Analysis of Microwave Radiometry of Snow Cover with SSM/I Data in a Taïga Area: The Case of James Bay Area (Québec)

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ABSTRACT

The focus of this study is a spatio-temporal analysis of brightness temperatures (Tb) over a taïga landscape from a dataset of 2 winters seasons (1997 and 1998). A second objective is to evaluate the impact of the land cover on Tb variations.

Analysis of Tb variations at 37 GHz for a SSM/I time series has shown that Tb decreased when SWE or snow thickness increased and that the relationship was inverted when the SWE exceeded 150 mm. The iversion of the relationship seems to be related to a decrease in penetration depth and, to a lesser extent, an increase in the physical temperatures of snow. At 19 Ghz, the variations in Tb are mainly associated with variations in air temperature and, to a lesser extent, to ground temperature. Land cover variability within a pixel is an important factor because it strongly influences the snow signature, and therefore the efficiency of algorithms estimating the SWE. For the study area, two land use classes have a major influence on the radiometric values of the snow cover: lakes and reservoirs (LR) and closed forest (CF).

Key words: Snow water equivalent, SSM/I data, spatio-temporal analysis, land cover impact,

INTRODUCTION

A steady flow of information on snow cover extent and water equivalent is crucial for hydrologic forecasting, particularly in regions where a large percentage of total precipitation falls as snow. However, because of inaccessibility and the large extent of northern areas, snow surveys are expensive, more so when accurate estimations of the spatial distribution of the snow cover variables are required. Combining snow surveys with remote sensing data offers an alternative to estimate SWE. Furthermore, the exploitation of passive microwaves is advantageous for snow mapping, since the microwaves are relatively independent of atmospheric constraints and solar illumination. The intensity of the radiation from the earth surface at passive microwave wavelengths is expressed in terms of brightness temperatures which is a function of the surface emissivity (e) and the physical temperature of the objects (Ts) in degrees Kelvin (K). For snow-covered terrain, the microwave radiation emitted from the underlying ground surface is scattered by randomly spaced snow particles (volume scattering) in all directions, particularly for frequencies higher than 15 GHz (Ulaby *et al.*, 1986). So, for frequencies higher than 15 GHz, snow emission tends to decrease as the snow cover thickens or more precisely, as the snow water equivalent (SWE) increases. However, some researchers (Hall *et al.*, 1982 ; Rott and Künzi, 1983 ; Chang *et al.*, 1990) have noted significantly different Tb values for similar snow depth

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Those differences are attributed to the snow characteristics (crystal size, stratification, temperature, and moisture) and to the vegetation cover.

The sensitivity of microwave radiation to SWE lead to the development of various algorithms (Künzi *et al.*, 1982, Hall *et al.*, 1982 ; Chang *et al.*, 1990, Hallikaïnen and Jolma, 1992, Goodison and Walker, 1995) using passive microwaves to monitor the snow cover.

Since September 1995, the *Institut National de la Recherche Scientifique* (INRS-*Eau*) has teamed up with the Atmospheric Environment Service (AES) as part of a multidisciplinary project on changes to the cryosphere named CRYSYS (Use of the CRYospheric SYStem to Monitor Global Change in Canada). The research has focused on the development of algorithms to derive snow cover information using active and passive microwave remote sensing data.

A study conducted in Quebec and based on a spatio-temporal analysis of SSM/I (Special Sensor Microwave/Imager) data acquired over the James Bay area (1994-1996) confirmed that brightness temperatures (Tb) in passive microwaves could help to characterize the snowpack, but that the behavior of the snow brightness temperature was a function of snow characteristics varying with time (De Sève *et al.*, 1997). The main objectives of this work were to (a) determine if this trend still exists within the 1996-1997 and 1997-1998 data set and (b) make an analysis of the general behavior of brightness temperature (Tb) when different land covers co-exist within a pixel.

THE STUDY AREA

The region of interest is located in the province of Quebec, Canada, between James Bay and Schefferville and covers an area of 1 163 750 km^2 (Fig. 1). It is divided into three morphological units from west to east: coastal plain, undulating plateau and mountainous area. The climate of the study area is of the cold continental subarctic type with taïga vegetation (open forest and wetland). Thus, it is characterized by short and mild summers and by long and arduous winters. The annual average thickness of the snow cover for the James Bay area is approximately 0.90 m, with mean densities around 250 kg/m^3. In the case of the Caniapiscau reservoir and the Schefferville region, solid precipitation are greater, with annual average snow thickness reaching 1.30 m. Snow cover densities are, varying from 150 to 350 kg/m^3 from the surface to the base of the snowpack.

