A TIME SERIES ANALYSIS TO ASSESS THE EFFECT OF SNOWPACK DYNAMICS ON SSM/I BRIGHTNESS TEMPERATURES FOR VARIOUS LAND COVERS IN GREAT LAKES AREA

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Abstract- Using satellite technology to estimate snow characteristics has been employed for years. Despite considerable progress, challenges still exist with respect to accuracy and reliability. It is the aim of this study to estimate snow depth using Special Sensor Microwave (SSM/I) channels and Equal-Area Scalable Earth Grid (EASE-GRID). The study focuses on the Great Lakes Region in the United States. Fifteen SSM/I and EASE-GRID formatted pixels were selected, each 25 by 25 kilometers in size. The pixels were selected based on latitude and land cover characteristics that would produce data significant for a comprehensive study of brightness temperature (TB) of the different SSM/I channels. The actual values for snow depth or 'ground true data' were obtained from the National Climate Data Center (NCDC) and the National Operational Hydrological Remote Sensing Center (NOHRSC). The NCDC provided daily snow depth measurements reported from various stations located in the study area. The measurements were recorded and projected to match EASE-GRID formatting. The NOHRSC SNODAS data set was produced using airborne Gamma radiation and gauge measurements combined with a physical model. The data set consisted of different snow characteristics such as SWE and snow depth, both available in gridded format through the National Snow and Ice Data Center (NSIDC). SSM/I channel signatures – GTVN (19V-37V), GTH (19H-37H), and SSI (22V-85V) – were used along with SWE and Snow Depth to establish a relationship between these data. The results of this study displayed up to 85 percent correlation between snow depth on a specified pixel with various channels and their anomalies. The highest sensitivity is observed for (19V-37V) and (19H-37H) for the three year period observed. This is in accordance with the literature though it indicates necessity of further research to establish an algorithm to estimate SWE/Snow depth for our study area.

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Introduction

Global scale snow cover is an important variable for climate and hydrologic models. It directly influences energy and moisture budgets. Due to its high albedo, snow cover is a primary factor in controlling the amount of solar radiation absorbed by the earth. Decreases in the snow cover extend results in an increase in solar absorption and additional heat which results in additional melt of snow, Armstrong (1994). In regional scale snow water equivalent (SWE) and snow depth are major factors influencing the water resources. Information about the available water during melting season can be used in flood prediction and water resources management. Passive microwave has been employed by many scientists as a tool to estimate snow depth and identify snow cover extend.

Hallikainen (1984) introduced his algorithm for estimating SWE using passive microwave SMMR data. The process involved the subtraction vertical polarizations of 18 and 37 GHz frequencies. The subtracted value, *dT*, was used to define linear relationships between *dT* and SWE]. Chang (1987) suggested using the difference between the horizontally polarized channels SMMR 37 GHz and 18 GHz to derive snow depth –

brightness temperature relationship for a uniform snow field . Chang's method involved two assumptions: 1- the snow is homogenous with a density of 300kg/m^3 2- grain size is .3 mm for the entire snowpack regardless of location or condition of the pack. Rott and Nagler (1994) introduced a decision tree with various thresholds to estimate snow depth .The algorithm uses the spectral difference between vertically polarized channels (19V, 37V, and 85V). [Tb (19)-Tb (37)] shows a positive correlation to snow depth. [Tb (37)-Tb (85)] reaches the maximum value at 7cm of snow depth. The final product of the decision tree is the snow depth, SD= B1+ B2 (19V-37V) + B3 (37V-85V). Goodison and Walker (1994) introduced the most widely used algorithm for North America. The algorithm was originally for Canadian prairies. It defines a linear relationship between GTV ((37V-19V)/18) and snow water equivalent. They also suggested using 37H and 37H polarization differences for identifying wet snow . Grody (1996) suggested a filtering decision tree algorithm for global snow cover identification using SSM/I passive microwave. Grody's algorithm consists of a decision tree which establishes sensitive thresholds to filter out precipitation, warm desert, cold desert and frozen surfaces . De Seve (1997) applied two previously developed models to James Bay area in La Grande River watershed, Quebec, Canada to estimate SWE using SSM/I images. They applied the algorithms suggested by Goodison and Walker (1994) and Hallikainen. The investigations revealed that both models tend to underestimate SWE especially when SWE is more than 200mm. They suggested an improvement for the above algorithms by introducing 200mm as the threshold showing that snowpack observation follows different patterns for SWE > 200mm than SWE < 200mm. They offered modified equations for estimating SWE.

