Statistical Analysis of the Impact of Temperature and Vegetation Cover on Snow Water Equivalent Using SSM/I Data over New Brunswick and Southern Québec

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ABSTRACT

The objective of this study is to understand the influence of vegetation cover and air temperature variations on the estimation of snow parameters (snow depth and water equivalent) using passive microwave data in deep snow and high density vegetation conditions. The study area spans New Brunswick and Quebec in Eastern Canada. The objective of the statistical analysis was to understand how well passive microwave brightness temperatures and particularly the scattering index (difference between vertically or horizontally polarized brightness temperatures in 19 and 37 GHz) are sensitive to snow parameters under the environmental conditions considered. The results obtained indicate that the scattering index is related to snow depth over low vegetation conditions (tundra and taiga covered terrain). However, in highly vegetated areas, there is almost no relationship between the scattering index and snow depth or snow water equivalent. Rather, variations in brightness temperatures and scattering index are strongly related to variations in air temperature, which we assume representative of the actual surface temperature.

Key words : SSM/I EASE-Grid passive microwave data, snow depth, snow water equivalent, forest cover, air temperature.

INTRODUCTION

Spaceborne microwave remote sensing can provide useful information on snow cover characteristics for various hydrological, climatological and meteorological applications. Remote sensing techniques offer a unique way to complement and extend conventional ground-based measurements of snow to regional and global scales. Past years results of snow water equivalent (SWE) or snow depth (SD) estimation using passive microwave data have shown an important influence of land cover type and conditions in the behavior of algorithms in forested areas. Using 1994 BOREAS winter campaign experimental data, two empirical algorithms were found respectively for coniferous and deciduous forests (Goïta et al., 1997). Like most of the algorithms in the literature, the models developed were based on the scattering index, corresponding to the difference of vertically polarized brightness temperatures at 37 and 19 GHz (V37-V19). The scattering index is used to account for and remove some of the variability associated with surface and air temperature (see for example Chang et al., 1987) This index has proven to be an effective tool in SWE estimation in regions like the Canadian Prairies (see Goodison and Walker, 1995), but tends to underestimate SWE in presence of the vegetation cover. In fact, in forested areas, the canopy attenuates the microwave radiation emitted from underlying snow and contributes its own emission to the signal received at the satellite radiometer. In sparse vegetated zones, SWE

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estimation may be improved by introducing a canopy cover fraction as proposed in Foster et al. (1991) and Chang et al. (1991). The land cover influence on passive microwave data is discussed in Kurnoven and Hallikainen (1997), Foster et al. (1984) and Chang et al. (1996).

However, the behavior of microwave over dense vegetation during the winter season is not well known. In this paper, we examine the spatial and temporal variations of SSM/I 19 and 37 GHz brightness temperatures and its vertically polarized scattering index (V37-V19) as a function of SD, SWE and air temperature over selected heavily vegetated sites in New Brunswick and Quebec.

STUDY AREA AND DATA SET

The study area is located in Eastern Canada and spans the provinces of New Brunswick and Quebec. A number of meteorological stations with regular snow depth measurements and hourly air temperature data were chosen, mainly in the dense forest of southern Quebec. Meteorological data were obtained from The Mackenzie data archive under an agreement with the Canadian cryospheric program (CRYSYS). Hourly air temperature measurements were considered in order to determine the temperature corresponding to satellite overpass times. Stations close to large lakes, the sea or urban areas were discarded because they may not be really representative of the actual temperature conditions in the forest. With all of these restrictions, one station was found in New Brunswick (St-Leonard) and eight in southern Quebec. To contrast with the previous stations, we chose an additional station (Schefferville) in northern Quebec, located in lower vegetation, in the transition zone between taiga and tundra forest. In hydrological and climatological applications, SWE is more important than snow depth. Unfortunately, only snow depth measurements are available from meteorological stations. Also snow density must be known in order to derive SWE from snow depth. We were able to acquire SWE data covering the period of 1992 to 1998 from the Catamaran River project initiated by Fisheries and Oceans Canada. The Catamaran River is located in central New Brunswick in a very dense and mature mixed forest. All of the sites considered in the study are shown in Figure 1 and their central coordinates and corresponding land cover categories are given in Table 1.

