Remote Sensing of Environment 114 (2010) 1699–1709

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Development of a tundra-specific snow water equivalent retrieval algorithm for satellite passive microwave data

C. Derksen [a],*, P. Toose [a], A. Rees [b], L. Wang [a], M. English [b], A. Walker [a], M. Sturm [c]

[a] Climate Research Division, Environment Canada, Toronto, Ontario, Canada
[b] Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario, Canada
[c] Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, Fort Wainwright, Alaska, United States

ARTICLE INFO

Article history:
Received 25 November 2009
Received in revised form 23 February 2010
Accepted 26 February 2010

Keywords:
Snow water equivalent
Passive microwave
Tundra
Sub-Arctic

ABSTRACT

Airborne and satellite brightness temperature (T_B) measurements were combined with intensive field observations of sub-Arctic tundra snow cover to develop the framework for a new tundra-specific passive microwave snow water equivalent (SWE) retrieval algorithm. The dense snowpack and high sub-grid lake fraction across the tundra mean that conventional brightness temperature difference approaches (such as the commonly used 37 GHz–19 GHz) are not appropriate across the sub-Arctic. Airborne radiometer measurements (with footprint dimensions of approximately 70 × 120 m) acquired across sub-Arctic Canada during three field campaigns during the 2008 winter season were utilized to illustrate a slope reversal in the 37 GHz T_B versus SWE relationship. Scattering by the tundra snowpack drives a negative relationship until a threshold SWE value is reached near 130 mm at which point emission from the snowpack creates a positive but noisier relationship between 37 GHz T_B and SWE.

The change from snowpack scattering to emission was also evident in the temporal evolution of 37 GHz T_B observed from satellite measurements. AMSR-E brightness temperatures (2002/03–2006/07) consistently exhibited decreases through the winter before reaching a minimum in February or March, followed by an increase for weeks or months before melt. The cumulative absolute change ($\Sigma|\Delta 37V|$) in vertically polarized 37 GHz T_B was computed at both monthly and pentad intervals from a January 1 start date and compared to ground measured SWE from intensive and regional snow survey campaigns, and climate station observations. A greater (lower) cumulative change in $|\Delta 37V|$ was significantly related to greater (lower) ground measured SWE ($r^2 = 0.77$ with monthly averages; $r^2 = 0.67$ with pentad averages). $\Sigma|\Delta 37V|$ was only weakly correlated with lake fraction: monthly r^2 values calculated for January through April 2003–2007 were largely less than 0.2. These results indicate that this is a computationally straightforward and viable algorithmic framework for producing tundra-specific SWE datasets from the complete satellite passive microwave record (1979 to present).

1. Introduction

A number of high priority science questions require snow water equivalent (SWE) information across high latitude regions, including:

- determining whether there is an increase in high latitude winter season precipitation to corroborate recent evidence from model simulations and the sparse network of conventional observations (Min et al., 2008; Zhang et al., 2007).
- identifying the role of snow cover variability and change in the potential intensification of the high latitude water cycle through increased precipitation, earlier melt, higher peak runoff, and greater freshwater input to the Arctic Ocean (see Dery et al., 2009).

Conventional observations are not adequate to answer these questions because the station network is sparse and coastally biased, and the measurements themselves are uncertain. Snowfall gauge and shield combinations are not standard between countries (Yang et al., 1999), and the required auxiliary measurements for systematic undercatch correction (such as wind speed at gauge height) are often not available. Point snow depth measurements are subject to local scale wind drifting or scour and may not represent the prevailing regional conditions. Even when they do, the large distances between stations does not allow for meaningful spatial interpolation (i.e. kriging), and coastal stations do not represent vast inland areas.

Satellite passive microwave measurements address the spatial limitations of conventional observations, but not necessarily the uncertainties in snow cover information. A large imaging footprint (25 km grid cell dimensions), wide swath, and general insensitivity to cloud cover produce spatially continuous daily brightness temperatures (T_B) across latitudes north of approximately 60 °N. The response

---

* Corresponding author.
E-mail address: Chris.Derksen@ec.gc.ca (C. Derksen).

0034-4257/$ – see front matter. Crown Copyright © 2010 Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2010.02.019

Table 1
Summary of sub-Arctic in situ snow cover measurements.

Location	Coordinates	Time period	Distance (km)	Measurements (n)			SWE (mm)			
				Snow depth	SWE	Snowpits	Mean	Min	Max	SD
Puvirnituq, QC	59.83N–76.39W	February 2008	18	~12,000	369	10	101	21	431	66
Daring Lake, NT	64.85N–111.63W	April 2008	33	~4400	668	23	100	3	428	64
Trail Valley Creek, NT	68.70N–133.62W	April 2008	28	~5900	757	27	111	15	534	61

of these T_B measurements to seasonally evolving sub-Arctic snow and lake ice cover is poorly understood, however, and the performance of hemispheric SWE retrieval algorithms (for example, Biancamaria et al., 2008; Chang et al., 1990; Kelly et al., 2003) across northern regions is not well documented due to the lack of high latitude measurements for algorithm validation. Algorithms developed for regional application across the boreal forest and open prairies do not perform well over the tundra (Derksen et al., 2005; Koenig & Forster, 2004; Rees et al., 2006) because of the unique physical properties of tundra snow and the microwave contribution of the high fraction of sub-grid lakes. The extreme variability of tundra snow on meter-to-meter length scales further complicates tundra algorithm development and validation at the scale of satellite microwave measurements due to the complexity in characterizing 'ground-truth' SWE.

