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Quantifying the relationships between lake fraction, snow water equivalent and snow depth, and microwave brightness temperatures in an arctic tundra landscape

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ABSTRACT

This study investigates the effects of sub-grid lake variability on brightness temperature measurements and snow mass retrieval from passive microwave satellite data in the North Slope of Alaska. In situ snow measurements of water equivalent, depth and density collected from field surveys during 1996–2004 snow seasons were collocated with gridded SSM/I brightness temperatures. Sub-grid lake fraction was computed from a high-resolution land cover map derived from LANDSAT imagery. Another dataset was created consisting of multi-year time series of SSM/I and AMSR-E brightness temperatures and computed lake fraction. Consistent with other studies, it was found that lake fraction was negatively correlated with in situ snow depth and snow water equivalent and positively correlated with snow density, which indicates that lakes have a direct effect on snow cover distribution: They accumulate less but denser snow than surrounding land areas. Additionally, lake fraction was positively correlated with the brightness temperature measurements at 18 GHz and above, but negatively correlated with the AMSR-E brightness temperatures at low frequency channels (6 and 10 GHz), with the highest correlation values for the SSM/I ($r=0.57$) and AMSR-E ($r=0.65$) at 37 GHz dominating the response. Brightness temperature-based lake fraction algorithms were derived using stepwise regression. Performance assessment showed that the AMSR-E algorithm was superior to the SSM/I algorithm due to the use of the low frequency measurements not available from the SSM/I instrument. Combined lake fraction- and SSM/I brightness temperature-based snow depth and snow water equivalent algorithms were also derived using stepwise regression, with improved performance compared to conventional brightness temperature-based algorithms.

1. Introduction

Snow is the most variable surface cover feature on the Earth, ranging from 46.5×10^6 km^2 in January to 3.8×10^6 km^2 in August in the Northern Hemisphere (Engen et al., 2004). Snow is a sensitive indicator of climate variability (Cohen, 1994; Comiso et al., 2003; Nghiem & Tsai, 2001), and directly affects climate on regional and global scales through its high albedo and low thermal conductivity (Foster et al., 2004; Hall et al., 1991; Liston & Sturm, 2002). Snowmelt is a principal factor in the overall freshwater input to oceans, and a vital freshwater resource, contributing over 70% of total water resources to the western United States (Pagano & Garen, 2006).

Traditionally, most information on the snow cover distribution has been obtained from ground-based meteorological stations. Traveling to remote sites in harsh winter conditions of the high-latitude areas makes direct human measurement of snow pack difficult and expensive, and thus this method is not feasible over large expanses in these regions. Automated monitoring, on the other hand, allows remote collection of snow measurements, but the spatial coverage of automated stations is also limited. Space borne remote sensing has become a viable method for providing information on snow cover distribution with much improved spatial coverage and temporal frequency that cannot be matched by in situ measurements.

In the use of space borne remote sensing of snow cover it is desirable to obtain three main parameters: Snow Cover Area (SCA), Snow Depth (SD) and Snow Water Equivalent (SWE). SCA is easily observable at optical (visible and near-infrared) wavelengths because of the strong albedo contrast between snow covered and snow-free land. Most current meteorological satellite instruments collect observations in optical spectral regions and conduct SCA monitoring routinely, e.g., the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites (Hall et al., 2002), the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard NOAA polar orbiting satellites (Baum & Trepte, 1999) or optical instruments

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on board the geostationary weather satellites (Romanov & Tarpley, 2006; Romanov et al., 2000). However, SWE and SD are nearly impossible to measure directly from optical imagery because the electromagnetic radiation coming from the top few centimeters of snow dominates the remote sensing signal at optical wavelengths. In addition, snow retrievals from satellite optical measurements require clear sky conditions and sufficient daylight. Microwave (MW) radiation is unhindered by darkness and clouds and at specific bands penetrates a deeper layer of snow cover. A major disadvantage of current passive MW remote sensing instruments (available only) on board the polar-orbiting satellites is the coarse frequency-dependent spatial resolution (Table 1) and less frequent views than optical sensors on board the geostationary satellites.

The traditional passive MW retrieval algorithms for SD and SWE monitoring use the approach described in Chang et al. (1987) whereby the difference in measured brightness temperature at two lower frequency atmospheric window channels (e.g., 19 and 37 GHz for the SMMR, SSM/I and AMSR-E) is linearly related to variations in SD or SWE. A decrease in measured brightness temperature with increasing frequency in the 20–100 GHz region is a typical snow signature (Mätzler, 1994). At these frequencies and grain sizes, Rayleigh scattering predominates with the exception of very large grain size layers. Based on numerous investigations (Derksen et al., 2003; Foster et al., 2004, 2005; Koenig & Forster, 2004; Sturm et al., 1993; Walker & Goodison, 1993), other major factors such as grain size distribution and stratigraphy, forest cover and liquid water have been shown to alter snow MW brightness temperatures, introducing uncertainty in SD and SWE retrievals.

