Comparison of SSM/I Satellite Data with Modeled Snowpack Water Content for Areas of Northern and Southern Ontario

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ABSTRACT

Passive microwave data from the Special Sensor Microwave/Imager (SSM/I) is being used to measure snow-water equivalent (SWE) in the non-forested landscape of the Canadian prairies. To extend this approach to forested areas in Ontario, SSM/I data from three winters for a Northern Ontario (forested) site, as well as a more southerly non-forested site, were compared to SWE modelled by ASAAM, a snow accumulation and ablation model. A linear regression was used to fit the difference between the vertically polarized 19 GHz and 37 GHz SSM/I channels to the modelled SWE. Data were screened to remove bare ground and wet snow points.

The parameters in the proposed algorithm include adjustments for snow density and forest cover between the two sites. The result improves upon the algorithm outlined by Goita *et al.* (2003) for the years and sites studied.

Keywords: snow-water equivalent, snow density, passive microwave, algorithm development

INTRODUCTION

Passive microwave radiometric data from satellite receivers can provide information on the properties of land-surface snowpacks. The first application of such data to snow hydrology was in the measurement of the areal extent of snow-covered surfaces (Chang *et al.*, 1976; Grody and Basist, 1996; Tait *et al.*, 2001). More recently, algorithms have been developed to use microwave data to estimate the extent of wet snow within the snow-covered area and to estimate the snow water equivalent of dry snowpacks (Goodison and Walker, 1995; Goita *et al.*, 2003)

One successful application has been the preparation of maps of the areal variation of snow water equivalent of the snowpack in the prairie provinces of Canada using the Special Sensor Microwave Imager (SSM/I) onboard the US Defence Meteorological Satellite Program (DMSP) series of satellites (Goodison and Walker, 1995). The SSM/I sensing system is robust, providing data during cloudy conditions and during the night. A special advantage for snowpack monitoring is the high frequency of coverage for most areas, usually between 2-6 passes per day depending on the number of satellites in operation (Pietroniro and Leconte 2000), which allows monitoring of the rapid temporal changes in the snowpack during periods of rapid ablation.

The SSM/I data provide areal coverage of brightness temperatures at 19, 22, 37 and 85 GHz at vertical and horizontal polarization (except at 22 GHz where only vertical polarization is measured) with each pixel representing an area of about 625 km^2. Various algorithms exist for determining snow water equivalent by a passive microwave means but most are based on changes in the difference between brightness temperatures at two or more frequencies. In dry snow, the

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dominant scattering mechanism for microwave radiation is stronger at higher frequencies. Algorithms generally use the difference between the high scattering frequencies (85 or 37 GHz) and low scattering (19 GHz) to calculate the brightness temperature index (Singh and Gan, 2000).

Application of microwave data from systems such as SSM/I to interpretation of snow properties in forested areas has been more challenging than the application to areas with sparse, low-height vegetation because of the interactions of the taller vegetation with the microwave radiation. In a mature forest in central New Brunswick, it was found that the SSM/I signal was more related to air temperature than to snow depth (Smyth and Goita, 1999). In a study in the boreal forest in northern Canada, an algorithm that incorporated vegetation effects was developed as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) (Chang et al., 1996).

The contrasting results between the prairie and forested areas demonstrate the need to adapt algorithms to different environments. Walker and Goodison (2000) concluded that none of the available algorithms is able to cope with the whole range of possible local variations in landscape and snow properties. The varying landscape of Ontario, particularly the existence of large forested areas, requires a set of algorithms that can be used selectively to interpret useful hydrologic snow properties such as the snow-water equivalent.

In this study, two test areas have been chosen: a forested area in northern Ontario and an area in southern Ontario that is 75% open fields and 25% forested. The objective of the study was to use a comparison of the SSM/I data between these two areas with differing amounts of forest cover to establish the effects of vegetation on the best-fit algorithm for estimation of the snow-water equivalence of the winter snowpack.

Study Areas

In order to examine the feasibility of using satellite-based data to interpret the water-equivalent content of the snowpack in forested areas two study areas were chosen that represent different forest-cover conditions in Ontario. The Mattagami Watershed site in the Timmins area of Northern Ontario was chosen because of its relatively uniform forest cover and undeveloped landscape typical of much of northern Ontario. This specific site was selected to take advantage of preliminary hydrological modelling results (Schroeter *et al.*, 2000) and the assembling of meteorological data that had been done for this modelling. The second area, near Corbetton in the upper Grand River watershed, was chosen to include a mixed field and forested area representative of the northern fringe of agricultural land in Southern Ontario. Corbetton is the site of a snowcourse sampled by the Grand River Conservation Authority (GRCA) and modelling of snow cover at this site had been done by Schroeter (1988).