Table 1. Simplified land categories in percentage in the SSM/I EASE-Grid cells corresponding to the meteorological stations considered.

Station	Longitude	Latitude	Needleleaf	Mixed/ Broadleaf	Low vegetation	Other
1. Schefferville	66.80	54.80	38	0	53	9
2. Chibougamau	74.53	49.77	62	9	24	6
3. Bagotville	71.00	48.33	1	75	19	5
4. Rouyn	78.83	48.22	26	67	7	0
5. Val d'Or	77.78	48.07	28	56	11	4
6. St-Leonard	67.83	47.15	6	43	51	0
7. Catamaran	66.10	46.90	12	85	3	0
8. Maniwaki	75.97	46.38	1	95	0	3
9. Ste-Agathe	74.28	46.05	1	98	2	0
10. St-Hubert	73.42	45.52	0	6	93	1
11. Sherbrooke	71.86	45.43	0	76	18	6

The passive microwave data used in the study are SSM/I 19 and 37 GHz data from 1988 to 1992 in EASE-Grid format. These data are provided by the US National Snow and Ice Data Center (NSIDC). Each grid cell has a spatial resolution of 25 km by 25 km.

The land cover information for each EASE-Grid cell considered was extracted from the 1995 NOAA-AVHRR 1-km land cover map produced by the Canada Centre for Remote Sensing in collaboration with the Canadian Forest Service (Cihlar and Beaubien, 1998). This map gives a detailed description of the land cover types (31 classes). A subset covering our study area is illustrated in Figure 1. The percentages of land cover types in each grid cell were estimated and an aggregated summary is given in Table 1. The forested lands (needleleaf, mixed or broadleaf) are dominated by trees with a height exceeding approximately five meters in most cases. The

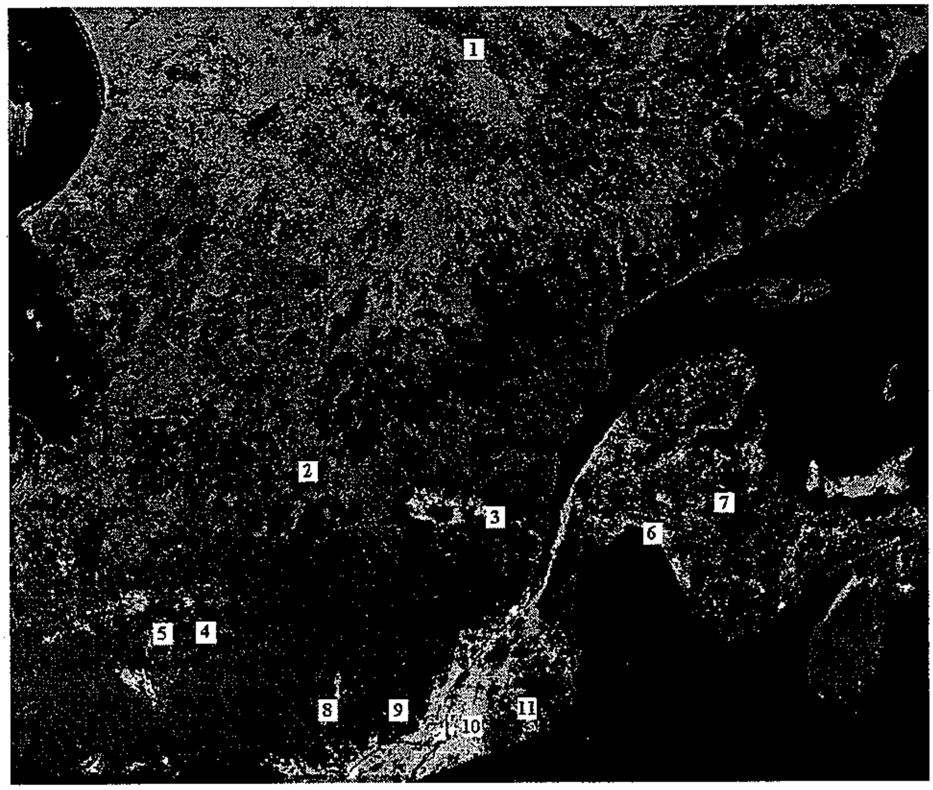

Figure 1. Meteorological stations considered in the study on top of a subset of the 1-km 1995 AVHRR land cover map from Cihlar and Beaubien (1998). The coordinates and names of the stations are given in Table 1.