Most of the suggested methods to estimate SWE and snow depth rely on the spectral difference between channels. In addition, all of them have been designed and tested only for high latitude areas. In this study we explore the potential of SSM/I channels and suggested SWE estimation algorithms for a large study area covering Great Lakes area, United States, which consists of varying land

Study Area

The study area is located in Great Lakes area between latitudes 41N-49N and longitudes 87W-98W. It covers parts of Minnesota, Wisconsin and Michigan states. The area has various land covers (Fig 1). The area is covered by 980 (28 by 35) EASE-Grid pixels. To do the time series analysis 19 pixels were selected. The pixels were selected based on their latitude and their land cover type. Table-1 shows the coordinates center of the selected pixels.

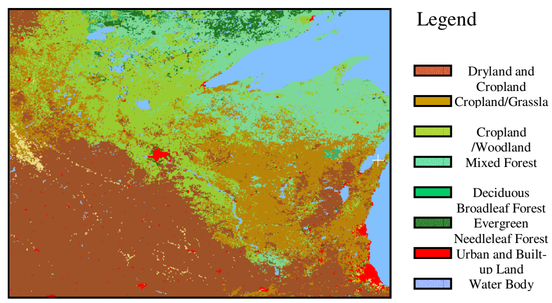

Figure 1. Land cover map of the study area

Table 1. Coordinates of Selected EASE-Grid pixels

Pixel Label	SSM/I Co-ordinates - Centre	
	Latitude	Longitude
1	42.33	-93.62
2	42.89	-91.97
3	43.63	-91.43
4	44.14	-90.57
5	44.39	-89.12
6	45.12	-89.11
7	46.07	-88.19
8	45.59	-88.21
9	46.09	-88.79
10	46.80	-88.46
11	46.80	-88.16
12	46.83	-89.69
13	45.36	-91.18
14	45.56	-92.68
15	47.26	-92.78
16	48.01	-91.88
17	47.92	-94.08
18	48.40	-95.99
19	47.47	-97.47

Data

SSM/I

SSM/I passive microwave radiometer with seven channels is operating at five frequencies (19, 35, 22, 37.0, and 85.5 GHz) and dual- polarization (except at 22GHz which is V-polarization only). The sensor's spatial resolution varies for different channels frequencies. In this study we used Scalable Equal Area Earth Grid EASE-Grid SSM/I products distributed by National Snow and Ice Data Center (NSIDC). EASE-Grid spatial resolution is slightly more than 25km (25.06) for all the channels (NSIDC) although the recorded resolution of the sensor for longer wavelengths is more than 50km. The three EASE-Grid projections comprise two azimuthal equal-area projections for the Northern or Southern hemisphere, respectively and a global cylindrical equal area projection. In our study we used a Northern hemisphere azimuthal equal-area.

Ground Truth Data

Point Gauge Measurements
Snow depth data for the study were derived from point gauge measurements provided by National Climate Data Center (NCDC). The point measurements were averaged and gridded to 25km spatial resolution to match EASE-Grid SSM/I spatial resolution. To increase the reliability of the analysis only pixels with at least one gauge in them were used. In some of the pixels up to three gauge measurements were combined to derive the averaged snow depth for the pixels.

