The Contribution of AMSR-E 18.7 and 10.7 GHz Measurements to Improved Boreal Forest Snow Water Equivalent Retrievals

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ABSTRACT

Four seasons (2004-2007) of snow surveys across the boreal forest of northern Manitoba were utilized to determine the response of Advanced Microwave Scanning Radiometer (AMSR-E) brightness temperatures to variability in snow water equivalent (SWE). Regression analysis identified moderate strength, yet statistically significant relationships between SWE and brightness temperature differences (37V-19V; 37V-10V; 19V-10V) for individual seasons. When multiple seasons were considered collectively, however, the 37V-19V and 37V-10V differences were insignificant because the seasonal linear relationships shifted from year to year over the same brightness temperature range regardless of SWE. More encouraging results were found for the 19V-10V difference: the relationship with SWE remained statistically significant when multiple years were considered together. Unlike the frequency combinations that included 37 GHz, the 19V-10V difference was not significantly associated with vegetation density as approximated by a forest transmissivity dataset. Snow survey data from the Northwest Territories (2005-2007) were used to verify the 19V-10V relationship with SWE across the northern boreal forest.

Keywords: snow water equivalent, passive microwave, boreal forest, AMSR-E

INTRODUCTION

The boreal forest is an expansive biome covering large tracts of North America and Eurasia. Snow cover is a persistent component of the boreal landscape, influencing the regional energy budget, freshwater flow into the Arctic Ocean, ecosystem phenology, geochemical cycling, and summer fire risk. The conventional snow cover observing network across the boreal forest is sparse, necessitating the use of satellite measurements to produce spatially and temporally continuous datasets. Passive microwave snow water equivalent (SWE) retrieval algorithms typically exploit the difference between a measurement frequency sensitive to snow grain volume scatter (~37 GHz) with a measurement frequency considered insensitive to snow (~19 GHz). These particular frequencies are commonly used because they extend continuously through the satellite record (1978 to present) even as the measurement characteristics of various sensors have evolved. This algorithmic approach, however, is problematic in the boreal forest for two reasons:

(1) Deep snow: Volume scatter at 37 GHz increases only to a threshold SWE value of approximately 120 mm (Armstrong et al., 1993). Beyond this point, brightness temperatures increase again due to emission from within the snowpack (De Seve et al., 1998). Assuming a snow density of 0.2 g/cm^2, the 120 mm SWE threshold is reached at a relatively modest snow depth of 60 cm. Assuming a typical depth range of 30-120 cm for the taiga (as identified by Sturm et al.,

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1995) passive microwave SWE estimates based on the 37 and 19 GHz brightness temperature difference will underestimate both maximum SWE and the degree of interannual variability.

(2) Vegetation: In general, there is a latitudinal evolution from closed canopy boreal forest in the south, to open canopy forest in the north. This vegetation gradient will influence the efficiency of snowfall interception and retention on the surface and complicates microwave SWE retrievals by confounding the scattering signal of snow covered ground (Derksen et al., 2005). Previous passive microwave SWE algorithm development for the boreal forest in Canada utilized BOREAS-era datasets across areas with a closed forest canopy and relatively shallow snow depth (Chang et al., 1997; Goita et al., 2003). These algorithms (based on 37V-19V measurements) are presently applied across the non-mountainous forested areas of western Canada with no consideration for the latitudinal gradient in snow and vegetative properties.

Recent developments make a re-examination of brightness temperature behaviour over the boreal forest timely. First, from 2002 onwards, the Advanced Microwave Scanning Radiometer (AMSR-E) has acquired data at an enhanced spatial resolution compared to the previous generation of passive microwave sensors, and includes a 10.7 GHz channel not available from a spaceborne sensor since 1987. Second, a multi-season dataset (2004-2007) of in situ snow surveys across the boreal forest of northern Manitoba is available for analysis, with site locations selected to capture the transition from closed to open canopy forest, and the measurement protocol designed for comparison with coarse resolution satellite measurements.

The objectives of this study are to present results from a comparison of AMSR-E data and the northern Manitoba snow cover measurements to assess the uncertainty associated with using conventional 37 and 19 GHz measurements, and determine the potential contribution of 10.7 GHz measurements for improving northern boreal forest SWE retrievals.

