DEVELOPMENT OF MICROWAVE EMISSION MODEL FOR FROZEN SOIL WITH CONSIDERING THE VOLUME SCATTERING EFFECT

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ABSTRACT

Land surface freeze/thaw (F/T) has an important influence on the carbon cycle of the ecosystem, hydrological and meteorological. Affected by the frozen of water in soil, the frozen soil would become larger soil particles due to condensation, resulting in its soil particles being larger than those of the melting soil. The microwave radiation of frozen soil has a significant volume scattering effect in the high frequency band due to large particles of frozen soil. This paper developed a frozen soil microwave emission model considering the volume scattering effect of frozen soil particles based on dense media radiative transfer (DMRT) model [1] by combining experimental data and numerical simulation. The simulation results of the frozen soil microwave emission model, combined model for cold land [2] and the three-layer incoherent media model [3] were validated and compared with the experimental data. Results show that frozen soil microwave emission model which considering the volume scattering effect of frozen soil is better than the other two models. It is necessary to consider the volume scattering effect of frozen soil.

Index Terms— freeze/thaw, volume scattering, DMRT, frozen soil radiative transfer model

1. INTRODUCTION

Seasonal frozen soil is widely distributed in the northern hemispheric. The land surface freeze/thaw (F/T) have an important impact on climate, ecosystem, hydrological and energy balance [4]. Passive microwave remote sensing with a certain penetration is sensitive to F/T changes and can be used to detect the F/T state of land surface. Existing F/T detecting algorithms, such as the decision tree algorithm [5] and the seasonal threshold algorithm [6, 7] relies heavily on the auxiliary data. The double index algorithm, which considers the volume scattering darkening effect of frozen soil, monitors F/T state according to the negative spectral gradient between the two frequencies. The discriminant function algorithm based on simulated and measured data also considered the influence of frozen scattering effects on different frequencies. Researchers have simulated the microwave radiation of frozen soil volume scattering by using a simplified first-order radiation transfer model [8], the effect of volume scattering of P and L band for frozen soil using two-layer soil scattering model [9]. In the simulation work in [8], the volume scattering characteristics of frozen soil are considered, and the relationship between the single scattering albedo of frozen soil and the physical temperature of soil is deduced. However, this model has not been verified by the in situ observation data. Later, some researchers used experimental observation data to validate the accuracy of the frozen volume scattering model [8], and the results showed that the simulation result of this model for V polarization was good, while for the H polarization is not good. It is very important to develop an accurate microwave radiation transmission model of frozen soil and explore the effect of frozen soil volume scattering on the improvement of F/T monitoring algorithm. In this paper, we introduce the dense media radiative transfer (DMRT) model [1] to develop the microwave radiation transfer model of frozen soil considering the volume scattering effect and validate the model with the ground-based radiation data.

2. FIELD EXPERIMENT

On 10 and 11 March, 2008, the Truck-mounted Multi-frequency Microwave Radiometer (TMMR) made continuous observations of the alpine meadows at A'rou (100º26' E, 38º03' N) [2]. TMMR was loaded onto the truck and had four channels of horizontal and vertical polarization measured at 18.7 and 36.5GHz. Before the observation, the radiometer was absolutely calibrated, and TMMR was calibrated by the four-point calibration method, which can accurately calibrate the errors caused by noise gain fluctuation and system nonlinearity. In order to measure the snow-free F/T soil, an area slightly larger than the field of view was cleared prior to the observation. The snow-free surface was observed with a radiometer at azimuth Angle of 240º and incidence Angle of 50º, and approximately 20 measurements were obtained per minute, and the average measurement was calculated as the brightness temperature (Tb) of per minute. The soil temperature was measured by four thermistors, and the resistance value was collected by the data collector (the sampling interval was 1 minute). Then the temperature was calculated by the calibration equation of the thermistor, and the measured depth was 0~1, 1~4 and 4~7cm. At the same time, the soil moisture content of 0~2cm was measured. During the observation period, the gravimetric soil moisture in the observation area was 26.4%, and change little during observation period. Observed Tb in A'rou is shown in Figure 1. Table 1 is the ground parameters around radiometer in A'rou.

