A Comparison of Airborne Microwave Brightness Temperatures and Snowpack Properties Across the Boreal Forests of Finland and Western Canada

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***Abstract*—The seasonal snowpack across the boreal forest is an important national resource in both Canada and Finland, contributing freshwater for agriculture, human consumption, and hydropower generation. In both countries, satellite passive microwave data are utilized to provide operational information on snow depth and snow water equivalent (SWE) throughout the snow cover season. Airborne passive microwave surveys conducted independently across Finland and western Canada during March and April 2005 and March 2006 provided the opportunity to assess the level of similarity in snowpack physical properties and brightness temperature response to snowpack qualities using two independent data sets. The primary objectives of these campaigns were to determine the influence of small-scale heterogeneity on satellite data, using relatively high resolution airborne measurements, and to assess the Helsinki University of Technology (HUT) snow emission model capability of predicting emitted brightness temperatures under varying snowpack and landscape conditions. Comparisons of brightness temperature emissions over different land cover types showed a clear distinction of wetlands and snow-covered ice from forested and open areas. This is reflected also as a strong relationship between 6.9-GHz measurements and fractional lake cover in both Canada and Finland, with relationships at 18 and 37 GHz being less consistent between data sets. Comparisons of experimental data versus HUT snow emission model predictions showed relatively good agreement between the simulations and airborne data, specifically for the Finnish data set.**

Manuscript received April 25, 2008; revised July 30, 2008 and August 22, 2008. First published January 23, 2009; current version published February 19, 2009.

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Digital Object Identifier 10.1109/TGRS.2008.2006358

***Index Terms*—Radiometry, remote sensing, snow water equivalent (SWE).**

I. Introduction

The WINTER season land cover in Finland and large portions of northern Canada is very similar: a latitudinal transition from closed-canopy forest to open-canopy forest to open tundra, all with a persistent snow cover. It is similarly important to both nations to retrieve temporally and spatially continuous information on snow water equivalent (SWE) for issues such as flood forecasting and reservoir management for hydropower generation. *In situ* networks for snow cover measurements are drastically different between the two countries—Finland has a relatively small land mass with a dense observation network of long-transect (~4 km) snow survey sites, while Canada is a relatively large country with a comparatively sparse network of measurement sites composed mainly of automated single-point snow depth (SD) measurements. A common source of information on SWE in both Finland and Canada is passive microwave satellite data [1], [2]. In Canada, regional SWE retrieval algorithms are operationally applied to prairie and boreal forest regions of Manitoba, Saskatchewan, and Alberta. In the case of Finland, satellite estimates are derived for the whole country. Microwave brightness temperatures exhibit a frequency-dependent sensitivity to snowpack volume scatter that allows the estimation of SWE, but which is also sensitive to both the physical structure of the pack (density, grain size, snow wetness, and stratigraphy) and land cover characteristics (vegetation properties and fractional lake cover). The general similarity in these properties between Finland and Canada provides an excellent opportunity to compare data sets and methodological approaches to the estimation of SWE from satellite passive microwave data.

The Climate Research Division of Environment Canada (EC) has a long-standing research program in the development of spaceborne passive microwave SWE data sets for specific landscape regions in Canada. Algorithms of an empirical nature [3], [4] were developed to retrieve SWE for open prairie and forested regions in western Canada, with a current emphasis on the development of new algorithms for northern boreal forest and tundra environments [5]. The Laboratory of Space Technology at the Helsinki University of Technology (TKK, previously abbreviated as HUT) has developed and adopted a

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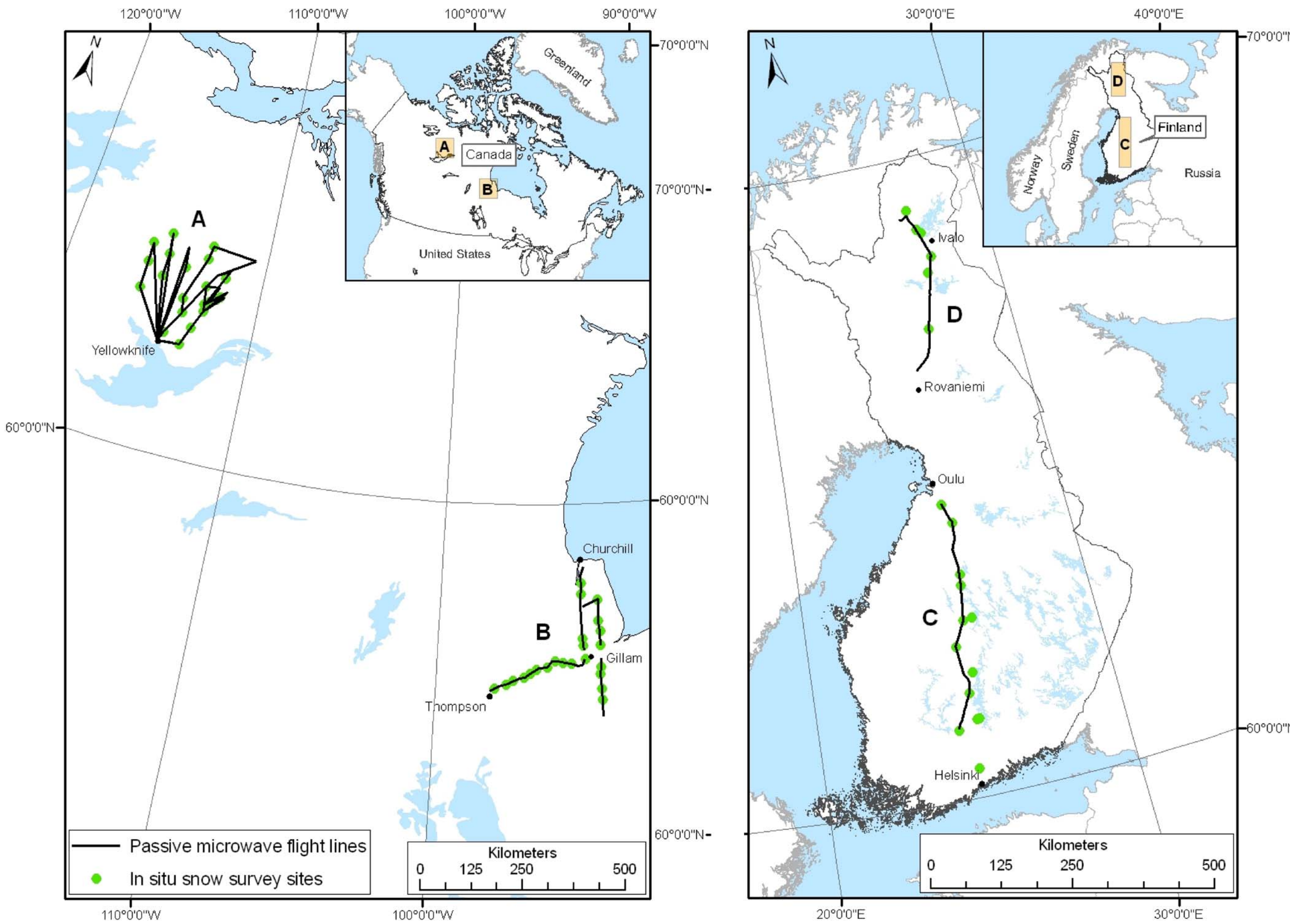

Fig. 1. Overview of ground and airborne sampling sites during the 2005 and 2006 airborne passive microwave campaigns in (left) Canada and (right) Finland. Flight lines A–D are indicated.

semiempirical radiative transfer model approach (the HUT snow emission model) for estimating SWE [6]. Recent model application to SWE retrievals across northern Eurasia included the assimilation of ground observations [7]. While the approaches adopted at EC and TKK differ methodologically, commonalities in the research programs include the use of high-resolution airborne passive microwave brightness temperatures for algorithm development activities, and the acquisition of detailed ground measurements for validation purposes.

