In-situ passive microwave emission model parameterization of sub-arctic frozen organic soils

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ABSTRACT

Many passive microwave remote sensing applications such as land surface temperature, snow water equivalent and soil moisture retrievals need to take into account a soil parameterization to the overall surface signal emission. Soil emission modeling presents large uncertainties when the soil is frozen. In this paper, an empirical retrieval method is presented, specifically for rough frozen soil permittivity estimates at 10.7, 19 and 37 GHz. The method was tested and validated using in-situ passive microwave measurements at incidence angles from 0 to 60° of sub-arctic frozen organic soils in Northeastern Canada. The retrieved permittivity values give an overall RMSE between the measured and simulated brightness temperatures of 4.6 K for all frequencies combined. A sensitivity analysis was conducted on the different soil parameters optimized in this study. This analysis suggests that the accuracy of the retrieved parameters, using the method given here, is of ± 1.00 for the permittivity and ± 0.12 cm for surface roughness. Also, a comparison was conducted between the parameterization used in this study and the one of Wegmüller and Mätzler (1999) to estimate the soil contribution to the emitted brightness temperature of snowpacks. An improvement of 66% of the RMSE between the modeled and measured snow brightness temperatures was observed when using the approach of this study compared to the previous work. The method shows great potential to improve the estimation of the frozen soil contribution to the measured passive microwave brightness temperature.

1. Introduction

For many years, scientists have studied bare soil reflectivity modeling (Wang and Choudhury, 1981; Choudhury et al., 1979; Wegmüller and Mätzler, 1999; Schwank et al., 2010; Wigneron et al., 2011), partly motivated by the ability to retrieve soil moisture from satellite data, such with the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001, see also the review by Wigneron et al., 2017). The Soil Moisture Active and Passive (SMAP) mission (Brown et al., 2013) also studies soil moisture from satellite-based data, as well as the soil state (frozen/thawed) in northern regions (Spencer et al., 2013; Derksen et al., 2017). The majority of these studies mainly focus on L-band rather than higher frequencies (Kerr et al., 2012, Mialon et al., 2012, Wigneron et al., 2011, Lawrence et al., 2013, Shi et al., 2002), given the ability of such wavelengths to penetrate vegetation and snow. Some soil moisture products retrieved from higher frequencies such as the Advanced Microwave Scanning Radiometer for Earth Observation (AMSR-E) (Njoku, 2004; Zeng et al., 2014) and soil state products (frozen, thawed) using the Special Sensor Microwave Imager (SSM/I) exist (Kim et al., 2012). Nonetheless, these products are limited to areas where there is no dense vegetation, no snow cover and where the soil is not frozen. Also, they do not parameterize the soil properties.

For cryospheric studies, frequencies up to 37 GHz are commonly used (Dietz et al., 2012) and some studies have shown that, even at these high frequencies, the soil contribution to the emitted signal at the surface of the snowpack has to be considered (Montpetit et al., 2013; Roy et al., 2013). A major issue with the estimation of the soil contribution to the emitted signal at the surface is the estimation of frozen soil permittivity. Different models exist such as the one developed by Zhang et al. (2010) but still need further validation and information on soil characteristics (soil bulk density, volumetric moisture, temperature, etc.) that are complex to extract in remote arctic soils. Previous studies have tried to parameterize the soil using passive microwave measurements acquired at the surface of the snowpack using optimization schemes to limit the soil emission modeling errors (Montpetit et al., 2013; Roy et al., 2013; Pulliainen, 2006). No study has properly parameterized the frozen soils using passive microwave measurements of bare frozen soils at higher frequencies. This study aims to retrieve
empirical parameters of a sub-arctic frozen organic soil using a simple model to account for passive microwave soil emission at frequencies commonly used in cryospheric studies (10.7, 19 and 37 GHz) and characterize its impact on results of studies using passive microwaves to retrieve snow properties.