SNODAS SWE
NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) started producing SNOw Data Assimilation System (SNODAS), beginning 1 October 2003. SNODAS includes a procedure to assimilate airborne gamma radiation and ground-based observations of snow covered area and snow water equivalent, downscaled output from Numerical Weather Prediction (NWP) models combined in a physically based, spatially-distributed energy and mass balance model. The output product has 1km spatial and daily temporal resolution. To match the EASE-Grid pixels the SNODAS SWE was averaged over 25 by 25 pixels.

Methodology and Discussion

Nineteen EASE-Grid pixels were selected in study area. The selection began with pixels in low latitudes and dry land to pixels located in the northern part of the study area with ever green needle leaf forest type as shown in Figure 2. The goal is to verify the correlation between SSM/I channels and snow depth and SWE for different types of land cover located in different latitudes.

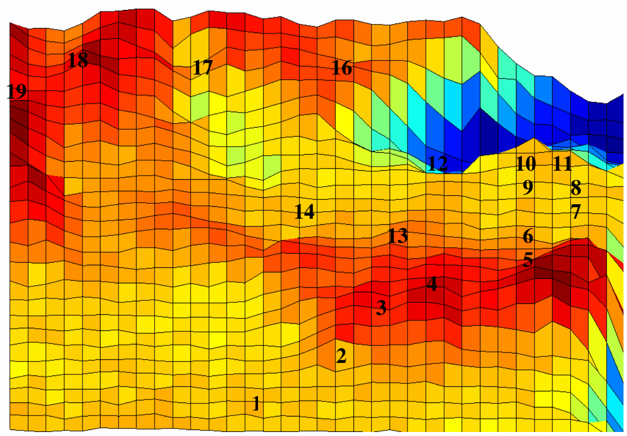

Figure 2. SSM/I image (19V-37V) and points selected

A three year time series (2002-2004) of SSM/I channels vs. Snow depth and SWE for each of the selected points was derived. Figure 3 illustrates the trend of SSM/I signature of GTVN (19V-37V) vs. snow depth at point 9. The plot shows that the discrepancy GTVN (19V- 37V) increases with increasing snow. On the other hand, at points located in low latitudes such as 1 and 2 this pattern can not be detected (Figure 4). To quantify the relationships, correlation coefficient of various SSM/I signature vs. snow depth and SWE are presented in Table 2. The SNODAS SWE is available from 1 October, 2003 which limits our SWE data set to winter 2003-2004. There are three SSM/I signatures used in this analysis. The first one named GTH (19H - 37H) is the difference between 19 and 37GHz in horizontal polarization. The second signature, GTVN (19V-37V) shows the discrepancy between vertically polarized 19 and the discrepancy between vertically polarized 19 and 37GHz.