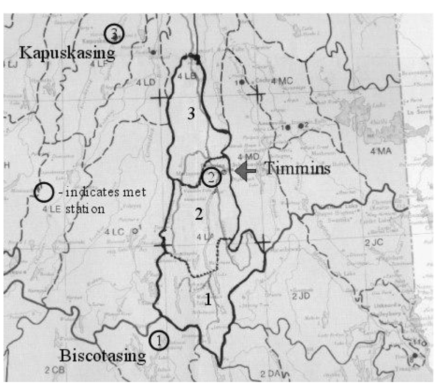


Figure 1: Map of the Timmins area (Schroeter *et al.*, 2000).

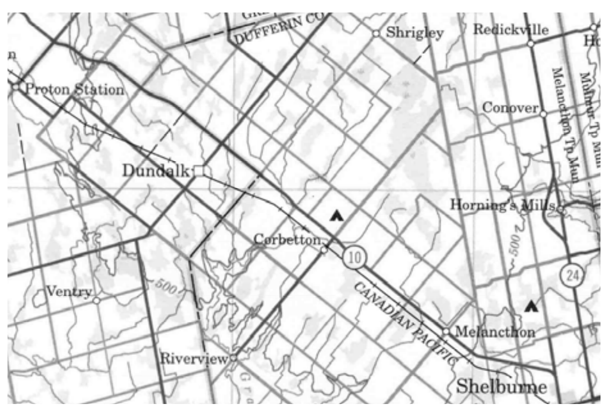


Figure 2: Map of the Corbetton area (Canada Centre for Mapping, 1996).

Mattagami Study Site

The main locator for the Mattagami River watershed is the City of Timmins (Figure 1), which is located at the downstream end of the watershed. The watershed is mostly forested; less than 10% of the watershed surface is categorised as lake or unforested wetland (Cihlar and Beaubien, 1998). The annual precipitation in the area is 830 mm with one third of this precipitation falling as snow. A snowpack usually forms in November and remains until April (Environment Canada, 2000). Measurements of fresh-snow depth and accumulated snowpack depth are taken daily at the Timmins Airport (48°34' N, 81°24' W). Ontario Hydro, and its successor Ontario Energy make bi-weekly measurements of snow depth and snow water equivalent at several snowcourse lines in the general vicinity of the watershed. Data from the meteorological station at the Timmins airport was used for modelling and comparison with satellite data and the Ontario Hydro snowcourse data was used to judge the success of the snowpack modelling.

Corbetton Study Site

The Corbetton snowcourse of the Grand River Conservation Authority (44°10' N, 80°18' W) is located in the headwaters of the watershed of the Grand River in southern Ontario. The surrounding area is predominantly agricultural with patches of forests (less than 25% of the area) scattered throughout (Centre for Topographic Information, 1999). In this area, the annual precipitation is 1040 mm, with just less than one third of the precipitation due to snowfall. The snowpack accumulation period usually runs from December through March (Environment Canada, 2000). Snowcourse measurements are taken at Corbetton approximately every two weeks throughout the snow season for seven points in a pasture and three points in an adjacent forested area.

Comparisons can be made between the satellite data and snow course observations of SWE, snowpack depth and the derived quantity, snowpack density. Additionally, data from nearby meteorological stations, Ruskview (44° 14', 80° 08') and Proton Station (44° 10', 80° 31'), shown above in Figure 2, were used for snowpack modeling.

ASAAM model

In this study results from a calibrated snowpack model are used as the "ground truth" in the development of the algorithms for SSM/I-based estimates of SWE. We used the Areal Snow Accumulation and Ablation Model (ASAAM) developed at the University of Guelph in the late 1980's. This model was specifically designed for shallow ephemeral snowpacks in rural watersheds in Southern Ontario (Schroeter, 1988).

The required inputs for the model are all commonly measured climatic variables such as daily maximum and minimum temperatures, rainfall, snowfall and average daily windspeed (Schroeter and Whiteley, 1987). The model is calibrated for a specific location, principally by the adjustment of the temperature-based melt factor and of the factors influencing the increase in density of the snowpack with age.

ASAAM was used to model the snow-water equivalent (SWE), snow depth and liquid water content (LWC) of the snowpack throughout the winter season for the two study sites at Corbetton and Timmins.