In this paper, we present a simple method to retrieve effective passive microwave soil properties from brightness temperature measurements using the semi-empirical model developed by Wegmüller and Mätzler (1999) (hereafter referred to as WM99) and validate these properties using an independent dataset taken at different sites in northern Québec (see Section 2). We first describe the study sites and the geophysical and radiometric measurements. Then, the models and the optimization method will be detailed. The optimization and validation results will then be presented and discussed. Finally the importance of a proper frozen soil parameterization will be discussed for passive microwave snow studies.

2. Data and methods

2.1. Study sites and field measurements

The soil and radiometric data for this study were first collected in the James Bay area, Québec (53°26′N, 76°46′W, 186 m a.s.l.) during three intensive measurement periods (IMP) in January (8th to 12th, IMP1), February (12th to 17th, IMP2) and March (19th to 23rd, IMP3) of 2013. More data was also acquired near Umiujaq, Québec (56°33′N, 76°30′W, 74 m a.s.l.) during one intensive period in January (21st to 28th of 2014). The bare soil measurements were done in clearings with minimal influence from the environment (topography, vegetation, etc.) to the measured microwave brightness temperature ($T_B$). Fig. 1 shows an example of the soil measurement sites where the snow was removed to acquire the soil $T_B$ measurements. A total of 8 sites were selected in this study where the soil composition mainly consisted of organic matter.

The soil $T_B$ measurements were acquired using surface-based radiometers on a mobile sled at 10.7 (hereafter referred as 11 GHz), 19 and 37 GHz in both horizontal (H-Pol) and vertical (V-Pol) polarizations. Calibrations were done on a regular basis throughout the winter season using a warm and cold target as described by Asmus and Grant (1999). The downwelling $T_{Bsky}$ were estimated with an atmospheric absorption microwave model (Liebe, 1989) implemented in the Helsinki University of Technology (HUT, Pulliainen et al., 1999) model, using the 29 atmospheric layers above surface of the North American Regional Reanalysis (NARR Mesinger et al., 2006) data (see Roy et al., 2012). The measured $T_B$ at frequency $f$ and polarization $p$ can then be described by:

$$T_{B,soil}(f, p) = \varepsilon_f, p T_{Bsky}^f + (1 - \varepsilon_f, p) T_{B,sky}(f, p)$$

where $\varepsilon_f, p$ is the rough soil emissivity at polarization $p$ and $T_{B,sky}^f$ is the effective soil physical temperature. Temperature profiles were taken using a Traceable 2000 digital temperature probe with an accuracy of 0.1 °C for depths of 0 to 10 cm with an interval of 2 cm. Since the soil is considered a homogeneous medium for this study, the effective soil temperature was estimated to be the averaged temperature over the first 5 cm. Other soil geophysical parameters such as soil roughness were not measured due to logistic challenges of working in remote sub-arctic environments.

Among the 8 sites analyzed, one James Bay site, measured on February 13th 2013, was considered for model calibration purposes (hereafter referred to as the BJcal site) since it was the only site where a wide range of incidence angle (0° to 60°) was measured with the surface-based radiometers. The site consisted of a bare soil area where the snow was removed (20 m long by 5 m wide) to eliminate any possible contribution coming from the snow walls around the bare soil surface. The BJcal site was revisited during the winter IMPs and other sites were measured during the 2013 winter campaign for validation purposes (hereafter referred to as BJval sites). The BJval sites are thus considered independent from the BJcal site since the soil properties were not the same ($T_{B,sky}^f$ for example). The BJval sites were also clearings and soil temperatures varied from $-$13°C to −5°C. Three other validation sites were measured during the 2014 winter campaign in Umiujaq (hereafter referred to as UMIval sites). The UMIval sites were clearings and soil temperatures varied from $-$17°C to $-$10°C. Table 1 shows the mean $T_{B,soil}$ $T_{B,sky}^f$ measurements and the measured incidence angles for the 2013 and 2014 winter campaigns.