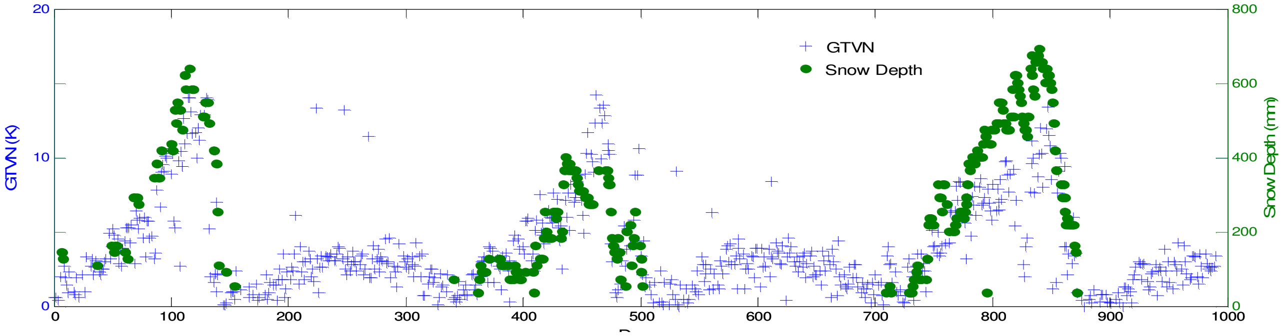

Figure 3. Three year time series of GTVN (19V-37V) vs. Snow Depth for point 9

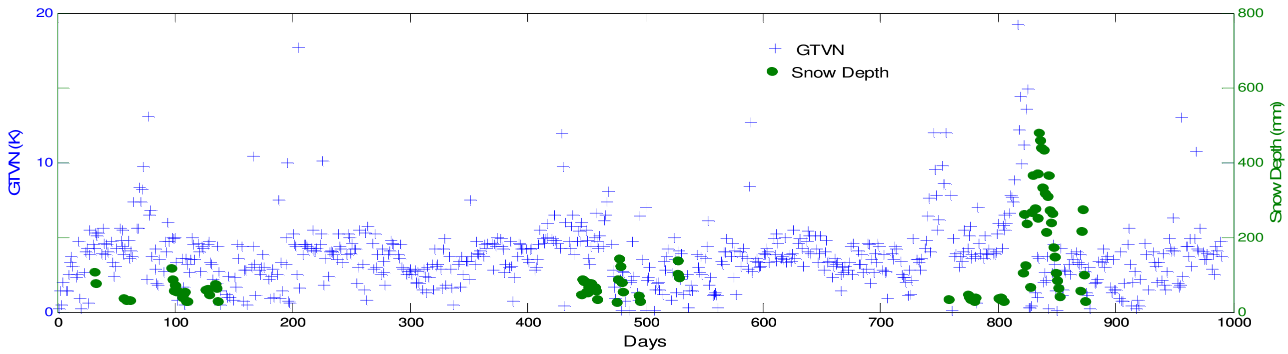

Figure 4. Three year time series of GTVN (19V-37V) vs. Snow Depth for point 2

Table 2. Correlation Coefficients of Snow depth vs Signatures of SSM/I Channels

Pixel Label	2001-2002 Correlation Coefficient			2002-2003 Correlation Coef.			2003-2004 Correlation Coefficient		
	GTH vs. SD	GTVN vs SD	SSI vs SD	GTH vs SD	GTVN vs SD	SSI vs SD	GTH vs SD	GTVN vs SD	SSI vs SD
1	0.69	0.73	0.77	-	-	-	-	-	-
2	0.57	-	0.65	-	-	0.71	-	-	0.84
3	-	-	-	-	-	-	-	-	0.65
4	0.60	0.50	0.71	0.61	0.63	0.55	-	-	-
5	-	-	-	-	-	-	-	-	-
6	-	-	-	-	0.62	0.77	0.52	0.62	0.51
7	-	-	-	0.65	0.62	0.71	0.77	0.72	-
8	-	-	-	-	-	-	0.52	-	-
9	-	-	-	0.74	0.74	0.85	0.74	0.70	-
10	0.53	0.62	-	-	0.70	-	-	0.51	-
11	-	-	-	-	-	-	-	-	-
12	-			-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	0.59	-	-	0.53
15	-	-	-	-	-	-	0.51	0.53	-
16	-	-	-	0.57	0.53	-	0.61	0.64	-
17	-	-	-	-	0.62	-	0.77	0.76	-
18	0.53	-	-	0.76	0.74	0.57	0.85	0.83	0.64
19	-	-	-	-	-	-	-	-	-

Both GTH (19H-37H) and GTVN (19V-37V) have been used by researcher to estimate snow depth and snow water equivalent (SWE) [3, 5]. Finally, SSI (22V-85V) presents the difference between 22 and 85 GHz in vertical polarization. SSI can be used to identify shallow snow cover [6].