The results from the modelling were treated as field-based data for calibration of the SSM/I observations. Ultimately the SSM/I data was fit to the modelled data in order to develop algorithms to better interpret snow water equivalent from the SSM/I data. Three winters were modelled at each location and a number of trial algorithms were fitted to the model results. Table 1 shows the seasonal average of the modelled snow properties.

Table 1. Average modelled snowpack conditions for study periods

Study Site	Year	No. of days with snow	Mean Snow Depth (cm)	Mean SWE (mm)	Mean Snow Density (g/cm^3)
Timmins	1997	190	42.6	104.3	0.24
	1998	184	49.2	125.0	0.25
	1999	188	37.8	83.8	0.22
Corbetton	1998	76	21.3	34.3	0.16
	1999	99	21.8	28.4	0.13
	2000	141	44.4	114.9	0.26

Satellite data

In this study, interpreted brightness temperatures from the Special Sensor Microwave/Imager (SSM/I) system for the winters of 1997-1998 through the winter of 2000-2001 have been used. The SSM/I satellite data was retrieved from the National Oceanic and Atmospheric Administration Satellite Archive (NOAA, 2002).

The SSM/I pixels selected for each location were limited to those pixels whose centre was within a 25 km radius of the index location for each study area. For Mattagami, the index location was the Timmins airport; for Corbetton, the index location was the site of the snow course. For some passes this selection process resulted in more than one SSM/I pixel being selected for the area.

Previous research has suggested that data from the morning pass of the satellite is often better for estimation of SWE than data from the afternoon pass (Goodison and Walker, 1995; Tait, 1998) because there is greater likelihood of liquid water being present in the snow in the afternoon. In addition the ASAAM model results were used to remove SSM/I points for days when the snow was wet, so that SSM/I data from the morning satellite overpasses for days with a dry snowpack only where included in the dataset.

Brightness Temperature Difference Analysis

According to theory, the 19V channel represents the ground condition and passes through the snow with relatively little scatter. The 37V channel, at a wavelength of 0.81 cm that is approximately the size of snow grains, scatters as the microwaves pass through the snowpack, leading to a lower brightness temperature (Foster *et al.* 1984). The amount of scattering in the snow pack, which is representative of the mass of snow crystals present, can be represented by the difference between the two channels.

The difference between the 19 GHz and 37 GHz, vertically polarized channels, 19V-37V, was fitted to the modelled SWE using a linear regression. This analysis was done for each winter at each location; analyses using combined data from two winters with different snow properties were also done. Each analysis results in an expression of the following form.

$$\text{SWE} = \text{slope}*(19\text{V}-37\text{V}) + \text{constant} \tag{1}$$

where SWE = estimate of water equivalent of snowpack (mm liquid water)
slope, constant = the slope and intercept of the regression line
19V- 37V = brightness temperature difference between 19V and 37V channels

The coefficient of determination R^2 was used as an indication of how well the algorithm fit the SSM/I data to the modeled SWE. In addition an Adjusted Error of Estimate was used for algorithm evaluation

$$AE = \frac{1}{meanSWE}\sqrt{\frac{\sum (x-y)^2}{n(n-2)}} \tag{2}$$

where AE = adjusted error of estimate
mean SWE = average snow water equivalent predicted by ASAAM (mm)
x = independent variable
y = dependent variable
n = number of observations

For every winter in each of the study areas the best-fit algorithm was found. For the Timmins site, the regression was performed on the combined 1998-1999 and 1999-2000 winter datasets in order to include a winter with a large snowpack with a winter where the snowpack was smaller. As an alternative, the more similar 1997-1998 and 1999-2000 winters were also combined. At the Corbetton site, the results from the 1998-1999 winter season showed almost no correlation, leaving only the 1999-2000 and 2000-2001 winter datasets to be analysed together.

Table 2. Snow water equivalent algorithms resulting from brightness temperature difference analysis for Timmins and Corbetton

Study site	Year	R^2	Constant	Slope
Timmins	1997-1998	0.775	63.66	10.72
	1998-1999	0.378	100.39	10.60
	1999-2000	0.708	53.76	10.58
	97/98&99/00	0.758	59.6	10.87
	98/99&99/00	0.584	67.57	11.93
Corbetton	1998-1999	0.015	39.24	-0.67
	1999-2000	0.499	31.60	4.24
	2000-2001	0.588	54.70	5.15
	99/00&00/01	0.71	41.04	5.77

Comparing the fitted algorithms for various years at Timmins, the SSM/I data from the winters of 1997-98 and 1999-2000 fit the ASAAM SWE reasonably well with R^2 values of 0.775 and 0.708, respectively. For the combined year results, the 1997-98 & 1999-00 combined algorithm fits the ASAAM SWE results well. The 1998-99 & 1999-00 combined algorithm has a lower R^2 value, 0.584, but the slope and intercept is consistent with the algorithms created from the other datasets. The important result from the Timmins site is that the slopes and intercepts found from different years match one another reasonably well, which indicates that a similar algorithm will work for all three years.

