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Derivation of Snow Water Equivalent in Boreal Forests Using Microwave Radiometry

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ABSTRACT. Efforts have been made by several investigators to produce a reliable global microwave snow algorithm to estimate snow depth or snow water equivalent (snow volume) and snow extent. Complications arise when trying to apply a global algorithm to specific regions where the climate, snowpack structure and vegetation vary. In forest regions, the microwave emission from dense coniferous forests may overwhelm the emission from the underlying snow-covered ground. As a result, algorithms employing microwave data tend to underestimate snow depths. Preliminary results indicate that the amount of underestimation can be minimized when the fraction of forest cover can be accounted for and used as an additional input in microwave algorithms. In the boreal forest of Saskatchewan, the standard error between the measured and the estimated snow water equivalent was reduced from 2.7 to 2.1 cm by using a generalized snow retrieval algorithm that includes the percentage of forest cover. However, perhaps as much as 25% of the boreal forest of North America and Eurasia is too dense to enable satisfactory snow water equivalent determinations to be made using passive microwave techniques alone.

Key words: brightness temperature, boreal forest, microwaves, radiometer, snowpack

RÉSUMÉ. Plusieurs chercheurs ont tenté de créer un algorithme global fiable en vue d'estimer la profondeur de la neige ou l'équivalent d'eau de neige (volume nival) et l'étendue de neige à l'aide des micro-ondes. Les complications surgissent lorsqu'on essaye d'appliquer un algorithme global à des régions spécifiques où le climat, la structure de la neige accumulée et la végétation varient. Dans les régions forestières, l'émission de micro-ondes provenant des forêts denses de conifères peut prévaloir sur celle provenant du sol enfoui sous le couvert de neige. Il en résulte que les algorithmes qui utilisent les données des micro-ondes tendent à sous-estimer la profondeur de la neige au sol. Des résultats préliminaires indiquent que l'importance de la sous-estimation peut être réduite lorsqu'on fait entrer en ligne de compte la portion de couvert forestier et qu'on l'utilise comme une entrée supplémentaire dans les algorithmes de micro-ondes. Dans la forêt boréale de Saskatchewan, l'erreur normale entre l'équivalent d'eau de neige mesuré et celui estimé a été réduite de 2,7 à 2,1 cm lorsqu'on a utilisé un algorithme général pour retrouver la quantité de neige, algorithme qui tenait compte du pourcentage de couvert forestier. Il est cependant probable que jusqu'à 25 p. cent de la forêt boréale nord-américaine et eurasienne est trop dense pour permettre de déterminer de façon satisfaisante la quantité équivalente d'eau de neige en se servant uniquement de techniques passives de micro-ondes.

Mots clés: température de luminance, forêt boréale, micro-ondes, radiomètre, neige accumulée

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INTRODUCTION

The boreal forests that stretch across the northern tier of North America and Eurasia provide a treasure trove of natural resources (Fig. 1). Probably the most ephemeral of these resources is the seasonal snowpack, which covers the ground for at least half of the year. With the advent of satellite technology the boreal forests are now easier to monitor, but in many areas information about the underlying surface is still difficult to extract.

Snow accumulates to deeper depths and melts later in the spring in the boreal forests than in adjacent tundra or prairie areas. The boreal areas are always snow covered during the winter months, but because the canopy can obscure much of the snowpack from the view of satellite sensors, making accurate estimates of snow depth or snow water equivalent (SWE) is a challenge. Since the boreal forest of the Northern Hemisphere constitutes approximately 15% of the lands normally covered by snow during the winter and upwards of 40% of the land surface normally snow covered during the autumn and spring, more reliable measures of the snow depth and snow-cover extent in boreal areas are needed for improved energy balance and water balance estimates.