Results and Discussion

The presented correlation coefficients in Table 2 are for different winters from 2001-2004. In order to avoid wet snow conditions we used the data starting December 1 of each year to the February 28 of the year after. Three 90 day sets of data were derived for each winter. The correlation coefficients in table 2 show the following:

1- Points located in low latitudes (1, 2, 3, and 4) show no correlations between GTH and GTVN vs snow depth. On the other hand SSI shows correlations with snow depth in low latitudes. This is due to the saturation of channel 85GHz which makes SSI only suitable for estimating shallow snow cover.

2- Points located in mid- latitudes (6, 7, 8, 9) show some correlation between GTH and GTVN vs snow depth but SSI has no correlation with snow depth.

3- No correlations at points that are very close the lake or have a high percentage of water body within or in the neighboring pixels (10, 11, 12, 13, and 14). This is due to the different original resolution of SSM/I sensor in various bands. For instance, at 37GHz sensor has a 37km along track resolution. This decreases to 69km for 19GHz. However SSM/I EASE-Grid have 25km spatial resolution for all channels. When the point is close to the lake, in one channel the brightness temperature value is influenced by the lake but in the other is not. Since the average brightness temperature for the water bodies is significantly different from the land, the discrepancy between channels will be highly disturbed by the neighboring pixels. This spoils the correlation between SSM/I channels vs. snow depth and SWE.

4- Points in forested areas show satisfactory correlations between snow depth vs. GTH, and GTVN if they are not disturbed by the lake effect. In addition, scatter plots show the attenuation of brightness temperature due to forested land cover.

5- Both GTH and GTVN show satisfactory correlations making them potential estimators for snow depth and SWE. This originates from the sensors measured values in vertical and horizontal polarizations. In general, the measured brightness temperature in vertical polarization is higher than horizontal polarization for any specific time and location. Therefore the discrepancy between the channels is higher in vertical than horizontal polarization makes the vertical discrepancy a better choice to estimate SWE.

6- The highest correlation coefficients can be distinguished in high latitudes close to the Canadian border which is in accordance with the literature [5].

7- Table 3 presents the correlation coefficients of SSM/I signatures vs SWE obtained from SNODAS. The results show higher and more consistent correlation coefficients between SWE and the signatures compare to snow depth and SSM/I signatures.

Table 3. Correlation Coefficients of SD and SWE vs. Signatures of SSM/I Channels

Pixel Label	2003-2004 SWE vs. SSM/I Correlation Coefficient		
	GTH vs. SWE	GTVN vs. SWE	SSI vs. SWE
1	-	-	0.69
2	-	-	0.85
3	-	0.52	0.73
4	-	-	0.69
5	0.51	0.65	0.67
6	-	0.67	-
7	0.80	0.80	0.50
8	0.56	0.55	-
9	0.80	0.77	-
10	-	0.62	-
11	-	0.55	-
12	-	-	-
13	0.52	0.52	0.52
14	-	-	0.58
15	0.60	0.60	-
16	0.65	0.68	-
17	0.78	0.74	-
18	0.86	0.83	0.67
19	0.75	0.75	0.62

Comparison of scatter plots of Snow Depth vs. SSM/I signatures for points 2, 9, and 18 located in low, middle,

