

Comparison of Satellite-Based Data with Modeled Snow–Water Equivalent for Open and Forested Areas

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ABSTRACT

Interpreting microwave-frequency data acquired from the Special Sensor Microwave Imager (SSM/I) for snow–water equivalent is difficult because of the large number of factors that affect the microwave signal. So far, there has been limited success in the interpretation of the SSM/I data for the forested northern areas of Ontario. In this study, the effect of the different channels of the microwave signal, precipitation, air temperature and time of satellite overpass was investigated.

Brightness temperature difference (BTD), multivariable linear regression (MVLRL) and principle component analyses (PCA) were performed over the winter period of 1998–1999. Interpretation of the SSM/I data was improved when analyzed over separate snow periods (accumulation, transition and melt) rather than over the full winter data set. The MVLRL and PCA methods show that the use of additional SSM/I channels can improve the satellite data interpretation as the R^2 value improved from 0.467 to 0.931 and from 0.001 to 0.752, respectively. The MVLRL analysis also suggests that snow water equivalent can be interpreted from SSM/I data for a wet snow condition.

Keywords: SSM/I, passive microwave, snow–water equivalent, principal component analysis

INTRODUCTION

Passive microwave remote sensing has been used to estimate various snow properties such as snow covered area, wet snow and snow water equivalent. The Special Sensor Microwave Imager (SSM/I) data has been used successfully in determining snow covered area and snow–water equivalent (SWE) in the prairie area of Canada (Goodison and Walker, 1994).

Application of SSM/I in forested areas has been more challenging because of the interactions of the 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). An algorithm that incorporated vegetation effects was developed for the Boreal Ecosystem–Atmosphere Study (BOREAS) (Chang et al., 1996).

Cover types in Ontario are quite variable in comparison to the Canadian Prairies. In this study, two test sites have been chosen: a forested area in northern Ontario and a primarily open site in southern Ontario. A comparison of the SSM/I data between these two sites should give insight into the interactions of the signal with the variable Ontario landscape. Three different numerical techniques, brightness temperature difference (BTD), multivariable linear regression (MVLRL) and principle component analyses (PCA) will be used to find an algorithm that best fits the SSM/I data to the modeled snow water equivalent.

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SITE DESCRIPTIONS

Forested Site

The Mattagami River Watershed (47° 30' N and 81° 30' W) is located near Timmins, Ontario. The watershed has an area of 11,560 km², the majority of which is forested. Less than 10% of the watershed is lake or unforested wetland (Cihlar and Beaubien, 1998). The annual precipitation in the area is 880 mm, where one third of this precipitation is from a snowpack accumulation period running from November to April. Data from the meteorological station at the Timmins airport was used for modelling and comparison with satellite data.

Open Site

Corbetton (44°10' N, 80°18' W) is located in the headwaters of the Grand watershed in southern Ontario. The surrounding area is predominantly agricultural with patches of forests (less than 25% of the area) scattered throughout. Snowcourse measurements are taken approximately every 2 weeks throughout the snow season for seven points in an unforested pasture and three points in an adjacent forest block. Comparisons can be made between the satellite data and snow course observations of SWE, snowpack depth and density. Additionally, data from the nearby Shand Dam meteorological station will be used for snowpack modeling.

This analysis follows the initial work described by Bryant (2001). So far, analysis of the forested site has been undertaken. The comparison between the forested northern site and the open southern Ontario site will take place in the second part of this study.

DATA

This study included the use of data from a passive microwave satellite system and climate data necessary to run the snowpack model for study period of November 1998 through to June 1999.

Modelled Snowpack

An areal accumulation and ablation model, ASAAM, was used to model the snowpack throughout the 1998–1999 winter season. The modeling started November 1, 1998 and concluded in June of the 1999. 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). Meteorological inputs to the model were acquired from the Timmins airport station. For the forested site, the redistribution of snow by wind was not included, but will be included in the modeling of the snowpack for the open site.

Satellite Data

Brightness temperatures from the Special Sensor Microwave/Imager (SSM/I) system for the winter of 1998–1999 have been interpreted. The SSM/I satellite data, obtained from the National Oceanic and Atmospheric Administration (NOAA, 2002) satellite archive, provides coverage of the sites twice per day, on average.

The satellite returns brightness temperatures at 4 different frequencies (19, 22, 37 and 85 GHz) and 2 polarizations (vertical V and horizontal H) at each frequency, except 22 GHz, which operates at only the vertical polarization (NOAA, 2002). The five channels used in this study were 19V, 19H, 22V, 37V and 37H. The 85 GHz frequency was not available for this study.