2.2. Modeling and optimization framework

The WM99 model describes the rough soil reflectivity at a frequency $f$ and polarization $p (T_{B,ref})$ by its smooth Fresnel reflectivity in H-Pol ($T_{B,H,Fresnel}$), which depends on the incidence angle ($\theta$) and the permittivity of the soil ($\varepsilon_s$), weighted by an attenuation factor that depends on the standard deviation in height of the surface (soil roughness, $\sigma$), the measured wavenumber ($k$) and a polarization ratio dependency factor ($\beta_p$). Semi-empirical equations (Eqs. (2) and (3)) were determined by Wegmüller and Mätzler (1999) using a large set of soil $T_B$ measurements with a frequency range of 1–100 GHz and incidence angles of 20° to 70°. As shown in Montpetit et al. (2013, 2015), a modification to this model was applied for this study using a $\beta_p$ factor ($\beta_p = 0.655$ in the original WM99 model) in Eq. (3) to take into account the frequency dependency of the polarization reflectivity ratio. This model was chosen over other soil reflectivity models because of the fewer parameters to optimize (7 parameters total) compared to other models tested in Montpetit et al. (2015). The WM99 model for incidence angle lower than 60° is therefore described by:

$$[1 - \varepsilon_f, H(\theta, \varepsilon_s, \sigma)] = T_{H,eff}(\theta, \varepsilon_s, \sigma) = T_{H,ref}(\theta, \varepsilon_s, \sigma) \exp(-k\sigma/\cos\theta)$$

$$[1 - \varepsilon_f, V(\theta, \varepsilon_s, \sigma)] = T_{V,eff}(\theta, \varepsilon_s, \sigma) = T_{V,ref}(\theta, \varepsilon_s, \sigma) \cos\theta/\cos\theta$$

Using Eq. (1), for a given frequency and polarization, it is possible to derive the soil surface reflectivity using the measured soil temperature, the estimated downwelling $T_{Bsky}$ and the measured $T_{B,soil}$ at the soil surface.

The first part of the optimization process consisted in obtaining the two unknowns of Eq. (2), the soil permittivity ($\varepsilon_s$) and surface roughness ($\sigma$). Since the permittivity is frequency dependent and the surface roughness is a geophysical property of the soil surface considered frequency independent, four parameters (one permittivity per frequency and one soil roughness for all frequencies) were derived by minimizing

![Fig. 1. Example of bare soil site and the surface-based radiometers on a mobile sled.](image)
the error between simulated and measured TB in H-pol using Eq. (2) for all the incidence angles between 0° and 60°. The optimization algorithm used is the least squared error minimization algorithm of Levenberg-Marquardt (Marquardt, 1963, hereafter referred to as LM63).

In a second optimization process, using the four soil parameters (see Table 2) obtained in the first step, the single unknown of Eq. (3), the factor, was determined using the LM63 algorithm to minimize the error between the V-pol TB measurements and the simulations. As mentioned earlier, it is better to consider the factor as frequency dependent. Three parameters were thus retrieved in the second optimization step (see Table 2).

Once the optimized parameters were obtained, these retrieved parameters were inserted in the WM99 and the soil TB were modeled and compared to the measured TB of the BJval and UMIval sites (see Table 1).

3. Results

3.1. Soil parameterization

Table 2 shows the optimization results using the LM63 algorithm at H-pol and V-pol described in Section 2.2. The minimum RMSE of the first optimization step (RMSE TB (H-pol), see Table 2) is given as well as the three minimum RMSEs for the second optimization step (RMSE TB (V-pol)). It should be noted that the retrieved parameters of Eq. (2) (effective for each frequency and the soil roughness) are effective parameters and not physical parameters since they were not validated against actual measurements. It is known that the frozen soil permittivity can vary slightly with the soil composition and the ice fraction within the soil (Mironov et al., 2010). These parameters could however also take into account possible signal contribution coming from remaining snow and ice over the bare soil which can decrease the emissivity of the soil (Jiang et al., 2012). It should be noted that the snow is very difficult to completely remove in such complex and remote sites without perturbing other geophysical parameters of the soil. Since the soil roughness is considered as a geophysical parameter specific to the soil, it can