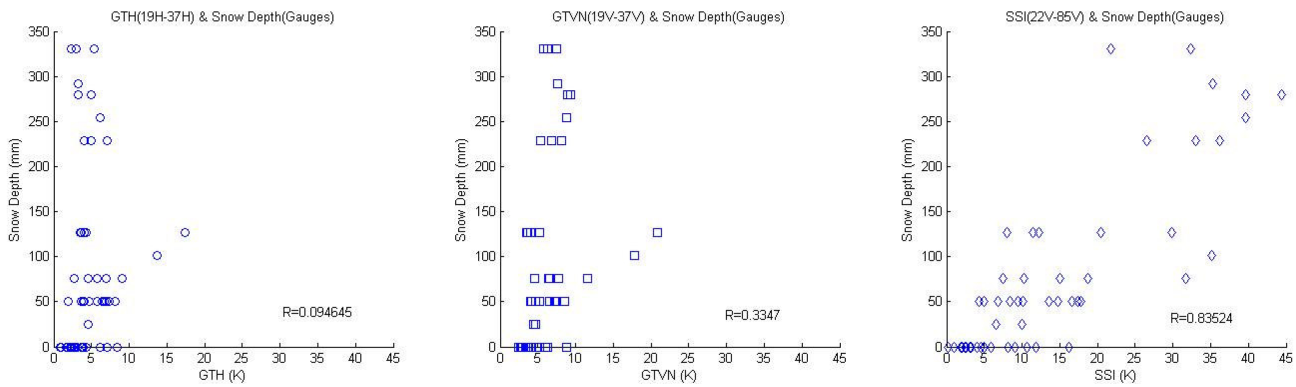

Figure 5. Scatter plots of SSM/I Signatures vs. Snow Depth for winter 2003-2004 at Point 1

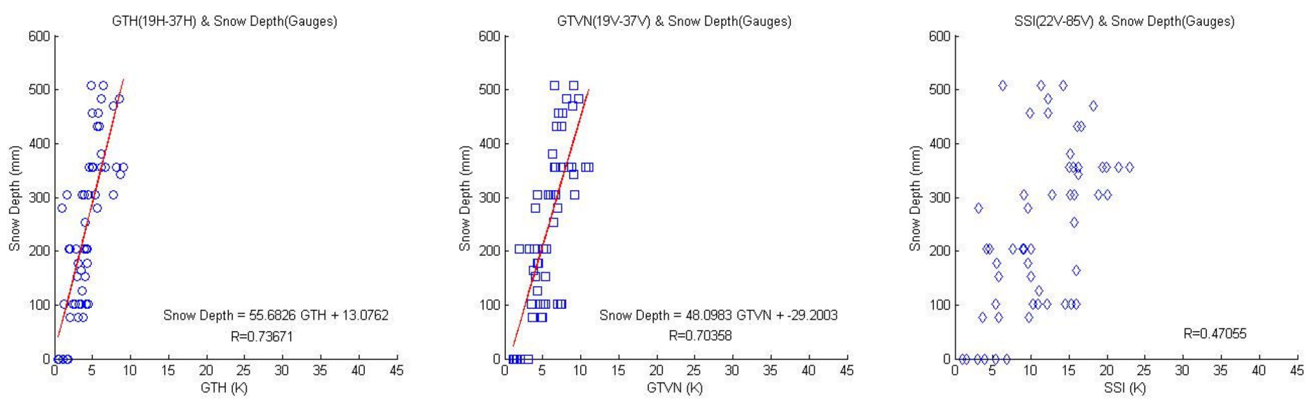

Figure 6. Scatter plots of SSM/I Signatures vs. Snow Depth for winter 2003-2004 at Point 9