The SSM/I data chosen for this analysis was compared with the modeled snow pack properties derived from the Timmins airport meteorological station. To accomplish this, SSM/I data was selected to correspond with the area around the Timmins airport. This process involved choosing the SSM/I reading when the center of the SSM/I pixel fell within the 25 km x 25 km area around the meteorological station. As a result, there are occasionally days with more than one SSM/I reading for the area. This method of choosing the matching SSM/I data point will be refined further in continuing studies.

RESULTS AND DISCUSSION

In this section, the results from three different analyses (brightness temperature difference, MVL, and PCA) will be shown for the Mattagami area during the 1998–1999 winter period. A comparison between the analysis methods will be discussed at the end of the section.

It has been found by other authors (Walker and Goodison, 1993 and Chang et al, 1996) that the difference of the brightness temperatures of 2 satellite channels (19V–37V) can be used to predict snow water equivalent. Figure 1 shows the SSM/I brightness temperature difference (BTD) and the modeled SWE as a time series plot.

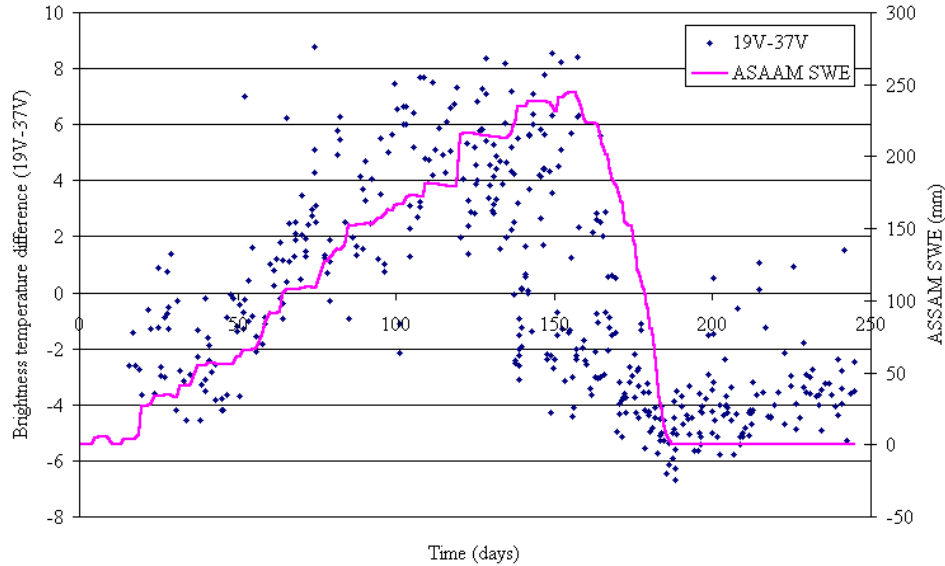


Figure 1. Time series plot of SSM/I brightness temperature difference and ASAAM snow–water equivalent.

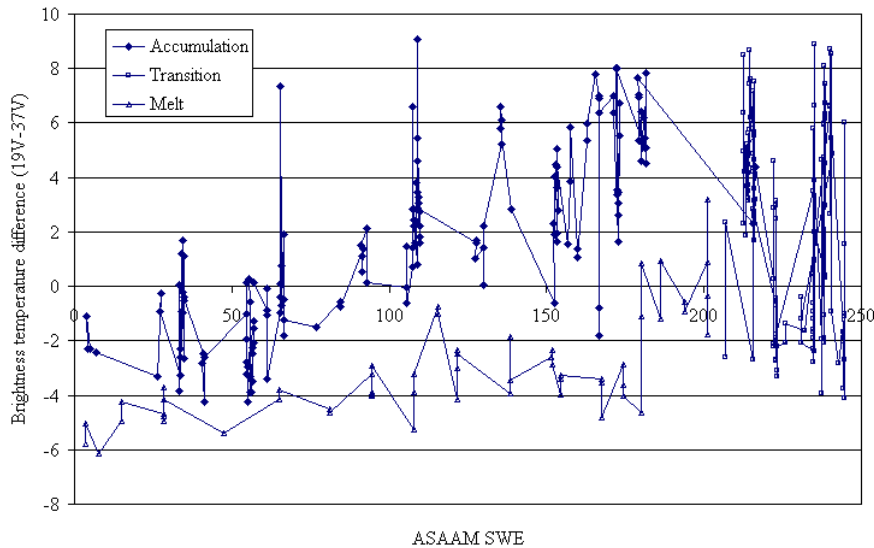


Figure 2. Brightness temperature difference against ASAAM snow–water equivalent for full snow period.