Table 1 Ground parameters around radiometer in A'rou

Sand content (%)	Clay content (%)	Bulk density (g/cm^3)	Gravimetric soil moisture (%)	Thickness of frozen soil (cm)
28.66	10.3	0.83	26.4	10

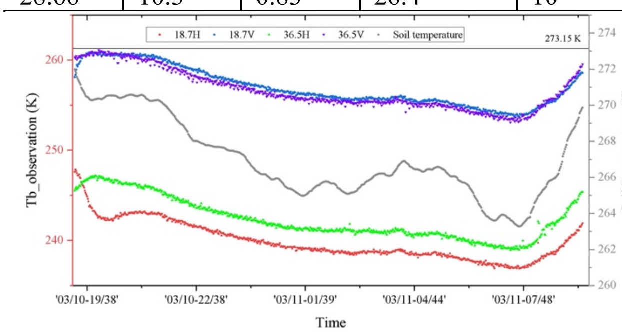

Figure 1. Observed Tb and soil temperature in A'rou

3. DEVELOPMENT OF MICROWAVE EMISSION MODEL FOR FROZEN SOIL

Frozen soil is a complex heterogeneous system consisting of soil matrix, water, ice and air. As soil freezing, liquid water gradually turns into ice crystals. Previous studies have shown that the volume scattering effect of dry soil has a significant effect on microwave radiation transfer [10], and the volume scattering effect of frozen soil containing both ice and soil particles cannot be ignored. Here we introduced the DMRT model describing the volume scattering of snow particles to describe the volume scattering of frozen soil. And, in order to figure out the improvement of considering volume scattering of frozen soil during simulating microwave radiation transfer, we chose another two models without considering volume scattering of frozen soil: the combined model for cold land with two-layer [2] and the three-layer media incoherent model [3] to compare with DMRT model for frozen soil.

3.1. Microwave emission model for frozen soil

In this research, the particles of frozen soil were treated as many densely packed spherical particles. The DMRT model that describing the volume scattering of snow particles was used to calculate the extinction and emission characteristics of frozen soil. And the distribution function was used to describe the correlation between frozen particles. The method for solving radiation transfer of DMRT is discrete eigenvalue. Here, we simulate the microwave radiation of three layers of air, frozen soil and thaw soil as the first layer, the second layer and the third layer in DMRT model for frozen soil. And the volume scattering effect of frozen particles was considered in developing DMRT model for frozen soil. The F/T soil dielectric constant model is briefly introduced below.

Based on the experimental results of a series of experiments conducted by microwave network analyzer, F/T soil dielectric constant was developed by extending the Dobson dielectric model that added ice components [11]. The equation is as follows:

$$\varepsilon_f^a = 1 + \left(\frac{\rho_b}{\rho_s}\right)(\varepsilon_s^a - 1) + \theta_{vu}^{\beta}\varepsilon_{fw}^a - \theta_{vu} + \theta_{vi}\varepsilon_i^a - \theta_{vi} \quad (1)$$

where, ε is dielectric constant, ρ_b is soil bulk density and ρ_s is soil specific density. Subscript s, vu and i represent soil, unfrozen water content and ice, respectively. The α is shape factor and the value is 0.65, and β is soil texture dependent coefficient. The unfrozen water content is closely related to the specific surface area (S) of the soil: the larger S of the soil, the stronger adsorption capacity generated by soil particles; the F/T process of the soil is relatively slow and the content of unfrozen water is high and vice versa. The model uses a semi-empirical method to determine the unfrozen water content of the soil:

$$\theta_{vu} = \alpha|T_s|^{-b} \quad (2)$$

$$lna = 0.5519lnS + 0.2618 \quad (3)$$

$$lnb = -0.264lnS + 0.3711 \quad (4)$$

S is mainly related to the soil texture, especially the amount of clay particles. In order to measure the effect of soil texture on the S, empirical regression formula was used:

$$S = 0.042 + 4.32clay\% + 1.12silt\% - 1.16sand\% \quad (5)$$

Through the above empirical relationship, the unfrozen water content in F/T process under any soil texture can be simulated. The emissivity of frozen soil was calculated by the DMRT model, and the reflectivity of sub-thaw soil was calculated by the Fresnel model.