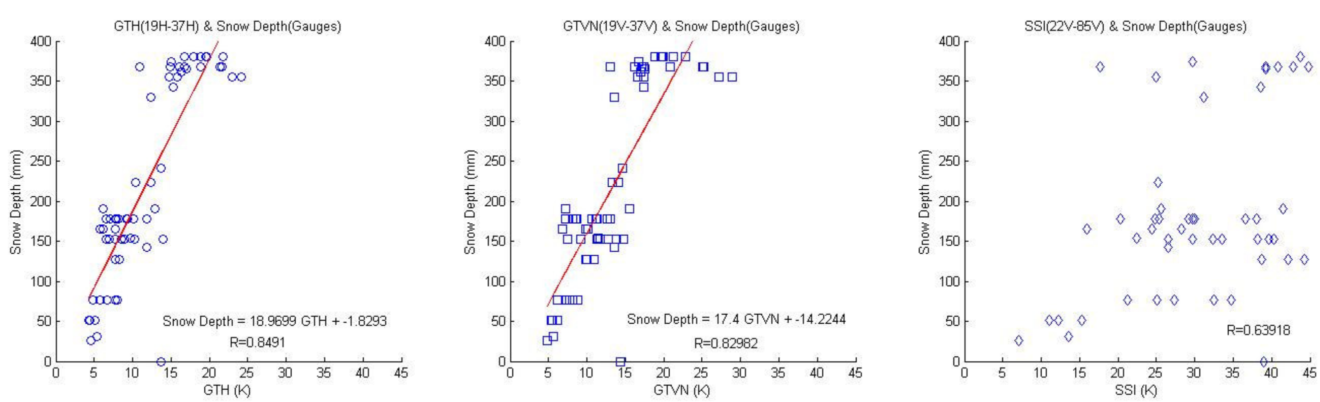

Figure 7. Scatter plots of SSM/I Signatures vs. Snow Depth for winter 2003-2004 at Point 18

Comparison of scatter plots of SNODAS vs. SSM/I for points 2, 9, and 18 located in low, middle, and high

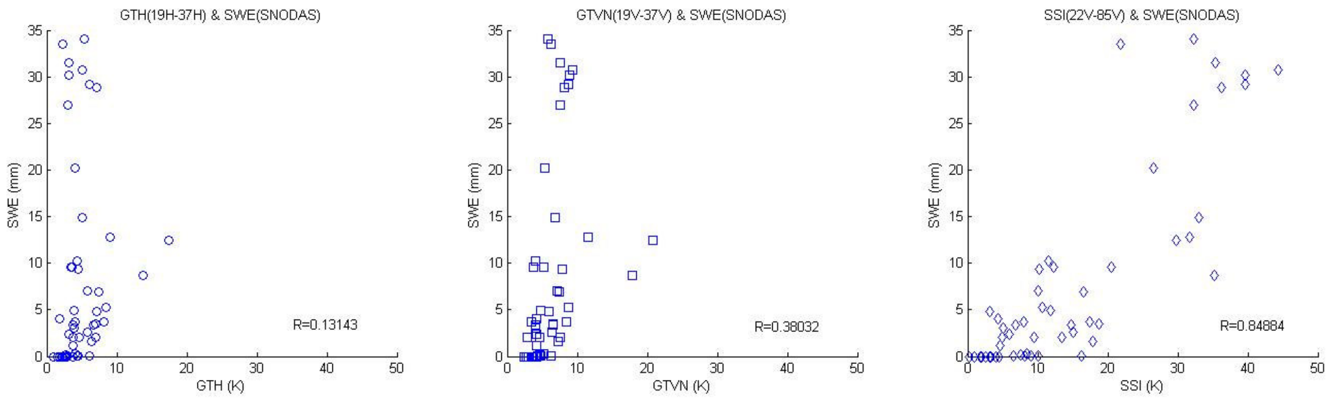

Figure 8. Scatter plots of SSM/I Signatures vs. SWE for winter 2003-2004 at Point 2