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Mean $T_{B,soil}$ (K)</th>
<th>Inc. Angle (°)</th>
<th>Mean $T_{soil}^{eff}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11V 11H 19V 19H 37V 37H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJcal</td>
<td>Feb. 13, 2013</td>
<td>255.5 250.0 255.1 251.9 253.2 250.7</td>
<td>0–60</td>
<td>−5.0</td>
</tr>
<tr>
<td>BJval</td>
<td>Jan. 8–12, 2013</td>
<td>257.4 247.7 259.4 251.6 245.9 236.7</td>
<td>55</td>
<td>−5.9</td>
</tr>
<tr>
<td>Feb. 12–17, 2013</td>
<td>253.0 234.6 253.7 246.9 251.2 242.3</td>
<td>55</td>
<td>−9.3</td>
<td></td>
</tr>
<tr>
<td>UMIval</td>
<td>Jan 23–25, 2014</td>
<td>248.9 242.3 248.8 243.1 247.2 242.2</td>
<td>55</td>
<td>−12.1</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$\varepsilon_{eff}$</th>
<th>$\sigma_{eff}$ (cm)</th>
<th>RMSE $T_B$ (H-pol) (K)</th>
<th>$\beta_f$</th>
<th>RMSE $T_B$ (V-pol) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>3.18–0.0061i</td>
<td>0.19</td>
<td>1.2</td>
<td>1.08</td>
<td>0.9</td>
</tr>
<tr>
<td>19</td>
<td>3.42–0.0051i</td>
<td>0.72</td>
<td>0.8</td>
<td>0.72</td>
<td>0.8</td>
</tr>
<tr>
<td>37</td>
<td>4.47–0.33i</td>
<td>0.42</td>
<td>0.4</td>
<td>0.42</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Fig. 2. Typical angular emissivity measurements (points) acquired at the BJCal site and the resulting simulations (lines) using the WM99 model with the optimized parameters of Table 2 at 11 (green circles and lines), 19 (red squares and lines) and 37 (blue triangles and lines) GHz at V-pol (filled shapes and full lines) and H-pol (empty shapes and dotted lines). $T_{soil}^{eff} = -5 \pm 2.5$ °C. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
be considered frequency independent (Wegmüller and Mätzler, 1999; Montpetit et al., 2015). A different soil permittivity per frequency was obtained with the LM63 optimization on H-Pol measurements in the first optimization step. An optimization per frequency was done for the $\beta_f$ factor in V-Pol to determine if the $\beta_f$ factor is frequency dependent. Given the different values of $\beta_f$ obtained, it can be concluded that the $\beta_f$ factor is frequency dependent as previously shown by Montpetit et al. (2013, 2015).

Fig. 2 presents the angular measurements acquired at the James Bay calibration site (BJcal). The results of the modeling using the WM99 model and the parameters of Table 2 are also given in Fig. 2. Fig. 2 shows the decrease in emissivity with increasing incidence angle. This means that the reflectivity increases with incidence angle (Eq. (1)), a result in accordance to what was previously obtained by WM99. It also shows that the decrease is stronger in H-Pol compared to V-Pol. This can be explained by a stronger increase of the surface reflectivity with incidence angle in H-Pol compared to V-Pol that is mostly driven by the Fresnel reflectivity.

