THE PROCESS OF UNFROZEN WATER FREEZING WITH DECREASING TEMPERATURE STUDIED BY DIELECTRIC MEASUREMENT IN THE CASE OF AN ARCTIC SOIL

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1. INTRODUCTION

The soils of the Arctic are quite distinct from those of temperate climes. In the cold environs of the high latitudes, plant decomposition is slow, and organic matter in the soil accumulates [1]. Passive microwave remote sensing has demonstrated its ability for long duration environmental monitoring of the entire region, a feat which is otherwise extremely difficult to achieve due to the vastness, variability, and remoteness of the Arctic [2]. To realize the promise of monitoring the hydrologic state of the permafrost, however, the soil dielectric must be known to link soil properties to microwave remote sensing signatures. Moreover, in the period of global warming, the phase state of soil water in permafrost and phase state changes are crucial for understanding the permafrost degradation process.

Earlier, we reported [3] the result of dielectric measurement with regard to the shrub and tussock tundra soils over the range of frequencies and temperatures from 1.0 to 16GHz and from −30ºC to 25ºC, respectively. The dielectric measurements were conducted using hardware which is similar to that used by Curtis [4]: a coaxial line container holds the soil samples while a Rohde & Schwartz ZVK Network Analyzer measures the complex transmissivity and reflectivity. During the dielectric measurements, a TABAI ESPEC thermal chamber stabilized the temperature of the soils to an accuracy of 0.5ºC. Measurements were made in 5ºC steps from -30ºC to +25ºC, with an additional measurement at -7ºC. The complex refractive index was found from the measurements as described in [5]. In that paper we analyzed the data measured using the Generalized Refracting Mixing Dielectric Model of [6] extended over frozen soils. As a result the spectral parameters of the GRMDM were obtained and their dependence on the temperature determined. Given these dependences, we validated the GRMDM model, finding good agreement between the dielectric data modeled and measured.

In this paper, using the dielectric data thus obtained, we analyzed the process of freezing of unfrozen water contained in the shrub tundra sample, which appeared to be out of scope of the analysis conducted in [5][1].

2. SOIL WATER PHASE STATES IN THE FROZEN SOIL

In total, four phase states for soil water were identified and analyzed, namely bound water, liquid water, transient bound water, and moistened ice. In the thawed soil, two phases of water were observed, that is, liquid water existing in soil pores and bound water confined by electrical forces of

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[1] This research was supported by the Siberian Branch of the Russian Academy of Sciences under Project No 10.4.6 and by the Russian Foundation for Basic Research under Grant 09-05-91061.

attraction near the surface of soil particles. While in the case of frozen soil, the water was seen to exist in the form of bound water, transient bound water, and moistened ice. The soil water in the form of transient bound water state is believed to be located in the finest soil pores as indicated in [7]-[9].

In Fig. 1, are shown the temperature dependences of maximum gravimetric fraction of bound water (MGFBW), m_{g1}, for both the thawed, in the range of temperatures −6ºC=Tf<T≤25ºC, and frozen, −30ºC≤T<Tf=−6ºC, soil alongside with the maximum gravimetric fraction of unfrozen water (MGFUW), m_{g2}, in a frozen soil, −30ºC≤T<Tf=−6ºC. Here Tf designates the temperature of freezing, at which the first portions of ice are formed in the soil. The values shown in Fig. 2 are the result of averaging over all the frequencies measured in the range from 1.0 to 16 GHz. We understand the MGFBW and MGFUW as upper limits for the amounts of bound and unfrozen water to be present in a given type of the soil.

In both the thawed and frozen soil, at moistures $m_g<m_{g1}$, only bound water is present in the soil. While in the thawed and frozen soils, the water in excess of MGFBW, mg−mg1, and MGFUW, mg-mg2, exists in a liquid and moistened ice phase state, respectively. At the same time, at moistures mg1<mg<mg2, the unfrozen soil water in excess of bound water, mg2-mg1 exists in a state of transient bound water.