Issues of measurement scale relative to subpixel variability are a primary concern for nearly all remote sensing applications but are particularly acute for passive microwave retrievals of snow cover properties. The large imaging footprint at microwave frequencies stands in stark contrast to the local-scale variability in snow cover distribution that is driven by meteorological conditions, interaction with vegetation, and changes in surface topography and land cover. There is a clear disconnect between the scale of satellite passive microwave measurements, typically at tens of kilometers, and the scale of snow cover variability (from meters to hundreds of meters, depending on land cover). The objective of this study was to compare results from airborne passive microwave campaigns conducted in 2005 and 2006 during the period of peak SWE in the northern boreal forest and open tundra of Finland and western Canada. These detailed ground measurements and relatively high resolution airborne passive microwave data sets were utilized to perform the following.

1) Determine the level of similarity in snowpack physical properties between the northern boreal forests of Canada and Finland.
2) Identify the subgrid-scale influences of vegetation type and lake fraction on brightness temperatures.
3) Assess the quality of HUT snow emission model predictions for different frequencies and land cover types.

II. Datasets

A. Airborne Data

Airborne passive microwave surveys with coincident surface sampling campaigns were conducted in Finland and Canada during the peak snow cover period in 2005 and 2006. Maps of the study areas are shown in Fig. 1. EC airborne radiometers (6.9, 19, 37, and 89 GHz) were deployed on the National Research Council Twin Otter across a network of flight lines in the Northwest Territories, Canada (flight line A in April 2005) and northern Manitoba, Canada (flight line B in March 2006). Both study areas contained forested regions within the climatological high SWE band described by Derksen and MacKay [8], with transitions across the boreal ecotone to open tundra. While

TABLE I
SUMMARY OF INSTRUMENT CHARACTERISTICS

	EC			TKK		
frequency [GHz]	6.9	19	37	6.9	18.7	36.5
bandwidth [MHz]	500	1000	2000	310	130	400
integration time [s]	1	1	1	0.5	0.5	0.5
sensitivity [K]	0.2	0.04	0.03	0.2	0.6	0.3
accuracy [K]	< 2	< 2	< 1	< 2	< 2	< 1
θ_{3dB} [°]	9	6	6	5	3	4
α_i [°]	53	53	53	50	50	50
scan method	sideways along track			along track		
flight altitude [m]	1000			600		
airspeed [m/s]	57			64		
footprint size [1] (w x l) (m)	70 x 120	70 x 120	70 x 120	7 x 41	4 x 37	6 x 39

1) ideal value for flat target; actual footprint varies according to aircraft maneuvering and ground elevation

similar at a general level, there are land cover differences between the two Canadian study areas. The Canadian shield terrain of line A is lake rich, with areas of exposed rock, and mixed forest cover. The tundra region is topographically complex, with highly variable SD due to wind scour and deposition. The Hudson Bay lowland region of line B is very flat, with a low lake fraction and highly variable forest stand density. The tundra region is a low-relief wetland complex, with a high fraction of small ponds. Vegetation is limited to areas surrounding the creek beds and larger lakes.

A number of different airborne flight patterns were surveyed during the 2005 and 2006 Canadian campaigns, including the acquisition of data in a radial pattern of three flight line segments that intersected at a central point coincident to surface measurement sites. Each flight line segment was approximately 3 km in length. Analysis in this study was limited to this radial pattern data set because the data are readily relatable to the ground measurements of snow properties, and they allow a straightforward means of comparing data from the 2005 and 2006 campaigns.

The Finnish data set is composed of long flight lines flown in southern Finland in March 2005 (flight line C) and in northern Finland in March 2006 (flight line D). The transects are located on the Fennoscandian (Baltic) shield, which is similar to the Canadian shield terrain of flight line A. The Helsinki University of Technology Radiometer system (HUTRAD; 6.8, 10.7, 18.7, 23.8, 36.5, and 94 GHz) was mounted on an SC-7 Skyvan aircraft. A summary of both Finnish and Canadian instrument characteristics, specifically for the frequencies used in the comparative analysis, is provided in Table I. All the airborne data acquisition occurred during subzero ground-level temperatures, before the onset of snow melt. General weather conditions were typically fair conditions with little or no precipitation—necessary conditions for low-level flying. If clouds were present, flight levels were always below the cloud deck.

The 2005 study region predominantly contained conifer-dominated boreal forests with a considerable number of bogs and lakes. Flight line D for 2006 included a transition from forest to open terrain. Summaries of all the airborne campaigns are provided in Table II.

The statistical distributions of measured airborne brightness temperatures are shown for comparative purposes in Fig. 2 (2005) and Fig. 3 (2006). A Kolmogorov–Smirnov (KS) test was performed on these paired data sets to identify the maximum difference (D) in the probability distributions at each frequency and season, together with the corresponding brightness temperature value at which the maximum difference occurred (Table III). The distributions were different at each frequency (6.9V, 19V, and 37V GHz), but the shapes at each frequency were consistent between the Canadian and Finnish data sets. The 6.9- and 19-GHz-frequency distributions exhibited similar shapes for both seasons, but the peaks are offset in 2006, as exhibited by the higher KS D values for this season. The tail of the distribution at 6.9 GHz corresponds to lower brightness temperatures measured over mixed terrestrial and lake footprints, with homogeneous lake measurements as low as 180 K. This strong (up to 70 K) difference in response over lakes versus terrestrial surfaces shows the sensitivity to fractional lake cover at 6.9 GHz, which will be presented in more detail later. Notable differences in the measurement distributions were observed at 37 GHz due to sensitivity to both snowpack and vegetation properties at this frequency. The generally sparser forest and larger grain size combined to shift the center of the normally distributed brightness temperatures lower in Canada compared to Finland for both seasons. The maximum difference in the 37 GHz distributions occurred at the same brightness temperature value for both seasons (223 K).

B. Ground Observations

Snow cover measurements in Finland were made at operational snow courses of the Finnish Environment Institute (SYKE), as noted in Fig. 1. Ground data were also acquired by snow pit measurements at 13 predefined locations in 2005 and six additional sites in 2006. Land cover was generally conifer-dominated mixed forest, with some open agricultural areas, bogs, and lakes (and open tundra in 2006). Operational snow courses consist of 2–4-km transects, with point measurements of SD, SWE, and density. Each snow course typically contains over 100 samples, which are also classified according to land cover type. Additional snow pit measurements consisted of five to ten points for definition of SD and snowpack stratigraphy, with one point being used for grain size estimation in different layers.

