth data: an evaluation of methods. Hydrological Processes, 20, pp. 2217–2232.

Luce C.H., Tarboton D.G. and Cooley K.R., 1999. Sub-grid parametrization of snow distribution for an energy and mass balance snow cover model. Hydrological Processes, 13(12-13), pp. 1921–1933.

Marchland, W.D. and Killingtveit, A,. 2004. Statistical properties of spatial snowcover in mountainous catchment in Norway. Nordic Hydrology, 35(2), pp. 101–117.

Mott, R., Faure, F., Lehning, M., Löwe, H., Hynek, B., Michlmayr, G., Prokop, A. and Schöner, W., 2008. Simulation of seasonal snow-cover distribution for glacierized sites on Sonnblick, Austria, with the Alpine3D model. Annals of Glaciology, 49(1), pp. 155-160

Mott, R., Schirmer, M. and Lehning, M., 2009. Understanding snow transport processes shaping the mountain snow cover. same issue.

Prokop, A., Schirmer, M., Rub, M., Lehning, M. and Stocker, M., 2008. A comparison of measurement methods: terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes. Annals of Glaciology, 49(1), pp. 210-216.

Raderschall, N., Lehning, M. and Schär, M., 2008. Fine-scale modeling of the boundary layer with wind field over steep topography. Water Resources Research, 44, pp. 1–18.

Riegl Laser Measurement Systems GmbH, 2008. Long-Range Laser Profile Measuring Sytem LPM-321: Technical Documentation & User's Instructions.

Schaffhauser, A., Fromm, R., Jörg, P., Luzi, G., Noferini, L. and Sailer, R., 2008. Remote sensing based retrieval of snow cover properties. Cold Regions Science and Technology , 54, pp. 164-175.

Xue, M., Droegemeier, K.K. and Wong, V., 2000. The advanced regional prediction system (ARPS) -a multi-scale nonhydrostatic atmospheric simulation model. Part I: Model dynamics and verification. Meteorology and Atmospheric Physics, 75, pp. 161–193.