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Estimation of snow depth and snow water equivalent distribution using airborne microwave radiometry in the Binggou Watershed, the upper reaches of the Heihe River basin

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ABSTRACT

We estimated the spatial distribution of snow depth/snow water equivalent (SD/SWE) in a mountainous watershed (Binggou, which is in the upper reaches of the Heihe River basin) by an airborne microwave radiometry observational experiment. Two microwave radiometers measuring at K band (18.7 GHz) and Ka band (36 GHz) were used to estimate the volume scatter from snowpacks and infer SD and SWE. Simultaneously, the snow physical properties (such as snow depth, density, grain size and temperature) over four sites were measured, and a simple multi-layer sample scheme was adopted to obtain the stratigraphic information. The microwave emission model of layered snowpacks (MEMLS) was used to simulate the brightness temperatures of snow cover for each measurement point. By comparing TB data that were simulated by MEMLS and observed by radiometers on the aircraft over the four sites, we obtained the retrieval algorithms of SD and SWE based on brightness temperature differences (TBD) at the K- and Ka-bands that are suitable to the local snow properties. The validation shows that the mean absolute and relative errors of SD estimates are approximately 3.5 cm and 14.8%, respectively. SWE from airborne microwave radiometers show that blowing snow and sun radiation are two main factors that determine the spatial distribution of SWE in Binggou Watershed.

The local angle of incidence of the microwave radiometer observation can be influenced by mountainous topography, and a sensitivity analysis suggests that changes in the local angle of incidence (e.g., the nominal angle of incidence) will not significantly influence the estimation of SD/SWE. The snow's stratigraphic condition is not an important factor for estimating SD/SWE in this study because the snow was not very deep in the Binggou Watershed. However, the field sampling scheme should be given more attention to obtain the spatial variations of snow properties and to support pixel-by-pixel validation in next field campaign.

1. Introduction

Snow cover plays an important role in the water and energy cycles at both a global and a regional scale. An accurate estimation of the snow water equivalent (SWE) can improve the understanding of the climate, land surface processes and, in particular, the cold regional hydrological model.

Spaceborne passive microwave (PM) radiometers have provided an opportunity to estimate SWE at both a regional and global scale (Chang et al., 1987; Foster et al., 1997; Che et al., 2003; Kelly et al., 2003). The core of these SWE algorithms is generally the brightness temperature differences (TBD) on two frequencies (generally using K- and Ka-bands), which are based on the volume scattering variations of snowpacks between different wavelengths, and the rule that a larger snow mass results in a larger volume scattering.

However, the spatial resolution from PM satellites is too coarse to introduce or assimilate the SWE into the hydrological process model at the basin scale (Li and Cheng, 2008). The observational data for snow in mountainous stations cannot represent the snow conditions within the PM footprint due to the spatial heterogeneity of the snow distribution. For example, snow data located in mountainous terrain have been removed for the development of the global AMSR-E SWE algorithm (Kelly et al., 2003). The relationship between TBD and *in situ* SWE in high elevation regions (>2000 m) is quite different from the low elevation regions (Che et al., 2003). It