### 3.2. Soil parameterization validation

Fig. 3 shows the results of the comparison between the simulations using the WM99 model optimized with the parameters of Table 2 against the measured emissivity derived from Eq. (1) of the James Bay sites (BJcal and BJval sites) acquired throughout the 2013 winter, and the Umiujaq sites (UMIVal) for an incidence angle of 55°. The measured and simulated emissivity values are, in general, in agreement with an overall RMSE ranging from 0.012 to 0.025 in emissivity (overall mean bias = 0.019) and 1.6 to 6.0 K (overall RMSE = 4.7 K) in temperature. The mean bias appears relatively small at −0.5 K. The RMSE of 0.014, 0.017 and 0.025 at 11, 19 and 37 GHz respectively are comparable or lower than the standard deviation of the measured emissivity values (0.027, 0.024 and 0.024 at 11, 19 and 37 GHz respectively). This indicates that the variability in the simulations is comparable to the variability in the measurements, which can be explained by the surface roughness variability. As such, keeping the same permittivity as obtained above (Table 2) and fitting an optimized roughness value for each site, over a range of 0 to 2 cm, reduces the RMSE from 4.7 K to 0.4 K. The range of surface roughness obtained in this optimization process was 0.1 ≤ $\sigma$ ≤ 2 cm, 0.36 ≤ $\sigma$ ≤ 2 cm and 0.01 ≤ $\sigma$ ≤ 0.23 cm at 11, 19 and 37 GHz respectively.

It is difficult to compare the permittivity values obtained in this study to previous studies because of all the factors and conditions (soil campaigns independently and the two campaigns combined.

The RMSE obtained at James Bay (4.7 K) is similar to the one of the Umiujaq sites (4.6 K) which suggests that the optimization process could be applied to other sites characterized by similar northern organic frozen soil composition. The mean bias appears relatively small at −0.5 K. The RMSE of 0.014, 0.017 and 0.025 at 11, 19 and 37 GHz respectively are comparable or lower than the standard deviation of the measured emissivity values (0.027, 0.024 and 0.024 at 11, 19 and 37 GHz respectively). This indicates that the variability in the simulations is comparable to the variability in the measurements, which can be explained by the surface roughness variability. As such, keeping the same permittivity as obtained above (Table 2) and fitting an optimized roughness value for each site, over a range of 0 to 2 cm, reduces the RMSE from 4.7 K to 0.4 K. The range of surface roughness obtained in this optimization process was 0.1 ≤ $\sigma$ ≤ 2 cm, 0.36 ≤ $\sigma$ ≤ 2 cm and 0.01 ≤ $\sigma$ ≤ 0.23 cm at 11, 19 and 37 GHz respectively.

Fig. 3. Validation results between modeled and measured emissivities at an incidence angle of 55° for a frozen bare soil using the WM99 model and the parameters of Table 2 at 11, 19 and 37 GHz at both H-Pol and V-Pol for all sites (see Table 1). The solid black line corresponds to the 1:1 line. The RMSE and biases between the simulated and the measured brightness temperatures are given in Table 3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>James Bay</th>
<th>Umiujaq</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (K)</td>
<td>RMSE (K)</td>
<td>Bias (K)</td>
</tr>
<tr>
<td>11V</td>
<td>−1.4</td>
<td>3.15</td>
<td>−0.73</td>
</tr>
<tr>
<td>11H</td>
<td>−0.1</td>
<td>3.8</td>
<td>−2.8</td>
</tr>
<tr>
<td>19V</td>
<td>−2.2</td>
<td>4.3</td>
<td>−2.2</td>
</tr>
<tr>
<td>19H</td>
<td>−1.3</td>
<td>3.6</td>
<td>−2.5</td>
</tr>
<tr>
<td>37V</td>
<td>1.4</td>
<td>6.0</td>
<td>−3.3</td>
</tr>
<tr>
<td>37H</td>
<td>3.0</td>
<td>6.3</td>
<td>−2.0</td>
</tr>
<tr>
<td>11</td>
<td>−0.7</td>
<td>3.5</td>
<td>−1.8</td>
</tr>
<tr>
<td>19</td>
<td>−1.8</td>
<td>4.0</td>
<td>−2.4</td>
</tr>
<tr>
<td>37</td>
<td>2.2</td>
<td>6.1</td>
<td>−2.6</td>
</tr>
<tr>
<td>All</td>
<td>−0.1</td>
<td>4.7</td>
<td>−2.3</td>
</tr>
</tbody>
</table>
types, soil ice fraction, soil temperatures, frequencies, etc.) that influence these values. Rautiainen et al. (2012) showed that at L-band the real part of the soil permittivity varied from 3.3 to 3.8 in frozen soils having temperature ranging between −6 °C to −3.7 °C. Schwank et al. (2004) showed that for L-band, the real part of the frozen soil permittivity varies from 3.5 to 4.5, while Hallikainen et al. (1985) showed that it varies from 5 up to 8 in the 10 to 18 GHz frequency range. Pulliainen (2006) used a fixed value of 6 to simulate the frozen soil TB at 19 and 37 GHz. Finally, Mironov et al. (2010) developed a temperature dependent permittivity model and showed that the permittivity could vary from 3 to 4.5 in the 10 to 16 GHz range for a frozen soil at −25 °C. Here, we obtained values of 3.19 at 11 GHz, 3.42 at 19 GHz and 4.47 at 37 GHz for soils between −13 °C to −5 °C (for the top 5 cm). This is in agreement with these different studies where lower soil permittivity values are found at lower frequencies.