3.2. Combined model for cold land [2]

The combined model for cold land is consist of dielectric constant model for F/T soil, advanced integral equation method (AIEM) and Helsinki University of Technology (HUT) snow microwave emission model. The F/T soil dielectric constant is calculated by the F/T soil dielectric constant model described in section 3.1. Combined model for cold land is established with F/T dielectric constant model, AIEM and HUT.

3.3. Three-layer media incoherent model [3]

A three-layer case was considered to simulate microwave radiative transfer of frozen soil and develop a parameterized model to retrieval frozen soil microwave radiation response depth [3]. Consider the three layers of media: the first layer is air, and the second and third layers are frozen and thaw soil, respectively. This is an incoherent model that not considering interference. It is assumed that the inner part of the soil layer is uniform, without considering the soil temperature and moisture profile. The F/T soil dielectric constant is calculated by the F/T soil dielectric constant model described in section 3.1. The results are taken as the input of Fresnel model to calculate the emissivity of F/T soil. Multiple scattering between two interfaces is considered in this model. See the article [3] for more details about this model.

4. RESULTS AND DISCUSSIONS

Figure 2 is the validation result of the observed Tb of frozen soil in the A'rou experimental area and simulated Tb by combined model for cold land without considering volume scattering. It can be seen that the simulation Tb of combined model for cold land at V polarization is close to the observation Tb, but the simulation Tb at H polarization is slightly different, especially for larger difference observed at higher Tb. Simulated Tb at H polarization is smaller than that of observed. For the combined model for cold land, which used AIME to calculate the surface scattering emission of frozen soil and ignore the volume scattering effect of frozen soil, the inaccurate result at H polarization may be because the volume scattering effect at H polarization is stronger than V polarization. In addition, H polarization is more sensitive to water changes caused by F/T changes, it is very important to accurately simulate microwave radiation of frozen soil at H polarization.

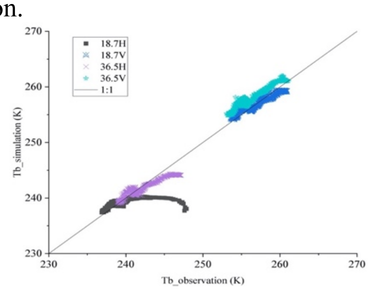

Figure 2. Validation of combined model of cold land with A'rou experimental data

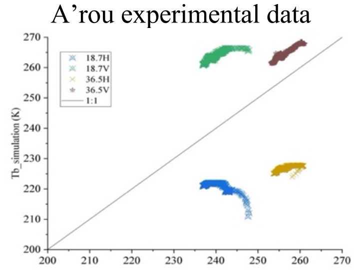

Figure 3. Validation of three-layer media incoherent model with A'rou experimental data.

Figure 3 shows the validation results of the three-layer media incoherent model, and it can be clearly seen that the simulation results of this model are quite different from the observation results. Simulated Tb at H polarization is smaller than observed Tb, while simulated Tb at V polarization higher than observed Tb. This is probably because the model used the Fresnel model to calculate the emissivity of F/T soil, ignoring the effect of soil surface roughness. Also, the three-layer media incoherent model ignored the volume scattering effect of frozen soil.