The conventional Chang et al. (1987)-based algorithms perform reasonably well over Prairie snow (e.g., Derksen et al., 2003; Goodison & Walker, 1995) but poorly over Arctic tundra snow covers (Derksen et al., 2009, 2010; Duguay et al., 2005). A variety of factors can cause this poor performance, among which are the effects of lakes on the brightness temperature measurements. In the Arctic tundra water bodies comprise a significant portion of the surface yet fractional lake area is presently not accounted for in conventional SWE or SD algorithms (Duguay et al., 2005). In the northern Hudson Bay Lowland, Canada, for instance, shallow lakes occupy as much as 41% of the landscape (Duguay & Lafleur, 1997). Other circumpolar high latitude regions such as Alaska, northern Scandinavia and northern Russia share this substantial areal coverage by lakes. On the North Slope of Alaska there are thousands of lakes that typically cover 20% of the land in most places, and as much as 40% near the coast. The presence of unfrozen water underneath the sections of lakes that have floating ice has been suggested as a possible error source in SWE retrievals (Duguay et al., 2005). Lake water possesses different microwave emission characteristics from land surfaces, i.e., increased brightness temperature with increasing frequency, which causes a reduced or even the reversal of the brightness temperature difference between 19 and 37 GHz channels (Derksen et al., 2005; Hall et al., 1981). In addition, water surfaces are associated with lower brightness temperatures and larger brightness temperature polarization difference than land surfaces especially at lower microwave frequencies. Another explanation for the observed reversal of the brightness temperature differential at 19 and 37 GHz is that the lower frequencies respond more to unfrozen water due to larger penetration depths whereas higher frequencies respond more to ice and overlying snow due to smaller penetration depths (Kang et al., 2010). Further, Chang et al. (1997) showed that the presence of layers of ice and snow causes multiple reflections of the emitted microwave radiation. This manifests itself as a brightness temperature oscillation modulated by lake ice thickness. This generally results in SWE underestimation, and may be related to ice thickness, different lake/land vertical kinetic temperature profiles, and significant stratigraphic differences (Derksen et al., 2005).

Recognizing the inadequacy of conventional algorithms in tundra landscapes, Derksen et al. (2010) developed a tundra-specific SWE retrieval algorithm based solely on time-cumulative brightness temperature measured at 37 GHz vertical polarization. The rationale for using only the 37 GHz channel was that at this frequency the brightness temperature is thought to be more sensitive to SWE accumulated over land and/or lake ice during the winter and less sensitive to water that might remain unfrozen beneath lake ice. The selective sensitivity to overlying lake ice or snow is related to a much smaller penetration depth at 37 GHz than at lower brightness temperature measurements performed with conventional satellite passive microwave instruments, e.g. at AMSR-E's 6, 10 and 18 GHz. In addition, measurements at vertical polarization are typically less sensitive to snow and ice stratification than horizontal polarized measurements. The use of a time-cumulative brightness temperature value at 37 GHz was justified on the basis that a cumulative value was found to be more uniquely related to SWE accumulations than a single instantaneous value. More recently, Lemmetyinen et al. (2011) incorporated lake fraction in the forward brightness temperature model component in an operational SWE retrieval scheme described in Takala et al. (2011). Derksen et al. (2012) evaluated a SWE retrieval scheme over tundra that included lake fraction.

This research is focused on directly quantifying the relationships between sub-grid lake fraction, SWE and SD and passive satellite brightness temperature measurements on the North Slope of Alaska. Sub-grid lake fraction estimated from high-resolution optical imagery and in situ measured SWE and SD are inter-compared with SSM/I and AMSR-E brightness temperature observations and their relationships analyzed using time series and multivariate regression. This analysis also includes exploration of new regression algorithms for SWE, SD and lake fraction retrievals, and a performance assessment of several conventional SWE algorithms on the North Slope. The layout of the paper is as follows: Section 2 provides a detailed description of the study area, the datasets used, their acquisition methodology, and the methods used in the data analysis. Included in this section is also a brief description of the conventional SWE algorithms whose performance was assessed with in situ data. Section 3 presents the study results and discussion, and lastly, Section 4 provides the summary and conclusions of this research.

Table 1
Characteristics of main microwave sensors used for snow cover mapping.

SMMR Nimbus 7 10/25/1978 to 8/20/1987	Frequency (GHz)	6.63	10.69	18	21	37	
	Wavelength (cm)	4.5	2.8	1.7	1.4	0.8	
	Pixel size	148 km × 95 km	91 km × 59 km	55 km × 41 km	46 km × 30 km	27 km × 18 km	
SSM/I DMSP F08, F10, F11, F13, F14, F15 6/19/1987 to present	Frequency (GHz)	19	37	22	85		
	Wavelength (cm)	1.6	0.8	1.4	0.4		
	Pixel size	70 km × 45 km	60 km × 40 km	38 km × 30 km	16 km × 14 km		
AMSR-E EOS Aqua 05/04/1972 to 10/4/2011	Frequency (GHz)	6.9	10.7	18.7	23.8	36.5	89
	Wavelength (cm)	4.3	2.8	1.6	1.3	0.8	0.3
	Pixel size	75 km × 43 km	51 km × 29 km	27 km × 16 km	32 km × 18 km	14 km × 8 km	6 km × 4 km
AMSR-E2 GCOM-W July 2, 2012 to present	Frequency (GHz)	6.9	10.7	18.7	23.8	36.5	89
	Wavelength (cm)	4.3	2.8	1.6	1.3	0.8	0.3
	Pixel size 7	62 km × 35 km	42 km × 24 km	22 km × 14 km	26 km × 15 km	12 km × 7 km	5 km × 3 km