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Research papers

Influence of topography and forest characteristics on snow distributions in a forested catchment

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ABSTRACT

Stored water within snowpack is important for the hydrological balance in many mountainous environments around the world. However, monitoring the spatial and temporal dynamics of snow in such mountainous environments remains rather challenging. We therefore developed a snow depth meter using small temperature loggers. Small temperature loggers were attached to poles at 20 cm intervals from the ground surface. Snow depths were estimated by assessing the daily variations in temperatures. Using this snow depth meter, we continuously observed snow depths at 21 stations in a forested catchment in Japan over three winter seasons. Using correlation analysis, we then analyzed the influence of topography (i.e., elevation and aspect) and forest (i.e., canopy openness) on snow depths. Moreover, we estimated daily snow distributions in the area using multi-regression analysis, thus describing seasonal characteristics of snow distributions. Finally we investigated the relation between number of stations and estimation accuracies of snow distributions using a Monte Carlo sensitivity analysis. We observed that the influence of topographical and forest characteristics changed considerably during the study period, with elevation having a major impact on snow depths. Further, aspect and forest cover had a great influence on the snow depths during the melting period. The regression of elevation slopes was 0.8–2.1 mm/m during rich snow years and 0.5–0.6 mm/m in little snow years. Also, the snow distribution during the melting period was found to be less uniform than during the snow accumulation period using histograms of snow depths. Monte Carlo sensitivity analysis shows that one station per 2.0–2.5 ha is enough to estimate accurate snow distributions. Given the above, we concluded that our proposed approach was quite useful for investigating the influence of topography and forest characteristics on snow accumulation and melting.

1. Introduction

Water contained within snowpack is a crucial element in the hydrological balance in many mountainous environments around the world (Viviroli et al., 2007) and plays a key role in many hydrologic and ecologic processes (Pohl et al., 2014). Therefore, it is extremely important to acquire a better understanding of the total amount of snow stored in a region and grasp how the distribution of snow changes both spatially and temporally (Grünewald et al., 2010). To measure snow depths in open and wide terrain areas, many researchers have successfully applied airborne laser scanning (ALS) techniques in recent years (e.g., Lehning et al., 2011; Schirmer et al., 2011; Deems et al., 2013; Grunewald et al., 2010, 2013; Varhola et al., 2013); however, ALS has drawbacks in that it usually involves high costs and flight schedules are negatively impacted by weather conditions. Therefore, it is often difficult to obtain a comprehensive understanding of the continuous changes of snow amount and snow depth distributions in these areas.

Snow accumulation and melting in forested catchments have been investigated primarily using two approaches: (1) time series observations and modelling with a detailed weather station, measuring air temperature, humidity, precipitation, radiation, wind speed, and so on at several points (e.g., Hedstrom and Pomeroy, 1998; Storck et al., 2002; Suzuki and Ohta, 2003; Whitaker and Sugiyama, 2005; Suzuki and Nakai, 2008; Andreadis et al., 2009); and (2) manual snow surveys at numerous points or transects (e.g., Jost et al., 2007; López-Moreno and Stähli, 2008; Musselman et al., 2008; Veatch et al., 2009; Anderson et al., 2014). As an example, Storck et al. (2002) measured snow interception in a mountainous maritime climate, reporting that approximately 60% of the snowfall was intercepted by the canopy. As

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another example, Suzuki and Nakai (2008) reported that approximately 26% of accumulated snowfall was intercepted by the canopy; however, mountain snowpack is highly heterogeneous even in the same study area (Anderson et al., 2014), thus it is difficult to extrapolate from these results to estimate total snow amounts in forested catchments.

Research studies that use manual snow surveys at numerous points can capture the heterogeneity of snow distribution in contrast to an approach involving time series observations at several points. As an example, Jost et al. (2007) set up a number of strata and investigated the spatial variability of snow water equivalent (SWE), concluding that elevation had the greatest influence on SWE, with a steeper gradient in snow rich year; however, manual snow surveys involve substantial effort and manpower, making it impossible to conduct continuous observations over long winter periods. Therefore, we need a new approach for monitoring the spatial and temporal dynamics of snow depths in mountainous environments.

In this context, Pohl et al. (2014) and Garvelmann et al. (2015) developed a low-cost standalone snow monitoring station called a SnoMoS and analyzed the impact of several topographic and forest characteristics on snow accumulation and melting throughout an entire winter period. Except for these works performed by Pohl et al. (2014) and Garvelmann et al. (2015), continuous monitoring at numerous stations in a forested area, to the best of our knowledge, has yet to be reported. Therefore, the above approaches have not been fully validated as of yet. Moreover, in Garvelmann et al. (2015), they only focus on a specific month to investigate rain-on-snow (ROS) events, although snow distributions change over a winter period. Fortunately, interpolation methods for estimating snow distributions have already been investigated by numerous researchers (e.g., Elder et al., 1998; Erxleben et al., 2002; Molotch et al., 2005; Erickson et al., 2005; López-Moreno et al., 2007 and so on). Therefore, the combination of continuous monitoring at numerous stations and an established interpolation method is the new approach that we adopted for our present study.