DATASETS

Measurements of snow physical properties were made at a network of sites across northern Manitoba during late winter 2004 through 2007. The timing of sampling varied from year to year (Table 1), but occurred in all cases before any spring melt events. The 18 sites shown in Figure 1 were sampled each year (these sites also correspond to airborne passive microwave surveys conducted in 2006 which will not be discussed further here). A fixed 70 meter measurement line was established at each site. Snow cores were taken every 10 meters with an ESC-30 sampler for direct measurement of SWE and bulk density. Snow depth measurements were taken every meter. A snowpit was excavated at the start of each line for snowpack stratigraphy measurements including density profiles, the identification of layering, and mean grain size for each layer. Mean site SWE was calculated directly from the core measurements, and by converting each individual depth measurement to SWE using the mean ESC-30 density. At most sites, adjacent lakes were also sampled following the same protocol.

Table 1. Summary of northern Manitoba field measurements.

		Snow Properties			Stratigraphy			
Year	Measurement Period	Depth (cm)	SWE (mm)	Density (g/cm^3)	New/Recent (%)	Faceted (%)	Hoar (%)	Grain Size (mm)
2004	March 4 – 8	53	96	0.183	30	37	33	2.1
2005	March 11 – 17	71	139	0.200	36	31	33	2.7
2006	February 26 – March 3	47	79	0.186	26	43	31	2.5
2007	March 19 – 23	95	178	0.202	34	38	28	2.1

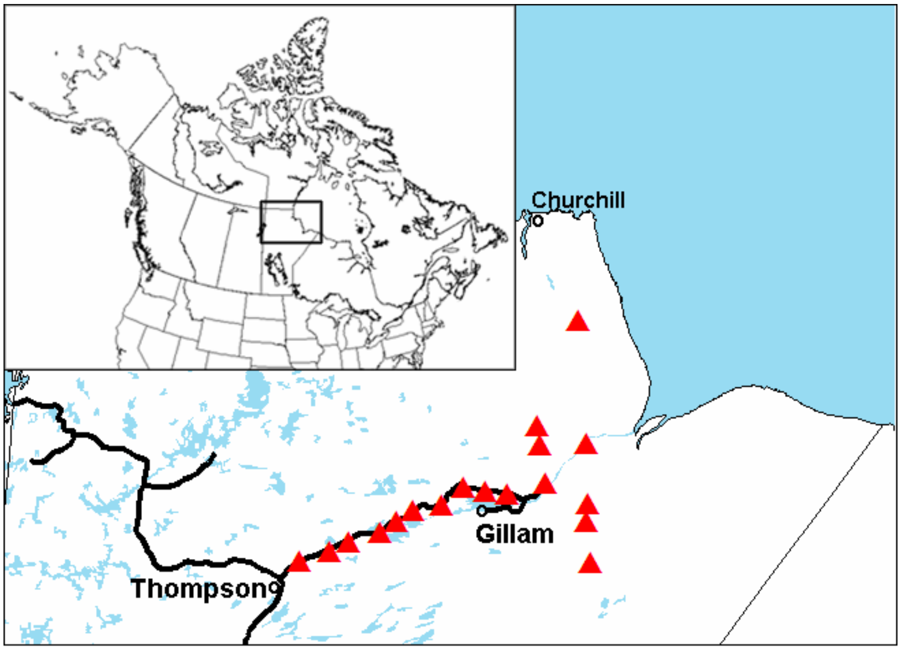

Figure 1. Location of field measurement sites (triangles).

AMSR-E brightness temperatures in both level 2 swath and EASE-Grid (Armstrong and Brodzik, 1995) projections were acquired for October 1 through April 30, 2004 to 2007. Use of the swath data is advantageous because the original frequency dependant imaging characteristics are retained. Inter-orbit variability in swath level footprint locations, however, necessitated use of the 25 km EASE-Grid dataset for the compilation of brightness temperature time series. A five day moving average was applied to the descending orbit (approximately 0130 local overpass time) AMSR-E data to reduce high frequency variability in brightness temperatures driven by atmospheric and physical temperature effects (Markus et al., 2006). Only vertically polarized data were explored in this study.