Canadian ground measurement sites corresponding to locations where radial patterns of airborne data were acquired are shown in Fig. 1. At each site, seven snow cores from a manual snow sampler were taken for direct measurement of SWE and bulk density, while snowpack stratigraphy measurements

TABLE II
SUMMARY OF AIRBORNE CAMPAIGNS CONDUCTED IN FINLAND AND CANADA

	Canada		Finland	
Flight line	A	B	C	D
Dates of Deployment	April 3-18 2005	February 28-March 13 2006	March 14 2005	March 16-17 2006
Study Domain	Snare and Yellowknife basins, Northwest Territories. Ground measurements at 15 locations	Nelson watershed, Manitoba. Ground measurements at 25 locations	Southern Finland. 6 snow course observation sites 13 additional observation sites	Northern Finland. 4 snow course observation sites 6 additional observation sites
Dominant ground types	Forested: 48% Tundra: 29% Lakes: 23%	Forested: 60% Tundra: 27% Lakes: 13%	Dense forest: 51% Sparse forest: 7 % Deforested areas: 9% Bogs: 3 % Lakes: 10%	Dense forest: 46% Sparse forest: 11% Deforested areas: 12% Bogs: 14% Lakes: 3%
Ground Measurements	Snow depth Snow water equivalent Snow density profiles Snow grain size profiles		Snow, soil, air temperature Snow depth Snow density and moisture profiles Snow grain size profiles and photographs	

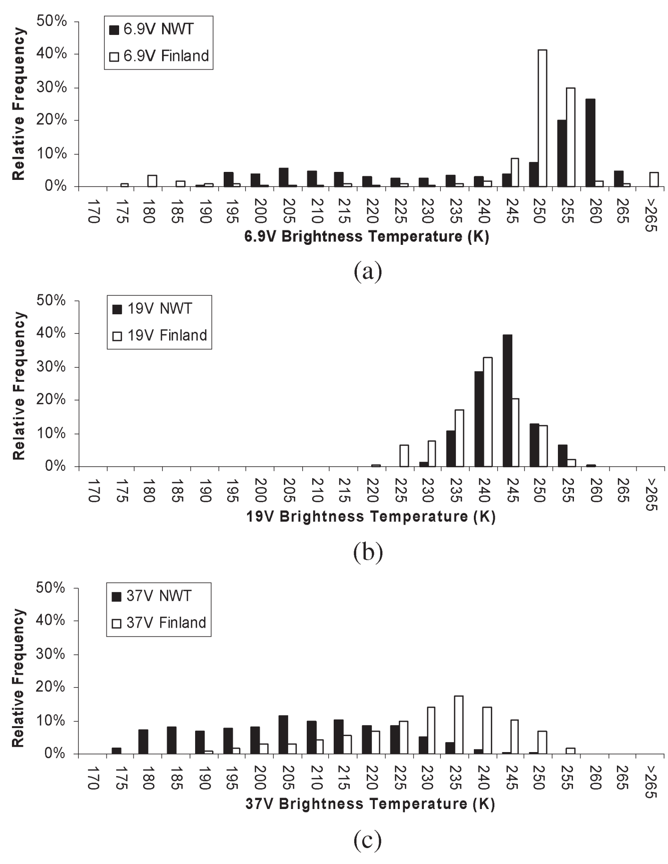

Fig. 2. Brightness temperature distributions for the 2005 Canadian and Finnish data sets (flight lines A and C). Vertical polarizations of three frequencies are shown: (a) 6.9 GHz, (b) 19 GHz, and (c) 37 GHz.

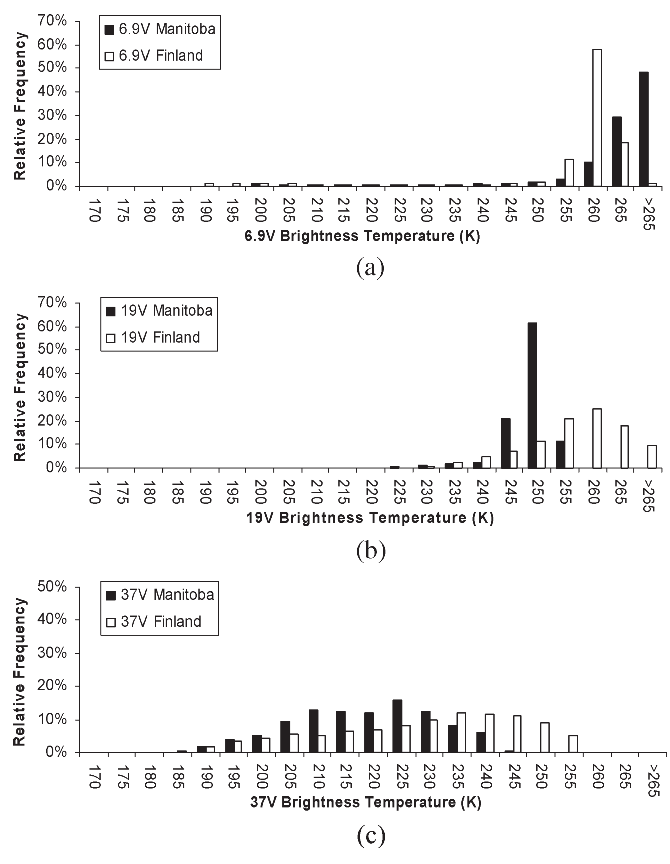

Fig. 3. As in Fig. 1 but for the 2006 data (flight lines B and D).

including density profiles, the identification of layering, and mean grain size (diameter; long and short axis) for each layer were also made. Thirty SD measurements were taken. Mean site SWE was calculated directly from the core measurements and by converting each individual depth to SWE using the mean density from the snow core measurements. When lakes were adjacent to the terrestrial site, measurements were repeated on the lake as well. Land cover in both Canadian campaigns was predominantly open-canopy boreal forest across a generally lake-rich (∼30%) environment. A small number of sites were located north of the boreal tree line in the open tundra.

A comparison of ground measurements showed some similarities in snowpack physical properties between Finland and Canada across the boreal forest (Fig. 4). Greater variation in depth and SWE was contained in the Finnish data set, a reflection of the range in land cover conditions contained along these

TABLE III
RESULTS OF KS TEST FOR BRIGHTNESS TEMPERATURE DISTRIBUTIONS ON FLIGHT LINES IN 2005 AND 2006. MAXIMUM DIFFERENCE OF PROBABILITY DISTRIBUTION FUNCTIONS (D-VALUES) AND POINT OF OCCURRENCE

	6.9 GHz	18.7 GHz	36.5 GHz
Flight Lines A, C (2005)	0.34 (252 K)	0.24 (240 K)	0.55 (223 K)
Flight Lines B, D (2006)	0.68 (261 K)	0.66 (252 K)	0.35 (223 K)

flight lines (forested, agricultural, and wetlands) in comparison to the Canadian sample sites that were largely open-canopy boreal forest with a small number of tundra sites. While variables related to the general properties of the pack were similar (depth, density, and SWE), the vertical stratigraphy between the data sets was different, as shown in Fig. 4(d) for mean grain size. For both data sets, grain size was estimated by identifying the mean grain size in each of the major layers in the snowpack. This was done visually by placing sample grains on a reference surface. The pack average was calculated by weighting each layer mean grain size by the proportional thickness of each layer. The cold continental climate across the boreal forest of central Canada produces ideal conditions for grain growth, in contrast to the maritime moderated climate in southern Finland (the snow classification system of Sturm *et al.* [9] classifies most of Finland as maritime snow). By April, the boreal snowpack in Canada contains a depth hoar layer that can compose over 50% of the total SD [5]. These large depth hoar crystals can exceed 10 mm, so, although small faceted, rounded, and fresh grains in the layers above the depth hoar are typically only 1–2 mm, the significant depth hoar layer increases the mean snowpack grain size.

In Finland, observed grain size also varied greatly, depending on the layer. Observations in 2005 included up to three distinct layers, with increasing grain size toward the bottom layer. Grain size ranged from a typical value of 1 mm in a 5–10-cm surface layer to 2 mm in several bottom layers. Observations in 2006 showed similar thin surface layers but mostly homogenous snowpacks below the surface, with a mean grain size smaller than 2 mm. It is important to note that unlike depth, SWE, and density, the determination of grain size in this study was somewhat subjective. However, the differing snow grain properties between Finland and Canada was highlighted previously by Roy *et al.* [10] as a major factor influencing the applicability of the HUT snow emission model to Canadian boreal snowpacks.