In the process of using DMRT model to simulate the volume scattering characteristics of frozen soil, the observed parameters (thickness of frozen soil, density, soil moisture, soil texture) are used as input for the model. The size of the spherical particles of frozen soil is taken as the sum volume of the soil and ice, and the only unknown parameter of the model is the diameter of frozen particles that obtained by a best fitting method. Considering that the size of frozen particle may be different at different temperatures, a set of data for each temperature from 266K to 272K was selected according to the experimental data. Table 2 shows the best fitting particle size for the A'rou experimental area. Perhaps because the frozen depth has reached 10 cm, there is little difference in the size of frozen soil under different temperatures. Figure 4 shows the validation results of frozen soil microwave emission model. It can be seen that both simulated Tb at H polarization and V are very good from frozen soil microwave emission model. It can be seen that the frozen soil microwave emission model can better simulate the high frequency (36.5GHz) with stronger volume scattering effect than the low frequency (18.7GHz).

Table 2 Best fitting particle size for different frequency

18.7H	18.7V	36.5H	36.5V
0.95389	0.87467	0.209	0.171

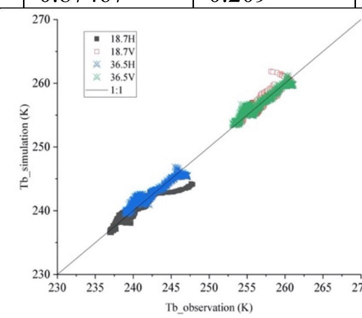

Figure 4. Validation of frozen soil microwave emission model with A'rou experimental data.

In order to further demonstrate the necessity of considering the volume scattering of frozen soil and its influence on the F/T monitoring, we refer to the simulation parameter setting and the developed F/T monitoring algorithm by [2], using these three models to simulate microwave radiation of F/T soil. Figure 5 is the spatial distribution of the Tb 36.5V and the Tb 18.7H/ Tb 36.5V simulated by the three models. It can be seen that the simulation results of combined model have the worst results after the linear discriminant, followed by the three-layer media incoherent model, and the frozen soil microwave emission model has the best classification results. The Tb 36.5V of frozen soil simulated by the frozen soil microwave emission model considering volume scattering is significantly lower than that simulated by the other two models without considering volume scattering. Frozen soil microwave emission model improved the misclassification of part of thawed soil by three-layer media incoherent model, and also improved the misclassification of part of the frozen soil by combined model. Therefore, considering the volume scattering effect of frozen soil can not only describe the microwave radiation of frozen soil more accurately, but also have great significance for improving the F/T detecting algorithm.

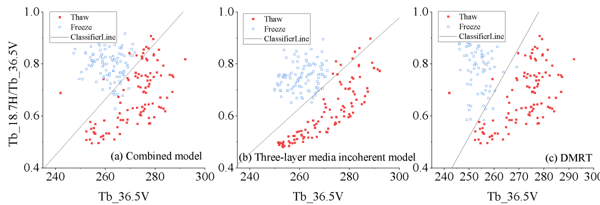

Figure 5. Spatial distribution of the Tb 36.5V and the Tb 18.7H/ Tb 36.5V simulated by (a) Combined model, (b) Three-layer media incoherent model, and (c) Frozen soil microwave emission model.

5. CONCLUSIONS

In this paper, we developed a microwave emission model for frozen soil with considering volume scattering based on DMRT model that describing the volume scattering of snow. We chose the existing combined model for cold land and three-layer media incoherent model without considering the volume scattering of frozen soil to model Tb of frozen soil for comparative evaluation. The simulations for these three models were validated by the observed Tb in the field. The results show that better than the other two models, the microwave emission model of frozen soil can accurately simulate the Tb at 18.7GHz and 36.5GHz of frozen soil, especially in 36.5GHz.

This shows that it is necessary to consider the volume scattering effect during microwave radiation simulation of frozen soil. Microwave emission model of frozen soil developed in this paper has been evaluated by the experimental data that had the ability to describe the volume scattering of frozen soil. Although, the size of frozen particle involved in this model may change with different soil texture and frozen depth, which will bring difficulties to the simulation of volume scattering of frozen soil in large scale. It also provides a new possibility for frozen depth retrieval.

In the future studies, more field observation data will be used to evaluate the performance of microwave emission model of frozen soil and explore the contribution of this model to the improvement of F/T detection algorithm.

6. ACKNOWLEDGEMENT

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