Assessing Snowpack Water Equivalent Distribution in an Open Tundra Environment Using Various Scales of Passive Microwave Data

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EXTENDED ABSTRACT

The areal extent and seasonal evolution of high latitude snow cover are important to quantify because they 1) influence the energy balance through changes in surface radiative properties, 2) control the ground thermal regime and vegetation dynamics, and 3) represent the amount of solid water storage during winter. Open tundra is the most prevalent high latitude landscape throughout the northern hemisphere, yet the distribution and volume of snow across the expansive tundra is largely unknown. Increasing development in northern regions, combined with observed and forecasted changes to high latitude climate conditions reinforces the need for regional snow cover monitoring. However, the rugged terrain and remoteness of tundra regions limit the ability to collect in situ snow cover measurements. As a result, there is a lack of appropriate data for the comparison and validation of global and regional climate model simulations of snow cover and the water balance. The use of satellite passive microwave remote sensing is appealing across remote tundra regions as it can provide spatially continuous, temporally consistent and synoptically sensitive data. Passive microwave data have proven useful for estimating snow extent and snow water equivalent (SWE) (for example Chang *et al*., 1990), however, no operational passive microwave snow cover retrieval algorithms currently exist for the tundra environment.

In 2003, a multi-agency, multi-year, field based research project was initiated in an open tundra study region of the upper Coppermine River basin in the Canadian Northwest Territories (NWT). The primary goal of the project is to develop a better understanding of open tundra snow cover properties and distribution for 1) the application to climate and hydrology research and 2) the improvement of satellite passive microwave SWE algorithms. Pre-melt in-situ snow survey data were first collected during a preliminary survey in 2003 for initial comparison with current satellite passive microwave estimates. The objectives of the 2004 field campaign were specifically; they were to determine 1) the variability of snow depth and density within and between SSM/I grid cells throughout the region and 2) the effect of terrain and lake cover on snow distribution. A total of 240 sites were visited where snow depth and bulk density were measured and snow pits were sampled for density profiles and stratigraphy. Terrain units were delineated based on both topographic character (slope and aspect) and landscape character (lake, wetland, vegetated and boulder field). During the 2005 field campaign, airborne and ground based passive microwave radiometers were deployed to compliment a similar network of in-situ surveys.

In-situ snow data collected during the 2003, 2004 and 2005 surveys show a marked underestimation of retrieved SWE using the current Meteorological Service of Canada (MSC) open ground algorithm (Table 1).

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Table 1. Comparison of In-situ Measured SWE with SSM/I Estimated SWE

Survey Year	Measured SWE*	SSM/I Estimated SWE**
2003	123 mm	79 mm
2004	196 mm	49 mm
2005	134 mm	73 mm

* Measured SWE based on arithmetic mean of all samples from each field campaign
** SSM/I SWE Estimated using the existing MSC Open Ground Algorithm

The inability of the existing MSC open ground algorithm to reasonably estimate SWE is not surprising as it was developed primarily for use in prairie regions and has not been thoroughly tested in tundra environments. Improving SWE estimates will depend largely on identifying and including factors not considered in the current algorithm. This involves addressing the predominant sub-grid cell snow and terrain features present in open tundra environments, namely 1) highly variable snow depth caused by wind re-distribution 2) differences in snow density and grain size (depth hoar), 3) forest–tundra transitions, and 4) a significant lake cover fraction.

The snow surveys conducted between 2003 and 2005 showed the distribution of snow in the open tundra to be very heterogeneous and largely dependant on topography and landscape. As noted by other researchers, slope length, angle, aspect, ground cover, along with wind direction, magnitude and fetch, all control snow distribution patterns (Essery and Pomeroy, 2004; Hirashima et al., 2004). Snow depth and SWE were found to be lower and less variable on gently sloping terrain units, such as flat terrain, lakes, upland plateaus, and on predominantly windward slopes (Figure 1). Snow depth and SWE were greatest on leeward slopes where significant deposition occurred. Surprisingly, there was found to be no inter-annually consistent relationship between snow depth and slope azimuth.