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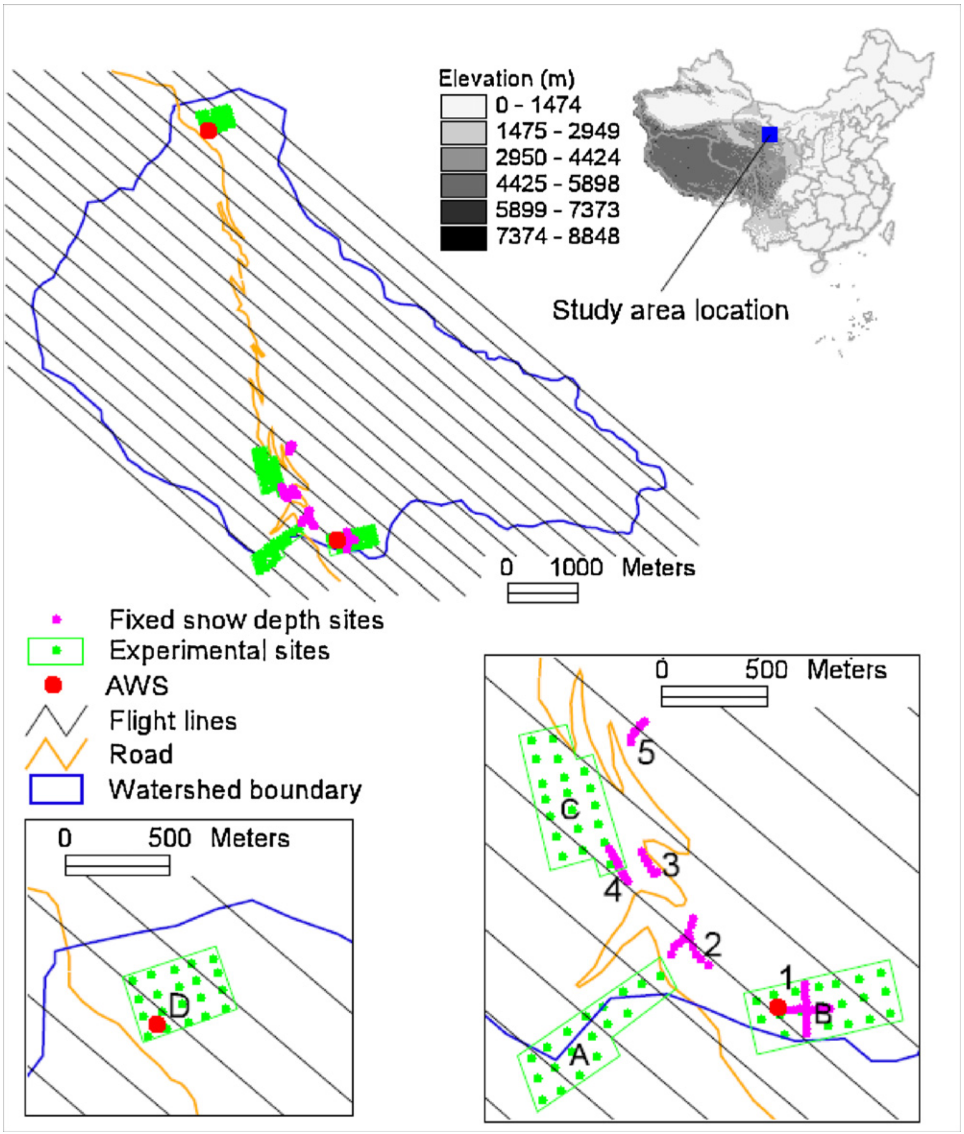

Fig. 1. Location of the experimental area and layout of measurements based on airborne and ground data. Fixed snow depth sites: there are 51 snow-stakes (marked with pink points) which can be divided into five groups based on their topographic features (group 1: flat, group 2: northern slope, group 3: northeastern slope, group 4: northwestern slope, and group 5: southern slope). Experimental sites: there are four sites with 78 sampling points (marked with green points) which numbered with A, B, C and D, where sites A, B, and C are located at high elevation regions and site D is closed to the outlet. AWS: the two Automatic Weather Stations (AWS, marked with red points) are closed to ridge (4101 m) and outlet (3407 m), respectively.

is not surprising to find large errors in the global SWE product algorithm in mountainous regions (Andreadis and Lettenmaier, 2006). Therefore, the estimation of SWE in mountain regions requires further improvements because of (1) the coarse spatial resolution of PM on the satellite and (2) the complexity of the topography. Airborne microwave systems can provide data at higher resolutions, and thus, they were considered as a bridge between the ground and spaceborne observations.

Two airborne passive microwave remote sensing experiments were implemented on the BOREAS campaign to estimate the SWE in February of 1994 and 2003, respectively (Chang et al., 1997; Parde et al., 2007). The results from the experiment in 1994 revealed that the boreal forest was one of the most important factors in estimating SWE (Chang et al., 1997), and thus, a forest modification algorithm was proposed (Foster et al., 1997). Spatial consistency between ground snow measurements and airborne pixel locations was difficult, so the mean measurement on each airborne segment was used to validate the results (Parde et al., 2007). The SWE retrieval algorithm was based on a snow emission model (HUT) that was initialized using standard meteorological measurements (snow depth and air temperature), and this algorithm can estimate the SWE and snow grain size simultaneously.

The Cold Land Processes Experiment (CLPX) in 2003 and 2004 used the airborne polarimetric scanning radiometer to obtain multi-frequency brightness temperature data of different snow conditions (dry, wet, and refrozen). A series of empirical SWE retrieval algorithms, which were similar to the Chang algorithm but with more frequencies and polarizations, were analyzed according to the relationships between emissivity and snow properties (Stankov et al., 2008). Their results also suggested that a new algorithm should be developed to account for local conditions, such as snow properties and land cover.

Recently, two experiments between Canada and Finland were carried out to compare airborne microwave brightness temperature and snow properties in these two regions in 2005 and 2006, respectively (Lemmetyinen et al., 2009). The comparison showed that larger snow grain sizes lead to a lower brightness temperature, which indicates that grain size is an important factor in the volume