In the Northern Hemisphere, the mean monthly snow cover ranges from about 7 to over 40% of the land area, thus making snow the most rapidly varying natural surface feature. The mean monthly snow storage (excluding Greenland) ranges from about 1.5×10^{16} g in summer to about 300×10^{16} g in winter (Chang *et al.*, 1990a). Snow cover is a sensitive indicator of climate change, with the position of the southern boundary of snow cover in the Northern Hemisphere of particular significance, as it is likely to retreat northward if there is sustained climate warming (Barry, 1984). Snow depth is highly variable in forests, particularly when a mixture of small openings and stands of different species and sizes is present and when melting produces depth variations around individual trees. It is well known that to obtain a mean value that lies within the required confidence limits, the number of samples needed increases directly with the variance (Freese, 1962). In terms of a forest snow cover, many samples are required to provide a reliable mean snow depth because of the large variance involved. This can be expensive and time consuming and may not be practical in spring, when differential melt changes the snow distribution pattern rapidly from day to day (Woo and Steer, 1985).

The use of remote sensing techniques offers a way to complement and extend conventional ground-based measurements of snow to the regional and global scales. Passive microwave remote sensing is particularly suited to subpolar and polar latitudes, since these wavelengths are able to penetrate most clouds and are indifferent to varying degrees of daylight or darkness.

The objective of our study is to develop an improved algorithm for the retrieval of snow depth and snow water equivalent information in boreal forest areas using passive microwave satellite data. The methodology involved in microwave radiometric techniques and the problems encountered in determining the effects of vegetation on the microwave response in snow-covered areas are presented in the next two sections.

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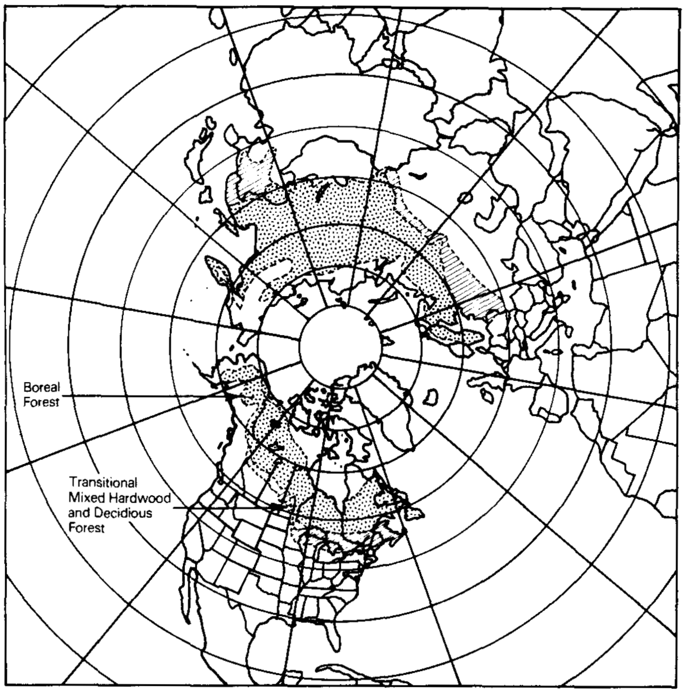

FIG. 1. Map showing the extent of the boreal forest in North America and Eurasia.

The study area is in the province of Saskatchewan, Canada (latitude 49° - 60°N, longitude 101° - 110°W). The northern part of the province (north of about 53°N) is in the boreal forest, while the southern part is primarily prairie (Figs. 1 and 4). Lakes cover about 13% of the entire province but account for upwards of 25% of the surface area of the boreal forest. In the northern portion of the boreal forest, the Canadian Shield rock is expressed at the surface, resulting in a rock-strewn landscape with scrawny conifers (National Geographic Society, 1985).

MICROWAVE RADIOMETRY

Microwave emission from a layer of snow over a ground medium consists of two contributions: emission by the snow volume and emission by the underlying ground. Both contributions are governed by the transmission and reflection properties of the air-snow and snow-ground interfaces and by the absorption or emission and scattering properties of the snow layer (Stiles and Ulaby, 1980).