3.3. Soil parameterization sensitivity

As mentioned above, one of the main difficulties in the retrieval process is the combined effect of permittivity and the surface roughness. Fig. 4 shows the sensitivity of the mean measured-simulated TB (V and H) RMSE (color scale) on the soil permittivity and the surface roughness, where an iteration process on roughness (0 to 1 cm) and permittivity (2 to 5) was applied. The simulations conditions are those of the Bjcal site.

Fig. 4 shows that the sensitivity to the surface roughness is weaker than for the permittivity. This observation justifies the optimization process used in this study where a permittivity was extracted per frequency and a single roughness parameter for all three frequencies thus simplifying the optimization process. Nevertheless, the sensitivity to surface roughness is not the same for each frequency. The optimization process to reduce the overall RMSE by using the surface roughness as a free variable of the previous section and the observations of Fig. 4 suggests that the effective surface roughness might be different for each frequency. Note that the pattern for 1 < σ < 2 cm (not shown) can be extrapolated from the one around σ = 1 cm. Also, for σ = 0 cm, a discontinuity results from the abrupt change in the Fresnel reflectivity to the rough surface reflectivity (Eq. (2)). For σ < 1 cm, it appears that an ensemble of (ε', σ) couples exists that provides an ensemble of solutions with low RMSE (dark blue in Fig. 4). However, when combining the three frequencies showing different behavior for the lowest RMSE values, the range where the minimum RMSE combining all three frequencies occurs for a limited range of σ: 0.1 < σ < 0.23 cm. The optimized (ε', σ) couples are found for σ = 0.19 cm (Table 2). The results from Fig. 4 and assuming variability in TB of the order of 5 K, suggest that the retrieved soil permittivity values can be defined with an accuracy of ± 1.00 and the retrieved surface roughness with an accuracy of ± 0.12 cm.

3.4. Implications for snow radiative transfer modeling

To demonstrate the importance of a proper estimation of the frozen soil emissivity, the parameterization suggested by Pulliainen (2006, herein referred to as P06) and the one proposed here in Table 2 were applied to snowpack radiative transfer modeling by coupling the WM99 model to the Microwave Emission Model of Layered Snowpacks (MEMLS, Wiesmann and Mätzler, 1999). The P06 parameterization consisted in a frequency independent permittivity (ε_eff = 6-1i), a surface roughness of 0.3 cm and the original β_f factor of the WM99 model (β_f = 0.655). Fig. 5 shows the comparison between the modeled and measured TB for the sites described in Montpetit et al. (2013) and sites where surface snowpack TB were measured during the 2013 James Bay campaign and the 2014 Umiujaq campaign at 10.7, 19 and 37 GHz (see Roy et al., 2016). The points circled in black represent sites where ice lenses were detected in-situ. Fig. 5 (left) shows the results of the simulations using the P06 parameterization and Fig. 5 (right) shows the results of the simulations using the parameterization of Table 2.

