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Effect of spatial variability of wet snow on modeled and observed microwave emissions

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ABSTRACT

Melting snow provides an essential source of water in many regions of the world and can also contribute to devastating, wide-scale flooding. Global datasets of recorded passive microwave emissions provide non-destructive, daily information on snow processes including the presence of liquid water in the snow, which can be an indicator of snowmelt. The objective of this research is to test the sensitivity of the emission signal as it relates to the spatial distribution of liquid water content in the snowpack. This signal response was evaluated over an area approximately the size of a microwave pixel to assess whether a relationship exists between the aerial extent of wet snow and the magnitude of the T_B response. A sensitivity analysis was performed using a high-resolution, physically based snow-emission model to simulate microwave emissions. The signal response to wet snow was evaluated given a range of spatially distributed snowpack conditions. Daily snow states were simulated for a 9-year period using a high-resolution (50 m) energy balance snow model over a 34 × 34 km domain. These data were fed into a microwave emission model to simulate brightness temperatures. A near-linear relationship was found between the T_B signal response over a spatially heterogeneous snowpack and the percent area with liquid water content (LWC) present. The results were confirmed by evaluating actual wet snow events over a 9-year period. The model output was also compared to AMSR-E passive microwave satellite data and discharge data at a basin outlet within the study area. The results are used to help understand the impact of spatially distributed snowmelt as detected by passive microwave data.

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1. Introduction

In snow-dominated basins, efficient water resource management requires accurate, timely estimates of both snow water equivalent (SWE) and snow melt onset. Melting snow provides a reliable water supply and can also produce wide-scale flooding, particularly when combined with rainfall. For hydrological purposes, an accurate estimate of the melt distribution is essential for correctly predicting the runoff response (Lundquist and Dettinger, 2005), and will also provide insight into important ecological and biogeochemical processes (Bales et al., 2006). However, snow characteristics can be highly variable across a landscape, and techniques for accurately characterizing the spatial distribution of snow properties remains elusive (Elder et al., 1998; Dozier et al., 2016).

The presence of liquid water in an existing snowpack, which can be an indicator of snowmelt, is particularly difficult to measure or detect over large areas (Kang et al., 2014). Increasingly over the past 30 years, satellite remote sensing techniques have been investigated for mapping wet snow (Tedesco, 2015). Optical and infrared imagery have been used to estimate snow melt based on albedo and surface temperature observations (Green et al., 2002). These data have the benefit of high spatial and temporal resolution, but are unable to observe the snow cover through cloud cover or at night. Microwave measurements are highly sensitive to the snowpack electromagnetic properties as the snow transitions from dry to wet (Mätzler et al., 1980). These data are minimally impacted by atmospheric conditions and do not require daylight to make observations. Synthetic Aperature Radar (SAR) C-band and X-band instruments have been used to accurately resolve wet snow on a hillslope scale at a high resolution (Nagler and Rott, 2000). However, because of the small swath size, SAR data are currently not suitable for monitoring snow melt over large regions. For basin-scale observations, passive and active microwave sensors have been used to estimate the timing of melt onset and detect wet snow. Active microwave sensors measure a reduced backscatter signal when liquid water is present in snow, caused by a significant change in the imaginary part of the snow effective permittivity. Scatterometer sensors have been used to map areas of active snow melt and the data have been shown to correlate to basin discharge events (Nghiem and Tsai, 2001; Rawlins et al., 2005).

Passive microwave observations are also sensitive to the presence of liquid water in the snow and have the benefit of a long historical record

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(since 1979). Microwave emissions are measured in units of brightness temperature (T_B), which in the microwave spectrum is equal to the thermometric temperature of the emitting material times the emissivity. Satellite measurements of T_B include primarily emissions from the Earth as well as reflected radiation from the sky. Ground emission signals can be affected as they pass through snow, vegetation and the atmosphere. The presence of snow causes signal scattering at certain frequencies. As a result, the measured T_B decreases due to signal extinction through the snowpack. Empirical SWE formulations relate snow depth to the difference between two microwave frequencies: one that scatters as it passes through snow and one that does not, approximately 36 and 18 GHz, respectively (Chang et al., 1982).

Microwave emissions are highly responsive to liquid water content (LWC), the volume of liquid water per unit volume of snow, due to the sensitivity of the radiance to changes in the dielectric constant (Stiles and Ulaby, 1980). The presence of water within a snowpack increases the emissivity resulting in a sharp T_B increase (Davis et al., 1987; Mätzler, 1987; Walker and Goodison, 1993). Passive microwave emissions cannot be used to estimate SWE during wet snow periods because of the reduced signal scattering. However, the signal response provides a clear indication of increased liquid water content, which overwhelms the impact of other snowpack properties on the microwave signal (Wang et al., 2001). T_B increases occur with as little as 1–2% liquid water content in the snowpack (Cagnati et al., 2004; Stiles and Ulaby, 1980; Tedesco et al., 2006). While 1% LWC is not enough to cause runoff, the satellite response to a wide-spread wet snow event likely indicates a significant melting or rain-on-snow event and greater than 1% LWC. Several studies have linked the microwave response at a coarse resolution to basin runoff and shown potential for hydrologic applications (Ramage and Semmens, 2012; Vuyovich and Jacobs, 2011; Yan et al., 2009).