As an electromagnetic wave emitted from the underlying earth surface propagates through the snowpack, it is scattered by the randomly spaced snow particles in all directions. Consequently, when the wave emerges at the snow-air interface, its amplitude has been attenuated. Dry snow absorbs very little microwave energy from the wave; therefore, it also contributes very little in the form of self-emission. When the snowpack grows deeper, the wave encounters more scattering, and so less radiation is received by the sensor (Foster *et al.*, 1987).

The effects of scattering microwave radiation by snow crystals have been reported by, among others, Chang *et al.* (1976), Kong *et al.* (1979), Rango *et al.* (1979), Tiuri and Hallikainen (1981), Kunzi *et al.* (1982), and Rott and Aschbacher (1989). Since November 1978, the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite has been acquiring passive microwave data that can be used to measure snow extent and calculate snow depth on an areal basis (Chang *et al.*, 1987). The capability to compute estimates of global snow storage, hence the depth of snow, has been developed using algorithms derived from microwave radiometric measurements of snow using ground-based, airborne, and spaceborne observations.

In the algorithm developed by Chang *et al.* (1987) the snow water equivalent/brightness temperature relationship for a uniform snow field can be expressed as follows:

$$\begin{aligned} SWE &= 4.8 * (T_{18H} - T_{37H})\ \text{mm} \\ & 4.8 * \Delta T_B \end{aligned} \tag{1}$$

where SWE is the snow water equivalent and T_{18H} and T_{37H} are the brightness temperatures (T_B) at 18 and 37 GHz horizontal polarization. The constant 4.8 was derived by linearly fitting the theoretically calculated brightness temperatures assuming a mean snow crystal size of 0.3 mm and a snow density of 0.3 g/cm^3 (Chang *et al.*, 1990c).

This algorithm has been used to generate global maps of snow volume and snow cover area. The SMMR data are interpolated for spatial and temporal gaps and averaged on a monthly basis into microwave brightness temperatures and displayed on color-coded maps using a polar stereographic projection. The maps are based on the average of six days of brightness temperature data taken during the middle of each month. The data are placed into ½° latitude by ½° longitude grid cells uniformly subdividing a polar stereographic map according to the geographic coordinates of the center of the field of view of the SMMR radiometers. Maps using a polar stereographic projection provide a synoptic representation of the brightness temperature data. A mask was constructed to remove brightness temperature data over oceans and bays so that only microwave data for land areas are displayed (Chang *et al.*, 1990b).

There are, of course, complications that arise when one tries to apply an algorithm based on average snow conditions to specific regions where the climate, snowpack structure, and vegetation cover vary. The sensitivity of the SWE/brightness temperature relationship will be modified by differences in terrain and vegetation cover (Fig. 2). A method to correct for the absorption of the snow signal by the forest cover will be described in the next section.

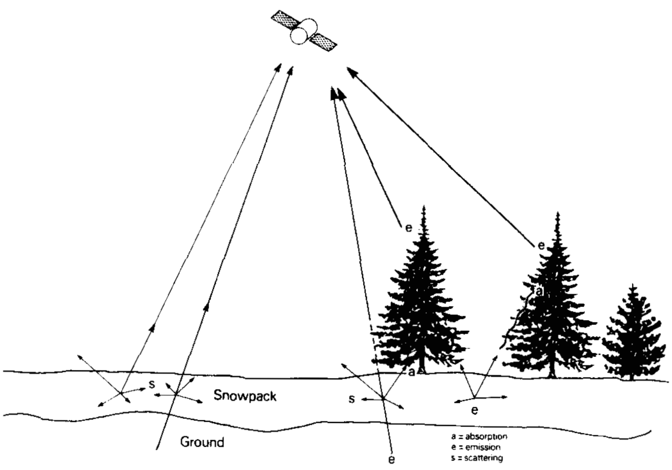

FIG. 2. Schematic showing scattering, emission, and absorption properties of snow and vegetation at 37 GHz.