Fig. 5 shows a significant improvement of the snowpack passive microwave radiative transfer modeling using the soil parameterization of Table 2. Even for measurements at higher frequencies, where the penetration depth of the measured signal is lower and thus the effect of soil should be less important compared to lower frequencies, we see an improvement in the simulations. Tables 4 and 5 show the biases and RMSE of the simulations of Fig. 5. An improvement of 66% in the
sites where ice lenses were measured in-situ (snow + ice).

By creating a barrier due to the higher interface re
efective permittivity and the

The RMSE is mainly explained by the frequency dependency of the ef-
flectivity of the ice

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Nathalie Thériault, Nicolas Marchand, Caroline Dolant and Bruno-

Table 5
Same as Table 4 for RMSE.

Channel Bias (K)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Bias (K)</th>
<th>Snow</th>
<th>Snow + Ice</th>
<th>All</th>
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<tr>
<td>P06</td>
<td>Table 2</td>
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<tr>
<td>11V</td>
<td>9.7</td>
<td>5.0</td>
<td>9.7</td>
<td>3.8</td>
</tr>
<tr>
<td>11H</td>
<td>17.7</td>
<td>11.4</td>
<td>23.4</td>
<td>7.5</td>
</tr>
<tr>
<td>19V</td>
<td>16.3</td>
<td>−3.4</td>
<td>−1.5</td>
<td>−8.3</td>
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<tr>
<td>19H</td>
<td>25.8</td>
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<tr>
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<td>15.0</td>
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</tr>
<tr>
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<td>24.5</td>
<td>4.5</td>
<td>6.5</td>
<td>1.2</td>
</tr>
<tr>
<td>All</td>
<td>19.7</td>
<td>0.9</td>
<td>5.7</td>
<td>−2.0</td>
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</table>

Overall RMSE is seen between the two parameterizations, showing the importance of an improved soil parameterization. This improvement of the RMSE is mainly explained by the frequency dependency of the effective permittivity and the βfi-factor (see Table 2). A higher RMSE for sites where no ice lenses were measured can be seen compared to sites where ice lenses were measured in-situ. This is explained by the fact that the ice lenses reduce the penetration depth of the measured signal by creating a barrier due to the higher interface reflectivities of the ice lenses (Montpetit et al., 2013; Roy et al., 2016). Thus, when ice lenses are present, the effects of the underlying soil to the overall snowpack TB are less important.

4. Conclusion

In this study, we show that the simple rough soil emission model proposed by Wegmüller and Mätzler (1999) can be calibrated for frozen soils using a least squared minimization function on the soil permittivity from in-situ brightness temperature measurements at several angles. This approach has been applied to retrieve the soil permittivity at 10.7, 19 and 37 GHz for one sub-arctic site in Northern Québec, and validated over different independent sites in the same region and at different dates during the winter covering a range of soil temperatures (−13 °C to −5 °C). The retrieved permittivity values of 3.18−0.0061i, 3.42−0.0051i and 4.47−0.33i, respectively at 10.7, 19 and 37 GHz, give an overall RMSE = 4.7 K between measured and simulated soil brightness temperatures.

These retrieved soil permittivity values are in the range of previous frozen soil studies. It was also shown that the retrieved real part permittivity is within an accuracy of ± 1 in permittivity value. Finally, the importance of a proper microwave soil emission modeling in snow emission modeling applications was shown. An improvement of 66% in the root mean squared error was observed when comparing the parameterization of the P06 to the parameterization of Table 2. This study shows the need to improve the modeling of frozen soil microwave physical properties such as its permittivity. This is of great relevance for winter geophysical parameter retrievals from passive microwave satellite observations. Future work needs to consider ice and snow fraction over the bare frozen soil in order to improve the quantification of the effects on soil emissivity parameterization.

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