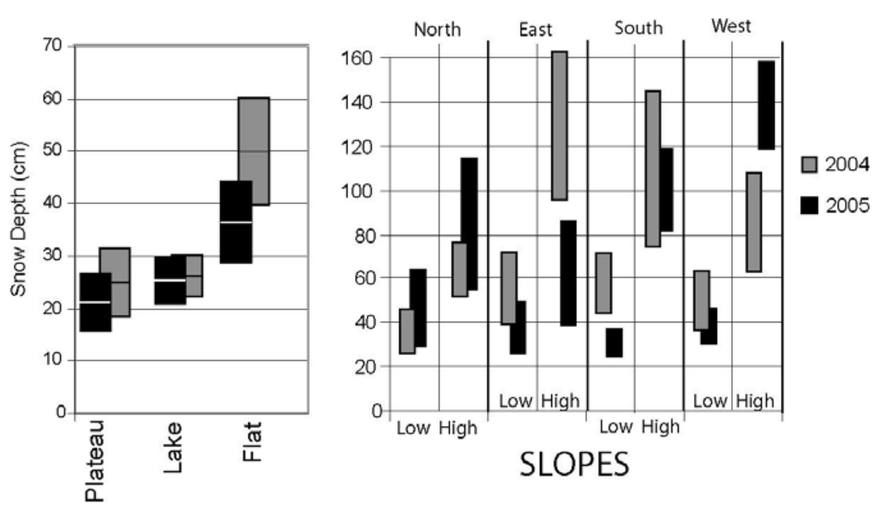

Figure 1. Terrain unit snow depth from the 2004 and 2005 in-situ surveys. Low slopes < 8 %, high slopes > 8%. Different y-axis used to accommodate higher range of snow depth on slope terrain units.

Snow density, however, was found to be much more consistent both within and between terrain types. A regional average snow density was calculated using density samples from slope sites and separately from non-slope sites. These average densities were applied to the depth measurements from all sites to generate SWE estimates. These estimated SWE values (depth x density) were then compared to measured SWE (collected with ESC-30 samplers), at each site. For both slope and non-slope sites, SWE estimated using the regional density related very strongly to measured SWE (Figure 2). This means that in such tundra environments, density is not significantly variable, and a regional value can be applied so that snow depth can be a used as a proxy for SWE.

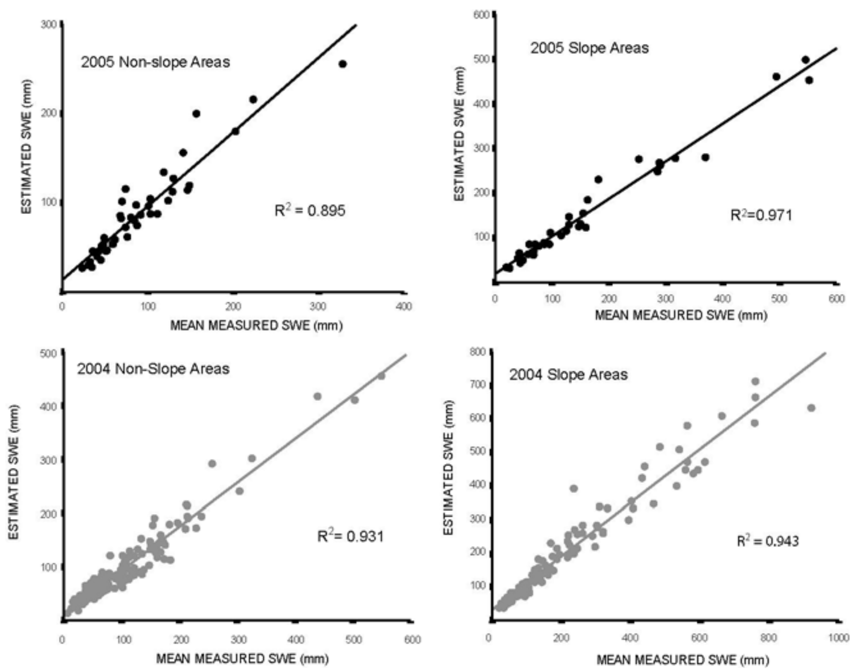

Figure 2. Mean measured SWE from slope and non-slope sites compared to estimated SWE from the 2004 and 2005 surveys. Estimated SWE is generated using the regional average density.