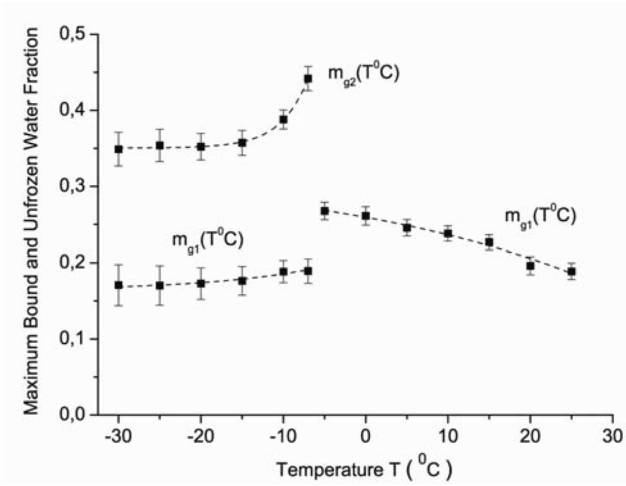

Fig. 1. The maximum gravimetric fraction of bound water, m_{g1}, and maximum gravimetric fraction of unfrozen water, m_{g2}, as a function of temperature. The data determined and their fits are shown with symbols and lines, respectively.

The exponential fits of this dependences are expressed in the form:

$$m_{g1}\ (\mathrm{g/g}) = 0.324-0.0651\exp(T(^\circ\mathrm{C})/33.2), \quad -5^\circ\mathrm{C} \le T \le 25^\circ\mathrm{C} \qquad (1)$$

$$m_{g1}(T)=0.164+0.0462\exp(T(^\circ\mathrm{C})/13.441), \quad -30^\circ\mathrm{C} \le T < -7^\circ\mathrm{C} \qquad (2)$$

$$m_{g2}(T)=0.35+0.757\exp(T(^\circ\mathrm{C})/3.311), \quad -30^\circ\mathrm{C} \le T < -7^\circ\mathrm{C}, \qquad (3)$$

According to (3), at the temperature of freezing $T=T_f=-6^\circ C$ the maximum gravimetric fraction of unfrozen water has the largest value, $m_{g2}(T_f) = m_{g2L}=0.474$. This value, along with the freezing temperature of liquid soil water $T_f = -6^\circ C$, can be considered as hydrological characteristics of this soil. Using the formulas (2), (3), let us separately analyze two cases: 1) soil with moisture greater than m_{g2L}, 2) soil with moisture less than m_{g2L}.

For m_g>m_{g2L}, the amount of ice in the soil at the temperature just below T_f is equal $m_g - m_{g2L}$. This amount of ice appears instantly when temperature passes the freezing point. As the temperature decreases below T_f, a certain part of initially transient bound water converts into ice. As a result, at a temperature $T < T_f$, an additional amount of ice, $m_{g2L}-m_{g2}(T)$, is formed out of transient bound water. As follows from (3), the least value of MGFUW is m_{g2l}=0.35, which, similar to m_{g2L}, is a hydrological characteristic of the soil. The maximum amount of ice that is formed at the expense of transient bound water is $m_{g2L} - m_{g2l}$ =0.124. Finally, if soil moisture meets the condition m_g>m_{g2L}, the total amount of ice is equal to $m_g-m_{g2}(T)$, and it consists of two parts. The one part, m_g-m_{g2L}, is formed out of liquid water as the temperature drops below freezing point, T_f. The other part, $m_{g2L}-m_{g2}(T)$, is formed by infinitesimal portions as the temperature further decreases below T_f. As seen from (3) and Fig. 1, the process of ice formation practically terminates at −20ºC.

In the second case m_g<m_{g2L}, the ice in soil can only be formed out of transient bound water. Equation (3) can be solved for the temperature of ice formation from transient bound water, provided m_{g2l} <m_g<m_{g2L}:

$$T_{twf}(m_g)\ (^{\circ}C) = 3.31\ \ln[(m_g - m_{g2l})/0.757]. \qquad (9)$$

This freezing temperature of transient water depends on soil moisture and is depressed relative to the freezing point temperature of liquid water, that is, $T_{twf}(m_g) < T_f = -6.0$ºC. Similar to the case m_g>m_{g2L}, the total possible amount of ice in soil is equal to m_g-m_{g2l}, and the process of continuous ice formation practically terminates at −20ºC. Using the dependences shown in Fig. 1, a temperature dependable dielectric model for the shrub tundra soil was developed [10] to reveal a good correlation with the dielectric data measured in the whole range of temperatures and frequencies given above.

3. CONCLUSION

In a frozen soil, we discovered gradual conversion, by infinitesimal portions, of transient bound water into moistened ice, with the temperature decreasing. Finally, not all transient water was found to be able to get converted into moistened ice. On the contrary, a residual amount of transient bound water was found to exist, with the temperature further decreasing. So far, different phase states of unfrozen water in a frozen soil have never been distinguished, and their conversion into each other with temperature decreasing have been not measured. Nevertheless, understanding of these phenomena is very important not only for dielectric modeling, but also for studies of mechanical and thermal physics characteristics of frozen soils.

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