At Corbetton, the constants and coefficients resulting from the 1999-2000 and 2000-2001 winters are similar, although there are larger between-year differences at Corbetton than at Timmins.. The best result for Corbetton for a single winter was found for the 2000-2001 winter, with an R^2 value of 0.588. For the 1999-2000 winter, the algorithm has a lower slope and a lower constant with an R^2 value of 0.499. Combining the 1999-2000 winter with the 2000-2001 winter for Corbetton, the fit of the one regression applied to the two winters together improves to an R^2 value of 0.71.

The SSM/I brightness temperature difference between the 19V and 37V channels for the 1998-1999 winter provided a poor match for the trend of the modelled snow pack for the Corbetton site. A large snow accumulation early in the snowpack period was shown by both modeling and by snow course measurements but was missed by the SSM/I data. The explanation for this is not known but may be caused by unusual snowpack characteristics or a very localized pattern of heavy snowfall for an early winter storm.

The 1998-1999 winter was also the least successful fit for the Timmins site. However, at the Timmins site, the low R^2 value is due to daily scatter in the SSM/I values as well as an underestimate of the snow pack later in the season, which contrasts with the early-in-the-season miss at the Corbetton site.

Referring back to Table 2, the slope of the relationship between brightness difference and SWE is reasonably consistent between years at each location but much larger at Timmins than at Corbetton Since the difference between the 19V channel and the 37V channel is much smaller for the Timmins site than the Corbetton site, a larger slope is needed to fit the modelled SWE. This opens the possibility of relating the slope of the brightness-temperature-difference equation to properties of the site.

One major difference between these two sites is the difference in brightness temperature between horizontal and vertical polarization for the 19GHz frequency. This difference can be linked to differences in vegetation cover. The SSM/I brightness temperature differences between the 19V and 19H channels were investigated for the period without snow. The differences shown in Table 3 are the average, per winter, of (19V-19H), combining results for the pre-snowpack and the post-snowpack period.

Table 3. 19 GHz polarization difference relationships with slope of regression lines for Timmins and Corbetton

Study site	Year	Fitted Constant	Fitted Slope	Average 19V-19H	Slope * (19V-19H)	Slope + (19V-19H)
Timmins	1997-1998	63.66	10.72	4.56	48.86	15.28
	1998-1999	100.39	10.6	4.39	46.51	14.99
	1999-2000	53.76	10.58	4.77	50.43	15.35
	3-year average	72.6	10.63	4.57	48.60	15.20
Corbetton	1998-1999	39.24	-0.67	10.48	-7.02	9.81
	1999-2000	31.6	4.24	10.48	44.44	14.72
	2000-2001	54.7	5.15	8.12	41.80	13.27
	3-year average	41.85	2.91	9.69	26.41	12.60
	2-year average without 1998-99	43.15	4.70	9.30	43.12	13.99

The 19 GHz polarization difference is consistent between years for each site for the no-snow period. The polarization difference is on average 5 K higher at Corbetton than at Timmins. Comparing these polarization differences to the slope of the regression between the 19V and 37V brightness temperature difference and ASAAM SWE, the higher slope at Timmins corresponds with a lower 19 GHZ polarization difference in comparison to Corbetton.

When the slope is added to or multiplied by the polarization difference, as shown in Table 3, the result is consistent between these two sites for all of the winters, excluding the 1998-1999 winter in Corbetton. For the multiplication of the slope by the polarization difference, the result is consistently between 40 and 50. Likewise, the sum of the slope and the polarization difference is 15.2 on average in Timmins and 14 in Corbetton. These results indicate that there is a possibility of predicting the slope of the regression line between the SSM/I 19V-37V brightness temperature difference and ASAAM-modelled SWE at different sites by using the difference between vertically and horizontally-polarized channels at 19 GHz.

Another possibility is to link the slope of the regression between sites and the percentage of forest cover, as was done by Chang *et al.*, 1996. The slope at Timmins is 10.6, on average, with 90% forest cover, and the slope at Corbetton is 4.7, on average, with 25% forest cover. If the relationship between forest cover and slope were linear, the equation, Slope = 2.5 + 8.9f, would fit these two points. It is interesting that the algorithm found by Goodison and Walker (1995) had a slope of 2.7 (49.27/18) for the Canadian prairies where fraction of forest cover, f, is approximately zero.