RESULTS

Snow Cover Measurements

A summary of the regional terrestrial snowpack conditions is provided in Table 1. A high degree of interseasonal variability in SWE magnitude was present in the in situ dataset, with shallow snow in 2004 and 2006 (mean SWE of 96 and 79 mm, respectively) and comparatively deep snow in 2005 and 2007 (mean SWE of 139 and 178 mm, respectively). Regional snow density varied in a more subtle way, with density during the deep snow years only 0.015 g/cm^3 above the shallow snow years. Density is clearly a more constrained variable than either depth or SWE (Sturm et al., 2003), with variability in SWE driven by depth, not density.

The general nature of the snowpack was consistent with the taiga snow characteristics described in detail in Sturm et al. (1995). The northern boreal forest snowpack evolves in a cold temperature, low wind speed environment. As such the inter-layer stratigraphy can be very subtle – macro features such as ice lenses and crusts were rarely observed. The general stratigraphic composition of the snowpack was consistent from year to year, proportioned approximately in thirds between new and recent snow overlaying faceted grains, with large, loose hoar crystals at the base. Grain size estimates (which were visually determined and subject to greater uncertainty than the other measurements) show only slight interseasonal variations in mean grain size. Grain size was observed to increase consistently with depth, so the mean values are an integration of fine surface layers (~0.5 mm grain size) and depth hoar that can exceed 10 mm. In general, the snow pack physical characteristics were considered similar for each year. The only dynamic variables are SWE and depth. Given that the regional land cover was unchanged over the four seasons, this represents an ideal framework for isolating the sensitivity of satellite passive microwave measurements to interannual variations in SWE.

A 'ground-truth' SWE dataset for comparison with AMSR-E brightness temperatures was derived by weighting the SWE measurements from terrestrial and lake sites by the fractional composition of each EASE-Grid cell. Lake fraction (determined from classification of Landsat imagery) ranged from 10% to 27%. In all cases for all years, SWE on lakes was lower than the adjacent terrestrial sites, so compensating for lake fraction served to lower the mean grid cell SWE compared to the consideration of only terrestrial measurements.

SWE vs. AMSR-E Brightness Temperatures

Before discussing results, it is helpful to revisit the potential contribution of 37, 19, and 10 GHz measurements to terrestrial SWE retrievals (for a complete theoretical review see Ulaby and Stiles, 1980). 37 GHz measurements are sensitive to the volume scatter of the snowpack. Traditionally, this frequency is differenced against 19 GHz measurements, which provide a background, non-scattering measurement. As the snowpack deepens, 37 GHz brightness temperatures decrease due to volume scatter while 19 GHz measurements remain unchanged. Hence, a larger 37-19 difference means higher SWE. At a critical SWE threshold (near 120 mm), however, 37 GHz measurements no longer continue to decrease because of the contribution of microwave emission from the pack itself. Coincidentally, volume scatter begins to influence 19 GHz measurements. These two factors combine to reduce the 37-19 brightness temperature difference even as the snowpack continues to deepen, resulting in systematic SWE underestimation. In theory, 10 GHz measurements should provide a more insensitive frequency to the snowpack than 19 GHz because of the longer wavelength. The 37-10 difference should, therefore, provide a greater range in retrieved SWE, and greater sensitivity to deep snowpacks when compared to 37-19. The 19-10 difference has typically not been used for SWE retrievals as these are both considered 'background' frequencies, but will be explored here as a potential means of addressing boreal SWE retrievals.

Regression Analysis

Regression analysis was performed on AMSR-E brightness temperature differences (37V-19V; 37V-10V; 19V-10V) versus estimates of mean grid cell SWE for each individual measurement season and the collective dataset. As summarized in Table 2, there was a moderate strength, yet statistically significant association between SWE and AMSR-E brightness temperatures for individual seasons. The potential value of brightness temperature differences that include 37 GHz is limited, however, by the notably weaker association when multiple years are considered together. *The seasonal linear relationships* (r^2 ranging from 0.48 to 0.59) *shifted from year to year, and did not fall along an interannually fixed linear relationship* (as evidenced by overall r^2 values of 0.04 and 0.17 for 37-19 and 37-10, respectively). The results for the 19V-10V GHz difference were more promising. The statistical relationship with SWE was maintained when multiple years were considered together. In this scenario, *the seasonal linear relationships* (r^2 ranging from 0.25 to 0.63) *fell along an interannually consistent linear relationship* (r^2 of 0.58).