Density profiles (not shown) in the Finnish and Canadian boreal forests were characterized by increasing density with depth due to settling and grain metamorphism. In the tundra, density maxima were observed near the surface due to well-defined wind slab layers that were typically 1–5 cm deep at the Finnish sites, but were observed at depths up to 20 cm in Canada. Ice lenses and crusts were weak and intermittent in the boreal forest and were created by early season melt and refreeze events. Snowpack layering in the tundra was largely the result of old wind slabs overlain with newer snow.

Similar processes govern local-scale variability in boreal forest and tundra snow cover in Canada and Finland. In forested areas, interaction between falling snow and standing vegetation controls SD variability on the ground. The variability in terrestrial SWE was driven by variability in depth, not density. Coefficient of variation (CV: standard deviation/mean) values for depth were approximately 1.6 times higher than for density at the Canadian forested sites and were 5.9 times higher than for density at the Finnish forested sites. Wind redistribution is the dominant process across the tundra, with depth again controlling SWE variability (depth CV 3.9 times higher than density at the Canadian tundra sites; 3.1 times higher at the Finnish tundra sites).

Snow cover properties on lakes are different from those of terrestrial surfaces ([5], [11]), so measurements were made at lake sites adjacent to the terrestrial sites when possible. While depth variability governed SWE variability in terrestrial snow cover, density was the primary control on SWE for lake snow. CV values for lake snow measurements showed that density variability was approximately 2.5 times greater than depth variability. Measurements in Finland also illustrated different snow conditions on lakes in comparison to land areas. Both in 2005 and 2006, snow layers on ice were thinner and denser than snowpacks on adjacent land areas, with a typical snowpack depth of 10 cm on ice compared with 40 cm on land.

III. RESULTS

A. Brightness Temperature Versus Land Cover Type

Data from flight line C, where surface sampling was most intensive, were selected for an assessment of brightness temperatures versus ground-measured SWE over different land cover categories. This line also had the largest variability in measured SWE. Fig. 5 shows the response of brightness temperatures at different frequencies as a function of SWE. Original data at the spatial resolution of 100 m were divided into five different land cover categories, derived from generalized CORINE2000 land use classifications. The generalized categories were defined as dense forest, sparse forest, open areas, bogs, and lakes. Vertical error bars indicate the standard deviation of brightness temperatures around the SWE average (note that the mean SWE varied slightly for different land cover types). The relationship between 18.7-GHz brightness temperature and SWE was stronger than that at 36.5 GHz for all land cover categories except lakes (see correlation results in Table IV). However, the sensitivity to SWE was similar between both forested and open areas, indicating that the presence of vegetation does not severely affect the feasibility of SWE estimates over these land cover categories. The sensitivity to vegetation at 37 GHz is evident, however, as denser vegetation was associated with warmer brightness temperature due to the contribution to emission from the vegetation. Over bogs, the relation between 36.5 GHz and SWE weakens significantly, indicating that these areas may prove problematic for SWE retrievals.

Over lakes, 18.7-GHz brightness temperatures showed no relationship with SWE. However, at 36.5 GHz, a significant (albeit weak) relationship was identified. As satellite observations with coarse spatial resolution average brightness temperature over large areas, the presence of lakes evidently worsens the correlation with SWE, particularly at 18.7 GHz.

The results in Fig. 5 show that a larger range of brightness temperatures are associated with the same SWE at 36.5 GHz

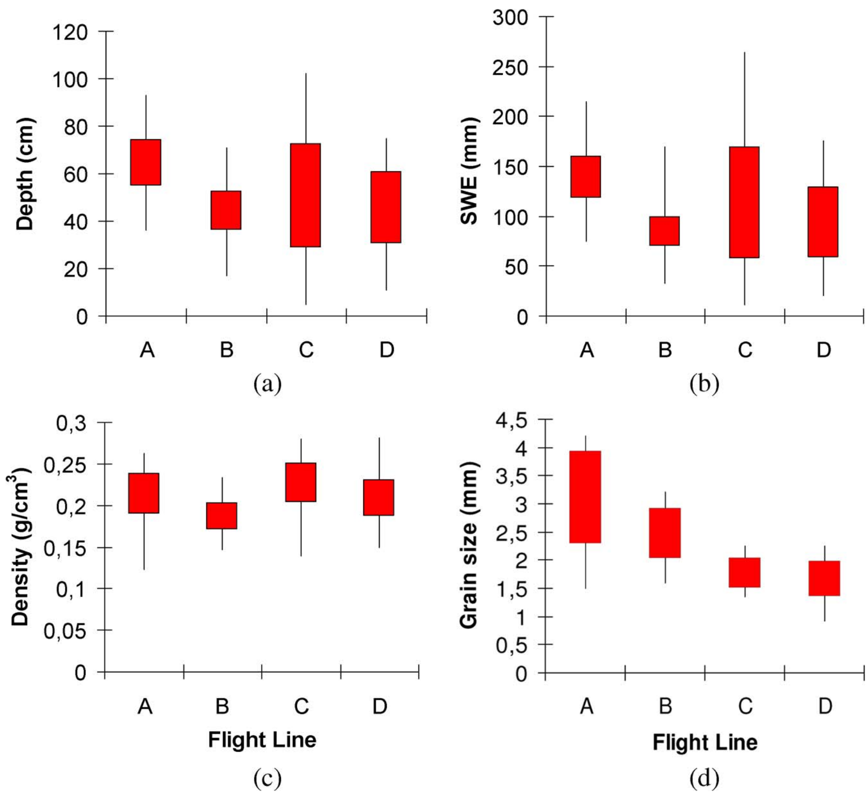

Fig. 4. Boxplots of snowpack properties on flight lines A–D: (a) SWE, (b) depth, (c) density, and (d) grain size.

(indicated by the error bars) when compared with 18.7 GHz. Contributing factors to this wider range include the effect of small- and large-scale spatial variations in snow grain size and vegetation [6]. The results for 6.9 GHz do not indicate any correlation between SWE and brightness temperature, as can be expected, although the distinction between lakes and terrestrial measurements is very large.

B. Brightness Temperature Versus Lake Fraction

Long-wavelength passive microwave radiation can be influenced by the water below free-floating lake ice, resulting in a drop in brightness temperatures over lakes compared to adjacent land, while shorter wavelength radiation is largely influenced by the snow overlying the ice [12]. Subsequently, the response of passive microwave measurements at low frequencies can vary significantly between land and lake surfaces due strictly to lake ice properties instead of snow. Lake ice features such as bubbles also scatter the microwave emission, further reducing the brightness temperatures. Over the course of the ice-growing season, the growth of ice and subsequent increase in its thickness increases the brightness temperature compared to thinly iced lakes [13]. The thicker ice reduces the influence of the lower emissivity of liquid water below the ice and emits its own microwave energy, thereby increasing the brightness temperatures over water bodies.

For this study, lake fraction across the Canadian study areas was determined by binary classification of Landsat 7 ETM mosaics obtained from NASA via http://zulu.ssc.nasa.gov/mrsid/. Brightness temperature versus lake fraction relationships were then calculated along 1-km flight line segments. The segments were located in the vicinity of the ground measurement sites shown in Fig. 1. Similarly, the Finnish airborne data were divided into 1-km segments along both flight lines C and D. The lake fraction in each segment was determined from national 25-m-resolution CORINE2000 data [14].