For over three decades, studies have investigated using this response to predict melt onset (Kunzi et al., 1982; Drobot and Anderson, 2001; Ramage et al., 2006), or to identify rain-on-snow (ROS) events (Grenfell and Putkonen, 2008). Two approaches have been developed to detect the timing of snowmelt using microwave signal response to wet snow. The Diurnal Amplitude Variation (DAV) approach identifies the onset of melt using the large differences in T_B between the morning and afternoon overpasses at the 37 GHz frequency (Kopczynski et al., 2008; Ramage et al., 2006; Tedesco et al., 2009). A DAV increase indicates the onset of the daytime melt/night-time refreeze cycle and the beginning of spring snowmelt. The high-DAV period that follows the onset of melt, referred to as the transition period, ends when the snowpack is continuously melting during day and night periods and the brightness temperature difference decreases. Another method uses the gradient and polarization ratios (GR and PR, respectively) to isolate the bulk emissivity of the snowpack and identify significant rain-on-snow events. In the Canadian Arctic, Grenfell and Putkonen (2008) demonstrated that the GR and PR can be used to identify the occurrence as well as the intensity of rain-on-snow events. Using a combination of these two approaches, Semmens et al. (2013) developed an algorithm for detecting early season melt events with AMSR-E passive microwave data, and were able to successfully identify melt events caused by both rain-on-snow and snowmelt alone.

These methods have successfully demonstrated an ability to detect the timing of snowmelt, which has implications for runoff; however, they do not provide information on the volume of runoff. The discharge magnitude during a snowmelt event is a function of the snowpack properties as well as the spatial extent over which snowmelt is occurring. An improved understanding of the satellite retrievals' response to the spatially distributed snowmelt is needed. Kang et al. (2014) and Pan et al. (2014) conducted the foundation work needed to characterize footprint scale emissions. They used the Microwave Emission Model for Layered Snowpacks (MEMLS) and the Helsinki University of Technology (HUT) snow microwave radiative transfer models, respectively, to successfully capture the emission signatures in wet snowpacks and compare the results to point observations. Both studies report a sharp increase in the T_B response immediately after wetting (the signal response used in detecting the onset of melt) despite differences in snowpack characteristics and wetness profiles.

The goal of this study is to understand the T_B response to spatially distributed wet snow within a satellite pixel and to begin to evaluate the relationship between the aggregated T_B response and river discharge. In this study, we investigate the sensitivity of T_B to spatially distributed wet snow using loosely coupled, physically-based snow and emission models. A long-term ecological research area in the northeast U.S. was selected as the study location because of its long record of meteorological, hydrological and snow observations (described in Section 2). The methods used to develop a relationship between the change in T_B and the fractional area affected by wet snow are described in Section 3. These include a sensitivity analysis to assess the impacts of artificially distributed LWC on the emission signal, and evaluation of the simulated and observed T_B during wet snow events over a nine year period. Results of the analysis are provided in Section 4 and include a comparison of the T_B response and increases in observed streamflow during wet snow events. In Section 5 we discuss the implications of these results with potential future directions.

2. Study area and data

The study domain is a 34 km by 34 km area in the White Mountains of New Hampshire, USA which includes the Hubbard Brook Experimental Forest (HBEF), a Long Term Ecological Research (LTER) watershed (Fig. 1). The HBEF watershed has an area of 31.6 km^2, which covers approximately 3% of the total study domain and is representative of the larger area. HBEF has more than 50 years of meteorological and hydrological observations, which have enabled decades of ecologic and hydrologic research. Approximately one-third of the annual precipitation falls as snow, with a mean annual maximum SWE for the period of record at HBEF of approximately 189 mm, and a snow cover that generally persists from mid-December to mid-April (Campbell et al., 2007).

The study domain is a mountainous region, characteristic of the northeastern United States Appalachian Mountains with elevations ranging from 120 to 1470 m. Land cover is Eastern Deciduous Forest, with evergreen forest and tundra at the highest elevations. Agricultural and developed areas are primarily limited to the lowest elevations and along rivers. Elevation data for the domain were developed from 30 m resolution National Elevation Data (NED) (USGS, 2009). Land cover data were obtained from the National Land Cover Database (NLCD) (Homer et al., 2015). Both the elevation and land cover data were clipped and resampled to a 50 m resolution. Stream channels in this region are generally steep with coarse-grained bed material. A shallow soil layer, with underlying bedrock approximately 1–2 m below the surface, means minimal loss to deep groundwater and relatively quick runoff response (Campbell et al., 2011). Discharge records demonstrate a seasonal snowmelt signal with the highest runoff volumes occurring in March–May.

Meteorological and snow course data from 1 October 2002 to 30 September 2011 at the Hubbard Brook LTER (Bailey et al., 2003) and National Weather Service stations were used in this study (Table 1). Daily temperature and precipitation observations were available from approximately 10 locations each year. The Hubbard Brook LTER data provided precipitation measurements over a representative elevation range. Relative humidity, wind speed and direction were available at three of the 10 observation stations. Only two stations lacked complete data coverage for the entire period of interest. Snow water equivalent was measured at five Hubbard Brook snow course locations on a weekly basis. HBEF also maintains an NRCS Soil Climate Analysis Network (SCAN) site; an automated station with a snow pillow to measure SWE, as well as measurements of snow depth, soil moisture and numerous meteorological variables. The station has been collecting hourly data since 2002.