It can be seen from this figure that there is an appreciable amount of temporal scatter. Figure 2 shows a univariate analysis to compare the brightness temperature difference to the ASAAM SWE. A linear regression analysis for this entire winter data set shows an R^2 value of 0.199.

When the data is connected by time, as shown in Figure 2, an apparent hysteresis effect is seen where the trend in the brightness temperature in the snow accumulation period is different from that of the snow melt period. The hysteresis seen in this graph indicates that the dataset may be better represented by three separate periods. Periods of snow accumulation (day 1–121), transition (day 122–163) and snowmelt (day 164–185) were chosen from the time series in Figure 1. The shift from the accumulation period to the transition period can be discriminated by a maximum daily air temperature reading above zero for day 122. This warm temperature caused melting to occur in the snowpack, which adds liquid water to the snowpack. The liquid water changes the dielectric properties of the snow pack (Hallikainen et al., 1987). Throughout the transition period, melt and refreeze occurs, as indicated by the scattered brightness temperature difference. The final melting phase has a consistently wet snow pack. Most algorithms using SSM/I for SWE estimation can be applied only to a dry snow pack (Walker and Goodison, 1993).

Performing a linear regression analysis on each of the three snow periods, the brightness temperature difference is fitted to the ASAAM SWE. The results are shown in Figure 3. The R^2 value for this fit is 0.831. This is a vast improvement over using the entire winter data set in the regression analysis.

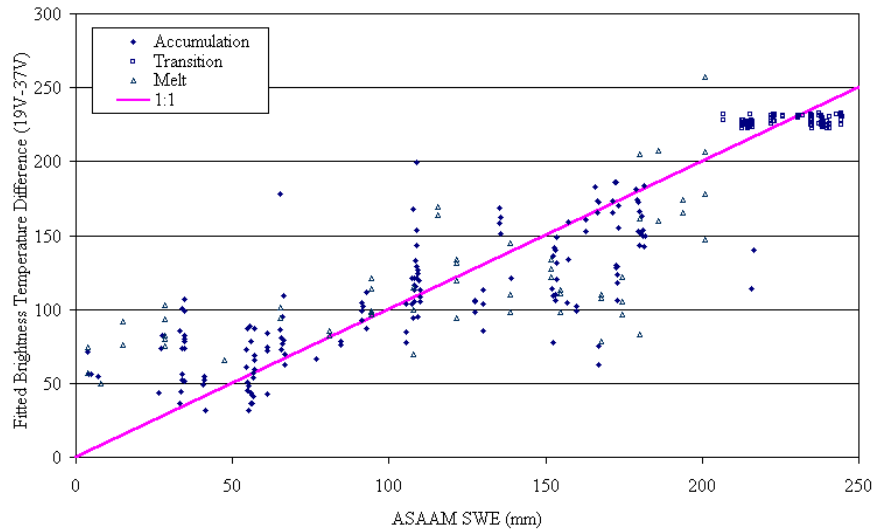


Figure 3. Brightness temperature difference fitted by snow period against ASAAM snow–water equivalent.

Within this regression, there is still a considerable amount of scatter. Possible causes of variation to be investigated or accounted for include cloud cover, precipitation, variations in air temperature and landcover, and the episodic presence of liquid water in the snowpack. Each of these variables, with the exception of landcover, will be investigated by the use of a multiple variable linear regression (MVL) and principal components analysis (PCA). Landcover will be investigated in a subsequent study.

Ten variables were chosen for both the multiple variable linear regression and the principal components analysis. Included are the 5 channels of SSM/I and the time of day of the satellite pass, as well as commonly measured climatic variables such as maximum daily air temperature, minimum daily air temperature, total daily rainfall and snowfall. Time of day was included, although its effect on the satellite-derived SWE has been shown to be minimal (Derksen et al, 2000).

In general, principal components analysis is used to reduce the dimensionality of a dataset. The outcome of the analysis yields one or more calculated variables that represent the full set of input variables. In this analysis, the 10 variables were analyzed over the entire winter dataset. Figure 4 shows the variable calculated from the PCA against the ASAAM SWE. An R^2 of 0.001 demonstrates that the PCA alone does not offer an improvement over the brightness temperature difference analysis for the full winter data set.