VEGETATION EFFECTS ON PASSIVE MICROWAVES

The vegetation canopy can be represented as a dielectric mixture consisting of discrete dielectric elements (leaves, stalks, branches, etc.) embedded in a matrix of air (Ulaby and Jedlicka, 1984). In the 37 GHz region, vegetation is a strong absorber of microwave radiation and dominates the upwelling microwave radiation (Wang, 1985). Based on a radiative transfer model, Choudhury *et al.* (1987) found that the vertical and horizontal (V and H) polarization difference at 37 GHz decreased rapidly with increasing vegetation and approached zero for vegetation with water content greater than 1 kg/m^2. For a pine-dominated forest the normalized surface emissivity derived from SMMR data is about 0.92 for both the 18 and 37 GHz horizontal polarizations (Hallikainen *et al.*, 1988).

The amount of thermal microwave radiation emerging from the earth's surface depends on the dielectric properties of the surface composition within each footprint or pixel. Since the passive microwave footprint is on the order of 20 km or larger, a mixture of features and surfaces within the footprints can be expected (Chang *et al.*, in press).

A simple model to separate the effect of the forest cover from the effect of the snow depth was developed for the SMMR 37 GHz channel (Hall *et al.*, 1982). By assuming that trees are the primary influencing factor affecting the T_B/snow depth relationship, the effective brightness temperature can be expressed as:

$$T_{BR} = T_B - f\, T_{BT} \qquad (2)$$

where T_{BR} represents the residual brightness temperature from which the effects of forest cover have been removed, f is the percentage of forest cover of the SMMR footprint, and T_{BT} is the assumed brightness temperature of the trees, which is calculated by multiplying the emissivity of the trees (0.9) by the average weekly maximum air temperature. A correlation coefficient of 0.8 between T_{BR} and snow depth was achieved for data over western Michigan in an area where the percentage of forest cover was well documented.

Over heterogeneous mountainous areas different algorithms are needed to retrieve the water equivalent of the snow cover. A mixed pixel model based on vegetation differences has been developed to simulate the microwave brightness temperatures for the Rio Grande basin (3419 km^2) in southwestern Colorado (Chang *et al.*, in press). A relationship was obtained between the difference in microwave brightness temperature at two different frequencies (18 and 37 GHz horizontal polarization) and the basin-wide average snow water equivalent. The areal snow water equivalent values derived from the model are consistent with values generated by a reliable snowmelt runoff model using snow cover extent data (Chang *et al.*, in press).

A generalized SWE retrieval that includes information about land cover has been reported by Rott and Aschbacher (1989),

$$\mathrm{SWE} = A_1 + A_2\, \Delta T_B \text{ mm} \qquad (3)$$

where A_1 represents the offset for a snow-free case and depends on regional variation of land cover type, A_2 is the coefficient to relate ΔT_B and the SWE, and ΔT_B is the brightness temperature differences between two channels. The value of A_2 varies greatly depending primarily on the morphology of the snow cover as well as on the obscuration of the surface by vegetation. Kunzi *et al.* (1982) reported an average value of A_2 = 4 mm/K for their study in Switzerland. Hallikainen (1984) noted significant variations of A_2 due to different types of vegetation cover. For specific test areas in Finland he found values of A_2 = 2.9 mm/K for bogland and 5.4 mm/K for forest. For an area with 30% forest cover in central Europe Rott and Aschbacher (1989) found A_2 = 3 mm/K.