Table 2. Summary of linear regression results (r^2), AMSR-E brightness temperature differences vs. in situ SWE. *Bold italics* indicate significance at 95%.

	Regression Results		
Year	37V-19V (r^2)	37V-10V (r^2)	19V-10V (r^2)
2004	***0.57***	***0.55***	***0.42***
2005	***0.59***	***0.59***	***0.53***
2006	***0.51***	***0.48***	0.25
2007	***0.50***	***0.55***	***0.63***
All	0.04	0.17	***0.58***

37V-19V Brightness Temperature Difference

The brightness temperature differences based on 37 GHz should theoretically contain stronger results for the shallow snow seasons of 2004 and 2006 when regional SWE was below 120 mm (above which volume scatter at 37 GHz can no longer be linearly related to SWE). Similarly, results for 2005 and 2007 should be weaker because of the deep snow conditions. Plots of 37V-19V brightness temperature and SWE separated by shallow and deep snow years are shown in Figure 2. During shallow snow years the linear relationship closely matches the existing coniferous forest algorithm that is part of the Environment Canada algorithm suite (Figure 2a). During deep snow seasons (Figure 2b) the linear relationships extend across the same brightness temperature range (-20 to -50 Kelvin), so interannual variations in SWE magnitude clearly do not have a strong influence on 37V-19V brightness temperature difference. Similar results were produced for the 37V-10V brightness temperature difference (not shown).

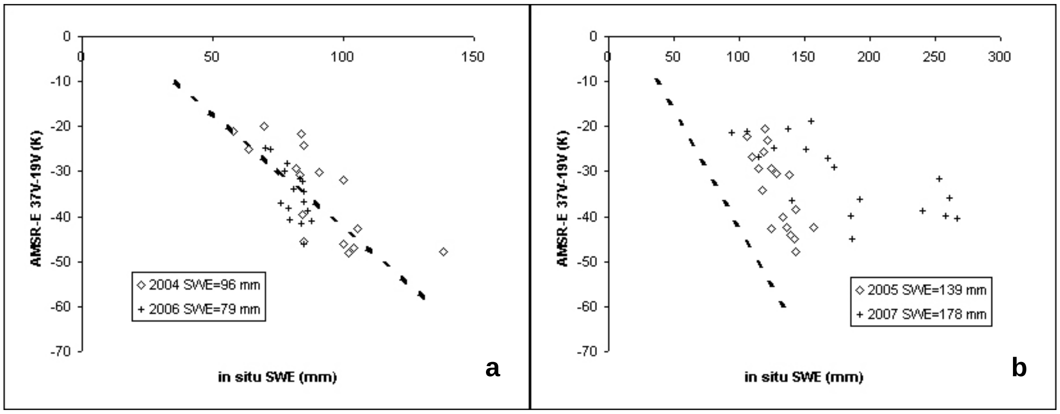

Figure 2. AMSR-E 37V-19V brightness temperature difference versus in situ SWE measurements, separated by shallow (a) and deep (b) snow seasons. Dashed line represents the linear relationship utilized in the Environment Canada coniferous forest algorithm.

19V-10V Brightness Temperature Difference

The 19V-10V regression results shown in Table 1 were promising for two reasons. First, the individual seasonal relationships vary (r^2 ranges from 0.25 to 0.63) which is reasonable given the ground measured range in SWE magnitude. The weakest regression results were identified for the shallowest snow season (2006; SWE = 79 mm) while the strongest results were obtained for the deepest snow season (2007; SWE = 178 mm). This is intuitively logical given that the 19 GHz measurements are responding to the volume scatter of the snowpack, while 10 GHz measurements provide the non-scattering background. A relatively deep snowpack is needed to initiate scatter at 19 GHz and produce brightness temperature differences at these two frequencies. Second, a single significant linear relationship (r^2=0.58) captured the interseasonal variation. As shown in Figure 3, this is in clear contrast to the 37V-19V data, although the 19V-10V differences extend over a relatively narrow brightness temperature range (~15 Kelvin versus ~30K for 37V-19V). Algorithmically, it is necessary to exploit interseasonally consistent relationships.