Still, passive microwave retrievals remain an attractive option for snow cover applications because of the theoretical relationship between SWE and T_B at 37 GHz (Matzler, 1994), and the considerable length of the data record (1978–present). In this study, we present a new framework for a tundra-specific passive microwave SWE algorithm developed through analysis of high resolution airborne passive microwave measurements coupled with detailed in situ snow measurements from three field campaigns across sub-Arctic Canada, and satellite data from the Advanced Microwave Scanning Radiometer (AMSR-E). Specifically, we address two fundamental challenges to develop a tundra-specific SWE algorithm:

1. *The unique radiometric properties of lake ice*, which can constitute up to 40% of the sub-Arctic tundra land surface (primarily through small sub-grid sized lakes). Derksen et al. (2009b) showed that lake fraction is a primary control on tundra T_B magnitude at all satellite measured frequencies and therefore must be considered as part of a tundra specific retrieval scheme.
2. *The slope reversal in the SWE versus 37 GHz Tb relationship*, that occurs between 120 and 180 mm water equivalent (Derksen, 2008; De Seve et al., 1997; Schanda et al., 1983). Below this threshold, increasing SWE is associated with lower T_B due to volume scatter. Above this threshold, emission from the snowpack produces higher T_B's with increasing SWE. Tundra snowpacks are typically shallow, dense, fine grained, and contain pronounced wind slab layers (Sturm et al., 1995). The influence of this stratigraphy on scattering and emission behaviour can be complex, but there is documented observational evidence of the scattering to emission transition during late winter (Kim & England, 2003).

Accounting for these two factors is essential to avoid the systematic SWE underestimation that is produced from contemporary brightness temperature difference algorithms in tundra environments (Koenig & Forster, 2004; Rees et al., 2006).

2. Data

Interpreting T_B response over tundra landscapes in winter requires in situ observations of snow cover properties and lake ice characteristics. Optimally, these measurements would be available at continuous intervals through the season and adequately capture sub-grid variability below the scale of satellite passive microwave measurements (25 km grid cell dimensions). In short, datasets with these spatial and temporal characteristics are not available. In this study, we utilize datasets from a series of field campaigns conducted during discrete time periods across the Canadian sub-Arctic tundra as part of International Polar Year activities between February and April 2008. As summarized in Table 1, these campaigns included the deployment of airborne passive microwave radiometers coupled with intensive in situ snow measurements. Collectively, these datasets provide the opportunity to determine relationships between snow cover properties and microwave T_B at multiple scales (airborne and satellite) from multiple tundra sites. In turn, these relationships can be used to develop the framework for a new tundra-specific SWE retrieval algorithm that can be applied to the entire passive microwave satellite data record that dates back to 1978.

2.1. Airborne radiometer measurements and in situ snow surveys

At all three tundra field sites (see Table 1; Fig. 1), airborne passive microwave measurements were acquired covering a wide range of tundra terrain. The radiometer installation (dual polarization 6.9, 19, 37, and 89 GHz) on the National Research Council Twin Otter aircraft is described in MacPherson et al. (2001) and Walker et al. (2002). The airborne radiometers (parameters for the 19 and 37 GHz radiometers used in this study are provided in Table 2) were calibrated pre- and post each flight using warm (ambient temperature microwave absorber) and cold (liquid nitrogen) targets as described by Solheim (1993). Uncertainty in the measurement of the calibration target temperature was estimated at +/-2 K. The 19 and 37 GHz radiometers were calibrated simultaneously so the same target temperature uncertainties for a given calibration apply to both frequencies. Estimates of inter-calibration receiver drift were made by examining the pre- and post-flight calibration target brightness temperatures. Radiometer stability was dependant on the frequency and varied somewhat from campaign to campaign, but overall uncertainty was estimated at +/−2 K at 19 GHz, and <1 K at 37 GHz.

Transects of snow depth and SWE measurements were acquired along segments of the radiometer flight lines, typically several kilometers in length. Snow depth was sampled using a self recording snow depth probe ('Magna Probe' U.S. Patent No. 5864059; cf. Sturm & Liston, 2003) linked to a GPS. At all sites, manual SWE cores (using an ESC-30 corer) were taken approximately every 250 m along the depth transects, in order to compute bulk density values used to convert the measured snow depth to estimated SWE. Average land cover specific snow densities were determined for each study site by relating each ESC-30 measurement to a landscape class determined from a Landsat classification (Natural Resources Canada, 2008). These land cover specific snow densities were used to estimate a SWE value for each snow depth measurement based on the land cover class it was measured in. Density is an inherently conservative variable across the tundra compared to snow depth, so this is an effective technique at converting a more straightforward measurement (depth) to a more

Fig. 1. (a) Study area overview showing the three IPY field campaign sites and the Baker Lake climate station. (b) SnowSTAR snow survey route and measurement sites; grid shows extent of AMSR-E EASE-Grid data used for analysis.