If a footprint is considered to be a mixed signature with f% forest cover and (1 - f)% snow cover, then ΔT_B in equation (1) will become

$$\Delta T_{BR} = (1 - f) * \Delta T_B \qquad (4)$$

where ΔT_{BR} is the residual brightness temperature difference from which the effects of forest cover have been removed, assuming the emissivities of forest for 18 and 37 GHz are the same (Chang *et al.*, 1990c). If f is not zero, then the ΔT_{BR} in equation (4) should be smaller than the ΔT_B in equation (1). The brightness temperature difference measured using equation (1) to derive SWE would underestimate the actual SWE. The amount of underestimating depends on the fraction of forest cover in equation (4). For the boreal forest of Saskatchewan this fractional value was estimated by using the SWE as measured at snow course sites and the observed SMMR ΔT_B. The measured SWEs were contoured so that an average weighted value was derived for each SMMR pixel. Snow depth values were used to infer the SWE when this data was not available. Figure 3 shows the relationship of the calculated ΔT_{BR} and the estimated SWE as a function of fractional forest cover. For example, a SWE weighted value of 40 mm and a ΔT_{BR} of 5 K would result in a fractional forest cover of 0.4.

To study the effect of vegetation on spaceborne SWE retrieval, Nimbus-7 SMMR-derived snow data and conventional snow course data from the northern portion of the province of Saskatchewan, Canada (Fig. 4) during the winter

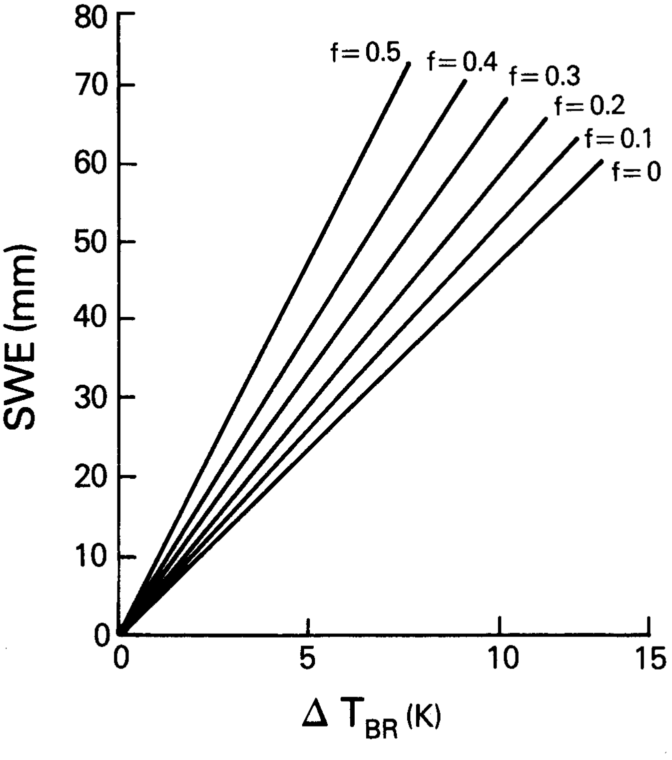

FIG. 3. Relationship of the calculated change in microwave brightness temperature and the estimated snow water equivalent as a function of fractional forest cover.

months (January-April) for the years 1980-84 were compared. The SMMR and snow course data were both sampled near the beginning of each month.

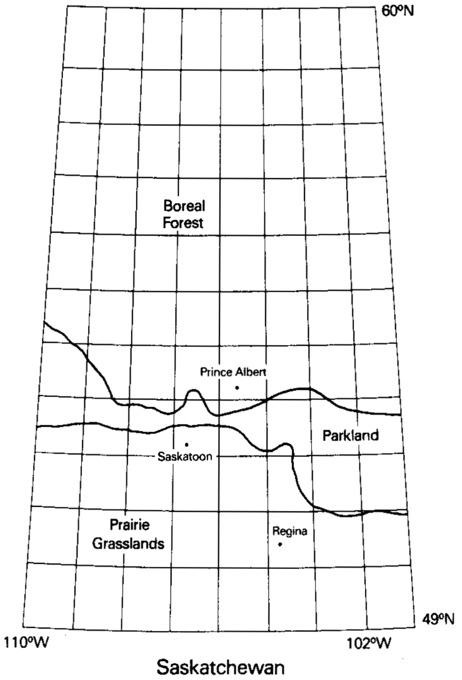

FIG. 4. Map of vegetation districts for Saskatchewan with superimposed SMMR grid network.