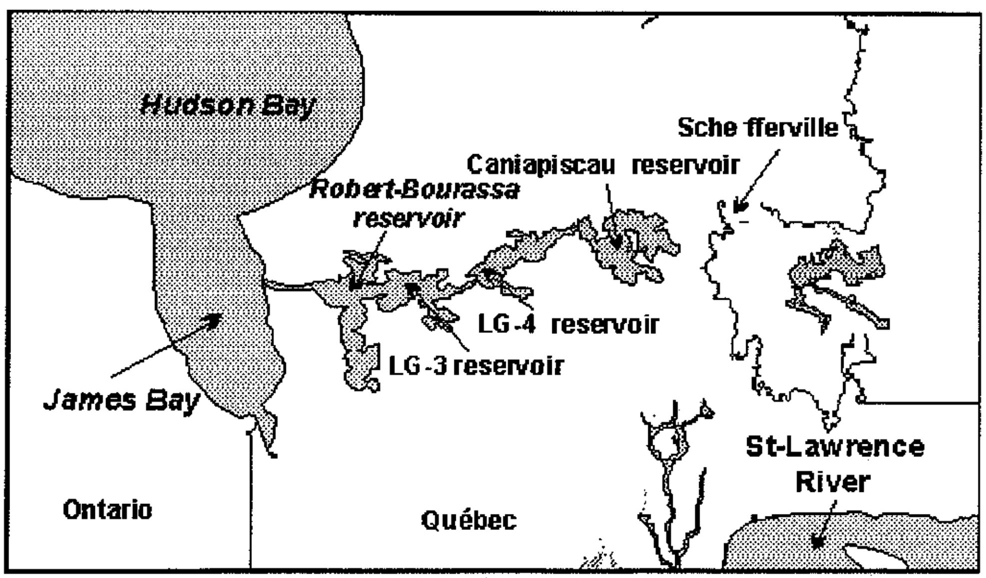


Figure 1. Study area

DATA AND PROCESSING OF SSM/I AND METEOROLOGICAL DATA

Over the last five winters (1994-1998), INRS-*Eau* has, in partnership with Hydro-Québec, conducted snow-survey field campaigns in the James Bay region (LG-4 reservoir). During the 1997-1998 season, intensive field campaigns were also conducted in three other areas: the Robert-Bourassa reservoir, LG-3, and Schefferville. In these campaigns, snow depth profiles were measured to estimate thickness, density, SWE, grain size, and dielectric constant for each snow layer. This information has been complemented with data on density, SWE, and snow thickness from Hydro-Québec snow survey lines.

The satellite database used to carry out this study is composed of multi-date passive-microwave data (1994 to 1998) provided by the SSM/I sensors on the U.S. DMSP F-11 and F-13 satellites. A classified NOAA/AVHRR imagery of Québec had been used for land cover information. Information on SSM/I data is given on Table 1. Classification of the NOAA/AVHRR image has been realized by the Ministère des Ressources Naturelles du Québec (Service des technologie à référence spatiale).

The SSM/I data were acquired in near real-time and provided as text files containing geo-referenced (longitude/latitude) Tb's at 19.35 and 37 GHz. Geographic coordinates were projected into a Lambert conical projection using a nearest neighbor interpolation method (De Sève *et al.*, 1997). The nearest neighbor algorithm was chosen to avoid the alteration of Tb's . The interpolated images were exported to a Geographic Information System (IDRISI) to facilitate the extraction of Tb's at 19.3 and 37 GHz. Information on the SWE for the first part of winter (October to January) were not available. To overcome this situation we have estimated the SWE from snowfall data at two weather stations operated by Hydro-Quebec. The estimations were performed using a simple SWE summation. During the snowmelting period a "day degree method" has been also used (De Sève, 1999).