needleleaf forest, which is dominant in the Chibougamau grid cell, varies from high to low density with a greater proportion of medium density. The needleleaf portion of the Schefferville station includes almost equally medium and low-density forest. The mixed/broadleaf forest that is present in almost all the cells is mostly high-density forest. Stations 3, 4 and 5 contain approximately 30% heterogeneous mixed forest, which is characterized by a patchy tree distribution typically caused by natural or human intervention. In the low vegetation category, the tree crown cover is less than 10%. This class includes shrubland, cropland and bare soils. It is the dominant category in St-Hubert and it also composes half of the territory in Schefferville and St-Leonard. The category "other" includes urban areas and water bodies.

DATA ANALYSIS

Spatial variability

SSM/I morning overpass time data were considered, with the assumption that air temperature at that time is very close to ground temperature. We considered meteorological data from January to mid-February to avoid important variations in snow structure. The statistics over each grid cell were calculated over a period of four years (1988-1991). Air temperature at the stations decreases with latitude except for the Val d'Or station. On average, air temperature varies between –7°C to –22°C with a standard deviation of approximately 7°C. Snow depth doesn't seem to be related entirely to the geographic position of the stations. Also, snow depth shows a greater inter-annual variability than the other parameters. On average, snow depth is between 11 cm at St-Hubert and 65 cm at St-Leonard with a standard deviation ranging from 8 to 20 cm. The scattering index (V37-V19) varies around –10 K for all stations, except for Schefferville, where it is significantly lower (-28 K) and has a much higher standard deviation.

The objective of the spatial variability analysis was to see i) if the stations considered are significantly different from each other in terms of snow depth and air temperature throughout the study area and ii) how microwave brightness temperatures and scattering index follow spatial patterns of meteorological data. To achieve this goal, an analysis of variance (ANOVA) and a comparison of means test (Dunett's T3) were performed on daily measurements of air temperature, snow depth and passive microwave data.

The results for air temperature indicate that the stations considered form two statistically distinct groups, located on either sides of the 48th parallel, warmer stations in the south (average temperature of –10°C) and colder stations in the north (average temperature of –17°C). However, there is no pattern for the homogeneous subsets of snow depth. The subsets include stations randomly located in the study area. This might be due to the microclimate of the different regions or to the accuracy of the measured data itself. The Brightness temperatures measured at 19 GHz form the same subsets as air temperature. This indicates that, at this lower frequency, the passive microwaves are more affected by air temperature than by land cover or snow. At 37 GHz, the subsets are differently arranged, showing some links with both air temperature and snow depth. However, these two factors are not obviously sufficient to explain the spatial patterns at 37 GHz. A mixture of elements, including land cover, affect the microwave data at 37 GHz. Accordingly, the V37-V19 index does not follow the same subsets as the snow depth.

Temporal variability

The temporal variability analysis consists of isolating constant snow depth periods to observe the effects of air temperature on microwave data over different land cover types. Air temperature affects the brightness temperature at both 19 and 37 GHz but the scattering index is virtually unaffected by air temperature in open areas. In dense forest cover, this index might react differently.

A comparison was made between the northern station (Schefferville) and the southern stations, in particular the St-Leonard station. Snow depth is approximately the same at both stations (up to 80 cm for the winter 1988-1989). Air temperature is slightly higher at St-Leonard, but it rarely rises above 0°C. The results show that, in both cases, the peaks for brightness temperatures are directly related to the peaks of air temperature. There is however an important difference between the stations when the scattering index is considered. In Schefferville, the index becomes greater as the winter progresses. This does not happen for St-Leonard and neither for the other stations characterized by dense forest cover. Indeed, the scattering index shows very little variation even with important differences in snow depth. An illustration of some of the results is shown in Figure 2, where three different snow depth conditions are considered. In the first column