RESULTS AND DISCUSSION

As expected, difference in forest density and species type affected the microwave emissivity (Hallikainen *et al.*, 1988) (Fig. 5). It can be seen from Figure 5 that most of the data points are located above the 1:1 line. This is because the boreal forest reduced the sensitivity of the snow depth determination, and therefore SWE is underestimated using equation (1). By using the percentage of boreal forest cover, according to Figure 3, the difference between the measured and the estimated SWE is smaller (Table 1). The standard error reduces from 2.7 cm to 2.1 cm. Thus, this adjusted algorithm reduces the variability of the SWE in the forested areas of Saskatchewan by about 22%.

For northern Saskatchewan using a fractional forest cover of 0.4 brings the adjusted algorithm (equation 4) into accord with the observations. In actuality the forest cover may be higher. But it should be kept in mind that significant areas of the boreal forest in northern Saskatchewan are populated by lakes and bogs, which are included when estimating the percentage of forest cover in a given SMMR footprint.

This technique, however, is not necessarily valid for other portions of the North American boreal forest zone or for the boreal forest of Eurasia. In fact, in the boreal forest of Quebec the SMMR data has been found to considerably underestimate the snow depth. In some months the SMMR-derived snow depth is as much as 50 cm less than that measured on the ground.

This finding was verified using hand-held radiometers at

TABLE 1. Comparisons of ground-based and SMMR-derived snow water equivalent measurements (in cm) in the boreal forest of Saskatchewan

			SMMR-derived estimates*			
	Ground-based measurements		Unadjusted algorithm (equation 1)		Adjusted algorithm (equation 4)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
1980						
Jan	4.8	1.0	2.9	2.0	3.5	2.0
Feb	9.0	2.7	6.5	2.9	9.2	2.9
Mar	10.5	3.8	8.3	3.3	11.5	3.3
Apr	7.7	2.4	6.7	3.4	9.0	3.4
1981						
Jan	9.1	2.6	3.2	2.5	4.3	2.5
Feb	9.4	1.3	6.9	3.2	10.3	3.2
Mar	9.5	3.1	6.8	4.0	11.2	4.0
Apr	5.8	3.9	3.5	3.7	7.8	3.7
1982						
Jan	9.2	1.8	5.6	2.9	8.4	2.9
Feb	11.0	1.8	9.2	3.2	13.1	3.2
Mar	13.0	2.3	10.8	3.5	15.2	3.5
Apr	11.5	2.2	9.2	4.8	15.2	4.8
1983						
Jan	10.7	2.2	5.5	2.9	7.0	2.9
Feb	13.8	3.2	9.4	3.0	12.4	3.0
Mar	14.2	3.4	8.0	3.8	12.1	3.8
Apr	12.5	3.2	9.4	4.0	14.3	4.0
1984						
Jan	6.4	2.2	5.4	3.2	4.7	3.2
Feb	8.7	3.7	6.4	3.1	6.4	3.1
Mar	8.9	2.7	6.4	3.4	9.0	3.4
	9.8	2.6	6.8	3.3	9.7	3.3

* The standard deviation is the same for the unadjusted and adjusted SMMR data. The standard error for the unadjusted algorithm it is 2.7 cm and for the adjusted algorithm it is 2.1 cm.