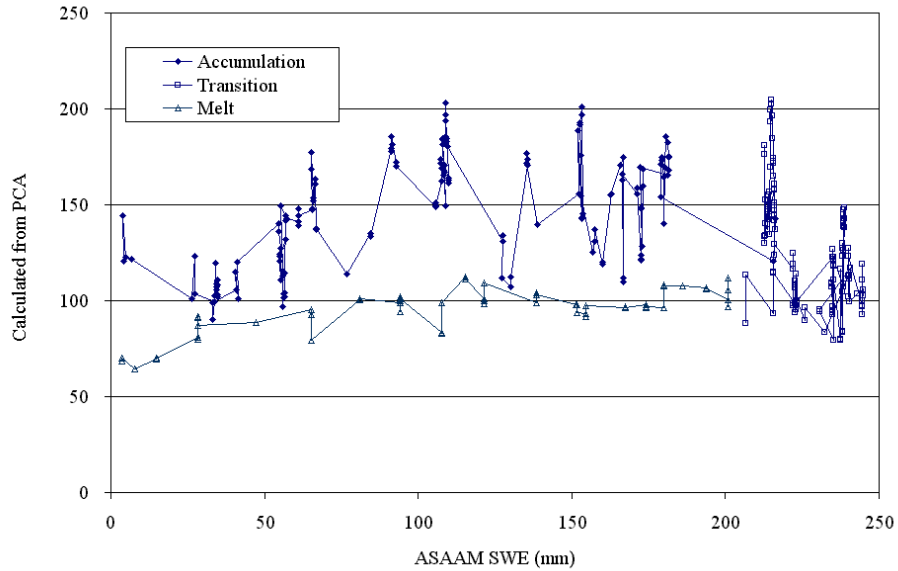


Figure 4. Calculated variable from PCA versus modeled SWE.

Figure 4 suggests that there is a hysteresis effect and that the use of three separate snow periods to fit the ASAAM SWE would be useful.

If the independent result of the PCA is fitted to the modeled SWE using the same accumulation, transition and melt periods as those discussed previously, the result is a closer fit to the modeled SWE (Figure 5). The R^2 for this analysis is 0.752. This represents a poorer fit than offered by the brightness temperature difference analysis for the three snow periods.

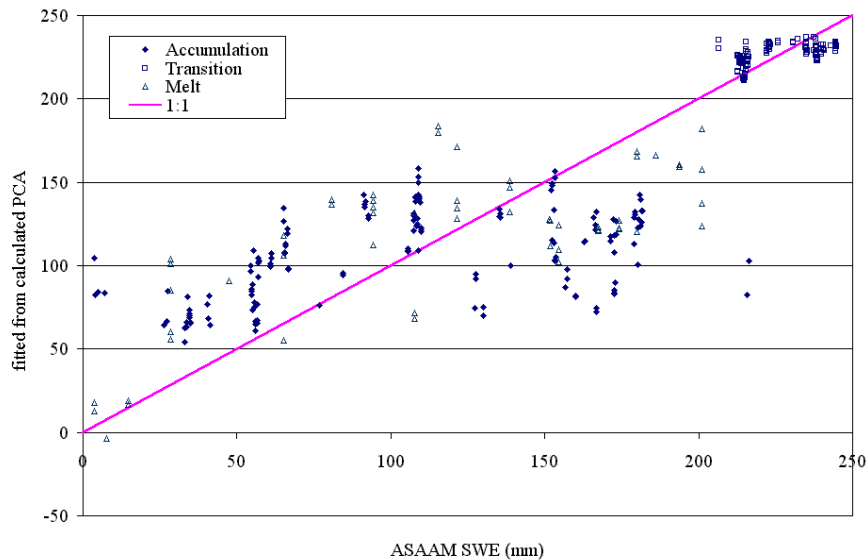


Figure 5. Calculated variable from PCA fitted by snow period versus modeled SWE.

Table 1 shows the calculated eigenvector of the covariance matrix of the dataset. The numbers listed next to the variables represent the weight given to each of the input variables. The PCA identified all of the channels of the satellite as being useful in the characterization of the data set. This suggests that an analysis such as brightness temperature difference, which utilizes only two of the channels, may be improved by including additional channels.

Table 1. Representation of the covariance of the variables

Variable	Weight
19V	0.355
19H	0.409
22V	0.372
37V	0.441
37H	0.460
T max	0.275
T min	0.294
Rain	0.009
Snow	0.006
Time	0.002

The MVLN analysis combined the ten variables together to fit the modeled SWE. It was initially performed for the full winter period as shown in Figure 6. The R^2 for this analysis was 0.467. This is an improvement over both the brightness temperature difference analysis and the PCA performed for the full winter data set as can be expected, as the MVLN is a fitting technique while the other two analyses were performed independent of the modeled results.