Results of a correlation analysis of the 1-km flight line segments are shown in Table V. The response of individual frequencies to lake fraction is shown in Fig. 6. The data segments have been classified according to their corresponding average lake fraction values from 0% to 70% in 10% increments; the average measured brightness temperatures and their standard deviation were calculated. There was a strong dependence between 6.9V brightness temperature and fractional lake cover at boreal forest sites in both Canada and Finland [Fig. 6(a)]. As explained previously, this can largely be explained by the influence of water under the ice at longer wavelengths. Measurements at 19 GHz were moderately related to lake fraction in both data sets, but over a very narrow range in brightness temperatures, which illustrated a general insensitivity to lakes at this frequency [Fig. 6(b)]. In the Canadian data set, 37-GHz measurements were moderately related to lake fraction across a brightness temperature range of over 20 K [Fig. 6(c)]. On the contrary, the 37-GHz results in the Finnish data set more closely approximate the narrow brightness temperature range that was observed at 19 GHz. The differing results in Canada at 37 GHz may be related to the generally greater lake fractions, thicker ice, and greater snow cover storage on the lake surfaces in comparison to Finland.

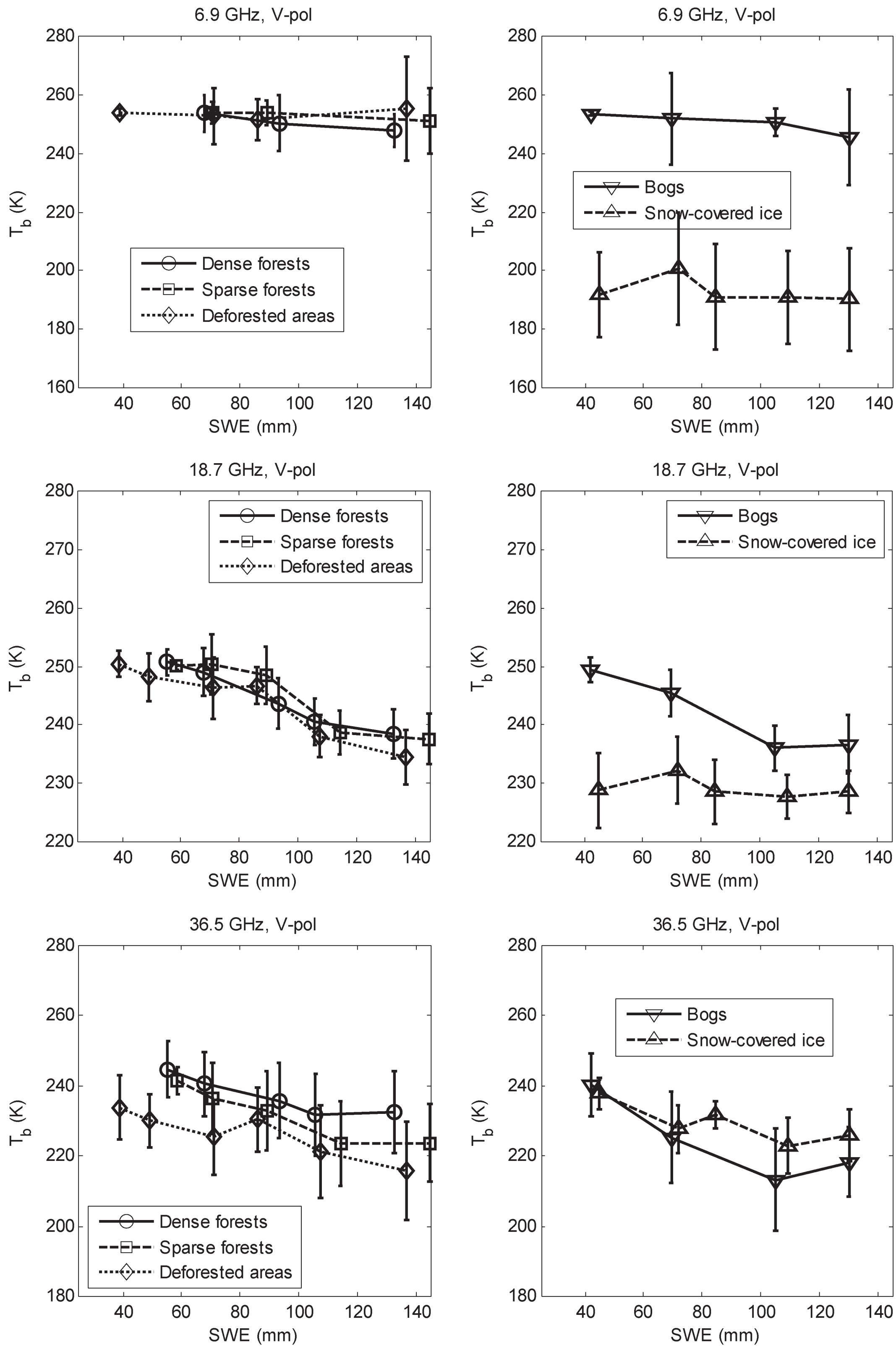

Fig. 5. Brightness temperature distribution versus surface SWE measurements for different land cover types, flight line C. Three frequencies are shown: (top) 6.9 GHz, (middle) 19 GHz, and (bottom) 37 GHz.

C. Comparison of Emission Model Predictions With Experimental Data

The HUT snow emission model [6] was used to simulate the brightness temperature of the snowpack in different land cover categories. The model describes the snowpack as a single layer and uses the delta-Eddington approximation to the radiative transfer equation, applying an empirical constant to determine the forward scattered intensity. The model can be applied for

TABLE IV
CORRELATION OF V-POL BRIGHTNESS TEMPERATURES VERSUS SWE OVER DIFFERENT LAND COVER TYPES ON FLIGHT LINE C

	Dense forests	Sparse forests	Deforested	Bogs	Lakes
Flight Line C					
6.9 GHz	0.04	0.04	0.01	0.03	0.01
18.7 GHz	0.57[1)]	0.52[1)]	0.56[1)]	0.32[1)]	0.02
36.5 GHz	0.15[1)]	0.16[1)]	0.13[1)]	0.08	0.16[1)]

[1)]results significant at 95 %

TABLE V
CORRELATION OF V-POL BRIGHTNESS TEMPERATURES VERSUS LAKE FRACTION

	6.9 GHz	18.7 GHz	36.5 GHz
Flight Lines A, B (Canada)	0.82[1)]	0.26[1)]	0.35[1)]
Flight Lines C, D (Finland)	0.77[1)]	0.30[1)]	0.02

[1)]results significant at 95 %

both dry and wet snow. The dielectric constant for wet snow is described through an empirical formula. The transmissivity and brightness temperature contributions of vegetation layers and the soil–snow reflectivity are considered using empirical model approaches ([15], [16]). Multiple reflections between different layers are included using an incoherent approach for a multilayer medium [17].

Model predictions were compared with brightness temperatures obtained from airborne measurements. The most significant input parameters for dry-snow model simulations include the following: average grain size, SWE, snow density, forest cover percentage within an imaged pixel, forest stem volume, and physical temperatures (ground, snowpack, vegetation, and air). Values for these parameters were obtained from ground measurements and available land cover reference data. Ground surface roughness was considered as a constant parameter. Physical temperatures were acquired from weather station data.

A summary of model input parameters for different land cover categories is provided in Table VI for flight lines A and B and in Table VII for lines C and D. Some parameters, such as the forest stem volumes, may vary greatly over a set of airborne data pixels—the given values are best estimates based on forestry data in both countries ([18], [19]). It should be noted that the land cover definitions used in this paper are not necessarily consistent regarding stem volume values. In the Finnish case, forest density definitions arise from canopy cover, not stem volume. Canadian "forested" areas and "dense forests" in the Finnish northern flight line D are, in fact, similar to "sparse forests" in flight line C in southern Finland, with average stem volumes of 50 m^3/ha. Densely forested areas in flight line C have stem volumes exceeding 100 m^3/ha.

Grain size has a strong influence on model predictions, particularly at higher frequencies. Variability in measured grain size was notable at a local scale. Also, the visual observation method for estimating grain size introduced uncertainty to the results. An error of ±0.5 mm for average grain size values was used in the model for calculating error bounds.