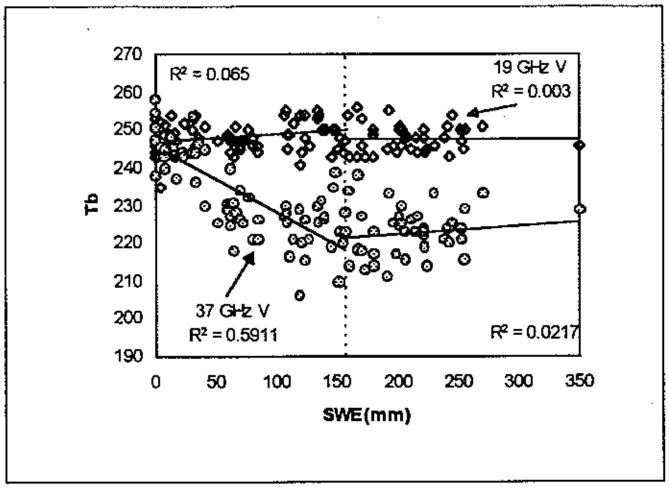
RESULTS

Temporal analysis at 37 GHz

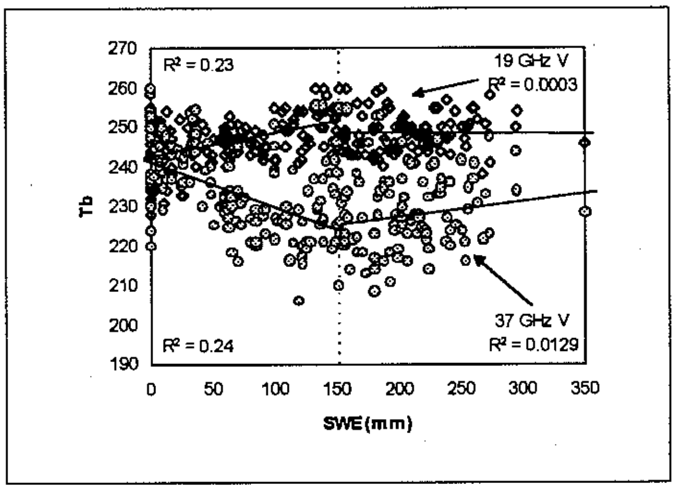
A first analysis conducted in 1996 on Tb variations at 37 GHZ has shown that Tb decreased when SWE or snow thickness increased but that the relationship was inverted when the SWE exceeded 200 mm (De Sève *et al.*, 1997). Analysis conducted for the winters of 1997 and 1998 have shown similar trends but with the inversion of the relationship between SWE and Tb closer to 150 mm. Figure 2a and 2b shows results for homogeneous open forest pixels and mixed pixels (pixels containing more than one land use class). For each figure, the scattering of points around the regression, can be explained by the vertical variability of the snow pack characteristics (density, crystal size etc.). However, on figure 2b the dispersion of points also result from the heterogeneity of the pixels. The decrease of Tb values at 37 GHz is directly related to an increase in volume scattering due to an increase in the thickness of the accumulated snow cover or, alternately, to an increase in crystal size (Ulaby *et al.*, 1986; Mätzler, 1994). The relationship is reversed when the SWE is higher than 150 mm, probably because the electromagnetic waves do not penetrate as deeply. As a result, there is less contribution from deeper snow layers. The increase in the snow cover's Tb values would thus be related to the fact that the radiation comes mainly from the snow cover's upper layers, which have a higher albedo (Table 2). The penetration depth accounts for the attenuation of the snow signature by a factor of $1/e$. At 37 GHzV, it varies from 1 metre to a few centimetres depending on the snow cover's structure (Ulaby *et al.*, 1986).

Table 1 SSM/I characteristics

Frequency (GHz)	19.3	22.2	37	85.5
Polarization	H and V	V	H and V	H and V
Spatial resolution (km)	69 x 43	60 x 40	37 x 28	15 x 13
swath width (km)	1394			



a) Homogeneous pixels



b) Mixed pixels and homogenous pixels

Figure 2. Variations of Tb at 37 and 19 Ghz with SWE for homogenous and mixed pixels.