Further research at sites with different vegetation cover is required to investigate the possible link between the slope of the regression of SSM/I 19V-37V brightness temperature difference and ASAAM-modelled SWE with the percentage forest cover or the difference between vertically and horizontally-polarized channels at 19 GHz.

Another interesting result from this analysis is that the intercept found for the equation appears to be related to the mean annual snow density. Rott and Aschbacher (1989) describe the intercept constant as being related to the snow morphology and vegetation cover. In dry-snow accumulation periods, density tends to increase with both increasing snow depth and increasing average crystal size, two important aspects of the morphology of the snowpack. Table 4 shows the mean snow depth, snow water equivalent and snow density along with the fitted constants from the 19V-37V brightness temperature difference. The density of the snow was calculated by dividing the modeled snow water equivalent by the modeled snow depth. The last column of the table contains the ratio of the constant to the snow density.

Table 4. Mean snow depth and snow water equivalent with brightness temperature difference algorithm results.

Study site	Year	No. of days with snow	Mean Snow Depth (cm)	Mean SWE (mm)	Mean Snow Density (g/cm^3)	Constant	Constant/ Density
Timmins	1997-1998	190	42.6	104.3	0.24	63.66	260
	1998-1999	184	49.2	125.0	0.25	100.39	395
	1999-2000	188	37.8	83.8	0.22	53.76	243
Corbetton	1998-1999	76	21.3	34.3	0.16	39.24	244
	1999-2000	99	21.8	28.4	0.13	31.60	243
	2000-2001	141	44.4	114.9	0.26	54.70	211

The consistency in the constant/density ratio between the study years at Timmins and Corbetton shows the possibility of a relationship between the constant of the brightness temperature difference algorithm and snow density. One problem with deriving the constant simply using this ratio is that it does not allow for a negative constant, as is used in the prairies by Goodison and Walker (1995).

Another possible way to estimate the intercept for this equation, more independent of the ASAAM results, is to substitute the average brightness temperature for the no-snow period into Equation 1 with SWE of 0 and solve for the intercept C_o as shown in Equation 3. The constant, C_o, is site specific and is derived from the average value of no-snow brightness difference; in this case three years of data were available at each site. The C_o value for Timmins was calculated to be 42.4 and 24.4 for Corbetton. The calculations are summarized in Table 5.

$$C_0 = - \text{slope } (19V\text{-}37V)_o \qquad (3)$$

where C_o = predicted intercept constant for small snow depths
Slope = slope of regression of SSM/I (19V-37V) vs ASAAM SWE, 10.6 for Timmins and 4.7 for Corbetton
$(19V\text{-}37V)_o$ = average brightness temperature difference for the no-snow period

As a snowpack develops adjustment can be made to the intercept Ca to include the effect of increasing snow density for deeper snowpack conditions. One possible way to include snow density is shown in Equation 4. This format of including the snow density allows for a negative constant as seen in Goodison and Walker (1995). The snow density, d, was calculated from ASAAM results. The reference snow density is a value that is site-specific and can be approximated at the minimum snowpack density. The values shown in the Table 5 were picked to fit the C_a value to the fitted constant with d_{ref} of 0.1 g/cm^3 and A of 185.

$$C_a = C_o + A(d - d_{ref}) \tag{4}$$

where C_a = constant adjusted for snow density
C_o = constant, as above
d = average snow density for season, g/cm^3
d_{ref} = reference (minimum) snow density, g/cm^3
A = adjustment factor for density

Table 5. Calculation of the density-adjusted constant, C_a

	Year	No-snow $(19V\text{-}37V)_o$	C_o	d	d_{ref}	C_a	Fitted constant
Timmins	1997-98	-4	42.4	0.24	0.1	68	63.66
	1998-99	-4	42.4	0.25	0.1	70	100.39
	1999-00	-4	42.4	0.22	0.1	65	53.76
Corbetton	1998-99	-5.2	24.4	0.16	0.1	36	39.24
	1999-00	-5.2	24.4	0.13	0.1	30	31.60
	2000-01	-5.2	24.4	0.26	0.1	54	54.70

This method of calculating C_a matches the fitted constant well. It is only for 1998-1999 in Timmins that the C_a value significantly underestimates the fitted constant. For the other years the average difference in predicted and fitted intercept is 4 mm SWE.