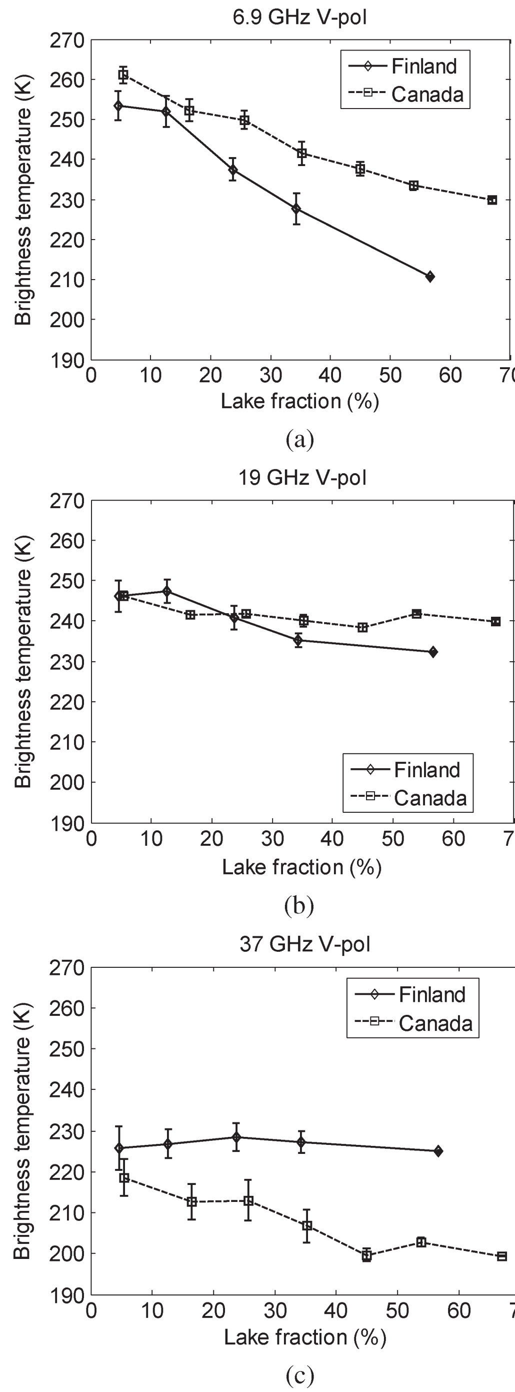

Fig. 6. Relationships between aggregated airborne brightness temperatures and fractional lake cover in Finland and Canada. Data combined from flight lines A to D (see Fig. 1). Results for (a) 6.9 GHz, (b) 19 GHz, and (c) 37 GHz. See Table I for the exact frequencies. Error bars indicate the standard deviation of brightness temperatures in data segments (low error values at over 50% lake fraction due to small number of segments).

Model and airborne results over densely forested areas versus reference SWE averages obtained from ground measurements are shown for all flight lines in Fig. 7. Fig. 8, in turn, shows model predictions for sparsely forested areas, deforested areas, and bogs of flight line D. RMS and bias statistics for the model versus measured results, for all flight lines and land cover types,

TABLE VI
HUT SNOW EMISSION MODEL INPUT PARAMETERS FOR FLIGHT LINES A AND B (CANADA)

	Forested	Tundra
Flight Line A		
Biomass volume (m^3/ha)	50	10
Grain size (mm)	1.6 to 3.6	2.7 to 3.0
SWE (mm)	110 to 162	61 to 80
δ (g/cm^3)	0.20 to 0.22	0.24 to 0.26
Flight line B		
Biomass volume (m^3/ha)	50	10
Grain size (mm)	1.6 to 3.0	1.8 to 3.4
SWE (mm)	73 to 95	50 to 90
δ (g/cm^3)	0.18 to 0.19	0.19 to 0.33
Constant values		
Incident angle (°)	53	
Snow wetness (%)	0	
Conductivity (ε) for frozen ground	1-6*j	
Surface roughness (mm)	3	

TABLE VII
HUT SNOW EMISSION MODEL INPUT PARAMETERS FOR FLIGHT LINES C AND D (FINLAND)

	Dense forests	Sparse forests	Deforested	Bogs
Flight Line C				
Biomass volume (m^3/ha)	150	60	30	30
Grain size (mm)	1.34 to 1.85			
SWE (mm)	38 to 150	38 to 150	59 to 163	56 to 146
δ (g/cm^3)	0.22 to 0.25	0.22 to 0.25	0.22 to 0.26	0.22 to 0.24
Flight line D				
Biomass volume (m^3/ha)	60	40	20	20
Grain size (mm)	1.25…1.4			
SWE (mm)	95 to 144	95 to 144	32 to 47	74 to 171
δ (g/cm^3)	0.18 to 0.22	0.18 to 0.22	0.18 to 0.22	0.18 to 0.23
Constant values				
Incident angle (°)	53			
Snow wetness (%)	0			
Conductivity (ε) for frozen ground	1-6*j			
Surface roughness (mm)	3			

are summarized in Table VIII. Model results indicate good agreement in densely forested areas with airborne measurements at 19 and 37 GHz, specifically for the Finnish transects. The model underestimates brightness temperature with both Canadian data sets at these frequencies, particularly for the high SWE values of flight line A. On line A, high SWE values coincided with large measured grain sizes. This causes the low brightness temperature values predicted by the model. A visual examination of Fig. 7(a), however, indicates that changes in airborne brightness temperatures at 19 and 37 GHz are also reflected in the modeled values albeit with a large offset. The changes in modeled values are, again, largely due to varying grain sizes between different sites. It is likely that this grain size effect also influenced the observed changes in the airborne measurements.

A revised method of calculating the extinction coefficient in the case of large snow grains was suggested by Roy *et al.* [10], adapting the HUT snow emission model at 37 GHz to the Canadian boreal environment. Examination of the Canadian data set showed improvement in the model predictions at 37 GHz using this revised method. RMS errors between modeled and measured values (see Table VIII) dropped to 11 K and 17 K, respectively, for forested areas in lines A and B when the method by Roy *et al.* was employed (from 13.5 K and 24.6 K, respectively). Improved model performance for lower frequencies was not produced, as expected. The data sets thus further support the use of the modified extinction coefficients in the case of large grain sizes and demonstrate the sensitivities between snow emission models, as also highlighted previously by Tedesco and Kim [20].

With the exception of flight line B, open areas (deforested and tundra) show poorer agreement with the model than forested areas (note the higher rms error values evident in Table VIII). Wind-created slab layers on the top of the snowpack are characteristic of open areas but not of forests, so the more substantial vertical layering in open areas may have caused the poorer model performance. For bogs, the model predictions significantly differed from brightness temperature observations at 37 GHz, which may result from a wet (partially unfrozen) peat surface and from an ice layer between the peat surface and overlying snowpack.

As mentioned previously, the HUT snow model does not require information on multiple layers within a snowpack as an input. Recent findings using the microwave emission model for layered snowpacks by Durand *et al.* [21] showed significantly lower errors between point-scale modeled and measured results when the snowpack was treated as a multilayer medium. While information on snowpack vertical layering was acquired at snow pit sites in this paper, we did not apply these measurements across the long regional flight lines.