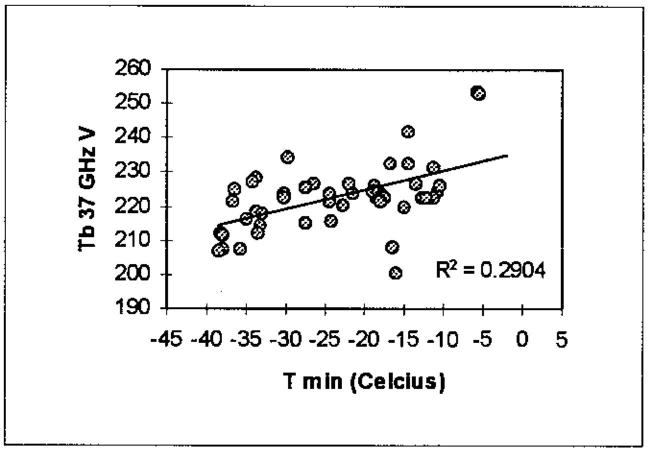
Calculations of transmissivity, albedo, and attenuation at two different sites in our study area show a decrease in the contribution from deeper layers (Table 2). Attenuation, due to volume scattering, is more pronounced in the snow cover's bottom layers than in its surface layers. For example, in February at LG-2, attenuation was 80 dB in the bottom layer compared to 0.36 dB in the surface layer. As well, attenuation increased in the bottom layer from February to March 1998 but remained relatively stable in the surface layer. Snow grains in the bottom layer expanded in size during this period, a factor that also causes an increase in volume scattering. Mätzler (1994) reported similar findings.

As well, we believe that the increase in Tb values may also result from thermal variations within the snow cover, given that, physically, Tb values are directly related to the physical temperature of objects. The physical temperature profiles of the snow cover at LG-4 shows an average increase of 10^0C in the uppermost layers between February and April and measurements on the study site also show a relationship between the variation of Tb's at 37 GHz and the air temperature, specially when the temperatures are above -15^0C (figure 3a).

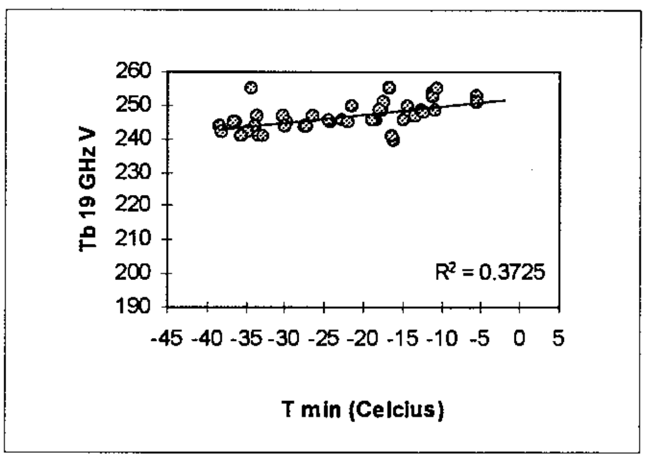
Table 2. Example of signal attenuation in a snow cover at two test sites.

Layer	*Robert-Bourassa Reservoir (February 1998)* Layer thickness (m)	radius grain size (mm)	a	t	A (dB)	*Shefferville area (March 1998)* Layer thickness (m)	radius grain size (mm)	a	t	A (dB)
5*	-	-	-	-	-	0.25	0.25	0.74	0.85	0.71
4	0.14	0.24	0.70	0.92	0.36	0.23	0.35	0.88	0.64	1.93
3	0.10	0.35	0.87	0.81	0.93	0.05	0.50	0.95	0.67	1.73
2	0.20	0.45	0.93	0.40	3.97	0.31	0.75	0.98	5.24 E-03	22.80
1	0.30	1.00	0.99	5.17 E-08	79.92	0.30	1.50	0.99	4.35 E-25	256

* surface layer, *a* albedo (ks/ke), *t* transmissivity, *A* Attenuation



a) Variation for Tb at 37 GHz



b) Variation for Tb at 19 Ghz

Figure 3. Comparisons of Tb at 37 and 19 GHzV and the minimum air temperature.

Temporal analysis at 19 GHz

Initial analysis of Tb variations at 19 GHz for the 1996-1998 series, generally indicates essentially no relation between Tb's and SWE for both homogeneous pixels (Fig. 2a) and heterogeneous pixels (Fig. 2b). However, as may be seen in figure 3b, variations in Tb at this frequency are mainly associated with variations in air temperature and, to a lesser extent, to ground temperature. So, over the season, the increase in Tb values at 19 GHz is related to gradually rising air temperatures. Hallikaïnen and Jolma (1986) have reported similar findings from a region of Finland. Finally, the variation of Tb at 19 GHz values around the curve is not significant in both examples (fig. 2a and 2b).