The objectives of this study are (1) to continuously observe snow depths at numerous stations in a forested catchment using low-cost robust sensors and to investigate the influence of topography and forest characteristics on snow accumulation and melting; (2) to estimate daily snow distributions in the area using an interpolation method based on multi-regression analysis and to reveal seasonal characteristics of snow distributions; and (3) to investigate the relation between number of stations and estimation accuracies and to show how intense the stations are enough for precise estimations of snow distributions.

2. Study site and instrument

2.1. Study site

Our research was conducted in the Forestry Experiment Station of Ishikawa Agriculture and Forestry Center (36°25′N, 136°38′E), which is located at the top of the alluvial fan area of the Tedori River that drains into the middle of the Japan Sea (Maruyama et al., 2015). Snowfall usually begins in late December and ends in the middle of March. The maximum depth of the snowpack for the period that we investigated ranged from 71 cm to 136 cm at the weather station, which was located in the lower elevation of the study area. Average air temperature ranged from 2.8 °C to 4.4 °C during the snow accumulation and melting season (i.e., December to March).

We established a study plot that covered an 800 × 400 m area, of which elevation ranged from 230 m to 530 m, thus indicating an elevation difference of 300 m. A planted cedar forest dominated the elevations between 230 m and 480 m, while a planted larch forest dominated the elevations between 480 m and 500 m, and a natural broad-leaved forest occupied the elevations between 500 m and 530 m. As summarized in Table 1, within this area, 21 snow observation stations were set up to investigate the influence of topography and forest characteristics on snow accumulation and melting, and also to estimate the snow distributions in the area. Study periods were comprised the following three winter seasons: December 2013 to March 2014; December 2014 to March 2015; and December 2015 to March 2016.

2.2. Snow depth meter using low-cost small temperature loggers

We used self-recording temperature loggers (Maxim iButtons) for our snow depth observations. These small loggers have been well investigated for snow observations (e.g., Lundquist and Lott, 2008; Reusser and Zehe, 2011; Dickerson-Lange et al., 2015, Fujihara et al., 2015) and have proven to be robust and low in cost. In this study, each temperature logger was wrapped in a plastic bag and attached to vertical poles at 20 cm intervals from the ground surface, i.e., at 0 cm, 20 cm, 40 cm, up to 200 cm. As such, we had a total of 11 loggers for each pole. Given the memory size of the loggers, temperatures were recorded at two-hour intervals, thus 12 temperature data were obtained in a given day.

To assess whether the loggers were exposed to air or covered by snow, the standard deviations of these 12 data were calculated for each day. The temperature logger was considered to be covered by snow when the daily standard deviations were less than a specified threshold. This threshold could not be determined physically, thus we preliminarily investigated five values (i.e., 0.1, 0.3, 0.5, 0.7, and 0.9 °C) in terms of estimation accuracy, and the threshold was set to 0.3 °C (Fujihara et. al., 2015).

Snow depths were estimated based on the above assessment method. When loggers from height H(1) to H(i) were covered by snow and loggers from height H(i + 1) and above were not covered by snow, height H(i + 1) was used as the snow depth estimate, thus the snow depth meter is a sensor with a resolution of 20 cm. By applying this meter at each station, daily snow depths for each station were estimated.

We compared the snow depths estimated by the temperature loggers with observed snow depths obtained by the sonic ranging sensor (Campbell SR50A) to validate the accuracy of our low-cost sensors. The sonic ranging sensor was installed at the weather station. Snow depth was measured at 1 h interval and the daily average value is compared with the estimation by the temperature loggers. Fig. 2 shows a time series comparison of the observed and estimated snow depths. As noted above, we set each temperature logger at 20 cm intervals, thus the output of the low-cost sensors consisted of discrete values; however, as illustrated in Fig. 2, there is no systematic error and the estimates agree with the observations; further, performance was quite good. Correlation coefficients (r) between our estimates and the observations were 0.93 for 2013–2014, 0.94 for 2014–2015, and 0.82 for 2015–2016.

3. Methods

3.1. Topography and forest characteristics on snow accumulation and melting

To investigate the influence of different topographic and forest characteristics on snow accumulation and melting, as well as the spatial distribution of snow depth within the study site, we selected elevation and aspect as our topographic properties. Although slope was indeed considered as a potential predictor,