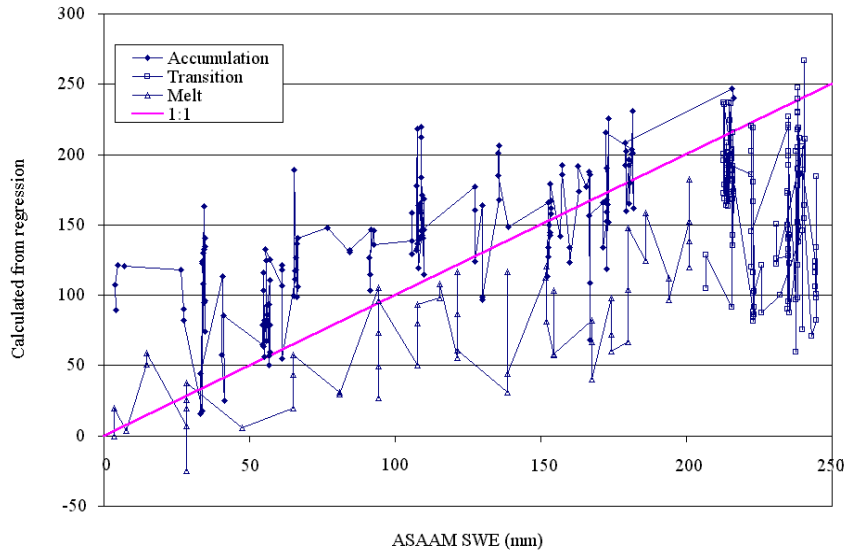


Figure 6. Multiple variable linear regression of selected variables against modeled SWE for full winter period.

Separating the winter into the three snow periods, the MVLN analysis was performed and the results are shown in Figure 7. The R^2 value is 0.931 indicating an improved fit over both the brightness temperature difference analysis and the PCA for the three snow periods.

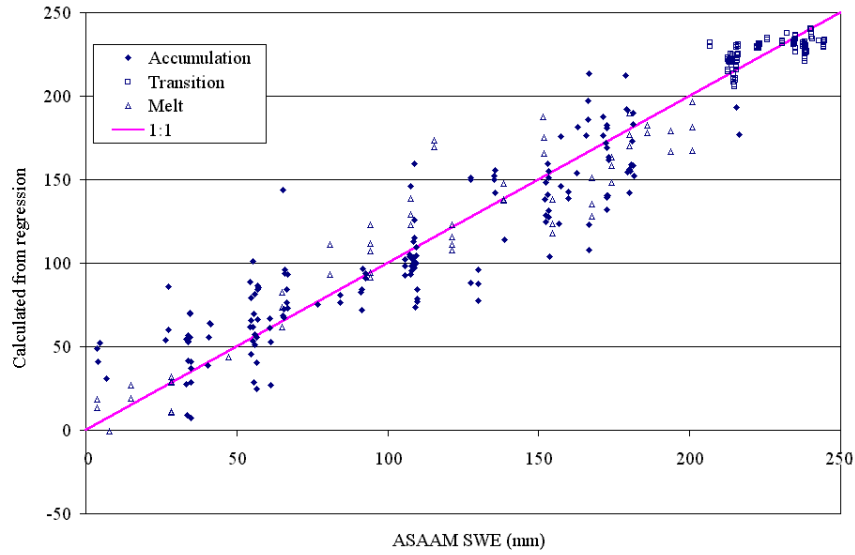


Figure 7. Multiple variable linear regression of selected variables against modeled SWE for separate accumulation, transition and melt periods.

Figure 8 shows how incorporating more channels and variables in the interpretation of the satellite data, by means of a MVLr analysis, is an improvement on the brightness temperature difference (Figure 1).