Land cover anlysis

In the visible domain of the spectra, images from low resolution sensors like AVHRR (NOAA) and VEGETATION (SPOT-4) have pixels with a mixed spectral signature, which is the radiometric weighted sum of the various elements comprising the surface (Fortin *et al.*, 1998). Because of the low spatial resolution of the SSM/I sensor, we assume that the radiometry of its pixels can also be related to the spectral mixture theory. In this sense, the variability of pixels at 37 and to 19 GHz, would not be only controlled by the fluctuation of the snow pack characteristics and by the air temperature, but also by the heterogeneity of the land use within a single pixel.

According to an analysis performed on monthly SSM/I data for each land cover class (De Sève, 1999), there are no significant differences between Tb of snow in open forest, lichen woodland and burned forest, and secondly, that snow radiometry in closed forests and on lakes and reservoirs are clearly different than in any other land use categories (De sève, 1999). Taking into account these observations, we have concentrated our efforts on the evaluation of the Tb variation of the snow according to these two land uses. We modified the mosaic of NOAA/AVHRR images of Quebec into three classes: closed forest (CF), lakes and reservoirs (LR) and the open forest (FO) (Table 3). For the analysis, we only kept the pixels containing open forest and either the LR or CF class, as to study the effect of one class at a time. More specifically, we evaluated the influence of the LR class on the radiometric variability of pixels for four specific cases: a) SWE = 0mm, b) SWE = 0-50 mm, c) SWE = 50-150 mm, d) SWE > 150 mm . Because of the availability of field data in some sectors of the study area, we have analyzed the influence of the CF class for slightly different cases: SWE = 0mm, b) SWE = 0-100 mm, c) SWE = 100-150 mm, d) SWE > 200 mm.

Table 3 Classification of a NOAA/AVHRR image of Québec

Land cover classes of NOAA/AVHRR image	Grouped Land cover classes of NOAA/AVHRR image
Water : lakes and reservoir James Bay and Hudson bay	Lakes and reservoir (LR)
Burned forest Lichen woodland Open forest	Open forest (OF)
Coniferous closed forest Mixed forest deciduous forest	Closed forest (CF)

Impact of Water (LR class)

The radiometric values of lakes and reservoir are very low in autumn, when ice has not yet formed on the water surfaces. The result is a decrease of Tb's both at 19 and 37 GHz (Fig. 4a and 4b), with increasing percentages of LR surface area within the pixel. According to Kirchhoff's law of radiation, water acts as a specular reflector because of the marked dielectric contrast between it and the air (Ulaby *et al.*, 1986). Specular reflection at the water/air interface becomes very high, so because the emissivity is low, the Tb values remain low.

