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The influence of snow microstructure on dual-frequency radar measurements in a tundra environment

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ABSTRACT

Recent advancement in the understanding of snow-microwave interactions has helped to isolate the considerable potential for radar-based retrieval of snow water equivalent (SWE). There are however, few datasets available to address spatial uncertainties, such as the influence of snow microstructure, at scales relevant to space-borne application. In this study we introduce measurements from SnowSAR, an airborne, dual-frequency (9.6 and 17.2 GHz) synthetic aperture radar (SAR), to evaluate high resolution (10 m) backscatter within a snow-covered tundra basin. Coincident in situ surveys at two sites characterize a generally thin snowpack (50 cm) interspersed with deeper drift features. Structure of the snowpack is found to be predominantly wind slab (65%) with smaller proportions of depth hoar underlain (35%). Objective estimates of snow microstructure (exponential correlation length; l_{ex}), show the slab layers to be 2.8 times smaller than the basal depth hoar. In situ measurements are used to parametrize the Microwave Emission Model of Layered Snowpacks (MEMLS3&a) and compare against co-located SnowSAR backscatter. The evaluation shows a scaling factor (ϕ) between 1.37 and 1.08, when applied to input of l_{ex}, minimizes MEMLS root mean squared error to < 1.1 dB. Model sensitivity experiments demonstrate contrasting contributions from wind slab and depth hoar components, where wind rounded microstructures are identified as a strong control on observed backscatter. Weak sensitivity of SnowSAR to spatial variations in SWE is explained by the smaller contributing microstructures of the wind slab.

1. Introduction

Across the Northern Hemisphere, snow on the ground plays a critical role in climatological, hydrological and ecological processes, represents an essential freshwater resource, and influences natural hazards. Improved understanding of where, and in what ways, snow mass is changing is an important consideration for advancement of associated studies, including numerical weather prediction and hydrological forecasting, where spatially continuous observations with high temporal availability are desirable (Carrera et al., 2010; Bernier et al., 2011). Sparse in situ measurement networks have made satellite remote sensing an attractive option to satisfy observational requirements for initialization and verification of land surface models within these forecast schemes, and in a more general sense, appear key to monitoring of global snow resources (Takala et al., 2011).

While progress has been made in the retrieval of snow cover extent from missions such as MODIS (e.g. Hall et al., 2010), retrieval of volumetric properties, including snow water equivalent (SWE), remain a challenge. Current space-borne methods rely on passive microwave radiometry, an approach inherently limited in spatial resolution and negatively impacted by spatiotemporal variations in snow microstructure (Kelly et al., 2003; Tedesco and Jeyaratnam, 2016). As a

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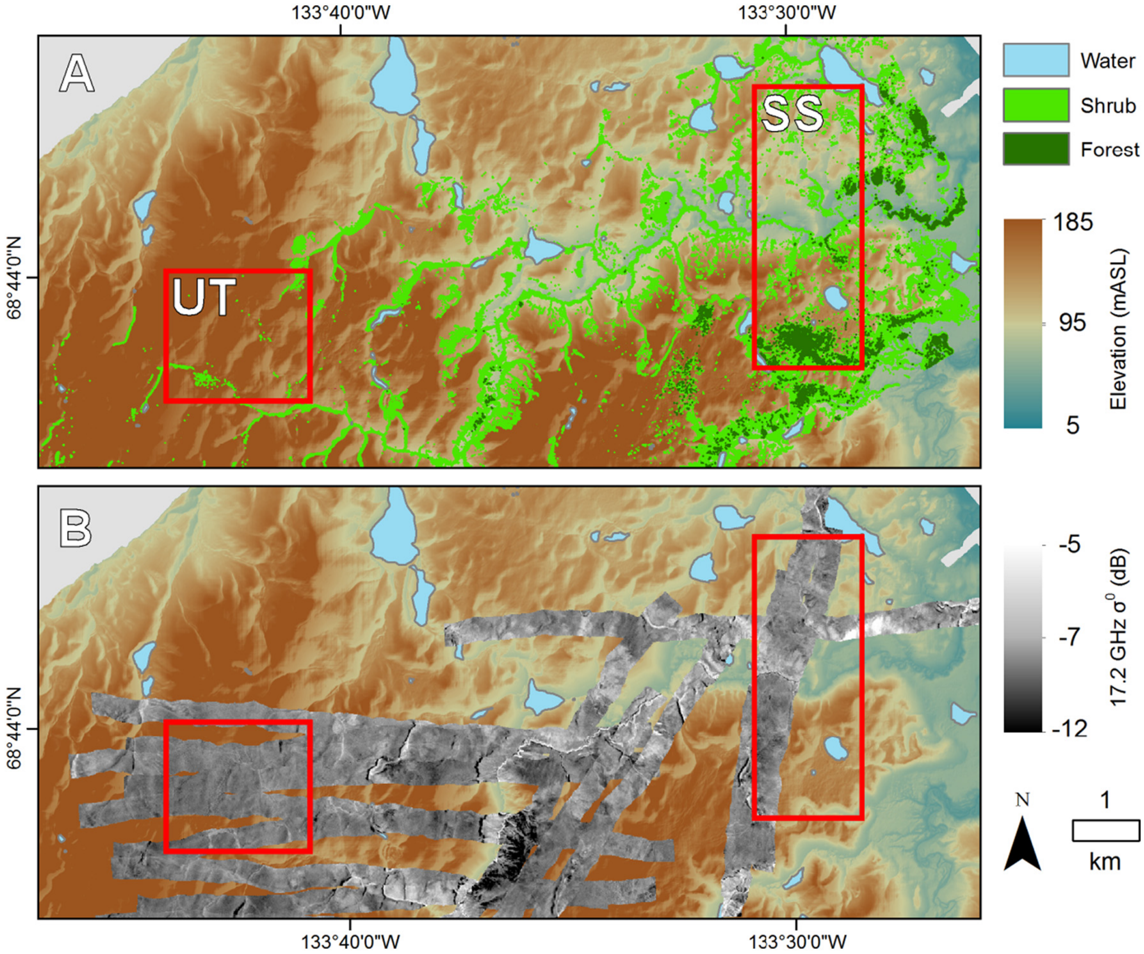