IV. CONCLUSION

SWE is a highly sought after variable for model evaluation (climate, numerical weather prediction, and hydrological), studies of the cryosphere–climate system, and hydrometeorological applications [22]. While the potential of satellite passive microwave data to provide SWE estimates has been evident since the availability of Scanning Multichannel Microwave Radiometer data in the late 1970s [23], widespread use of microwave-derived data sets, particularly at the hemispheric scale, is limited by high levels of uncertainty. Dynamic algorithmic approaches that consider evolving snow grain size show regional potential [24], but uncertainty can be very high at the hemispheric scale [25]. The potential contributing factors to this

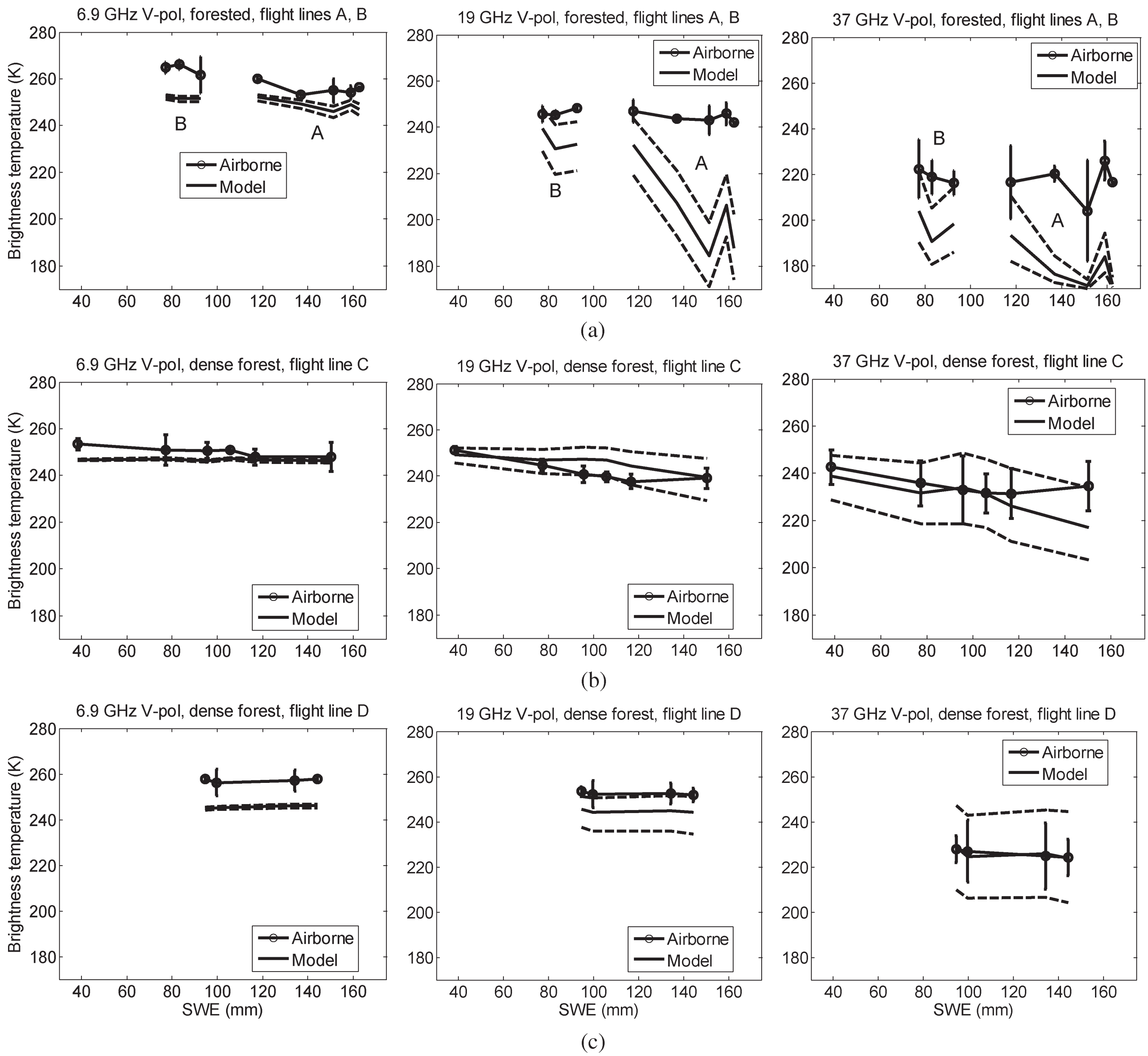

Fig. 7. Comparison of modeled and airborne brightness temperatures versus reference SWE over flight lines (a) A and B, (b) C, and (c) D over forested areas. Solid lines with error bars indicate the average airborne observations and ± standard deviation from the average. Dashed lines indicate error bounds for model predictions within a grain size estimation error of ±0.5 mm from the average. Model values using average grain size are indicated with a solid line between these.

uncertainty are many and include characteristics of the land surface, along with snow cover physical properties. Regardless of specific issues, a constant factor in all snow-covered environments is a high degree of subgrid-cell heterogeneity within the relatively coarse resolution passive microwave footprints.

In this paper, complementary airborne passive microwave surveys conducted across Finland and Canada during the winter seasons of 2005 and 2006 were examined to identify high spatial resolution relationships between snow cover, lake fraction, vegetation, and brightness temperature. The snow survey results showed a generally similar bulk snowpack at the Finnish and Canadian sites (although composed of varying grain sizes), across a northern boreal vegetation zone of similar structure.

The airborne brightness temperature distributions were distinct at each frequency. Measurements at 6.9 GHz exhibited a strong right skew due to the response of lake ice, 19-GHz measurements were normally distributed across a narrow brightness temperature range, and 37-GHz measurements showed a broad distribution over a wide brightness temperature range. The distributions for each frequency were similar for the Canadian and Finnish measurements with the exception of 37 GHz. In that case, the considerably coarser grain size observed for Canada caused brightness temperatures significantly lower than those recorded for Finland. This supports previous studies, in the case of natural snowpacks, on the increasing influence of snow grain size with increasing frequency [26], [10].