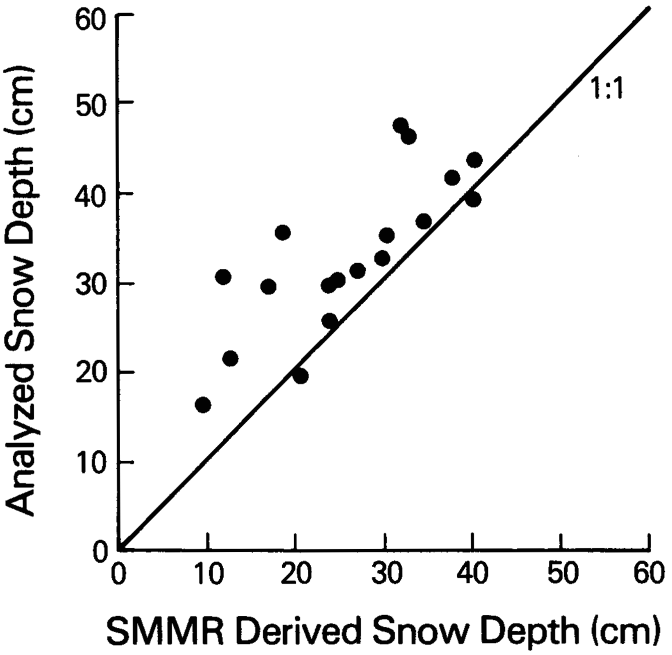

FIG. 5. Scattergram for SMMR-derived snow depth and snow depth derived from ground-based observations for the boreal forest of Saskatchewan.

the Howland Experimental Forest test site in north-central Maine. This site is in a predominantly spruce pine forest. A 26 m tower extends above the canopy, and a 35 GHz radiometer positioned on top of the tower was utilized to make measurements of snow covering the forest floor. Preliminary data are available for the winter of 1990, which is the first year of operation at this site (Table 2). At an angle of incidence of 50° (the look angle of SMMR) the canopy completely obscured the snow surface, and the T_B at 35 GHz averaged about 240 K. When the radiometer was pointed towards an area devoid of any vegetation the average T_B was about 186 K. The average snow depth in the view of the radiometer (at 50°) was approximately 50 cm. When directed at an area of deciduous saplings the T_B averaged about 206 K. The snow depth here averaged about 60 cm (Table 2). These experiments show the influence of the canopy when monitoring the snow surface. Regardless of snow depth, the dense coniferous canopy, when viewed at an angle of 50°, absorbs most of the upwelling radiation that emanates from the ground in the 35 GHz region. Hallikainen *et al.* (1988) showed that annual variations in brightness temperature in forests are small at the 10, 18, and 37 GHz frequencies for both horizontal and vertical polarizations. This demonstrates the limited capability of microwave radiation in penetrating dense vegetation. Thus, in dense forests current microwave methods of estimating snow depth are not viable.

Figure 6 is a composite minimum brightness chart for 11-18 January 1982. The most dense portions of the boreal forests of Canada are defined by very low surface brightness in eastern Manitoba, southern Ontario, and southern Quebec (Scialdone and Robock, 1987). SMMR data for mid-January 1982 show these areas to have shallow snow (< 10 cm). Actual snow depths were greater than 25 cm (Canadian Climate Centre, 1982).

Crown closure, basal area (the cross-sectional area of tree stems per unit ground area), and foliage biomass are all inversely related to visible reflectance and scene brightness of Landsat (MSS and TM) and NOAA (AVHRR) imagery (Franklin, 1986). As crown closure and basal area increase, reflectance decreases in the photosynthetic regions of the visible spectrum due to increased leaf area, absorption, and shadowing within the canopy.

TABLE 2. Effect of vegetation on microwave brightness temperatures as measured at the Howland Experimental Forest* in north-central Maine

Azimuth	Incidence angle	Brightness temperature (°K)
270°	60°	244
	50°	245
	40°	244
	20°	241
0°	50°	247
radiometer pointed toward deciduous saplings		
180°	80°	206
radiometer pointed toward non-vegetated area		
90°	70°	169
	60°	173
	50°	196
	40°	202
	30°	203
radiometer pointed toward sky (zenith)		
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* Howland Experimental Forest — mature hemlock, spruce, and white pine. Some snow present in the forest canopy. Snow depth on the forest floor averages approximately 50 cm and temperature -12°C. Measurements made with a 35 GHz radiometer.