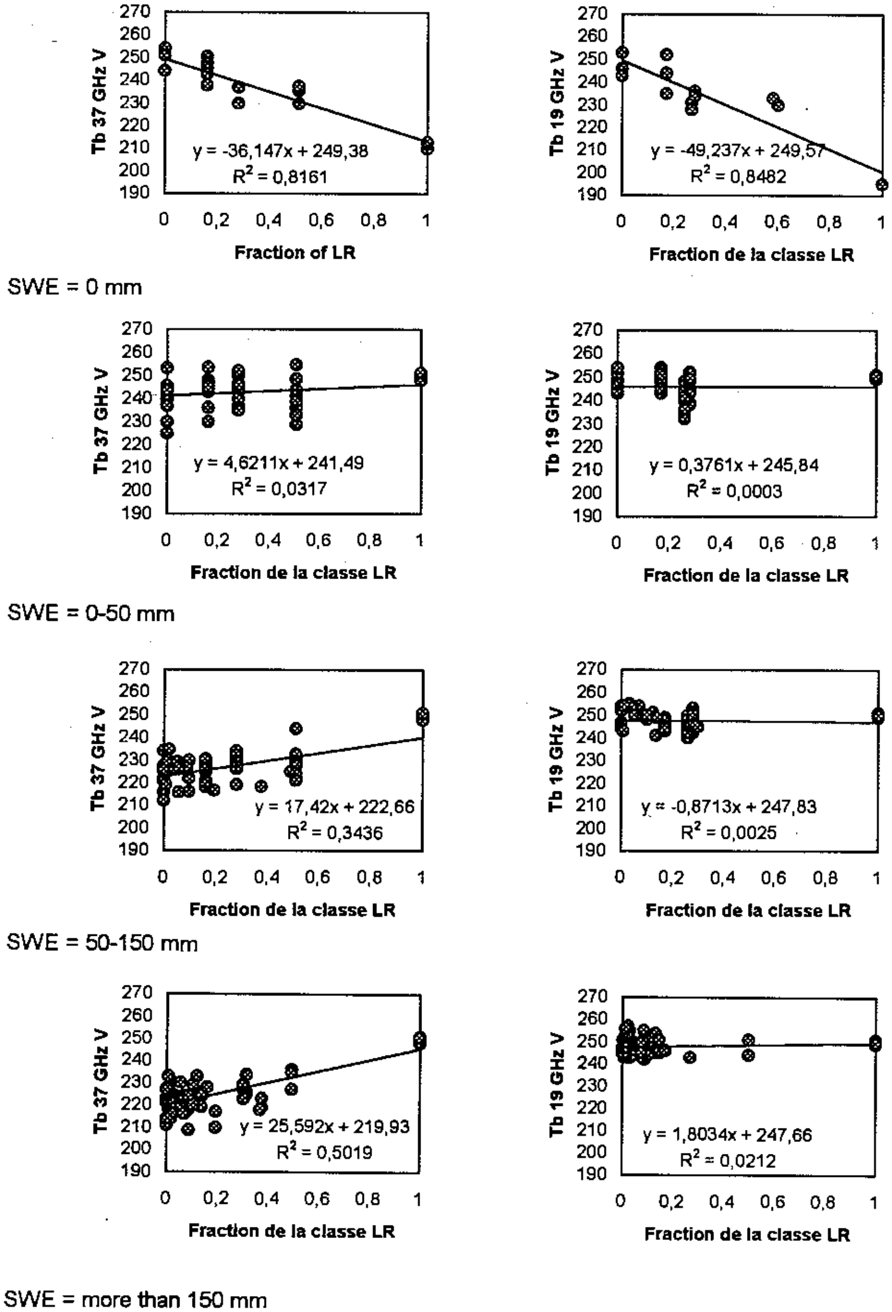


Figure 4. Variations of Tb at 37 and 19 GHz (V) in function of fraction of lackes and reservoirs (LR)

In early winter, when snow accumulation is increasing on the ground while ice is forming on the water surface, any increase in the percentage of LR surface area within the pixel has a negligible effect on Tb values at 37 and 19 GHz (Fig. 4c and 4d). Indeed, when snow cover is shallow, radiometric values reveal little contrast between the ice forming on the lakes and the rest of the territory.

The situation changes for Tb values at 37 GHz when SWE ≥ 50mm (Fig. 4e and 4g). A large radiometric difference is noticeable between snow-covered ground, where volume scattering dominates, and ice on the lake surfaces. In the winter, upwelling radiation from lakes comes mainly from the ice, which behaves as a microwave emitter (Cosimo, 1983). Thus, any increase in the percentage of lake ice cover within the pixel will lead to a higher radiometric value. At 19 GHz, Tb values reveal little contrast between the ice and the rest of the territory, since volume scattering is barely perceptible at this frequency. Variation in the percentage of lake ice cover thus has little effect on the radiometric values of the pixels (Fig. 4f and 4h).

Impact of Forest areas (CF class)

Figures 5a to 5h illustrate the relationships between Tb values (at 37 and 19 GHz) and the percentage of forest cover (for SWEs between 0 and 350 mm).

Figures 5a and 5b show a rise in Tb values at 19 and 37 GHz with increasing percentages of forest cover within the pixel, since the signature of forest cover is very high. As well, the radiometric contrast between open environments (open forest) and closed environments