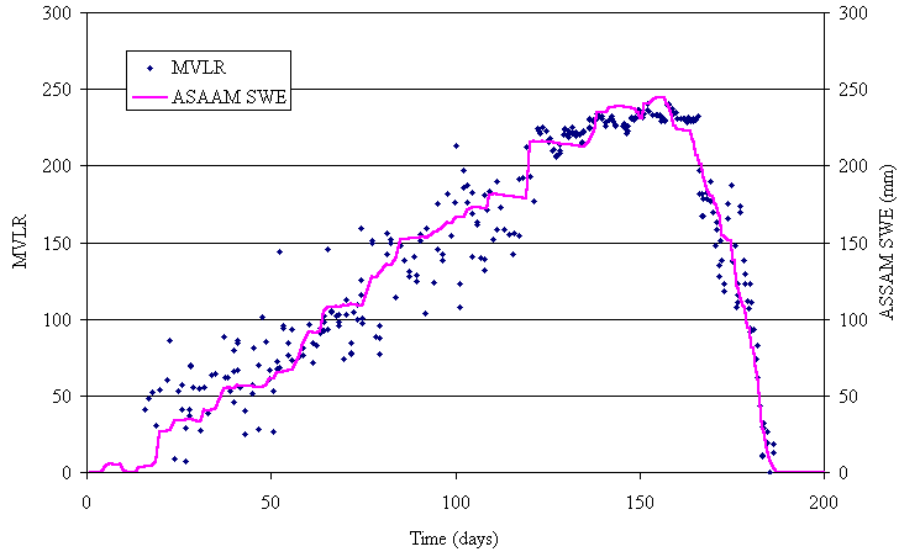


Figure 8. Time series of the three-period MVLr with ASAAM SWE.

The standardized coefficients calculated in this analysis for each of the three snow periods are summarized in Table 2. Coefficients marked as N/A in the table are due to the lack of rain or snow during the period.

Table 2. Standardized coefficients from regression analysis

Variable	Standardized Coefficient		
	Accumulation	Transition	Melt
19V	2.48	0.23	0.11
19H	-2.55	-0.12	0.59
22V	1.43	1.06	-0.69
37V	-2.54	-1.50	-0.45
37H	0.82	0.70	0.21
Tmax	0.24	-0.16	-0.57
Tmin	-0.35	0.31	-0.12
Rain	-0.11	0.10	N/A
Snow	0.16	-0.01	N/A
Time	-0.15	-0.05	0.04
R ²	0.800	0.375	0.883

The linear regression puts the greatest weights on the SSM/I channels, particularly for the accumulation period. In the accumulation period, the 19V and 37V channels have standardized coefficients of nearly the same magnitude but the opposite sign. The standardized coefficients, however, also show that the 19H and 22V channels have significant weights. This implies that for the forested area, use of the 19V and 37V channels alone is insufficient to fully interpret the satellite data. In the transition and melt periods, there are no factors with inordinately heavy weights. The data does however show an almost equally important weighting between the SSM/I channels for the transition and melt periods, again suggesting that all the channels may be significant for this area.

The standardized coefficients also indicate that the other factors are insignificant with the possible exception of maximum daily air temperature, which appears to be important in the melt period. Factors such as rainfall, snowfall and time of satellite overpass were also found to be insignificant in principal component analysis. Use of data from more than one winter would serve to clarify this point.

Table 2 also shows the R² values for each of the snow periods. The variable calculated from the MVLRL analysis for the accumulation and melt periods fits the modeled results well, while it fits poorly for the transition period. A poor fit for the transition period is likely due to the periodic presence of liquid water and the further complexities in the snowpack caused by freezing and thawing. An implication is that satellite interpretation of the transition period will be more challenging than for the accumulation or melt periods.

A good fit for the melt period is encouraging, however, because it suggests that SSM/I data can in fact be used for a non-dry snowpack.

CONCLUSIONS

Table 3 indicates that there is a striking improvement in the interpretation of the SSM/I data when analyzed over separate snow periods rather than over the full winter data set. This is true over all of the analysis techniques employed. This suggests that satellite data should be interpreted by separately considering a snow accumulation, transition and snow melt period.

Table 3. Summary of the R² values for each analyses

Analysis	Full Winter	3 Periods
19V–37V	0.199	0.831
PCA	0.001	0.752
MVLR	0.467	0.931

The MVLR and PCA methods show that the use of additional SSM/I channels can improve the satellite data interpretation. Also, the MVLR analysis shows a good agreement between interpreted satellite data and modeled SWE even for a wet snow condition. The transitional period between snow accumulation and snow melt showed a relatively poor agreement, attributable to the presence of liquid water and freeze/thaw cycles.

Finally, rainfall, snowfall and time of satellite overpass were found to not be significant in both the PCA and MVLR methods.

RECOMMENDATIONS AND FUTURE WORK

The findings from this paper are only for the winter of 1998–1999, future work will include expanding the dataset into other winters and including landcover variation as a factor in analysis. Comparison with the open site will be done to better characterize the cause of the temporal variability seen in the dataset.

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