What is driving the positive results for the 19V-10V brightness temperature difference? Volume scatter at 19 GHz becomes evident when SWE exceeds 120 mm (Figure 4a). The 10 GHz data provide a non-scattering background measurement regardless of SWE (Figure 4b). The insensitivity of 37 GHz to interannual variability in SWE (Figures 2 and 3), and the scattering signal in the 19 GHz data illustrate the problem with 37V-19V and 37V-10V brightness temperature differences. For snowpacks with SWE above 120 mm, the 19V-10V frequency combination holds significant potential for retrieving SWE.

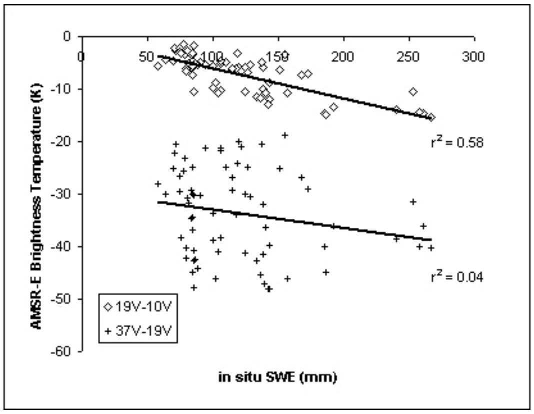

Figure 3. AMSR-E 37V-19V and 19V-10V brightness temperature difference versus in situ SWE, all measurements.

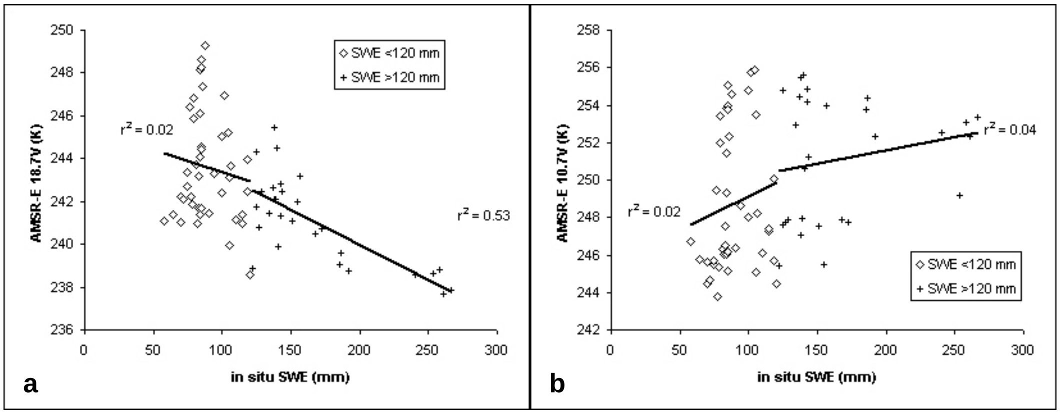

Figure 4. AMSR-E 18.7V (a) and 10.7V (b) brightness temperatures versus in situ SWE (all measurements).

The Influence of Vegetation

The 37V-19V and 37V-10V regression results were interseasonally consistent, driven by very similar brightness temperature differences from season to season. This was problematic – SWE magnitude varied greatly from year to year. So too then, should relationships with microwave frequencies sensitive to the volume scatter of the snowpack. Forest cover has a well documented impact on passive microwave emission (for example, Foster et al., 1991; Kurvonen and Hallikainen, 1997), and was explored as a controlling influence on the observed brightness temperatures. Forest inventory datasets such as stem volume or canopy closure are not available for large portions of northern Canada. In the absence of these datasets, forest transmissivity was derived from 500 m resolution Moderate Resolution Imaging Spectrometer (MODIS) data, following the method described in Metsamaki et al. (2005). This dataset was converted to EASE-Grid for comparison with AMSR-E data.

Regression results for brightness temperature differences versus forest transmissivity are shown in Table 3. Frequency combinations that utilize 37 GHz measurements are strongly influenced by forest cover. This influence is consistent from season and season, but becomes slightly stronger when the snowpack is shallower. If 37 GHz measurements are so strongly influenced by forest cover, why were statistically significant relationships with in situ SWE measurements identified in Table 2? The answer here is that forest stand density (as approximated by the transmissivity dataset) is related to snow catchment and retention. Assuming identical snowfall input, a closed canopy forest stand will intercept and subsequently lose more snow to sublimation than an open canopy stand (Pomeroy et al., 1998). This is a well understood process now included in land surface model parameterizations (i.e. Bartlett et al., 2006), and was reflected in the regression of forest transmissivity versus in situ SWE (Table 4). Apart from the exceptionally shallow season of 2006, a significant relationship was identified between these variables (r^2 of 0.40 to 0.58).