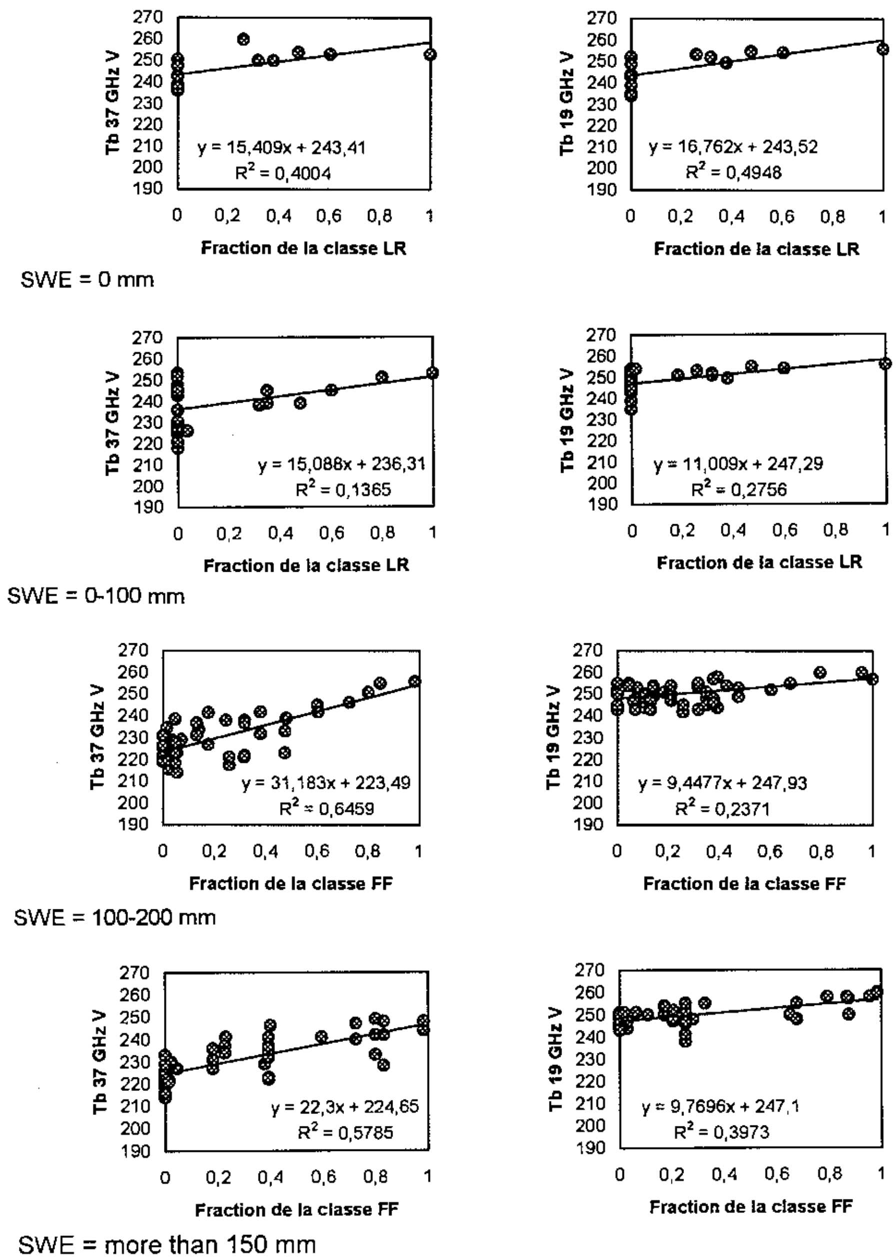


Figure 5. Variations of Tb at 37 and 19 GHz (V) in function of fraction of closed forest (CF)

(coniferous forest) is higher at 37 GHz than at 19 GHz. This is because Tb values at 37 GHz are more sensitive to changes in ground surface than values at 19 GHz (moisture and ruggedness; Ulaby *et al.*, 1986).

With the first snowfalls, Tb values at 37 GHz increase more steeply as a function of forest cover (%) within the pixel (Fig. 5c and 5d). This is because Tb values decline markedly in areas of open forest as a result of volume scattering by the snow. In more densely forested areas, Tb values stay relatively high all winter-long. The emissivity of trees is very high and masks the snow signature when the forest cover is dense. Tb values vary greatly in areas with a low percentage of forest as shown on figure 5c in particular. During early winter, the entire territory is subject to highly variable enviroumental conditions, especially ground conditions and snow cover (presence or absence of snow). This may lead to a steeper slope for the relation between Tb and forest cover.

When SWE ≥ 100 mm, the curves become less steep (Fig. 5e and 5g) because environmental conditions have become more stable over the entire territory (*i.e.*, the snow has covered it entirely and conifers may also be covered by snow). The situation is similar at 19 GHz. At this frequency, however, volume scattering has few effects and the impact of forest cover is subtler (Fig. 5f and 5h).

Statistical tests

We have shown that variation in the percentage of land cover within a pixel could affect the pixel's radiometric value. To verify whether a significant relationship really exists between the dependent variable Y (Tb) and the independent variable X (percentage of classes LR and CF), we tested the null hypothesis H_0 for the variable X. Student *t* and Fischer *F* tests were used.