Figure 3 compares the brightness temperature difference algorithms found for the Timmins and Corbetton site with the algorithm developed for the Canadian Prairies by Goodison and Walker (1995). The Timmins and Corbetton algorithms are shown with the calculated intercept of C_o based on the observed no-snow average brightness difference at each location. The prairie algorithm is as presented by Goodison and Walker (1995) and givens an apparent no-snow brightness difference of + 7.5 K, opposite in sign to the observed differences at Timmins and Corbetton.

For the higher-slope locations, (Timmins and Corbetton), an error in the 19V-37V brightness temperature difference produces a much larger error in SWE than would occur at the lower slope found for the prairies. This helps explain the considerable scatter in SWE estimates for Timmins and Corbetton.

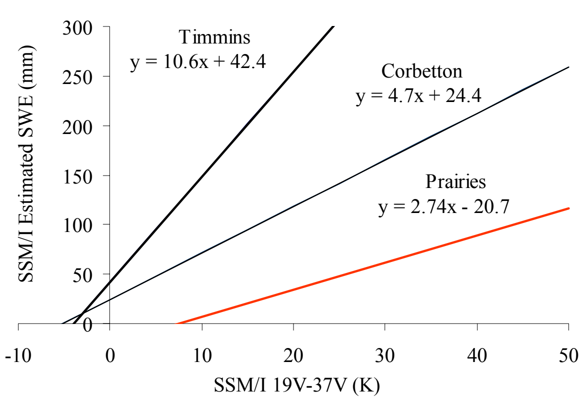


Figure 3: Comparison of Timmins, Corbetton and Prairie algorithm (Goodison and Walker, 1995)

More years of data for different study sites would be required to verify if a numerical relationship between mean annual snow density and the constant in the algorithm exists but the results definitely show that this parameter is not constant between years and linking the constant to snow density is a possibility for future study.

One way to apply this ratio for SSM/I SWE estimation would be to use ASAAM-predicted snow density to adjust the constant of the algorithm on a daily basis. The average slope of the 19V-37V regression lines calculated for the BTD analysis were used; a slope of m=10.6 for Timmins and m=4.7 for Corbetton. The algorithm fit improves as shown in Table 6. The Original R^2 refers to the results from Table 2 while the Density-dependent R^2 value refers to the fit resulting from Equation 1 with the constant calculated by Equation 4. The Adjusted Error is calculated as described in Equation 2.

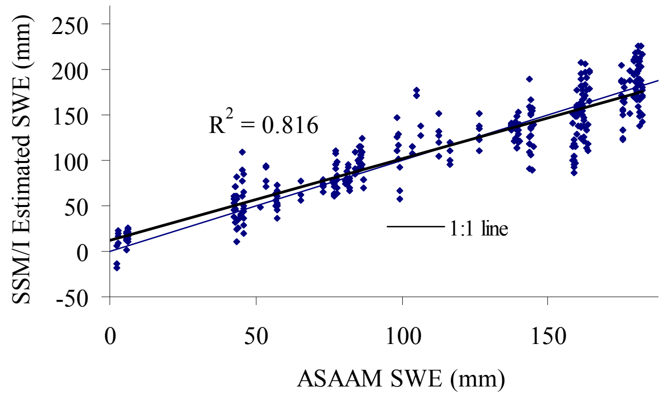
Table 6. Comparison of fitted 19V-37V brightness temperature difference algorithm with snow density adjusted 19V-37V brightness temperature difference algorithm.

Study site	Year	Mean SWE (mm)	Original R^2	Density-dependent R^2	Adjusted Error
Timmins	1997-1998	104.3	0.775	0.82	0.23
	1998-1999	125.0	0.378	0.43	0.43
	1999-2000	83.8	0.708	0.77	0.35
Corbetton	1998-1999	34.3	0.015	0.21	2.52
	1999-2000	28.4	0.499	0.43	0.66
	2000-2001	114.9	0.588	0.66	0.35

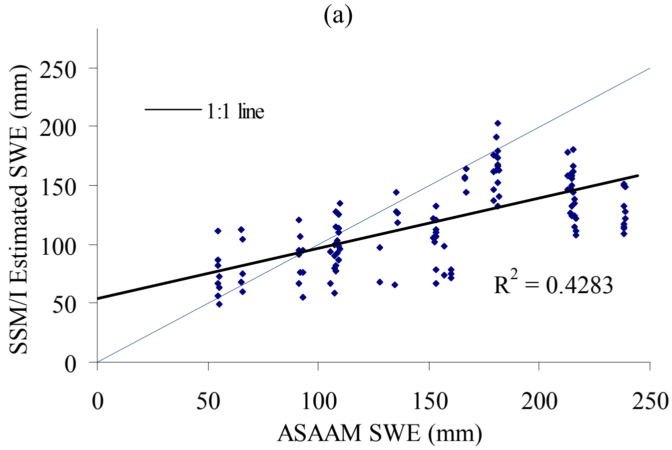
The R^2 values of the fit improve from the previous algorithms when the algorithm with a snow-density dependent intercept constant is fitted to the modeled SWE, with the exception of the 1999-2000 winter in Corbetton. This improvement is not surprising since the output of the model, snow density, is being used to predict the SWE values from the SSM/I data. Figures 4 and 5 show the density-dependent algorithm applied to the study periods in Timmins and Corbetton, respectively.