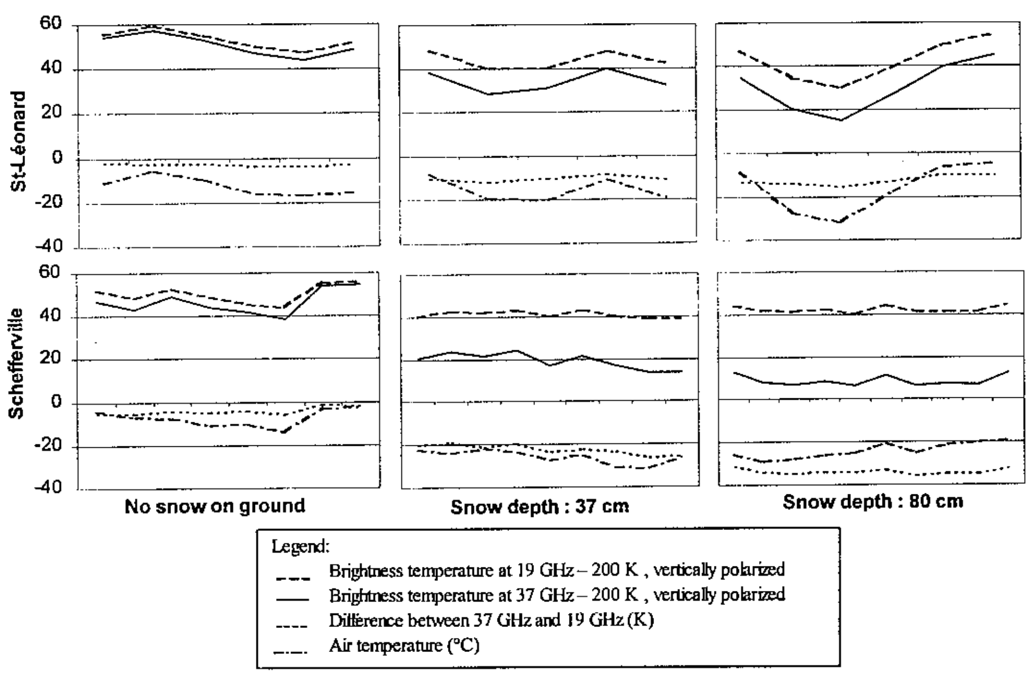

Figure 2 : Variations of passive microwave data for three different snow depth conditions at Schefferville (Quebec) and St-Leonard (New Brunswick).

of the Figure, the soil is frozen and air temperature is below zero for several consecutive days, but there is no snow on the ground. The second and third columns present situations with a constant snow depth of 37 cm and 80 cm for several consecutive days, respectively. It can be clearly seen that, at St-Leonard, the scattering index remains relatively constant even if the snow depth varies from 37 to 80 cm. Brightness temperatures, at 19 and 37 GHz, closely follow the same trend as air temperature. However, at Schefferville, there is a distinct variation in the scattering index as the snow depth varies from 0 to 80 cm.

A correlation analysis was conducted to further assess the relationships between SSM/I data and snow depth. Because of the similarities of the results for southern stations, only a summary for the winter of 1991 is given in Table 2 as an example. We see that for southern areas, the brightness temperatures and even the index are more related to air temperature. There is no relationship between snow depth and the scattering index for the two first stations. In the northern site, the microwave data is still related to air temperature but the relationship is not as strong. The scattering index displays a sensitivity to snow depth, but weaker than expected. In fact, Schefferville is not a bare area like the Prairies and it may be necessary to introduce correction factors, for example vegetation fractional cover, in order to improve the estimation of snow depth. The results obtained over the different years considered show that the relationships between snow depth and microwave data vary from year to year, due certainly to variabilities in snow structure. In contrast, the relationship with air temperature is fairly constant over the years. The use of horizontal polarization data does not improve significantly the relationships with snow parameters.

Table 2. Coefficient of determination (R^2) between SSM/I brightness temperatures in vertical polarization, scattering index (V37-V19), air temperature (T) and snow depth (SD) for St-Leonard, Catamaran and Schefferville stations for the winter of 1991.