Tableau 4a: Statistics for the regression analysis of lakes and reservoirs (LR)

		37 GHzV			19 GHzV		
SWE (mm)	n	t ∝ 95	F ∝ 95	P	t ∝ 95	F ∝ 95	P
0	15	-8.150[1] 2.160[2]	66.55[1] 4.54[2]	0.00001	-8.86[1] 2.160[2]	78.22[1] 4.54[2]	0
0-50	43	1.180[1] 2.021[2]	1.41[1] 4.03[2]	0.24	0.10[1] 2.021[2]	0.1079[1] 4.03[2]	0.91
50-150	64	4.400[1] 2.00[2]	19.42[1] 4.00[2]	0.00041	0.39[1] 2.00[2]	1.52[1] 4.00[2]	0.69
more than 150 mm	55	7.440[1] 2.00[2]	55.42[1] 4.00[2]	0.0000	1.11[1] 2.00[2]	1.23 4.00[2]	0.27

Tableau 4b: Statistics for tbe regression analysis of closed forest (CF)

		37 GHzV			19 GHzV		
SWE (mm)	n	t ∝ 95	F ∝ 95	P	t ∝ 95	F ∝ 95	P
0	13	2.71[1] 2.20[2]	7.34[1] 4.67[2]	0.02	3.42[1] 2.20[2]	11.75[1] 4.67[2]	0.005
0-100	33	2.21[1] 2.056[2]	4.90[1] 4.17[2]	0.03	3.10[1] 2.056[2]	12.55[1] 4.17[2]	0.0012
100-200	51	9.03[1] 2.00[2]	81.71[1] 4.00[2]	0	3.98[1] 2.00[2]	15.84[1] 4.00[2]	0.0002
more than 200 mm	49	8.71[1] 2.00[2]	75.78[1] 4.00[2]	0	5.44[1] 2.00[2]	29.66[1] 4.00[2]	0

1 Calculated value
2 Statistical table value
∝ Significant level

The results are presented in Tables 4a and 4b and confirm the observations made from Figures 4 and 5. When plotted against the percentage of class LR, Tb values at 37 GHzV yield slopes that are significantly different from zero, except when SWE values vary between 0 and 50 mm. In this particular case, the exceedance probability (P value) is around 0.24, indicating that in 24% of the cases the variation in Tb values is due to chance. At a frequency of 19 GHzV, the t and F values are always lower than statistical table values, except when there is no snow on the ground (SWE =0 mm). The null hypothesis H_0 is thus accepted, *i.e.*, the slope is equal to zero and no relationship exists between the two variables.

The null hypothesis H_0 is rejected, however, for the relationship between Tb values at 37 and 19 GHzV and percentage of CF class. Therefore, the percentage of CF class in a pixel does seem to affect Tb radiometry

V. CONCLUSION

Analysis of 37 GHz data over a 2-year period has enhanced our understanding of Tb behavior for snow at 37 GHz. First, it has confirmed the usefulness of the 37 GHz frequency for SWE retrieval of shallow snow cover. We have found, however, that the relationship reverses once SWE values exceed 150 mm. In Switzerland, Mätzler (1994) reported this same relationship with a ground-based sensor. Such a situation seems to be related to a decrease in penetration depth and, to a lesser extent, an increase in the physical temperatures of snow, particularly when snow temperatures are above -15^{0}C. Analysis of the time series at 19 GHz confirm the sensitivity of Tb's to air and ground temperature.

Land cover variability within a pixel is another important factor to keep in mind because it strongly influences the snow signature. We have also demonstrated that during the winter, the percentage of lakes and reservoirs within a pixel have a strong influence on radiometric values at 37 GHz, but not at 19GHz. In Fall, since the surface reflection is considerable at both frequencies, the pixel radiometry is strongly affected by the lakes and reservoirs.

As we have just shown, a significant relationship exists between the increase in Tb values and the increase in the percentage of surface area covered by LR and CF classes. In practice, this means that there is always an increase in the radiometric value of pixels that are contaminated by the presence of either land cover class. The radiometric value of an environment of snow-free open forest may thus be confused with that of a forest environment with much snow. This is a problem because over half the pixels being analyzed have a mixed radiometry. Pixel contamination thus results in a weakening of the relationship between 37 GHz Tb values and field measurements (i.e., SWEs). The algorithms used for SWE estimation are consequently less effective and always underestimate the SWE value.

Based on these finding, our works on the estimation of SWE will now take into account the land cover variability within a pixel. This should provide a better estimation of SWE.

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