The influence of forest density (as expressed by transmissivity) is consistent on both surface SWE and brightness temperature: dense (sparse) forest drives lower (higher) SWE and higher (lower) brightness temperatures. The 37V-19V brightness temperature association with in situ SWE is therefore spurious because of the strong influence of vegetation which happens to coincidentally agree with brightness temperatures and ground measured SWE. The 19V-10V brightness temperature difference exhibited a much lower association with transmissivity, suggesting this frequency combination is well suited to the boreal forest.

Table 3. Summary of forest transmissivity linear regression results (r^2). ***Bold italics*** **indicate significance at 95%.**

	Regression Results				in situ
Year	37V-19V (r^2)	37V-10V (r^2)	19V-10V (r^2)	SWE (r^2)	Mean SWE (mm)
2004	***0.67***	***0.62***	***0.37***	***0.58***	96
2005	***0.64***	***0.58***	***0.35***	***0.51***	139
2006	***0.72***	***0.66***	0.28	0.04	78
2007	***0.52***	***0.50***	***0.44***	***0.40***	179
All	***0.59***	***0.55***	0.23	0.10	

DISCUSSION AND CONCLUSIONS

SWE retrieval algorithms based on linear relationships between 37 and 19 GHz (or 37 and 10 GHz) passive microwave measurements are problematic across the northern boreal forest because of the dominant influence of vegetation at 37 GHz. Statistically significant linear relationships between 37V-19V brightness temperature difference and SWE for individual seasons are circumstantial, and exist only because forest density and SWE are similarly related due to snow/vegetation interactions. Results were much improved with 19V-10V GHz brightness temperature difference. When SWE exceeds 120 mm, volume scatter at 19 GHz is evident, while 10 GHz measurements remain unaffected by the snowpack. Relationships with vegetation are reduced. Collectively, these characteristics produced an interseasonally consistent linear relationship between SWE and 19V-10V brightness temperature difference.

In addition to the northern Manitoba dataset utilized here, a similar measurement protocol was followed in the Snare and Yellowknife river basins in the Northwest Territories in April of 2005-2007. Compared to Manitoba, the boreal forest composition in the NWT is mixed (deciduous and coniferous), the underlying geology is different (exposed shield), and the region is lake rich (up to 45%). The snowpack properties, however, are consistent. 26 NWT forest sites were sampled over the three seasons, with a mean SWE of 124 mm. Two simple SWE algorithms were compared to the NWT measurements: the Environment Canada coniferous forest algorithm that utilizes 37V-19V GHz measurements (Goita et al., 2003), and the 19V-10V linear relationship shown in Figure 3. The regression, bias and root mean square error calculations all point to the 19V-10V brightness temperature difference as key to the accurate retrieval of boreal forest SWE, and suggest the results from northern Manitoba can be extended to the NWT (Table 4).

Table 4. Assessment of SWE retrievals against the NWT field measurements.
Bold italics **indicate significance at 95%.**

	37V-19V	19V-10V
r^2	0.01	***0.40***
Bias	–22.2%	17.7%
RMSE	35 mm	27 mm

Because SWE above 100 mm is necessary to initiate volume scatter at 19 GHz, an approach based on the 19V-10V GHz difference is better suited to end of season, deeper snow conditions. For many applications (such as water resource management for hydropower applications) this temporal perspective is sufficient. For other applications, an accurate seasonal data record is necessary. Opportunities to assess potential algorithm performance through a complete winter season (to assess 19V-10V brightness temperature behavior under shallow snow conditions) are severely limited across the northern boreal forest of Canada because of the sparse observing network. Snow depth measurement sites are automated, and located in clearings not representative of the prevailing forest cover. The weekly manual snow course network is very sparse, but measurements within this study domain were available from Gillam, Manitoba (see Figure 1).