Deep snow drifts on leeward slopes are perhaps the most notable feature in the open tundra as they represent large volumes of water stored in localized areas. Deep drifts are therefore hydrologically significant at a local scale; however, from a landscape weighted perspective they occupy only a small percentage of a passive microwave grid cell area (<5%). Conversely, flat terrain, which occupies between 30 and 40 percent of the landscape (>60% when lakes are included), has a much shallower, less variable snow cover. To address these issues, topographic data were used to determine the area occupied by each terrain unit (Table 2). The percentage of grid cell occupied was applied to the average SWE for each terrain type to develop an improved measure of regional SWE (Table 3). The areally weighted SWE does compare more favorably to satellite estimated SWE; however, there remains a significant underestimation using the current algorithm.

TABLE 2. Percent of Grid Cell Area Occupied by Different Terrain Units

TERRAIN UNIT	% GRID CELL*
Flat	**38.8**
Lakes	**27.1**
North Low	**7.1**
North High	**1.8**
East Low	**5.5**
East High	**1.4**
South Low	**7.6**
South High	**1.9**
West Low	**7.8**
West High	**1.1**

*Percent of grid cell areas calculated for one representative grid cell within study area.

Table 3. Comparison of Areally Weighted and Arithmetic In-situ SWE with SSM/I Estimated SWE

Survey	Arithmetic SWE	Areally Weighted SWE	SSM/I Estimated SWE
2003	123 mm	104 mm	79 mm
2004	196 mm	127 mm	49 mm
2005	134 mm	102 mm	73 mm

To further improve satellite SWE retrievals, it is necessary to understand the difference in microwave emission from different terrain features. Snow covered and snow free frozen lakes, which occupy a significant percentage of most tundra grid cells (20 – 40%), have been shown to have very different microwave emission from frozen terrestrial surfaces (Hall *et al*., 1981). The snow depth on lakes is similar to some non-slope terrain features but is much less variable (Figure 1). Snow density on lakes is higher than on land but also much less variable. In general, of all terrain types, lake cover SWE was found to be the least variable between sites and field seasons. This compliments the results of snow studies conducted in Northern Manitoba (Derksen *et al*., 2005) and on the Alaskan North Slope (Sturm and Liston, 2003). The contrast in emissivity between land and lakes is a product of the difference in dielectric properties between ice and ground. A further complication is the potential for differences in emissivity between lakes of different size, bathymetry, thermal state and ice composition. These issues will be further investigated using the high resolution airborne (50 – 500 m) and ground based radiometer (1 – 2 m) data obtained during the 2005 field season. More specifically, these data will be used to examine and define microwave emission from unique terrain types and lake cover areas. This analysis will provide insight into how unique tundra snow cover and terrain features influence satellite passive microwave brightness temperatures, leading to the improvement of regional SWE estimates.

ACKNOWLEDGEMENTS

This continuing research project is supported by the Canadian Foundation for Climate and Atmospheric Sciences, Meteorological Service of Canada, Cold Regions Research Center – Wilfrid Laurier University, Northern Scientific Training Program, Polar Continental Shelf Project, B.H.P Billiton, Ekati Mine, Department of Indian and Northern Development, and the Government of Northwest Territories—Resources, Wildlife and Economic Development. Special acknowledgements to Claude Duguay, Arvids Silis, Natasha Neumann, Peter Toose, Dave McNichol, Dave Woods, Pat Chahil, and Ken Asmus for their assistance in the field.

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