Fig. 1. Overview of the Trail Valley Creek (TVC) research basin with vegetation (A) and SnowSAR 17.2 GHz VV backscatter overlaid (B). Boundaries of the Upland tundra (UT) and SikSik (SS) study sites are outlined in red. The higher elevation UT site was generally free of shrub or forest vegetation while SS contains discontinuous open coverage and a range of vegetated features. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

potential complement to existing methods, radar remote sensing is also sensitive to volumetric changes with the added advantage of higher spatial resolution to address uncertainty at scales relevant to snow physical processes (< 100 m). Recent advancement in radar-based observation of terrestrial snow was motivated in large part by the Cold Regions High Resolution Hydrological Observatory (CoReH20) mission concept. While not selected as the European Space Agency (ESA) Earth Explorer 7, CoReH2O provided the impetus for both technical study on instrument design (Rott et al., 2010), and applied algorithm development (Chang et al., 2014; King et al., 2015; Lin et al., 2016).

Although the theoretical response of radar is well documented (Ulaby and Stiles, 1980), the observed relationship between backscatter and SWE, much like in the passive case, is indirect due to the strong influence of snow microstructure and basal surface interactions. The response of two snowpacks with the same SWE, but differing stratigraphic composition (for example, predominantly rounded grains typical of taiga snow; faceted grains typical of tundra snow), can produce contrasting volumetric interactions, governed in part by the nonlinear relationship amongst observing wavelength, microstructure, and backscatter. The use of traditional grain size (i.e. Fierz et al., 2009) to address this uncertainty has clear limitations, both in the level of confidence that can be placed in the subjective values, and their applicability in microwave modeling (Durand et al., 2008; Löwe and Picard, 2015). Instead, specific surface area (SSA; Domine et al., 2007) and correlation length (Mätzler, 2002) represent metrics that can be robustly estimated in the field (Gallet et al., 2009; Montpetit et al., 2012; Proksch et al., 2015a), and applied in models to study snow-microwave interactions (Roy et al., 2013; Kontu et al., 2017; Sandells et al., 2017).

The use of airborne radar to determine first order sensitivity to SWE across basin domains remains relatively unexplored (see Yueh et al., 2009), with much of the recent focus given to plot-scale experiments (see King et al., 2015; Lemmetyinen et al., 2016; Lin et al., 2016). In this study, we introduce airborne dual-frequency (9.6 and 17.2 GHz) synthetic aperture radar (SAR) acquired with the ESA SnowSAR instrument within the Trail Valley Creek (TVC) research basin. The SnowSAR measurements are used to demonstrate backscatter diversity across a snow-covered tundra environment during a period corresponding closely with peak SWE. Concurrent in situ snow measurements, including objective estimates of microstructure, are used to identify and decompose backscatter contributions. We apply the Microwave Emission Model of Layered Snowpacks adapted to include backscattering (MEMLS3&a; referred to as MEMLS; Proksch et al., 2015b) to simulate perceived influences using field-based parametrizations. Extensive airborne lidar measurements facilitate spatial extrapolation of the snowpack and model analysis. The specific objectives of the study were to:

(1) Introduce co-located snow property and airborne SAR (9.6 and 17.2 GHz) measurements to characterize spatial variability and discuss geophysical attribution.
(2) Parametrize MEMLS using in situ measured snow properties to evaluate forward skill against SnowSAR backscatter and optimize