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Snow cover characteristics in a glacierized catchment in the Tyrolean Alps - Improved spatially distributed modelling by usage of Lidar data

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SUMMARY

In the present paper multi-temporal Lidar (Light detection and ranging) data and Landsat images are used to assess the spatial variability of snow at the end of the accumulation season (April–May) in a glacierized catchment (167 km^2) in Tyrol, Austria. Snow cover characteristics in the Tyrolean Alps have been analysed using regular snow measurements and snow course data. Results are used for the conversion of basin-wide Lidar snow depth into snow water equivalent (SWE). When considering different possible error sources, uncertainties of the mean basin-wide SWE obtained from Lidar are between 12% and 16%. Available distributions of SWE and snow covered area (SCA) in the catchment are used for the calibration and validation of the fully distributed hydrological model SES. The study focuses especially on the simulation of snow accumulation and the corresponding variability of snow. Observed accumulation patterns are related to the topography (elevation, slope and curvature), and according parameter settings of the hydrological model are derived by means of Monte Carlo simulations. The majority of the model runs simulates SCA for various datasets with an accuracy of 85–95%. The paper demonstrates that using SWE data is superior to SCA for constraining model parameter ranges. Results at the watershed scale are in agreement with respect to the total water volume of the snow cover with deviations lower than 5% between SWE from Lidar or from the hydrological model.

1. Introduction

Reliable information about the amount of water stored in a catchment́s snow cover is of high interest for many aspects of hydrology and water resources management, e.g. operation of reservoirs or flood forecasting. For instance, a melting snow cover can increase a storm hydrograph, e.g. Weingartner et al. (2003). In contrast, a deep snow pack can also support flood retention (Schöber et al., 2012). Especially the analysis of peak snow accumulation and the subsequent melt season has received a lot of attention in the literature (Deems et al., 2006; Elder et al., 1998; Grünewald et al., 2010; Marchand and Killingtveit, 2005; Trujillo et al., 2009; Winstral et al., 2002). The spatial distribution of snow at the end of the accumulation season was found to be influential for snow melt dynamics (Egli et al., 2012). Furthermore, glaciologists estimate the distribution of snow at the end of the accumulation season for the calculation of the winter mass balance of glaciers (Dadic et al., 2010; Escher-Vetter et al., 2009; Plattner et al., 2006; Sold et al., 2013). Worldwide, snow depth measurements outnumber snow water equivalent (SWE) observations since measuring SWE in the field is laborious (Sturm et al., 2010). However, most hydrological applications characterise the snow cover by its SWE, but information on the spatial distribution of this parameter in a catchment is generally still rare, even in well studied regions (Jonas et al., 2009), restricted to safely accessible locations, and hence measurements have to be interpolated even in small experimental catchments (Anderton et al., 2004; Luce et al., 1998).

Deriving the spatial distribution of the snow cover based on optical remote sensing techniques is a commonly applied technique in hydrological sciences in the last 20 years. Blöschl et al. (1991) rectified oblique aerial photos of a small catchment and

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manually identified the snow cover boundaries which were used for the parameterisation of a spatially distributed model. In contrast, the use of optical satellite data allows automatic mapping of the snow cover by means of combining the different spectral bands detected by the sensors (Dozier, 1989; Hall et al., 1995). Still, the spatial resolution of the remotely sensed data may not represent the scale of natural processes, especially in rugged, alpine terrain (Blöschl, 1999). In that context, Lidar (Light detection and ranging) is a promising technique since 1 m point spacings (airborne) to sub-meter point spacings (ground-based systems) are typical (Deems et al., 2013). With Lidar, snow depth observations can be made when utilising a digital terrain model obtained prior to the start of the snow season which later have to be subtracted from a second terrain model obtained after the snow has accumulated (Hopkinson et al., 2001). The resulting difference layers (Δz) are interpreted as snow depth but may also include other processes that lead to surface elevation changes (soil erosion, glacier dynamics, melt and sublimation). Still, the available Lidar datasets are especially suitable to analyse the variability of snow depth (SD) in topographically inhomogeneous areas. According to Clark et al. (2011), spatial variability of snow depends on the spatial scale of the data. Based on data from Lidar surveys, Deems et al. (2006) and Trujillo et al. (2007) showed that the variability of SD does not increase at spatial scales larger than 50 m. In these study areas the variability of SD and the scale break distance (i.e. the distance where variability does not further increase) was governed by vegetation and/or wind. In a small Swiss alpine catchment scale breaks of approximately 20 m were observed (Schirmer and Lehning, 2011). Scale breaks give guidance regarding the resolution of a model but for studies which aim to explicitly describe wind–snow interactions a resolution of 5 m is still insufficient (Mott et al., 2011). However, in the studies of Melvold and Skaugen (2013) and Schirmer and Lehning (2011), high inter-annual consistencies of snow depth derived from Lidar were found in different investigation areas and at different spatial scales.