A time series perspective for 2004 and 2007 is shown in Figure 5. The 37V-19V and 19V-10V SWE estimates are very similar for the shallow snow season of 2004 (Figure 5a) and track the seasonal increase in SWE captured by the weekly snow course measurements. Estimates diverge late in the season: the 37V-19V retrievals peak near 100 mm, very close to the locally measured SWE during the field campaign. The 19V-10V retrievals reach nearly 140 mm, which approximates the peak SWE measured at the snow course. This divergence at the end of the season is a reflection of the natural variability in SWE expected due to site specific snow catchment, and illustrates the challenge in validating large footprint satellite datasets. The time series is truncated in mid-March because of a significant rain on snow event.

The 37V-19V SWE retrievals during the heavy snow year of 2007 are very similar to 2004, and the retrievals are not sensitive to the large increase in SWE observed during March 2007 (Figure 5b). Uncertainty appears high for the early season 19V-10V retrievals, but agreement is strong from mid-December though March, and the peak estimates of 160 mm are close to both the snow course and field campaign measurements.

37 GHz data are broadly considered the primary measurement frequency for terrestrial SWE retrievals because of the theoretically strong sensitivity to snowpack volume scatter. 19 GHz measurements are generally regarded as the background measurement, and of little sensitivity to SWE itself. This analysis of four years of boreal forest snow survey data and AMSR-E brightness temperatures has highlighted the problematic dependence of 37 GHz measurements on vegetation, which can render relationships with SWE as spurious. 19 GHz measurements are not an appropriate background frequency across the northern boreal forest (particularly late in the winter season) because of sensitivity to snowpack volume scatter when SWE exceeds ~120 mm. Instead, 10 GHz measurements provide the necessary non-scattering frequency, and when paired with 19 GHz data, an interseasonlly consistent, statistically significant linear relationship with SWE was identified. While 19 GHz measurements are available across the satellite passive microwave data record (1978 to present), a 10.7 GHz channel was not included on the Special Sensor Microwave/Imager (SSM/I; 1987 onwards). AMSR-E is a science (not operational) sensor, so the future of the 10.7 GHz time series is dependant on the future GCOM-W mission proposed by the Japanese Aerospace Exploration Agency.

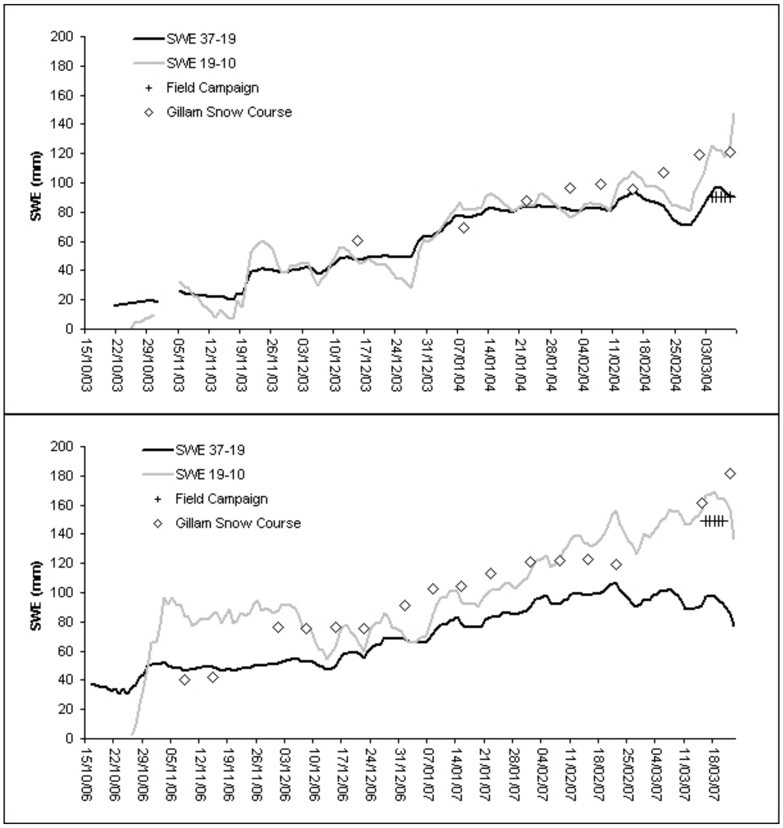

Figure 5. SWE time series from AMSR-E and surface measurements near Gillam, Manitoba: 2003/04 (a) and 2006/07 (b).

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