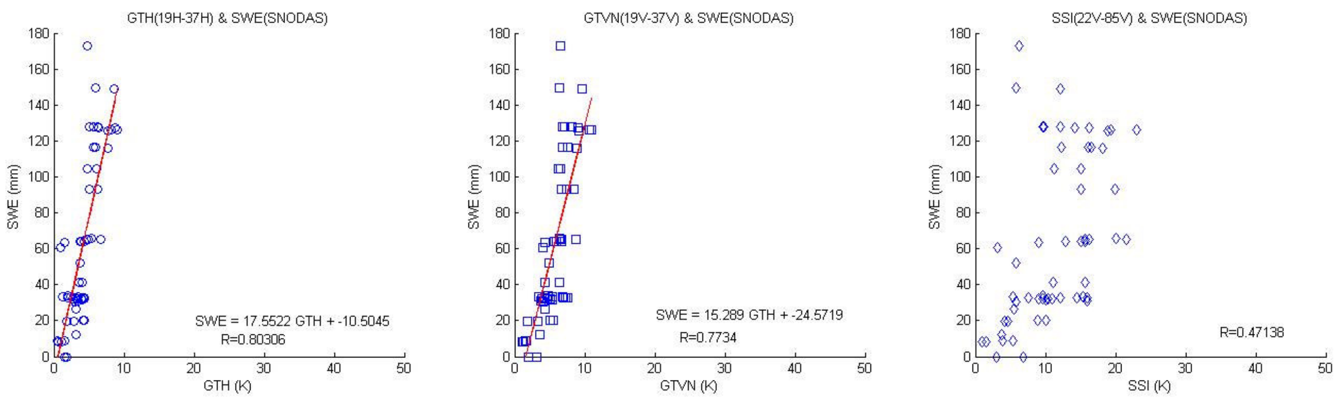

Figure 9. Scatter plots of SSM/I Signatures vs. SWE for winter 2003-2004 at Point 9

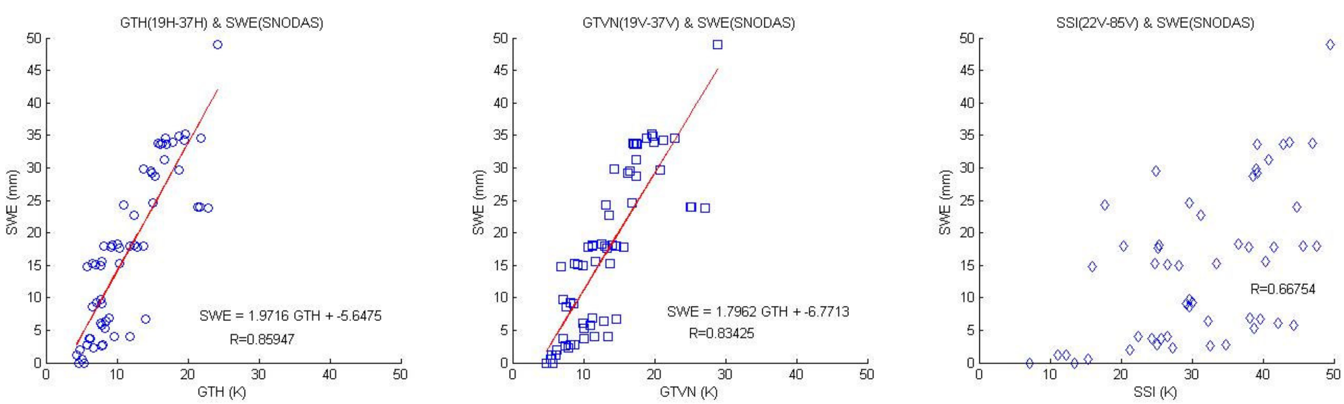

Figure 10. Scatter plots of SSM/I Signatures vs. SWE for winter 2003-2004 at Point 18

8- Figure 5 to figure 10 show the scatter plots of three selected points (2, 9, and 18). Lines fitted to each graph have various slopes and intercepts. This shows that having one linear algorithm for snow estimations in inadequate.

Conclusion

SSM/I data for three winter seasons of 2001-2004 with related snow depth, and snow water equivalent (SWE) were used to examine the sensors response to the changes in snow pack properties. The results indicates that SSM/I response in GTVN (19V-37V) and GTH (19H-37H) to snow depth or water equivalent changes is highly correlated in high latitudes of the study area. The correlations decreases in middle latitudes and is not existent in low latitudes. However, SSI (22V-85V) shows a reasonable correlation in low latitude, making it suitable for shallow snow identification. Also, points located in various parts of the study have different linear estimators of snow depth or SWE. Differences between slope and intercept for different points indicate the inadequacy of having one linear formula to estimate SWE from the SSM/I.

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