SSM/I data	St-Leonard		Catamaran		Schefferville	
	T	SD	T	SD	T	SD
V19	0.84	0.03	0.83	0.007	0.43	0.21
V37	0.79	0.05	0.79	0.007	0.32	0.32
V37-V19	0.52	0.09	0.46	0.004	0.25	0.37

Validity of SWE empirical models over dense forest

The relevance of using the general SWE retrieval algorithm in densely forested areas is analyzed here. The data provided by the Catamaran project is used to verify the validity of the empirical models developed in the past few years by different authors (see for example Hallikainen and Jolma, 1992; Goodison and Walker, 1995, Tait, 1998). Most models are represented by the following general equation :

$$SWE = A_1 + A_2(TB_{f1} - TB_{f2})/(f_1 - f_2)$$

Where A_1 = offset (empirically determined)
A_2 = slope (empirically determined)
TB_{fi} = brightness temperature acquired at frequency f_i in horizontal or vertical polarization (K). In general $f_1 = 37$ and $f_2 = 19$ or 18 GHz.

The coefficient A_2 represents the sensitivity of the brightness temperature gradient ($\Delta TB/\Delta f$) as a function of SWE. This coefficient varies considerably and is mainly dependent on land cover type and snow structure. Thus, it varies from region to region. The land cover is relatively stable over a period of time but the snowpack is easily affected by environmental conditions such as melting or freezing.

Using SWE data from the Catamaran site, we have tested several existing algorithms from the literature. Unfortunately, none of them was able to predict SWE values with satisfaction over the Catamaran mature forest. Rather, there is almost no correlation between the scattering index and SWE over this site as illustrated in Figure 3. On the other hand, the index is strongly linked to air temperature. The higher correlations between brightness temperatures and air temperature, especially other dense forests, may be explained by the fact that the physical temperature of the trees mimicks the air temperature. The microwave emission from trees dominates the overall brightness temperature resulting hence a higher correlation (see for example Chang et al., 1996; Foster et al., 1984).

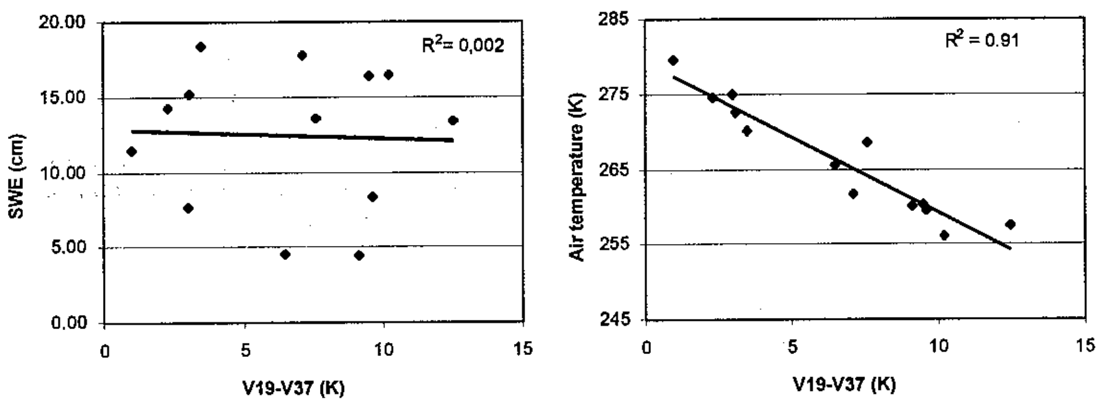

Figure 3. Relationships between passive microwave scattering index (V19-V37), SWE and air temperature over the Catamaran mature mixed forest in New Brunswick.

CONCLUSION

The spatial analysis conducted in this study indicates that the spatial pattern described by SSM/I brightness temperature at 19 GHz during the winter season is closely related to that of air temperature in forested areas. 37 GHz is influenced by air temperature, but is also affected by the presence of snow and the land cover type. Over dense forests the scattering index (V37-V19) seems to saturates around –10 K regardless of the snow depth on the ground. The correlation analysis shows that microwave data are more sensitive to variations of air temperature over forested areas and display almost no relationship with snow depth and snow water equivalent. Nevertheless, it is possible to differentiate between snow and no snow conditions in the forest. According to the results obtained in this study and to those from other regions, the land cover type and structure must be well known for a better parameterization of snow water equivalent and passive microwave data relationships.

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