Although the fit improved for the 1998-1999 winter in Corbetton, Figure 5 (a) shows that the slope of the relationship between ASAAM SWE and the estimated SWE is negative. Using the daily snow density calculated by ASAAM does not improve this fit since the model and the SSM/I data are so different, as noted previously.

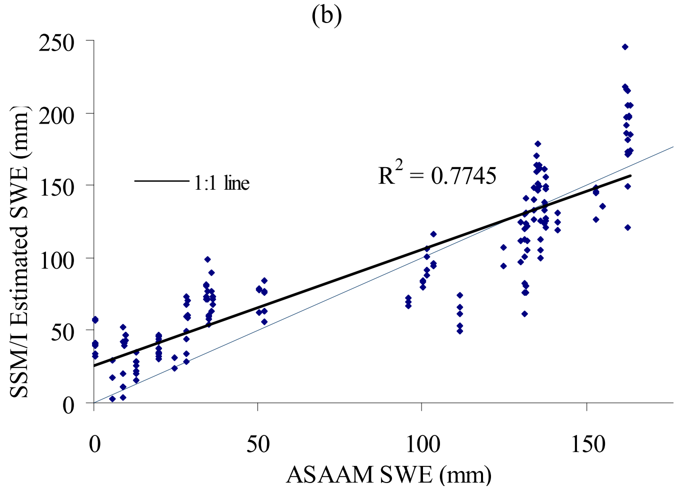
In Figure 5 (b), there is one day where the algorithm overestimates the snow-water equivalent because the snow density estimated by ASAAM is unreasonably high due to a low snow depth. With these points from this one day removed the R^2 value improves to 0.62, which is an improvement over the previous brightness temperature difference algorithm with an R^2 value of 0.499.



(a)



(b)



(c)

Figure 4: Density dependent algorithm plotted against ASAAM-modelled snow-water equivalent for (a) 1997-1998 winter in Timmins (b) 1998-1999 winter in Timmins (c) 1999-2000 winter in Timmins