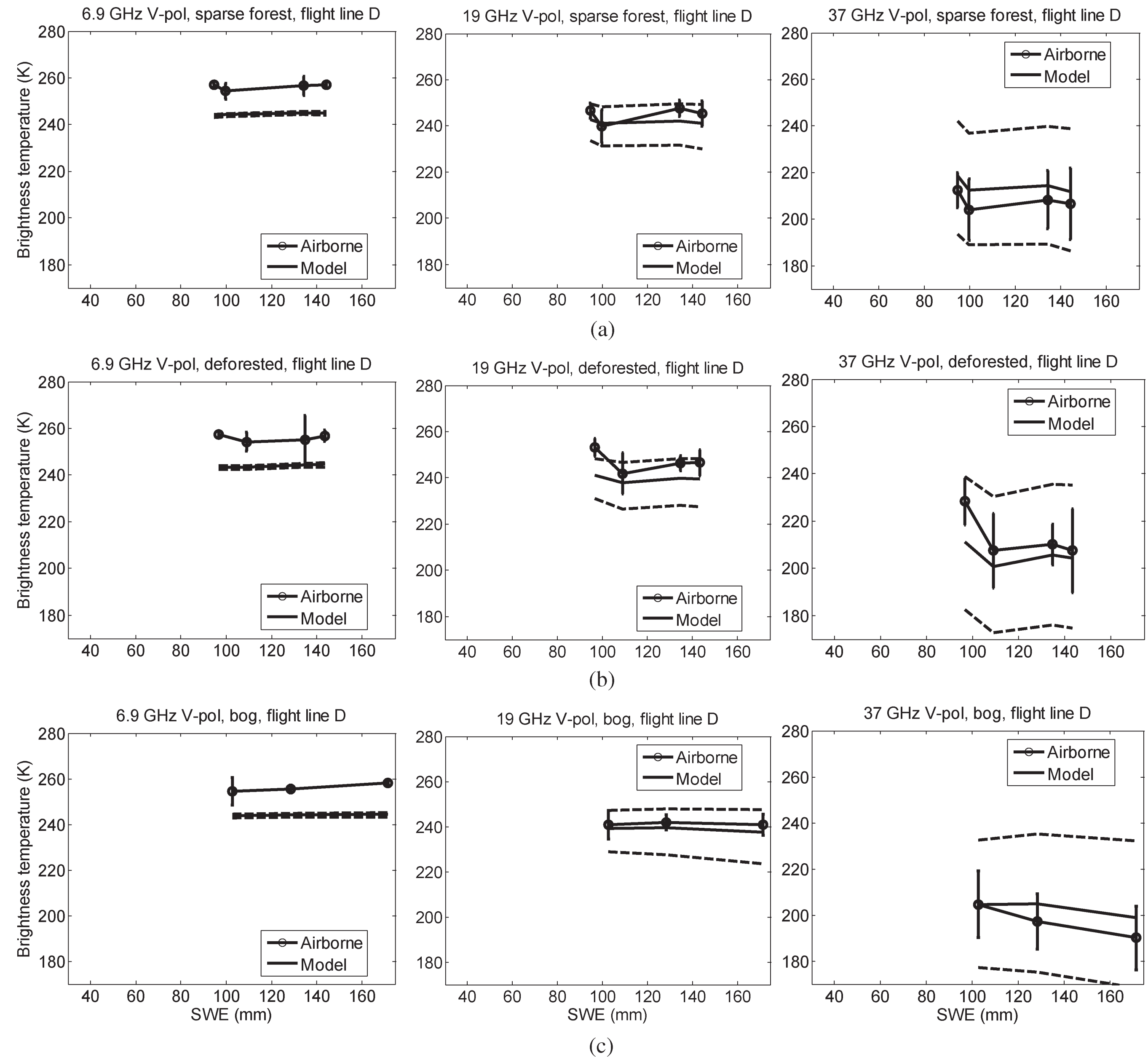

Fig. 8. Comparison of modeled and airborne brightness temperatures versus reference SWE over flight line D for (a) sparse forests, (b) deforested areas, and (c) bogs. Meaning of error bars and model error bounds as for Fig. 7.

Measurements at 6.9 GHz showed no relationship with ground-measured SWE, an expected result at this low frequency. Both 19- and 37-GHz brightness temperatures decreased with increasing SWE, with the relationship being more tightly constrained at 19 GHz than at 37 GHz. This was an unexpected result. Measurements at 19 and 37 GHz are typically used together to estimate SWE because measurements at 19 GHz are generally considered insensitive to the snowpack volume scatter that occurs at 37 GHz. These results suggest that when SWE exceeds approximately 100 mm, volume scatter also influences 19-GHz measurements. These field measurements confirm the deep-snow scattering at 19 GHz found in model simulations by Markus *et al.* [27] and satellite measurements by Derksen [28]. Weak relationships between ground-measured SWE and airborne brightness temperatures were found for wetlands and lake snow, necessitating a closer look at the influence of lake fraction.

The examination of airborne measurements found that 6.9-GHz measurements were systematically sensitive to subgrid-scale lake fraction. Measurements at 19 GHz showed some correlation with lake fraction in both data sets but over a very narrow brightness temperature range. A moderate statistical association was found at 37 GHz in Canada that was not found in the Finnish measurements. Lake ice and snow conditions were regionally different: late season ice thickness over the Canadian lakes was up to 1.5 m, and the lake snowpacks were over 30 cm in depth. In Finland, ice thickness was thinner (on the order of 50 cm in the south and 1 m in the north), and the measured snowpack was typically shallower (approximately 20 cm). These results support previous results that a high lake

TABLE VIII
RMS AND BIAS OF ERROR FOR MODELED VERSUS AIRBORNE BRIGHTNESS TEMPERATURES ON FLIGHT LINES A, B, C, AND D. VALUES IN KELVINS

Flight line	6.9 GHz		19 GHz		37 GHz	
	RMS	bias	RMS	bias	RMS	bias
A						
forest	12.8	12.1	13.2	7.6	13.5	9.0
tundra	12.3	8.6	25.6	13.7	38.5	24.3
B						
forest	6.8	5.4	37.0	31.3	24.6	20.5
tundra	1.7	1.7	8.3	7.7	24.9	24.7
C						
dense forest	5.7	3.5	5.3	-3.5	12.0	5.1
sparse forest	5.6	5.2	5.5	-4.1	10.9	0.0
deforested	7.4	5.5	6.5	-1.0	18.0	9.8
bogs	8.4	6.8	5.6	1.2	15.4	12.2
D						
dense forest	12.3	11.6	8.8	7.8	11.1	0.3
sparse forest	12.0	11.7	6.8	3.1	14.0	-6.5
deforested	13.1	11.9	9.9	7.3	17.0	7.8
bogs	12.9	12.3	4.9	0.5	19.6	-12.1

fraction may significantly affect the accuracy of SWE estimates based on the channel difference of 19 and 37 GHz, as suggested by Duguay *et al.* [29].

Model predictions versus airborne measurements showed good agreement for the Finnish transects. In general, scatter in observations was seen to increase when monitoring open environments such as deforested areas or bogs when compared to forested areas. Results for the Canadian data are less consistent in this regard. This may be due to reduced accuracy of the model with larger grain sizes. Both data sets exhibited larger errors at 37 GHz than at 19 GHz in almost all cases.

This paper has shown that parameters independent of the snowpack that vary on the sub-satellite grid-cell scale (such as lake fraction) had a systematic impact on high-resolution airborne brightness temperatures. Coincidentally, snowpack properties such as grain size and SWE also influenced measured and modeled brightness temperatures. These results illustrate the challenges in relating SWE to brightness temperatures at the coarse resolution of current satellite passive microwave measurements. A particular issue is the large measured range of airborne brightness temperatures at 37 GHz, the frequency that also exhibited the largest deviations from the HUT snow emission model simulations. Measurements at 37 GHz are utilized in most conventional SWE retrieval schemes due to the high theoretical sensitivity at that frequency to snowpack volume scatter, but these measurements also exhibited pronounced sensitivity to forest cover and grain size.

Problems related to model predictions at 37 GHz suggest some areas for further study. In particular, future models should be able to include multilayer treatment in the case of snow-covered lake ice, depth hoar, and wind-induced surface slab layers. In future measurement campaigns, ground observations should focus on the necessary stratigraphic measurements to contribute to modeling studies. Other areas of improvement include observations on the stem volume of forested pixels; so far, this has been treated as a common average value for all pixels representing a certain forest type (dense or sparse forests, and tundra) in a certain area.

In conclusion, the combined analysis of airborne passive microwave and surface snow cover data sets from Canada and Finland has illustrated similar multiscale brightness temperature response to fractional lake cover and SWE. In turn, this will allow assessment of the transferability of SWE retrieval techniques and contribute to the future generation of time series of satellite data sets extending across North America and northern Eurasia. Future analysis will consider the seasonal brightness temperature evolution with respect to variables such as forest transmissivity and lake fraction. This paper only considered relationships close to the timing of peak seasonal SWE. By considering the seasonal evolution, these variables can be introduced to retrieval schemes, either to improve the SWE estimates themselves or to contribute to attaching uncertainty estimates [30]. Treatment of uncertainty will become increasingly important as passive microwave information is utilized in land surface data assimilation schemes [31].

ACKNOWLEDGMENT

The authors would like to thank the National Research Council for coordinating Twin Otter aircraft logistics, A. Silis (Environment Canada) for leadership in the field, Northwest Territories Power Corporation (K. Dies) and Indian and Northern Affairs Canada (B. Reid) for the in-kind support for the field measurements in Canada, and the numerous persons working at TKK, FMI, and SYKE for the support for the field measurement activities in Finland.

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