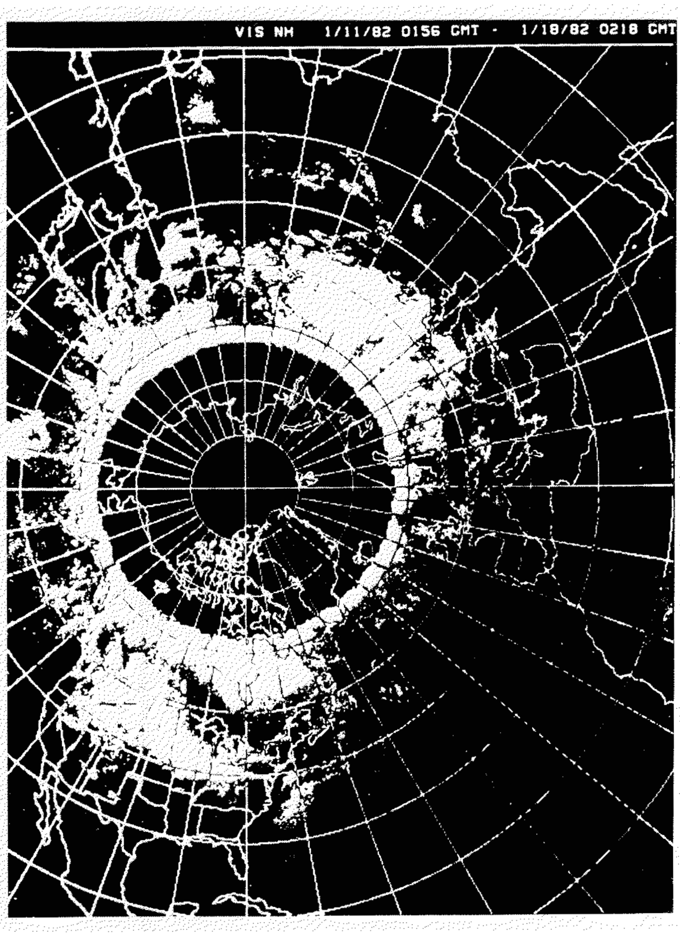

FIG. 6. Composite minimum brightness chart for 11-18 January 1982.

Despite greater interception of snowfall by the forest canopy, deeper snow typically accumulates in those areas of the boreal forest that appear dark on visible satellite imagery. This can be attributed to retarded snowmelt as a result of reduced solar radiation. Approximately 25% of the boreal forest in the Northern Hemisphere is most likely too dense to allow satisfactory snow depth determination using passive microwave algorithms. More realistic snow storage estimates may be attained if prescribed snow depth amounts, based on climatological data, are used instead. One way of doing this perhaps is to use the reflectance of sunlight in the visible wavelengths in combination with the T_B difference between 18 and 37 GHz data to assess where the forests are too dense to use microwave techniques for snow depth determination. Initial results indicate that if the reflectance is less than 0.3 and the T_B difference is less than 10 K, then prescribed snow depths should be used. The resultant snow depths would be more representative of a dense boreal forest snowpack than the depths obtained using the SMMR algorithms described earlier.

CONCLUSIONS

The arctic region is influenced by energetic subpolar systems transporting heat and momentum into the region, and it, in turn, influences the general circulation of the atmosphere by acting as a heat sink (Vowinckel and Orvig, 1970). For a better understanding of the energy exchange among the atmosphere, the snowpack, and the ground, snow depth and snow extent must be known for large areas.

Microwave algorithms have enabled measurements to be made of snow extent and snow volume on a regional and global basis. However, retrieval of snow parameters is complicated in forests due to their emission and absorption properties. Algorithms that are able to incorporate information on the fractional forest cover within a microwave pixel provide more reliable estimates of the snow water equivalent and thickness of a snowpack. Efforts are currently under way to estimate the fractional forest cover using only microwave measurements rather than relying on a combination of ground-based measurements and microwave techniques. But in the most densely forested areas, such as in the boreal forest of Ontario and Quebec, microwave techniques alone are not adequate in estimating the volume of snow underlying the forest canopy.

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