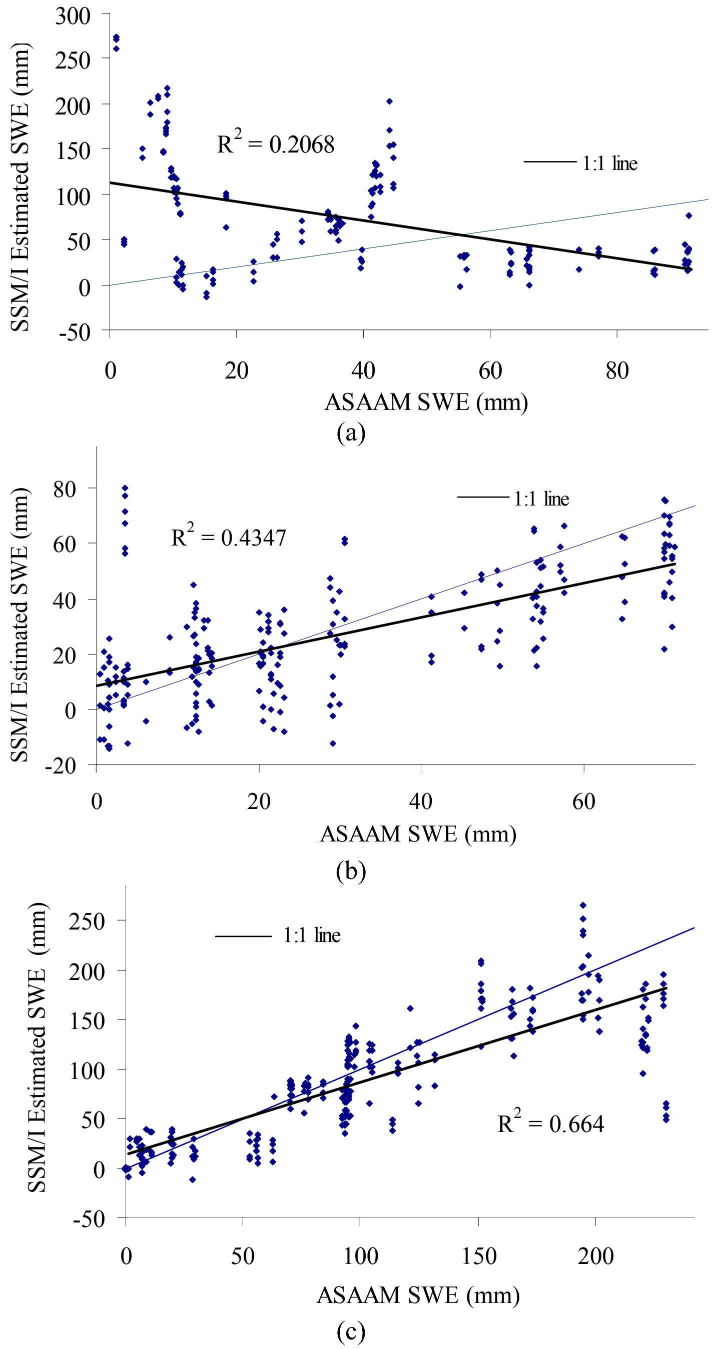


Figure 5. Density dependent algorithm plotted against ASAAM-modelled snow-water equivalent for (a) 1998-1999 winter in Corbetton (b) 1999-2000 winter in Corbetton (c) 2000-2001 winter in Corbetton

Using this combined method over modelling alone improves the SWE estimate from SSM/I and helps justify the use of SSM/I data to provide a spatial representation of the snow pack that cannot be achieved by current meteorologically-based models.

Comparison with existing model

The results from this study were compared to an algorithm created by Environment Canada. The Climate Research Branch at the Meteorological Services division of Environment Canada supplied the results from their algorithm (Goita *et al.*, 2003) for selected dates throughout the snow season. The algorithm combines four separate algorithms for prairie landscapes and coniferous, deciduous and sparse forest cover. The algorithms were developed for the prairie and boreal-forested area of Western Canada.

For each of the Corbetton and Timmins study sites, the Goita *et al.* (2003) algorithm captured some of the variation in the snowpack but was generally insensitive to the seasonal change in snowpack characteristics. This is another indication that the algorithms developed for one region even when adjusted for land-cover type, need to be adapted to the local environment of another region before they can be used successfully.

CONCLUSIONS AND RECOMMENDATIONS

SSM/I varies with snow water equivalent and has a potential to represent the snowpack in both open and forested areas. SSM/I response to dry snow at higher frequency channels scatters more than at lower channels. This response is masked by vegetation in forested areas, as can be seen in the magnitude of the brightness temperature difference, which is higher in Corbetton (little forest) than in Timmins (largely forest) and much higher again on the non-forested Canadian prairies. At sites with small differences in brightness temperature predictions of SWE are much more difficult and more prone to error.

The slope of the 19V-37V brightness temperature algorithm at Timmins was found to be different from Corbetton. The slope can be related to forest cover. Two ways to predict the slope of the regression line between the 19V-37V brightness temperature difference and modeled SWE are suggested. One method involves the use of the polarization difference in the 19 GHz channels to predict the slope. The second method suggests a linear relationship between the fraction of forest cover and the slope of the brightness temperature algorithm. Each of these methods needs to be tested at locations with varying forest cover to validate the relationship.

The intercept constant of the 19V-37V brightness temperature algorithm was variable between years studied. Preliminary results suggest that estimating a base intercept from non-snow brightness difference and modifying the SSM/I algorithm's intercept based on snow density may improve SSM/I SWE estimates. Studies including snow density information are needed to verify if this relationship exists for a larger dataset and for different locations.

The algorithms found in this study are an improvement on the Goita et al. (2003) algorithms when these are applied to the Ontario study areas, emphasizing the need for algorithms to be adjusted for site-specific landcover information. Landcover sensitive algorithms like Goita *et al.* (2003) could possibly be expanded for use in different locations if they are modified for local land cover

Further validation of the algorithms created for the Timmins and Corbetton sites is required. Extension of comparisons between modelled data or ground-based snow cover data and SSM/I SWE estimates to cover larger areas with variable landscape, vegetation and snowpack conditions would be needed to confirm the utility of such algorithms for estimates of SWE in Ontario. It is possible that a combination of snowpack modeling based on meteorological data and SSM/I-based areal variability of snowpack could be effective in producing useful information on snowpack condition for water management decisions.

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