At the watershed scale, the variability of SD and SWE is mainly shaped by processes associated to the elevation gradients whereas on the hillslope scale gravitational redistribution and drifting form the variability of snow (Clark et al., 2011). Elevation gradients of temperature and different amounts of consumed radiation due to variable exposition control the amount of melt. Snow and ice evaporation rates on the Tyrolean glaciers Hintereisferner (Kaser, 1983) and Vernagtferner (Escher-Vetter et al., 2005) are in the order of 150 ± 50 mm per year. In alpine catchments, the highest sublimation rates occur in the crest region due to the exposed snow cover to the generally higher wind speeds (Bernhardt et al., 2012; Strasser et al., 2008). The variability of the snow accumulations in glacierized catchments is especially related to the increasing precipitation with increasing altitude (Hoinkes and Steinacker, 1975; Magnusson et al., 2011) as well as to redistribution of snow by wind and avalanches (Dadic et al., 2010; Kuhn, 2003). Based on snow transects obtained by airborne ground penetrating radar (GPR), Machguth et al. (2006) observed a correlation between SD and altitude on the lower part of a glacier which was attributed to differences in available melt energy whereas wind caused large variability in the upper parts of the glacier. Recently, physically-based model experiments of the wind–snow interactions have shown that besides erosion and deposition processes especially preferential deposition in lee slopes during snow fall (i.e. in the absence of erosion and deposition) form the variability of snow in the ridge zone of a small experimental catchment (Lehning et al., 2008) or an entire glacierized catchment (Dadic et al., 2010). The latter work shows that the correlations between modelled wind fields and snow accumulation are a key feature for the understanding of glacier mass balances. These findings further prove the applicability of terrain based indices of wind shelter and exposure which characterise local changes of wind speed and the according relation to snow accumulation (e.g. Winstral et al., 2002). This approach was used in small experimental alpine catchments to generate distributed time series of snow accumulation rates using representative wind measurements (Schirmer et al., 2011; Winstral and Marks, 2002). Variability associated to gravitational deposition (sloughing of snow off steep slopes, avalanches) and redistribution due to wind was parameterised by the correlation of snow accumulation and terrain parameters such as slope and curvature (Bernhardt and Schulz, 2010; Blöschl et al., 1991; Farinotti et al., 2010; Warscher et al., 2013). Since snow distribution patterns associated to topographic controls undergo only small changes over time (Blöschl and Kirnbauer, 1992), these approaches are well-suited for long-term water balance studies and even for operational flood forecasting of large alpine catchments.

In a highly glacierized sub-catchment of the Ötztal Alps in the Austrian province of Tyrol, airborne laser scanning (ALS) surveys have been carried out since the hydrological year 2001/2002. These data have been used to monitor glacier surface elevation changes (Bollmann et al., 2011; Geist and Stötter, 2007). The aim of this paper is to assess the potential of the winter laser scans (obtained at the end of the accumulation season in April or May) in terms of estimating SWE at the watershed scale and for the calibration of a distributed snow-hydrological catchment model. Therefore, two approaches are developed to model the spatial distribution of SWE in the Vent catchment (166.8 km^2). First, a statistical snow bulk density model (Schöber, 2014) is used to convert the Lidar snow depth data into SWE and second, the spatially distributed hydrological model SES (Asztalos et al., 2007; Schöber et al., 2010) is used to simulate the distribution of SWE deterministically. To our knowledge, Lidar snow data was only used in the study of Melvold and Skaugen (2013) for the validation of a snow-hydrological model of a large catchment. In that work Lidar data of a 240 km^2 study region in Norway was used for comparison with modelled snow depth with a spatial resolution of 1 km. In the present study, the Lidar snow data is used – besides additional optical satellite data – for the calibration and validation of the SES model with a grid resolution of 50 m.

Parameters of the snow-hydrological model are varied within the frame of uniformly distributed Monte Carlo simulations (Bellinger et al., 2012; Finger et al., 2011). For the detection of suitable parameter settings, a multi-objective optimisation procedure (Gupta et al., 1998; Parajka et al., 2007) is applied which is based on skill scores accounting for snow covered area (SCA) or SWE derived from Lidar with special regard to the variability of SWE at the watershed scale. In the following sections characteristics of the glacierized study area, the used snow data and models are introduced. Analysis of the snow data gives guidance for the parameterisation of lateral snow redistribution. The model calibration is described and final results with respect to SWE at the watershed scale are discussed. Model uncertainties and possible measurement uncertainties of ALS snow data in a glacierized catchment (Helfricht et al., 2014; Sold et al., 2013) are discussed.

2. Snow data of the study area in the Ötztal

2.1. Airborne laser scanning data

Between October 2001 and May 2009 seventeen ALS surveys have been carried out in a highly glacierized headwater catchment of the Ötztal Alps in Tyrol. In this period, at least one flight campaign per year (at the end of the ablation season in autumn) was made. The two main glaciers which are located in this area are the Hintereisferner and the Kesselwandferner (see Fig. 1). Direct glacier mass balance measurements have been made for the