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An improved two-layer algorithm for estimating effective soil temperature in microwave radiometry using in situ temperature and soil moisture measurements

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ABSTRACT

The effective soil temperature (T_{eff}) is essential for the retrieval of soil moisture information, when satellite microwave remote sensing data are used. In this investigation, a new two-layer scheme (Lv's scheme) is developed to estimate T_{eff} considering wavelength, soil moisture, sampling depth, and soil temperature. The accuracy of the estimated T_{eff} is verified with data collected in a field experiment at the Maqu Climate and Environment Observatory in the source region of the Yellow River. In addition to clearly defining the physical meaning of Lv's scheme, this study explains the physical meaning of Choudhury's *C* parameter, which is empirically determined by a least-square method. It was found that Lv's scheme does not require the fitting parameters. Further, Lv's scheme can be used to estimate T_{eff} based on soil moisture data at surface level or any other specified soil depths, thus creating the opportunity to use observation and modeled data from different depths.

1. Introduction

Soil moisture is a key variable in hydrology, agriculture, as well as weather and climate forecasts because of its large heat capacity and rapid response to precipitation and irrigation (Njoku, 1977; Wen, Jackson, Bindlish, Hsu, and Su, 2005). In situ measurements of soil moisture profile are not always available due to high cost and complicated maintenance. It is therefore impossible to simply use ground networks to provide global coverage for soil moisture. This limits the number of studies on soil moisture in hydrology and climatology. As a result, remote sensing and model simulation are employed to provide effective methods for obtaining continuous global soil moisture products. In past decades, various techniques, models, and algorithms have been developed to estimate surface soil moisture using satellite remote sensing data (Barrett, Dwyer, and Whelan, 2009; Jackson and Oneill, 1987; Kerr et al., 2012; Njoku and Entekhabi, 1996; Owe and De Jeu, 2003; Wigneron et al., 2007). The principle of detecting soil moisture using passive microwave remote sensing is based on the difference in dielectric properties between free water and dry soil particles, and is considered to be the only effective technique for acquiring global soil moisture distribution information (Jackson and LeVine, 1996; Schmugge, Oneill, and Wang, 1986).

Actually, passive microwave remote sensing only offers a few bands appropriate for soil moisture retrieval. One of the key factors in passive microwave soil moisture retrieval is the sampling depth. Although the L-band is predicted to be most suitable for estimating soil moisture (Jackson, Bindlish, Klein, Gasiewski, and Njoku, 2003; Kerr and Njoku, 1990; Ulaby, Batlivala, and Dobson, 1978), its sampling depth (central wavelength at 21 cm) may vary from centimeters to even meters beneath the soil surface. Sampling depth will vary depending on variations in soil moisture, texture, as well as soil temperature. However, to calculate the soil emissivity (e) accurately, which is another key factor for soil moisture retrieval, it is necessary to determine the effective soil temperature T_{eff} accurately (Kerr et al., 2012; Tian et al., 2012). With the new satellites launched, microwave sensors play an increasing role in mapping global soil moisture distribution. Examples are the Soil Moisture and Ocean Salinity (SMOS) mission launched in 2009 and the Soil Moisture Active Passive (SMAP) to be launched in 2014 (Entekhabi et al., 2010; Kerr et al., 2012). Since these sensors share the L-band as their working channel (Entekhabi et al., 2010; Kerr et al., 2012), it is becoming more urgent to understand T_{eff}'s behavior where the T_{eff}'s calculation is heavily dependent on soil moisture and soil temperature information from deeper layers.

In fact, T_{eff} has been described accurately by plane stratified dielectric layers (Dobson and Ulaby, 1986; Jackson and Schmugge, 1989; Njoku and Li, 1999; Schmugge et al., 1986; Wang and Schmugge, 1980; Wilheit, 1978). However, plane stratified dielectric layers cannot describe situations in the field, where the soil is neither homogeneous

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nor continuously monitored vertically. Based on its original form in Wilheit's work (Wilheit, 1978), a simplified two-layer scheme with just one parameter (Choudhury, Schmugge, and Mo, 1982) has been well accepted in microwave remote sensing for soil moisture retrieval (Crow, Drusch, and Wood, 2001; Jackson, 1997; Jackson and Hsu, 2001; Njoku, Jackson, Lakshmi, Chan, and Nghiem, 2003; Schmugge and Jackson, 1994). The scheme was subsequently improved by considering both wavelength and surface soil moisture (Chanzy, Raju, and Wigneron, 1997; de Rosnay et al., 2006; Holmes et al., 2006; Wigneron, Chanzy, de Rosnay, Rudiger, and Calvet, 2008; Wigneron, Laguerre, and Kerr, 2001). The resulting algorithms have also been applied to provide accurate T_{eff} in other research (Njoku et al., 2003; Saleh et al., 2007; Wigneron et al., 2003, 2007). Nevertheless, the current existing schemes require parameter calibration for Holmes' scheme or soil texture for Wigneron's, and have relatively stringent requirements regarding field observation depth (e.g. at both the surface and a certain specified depth). More information about these models may be found in the T_{eff} models inter-comparison study by de Rosnay, Wigneron, Holmes, and Calvet (2006).

In this paper, after analyzing Choudhury's scheme, a new two-layer scheme (Lv's scheme hereinafter) was developed (Section 2). After explaining the physical meaning of each variable in Lv's scheme, Section 3 demonstrates how wavelength, soil moisture, sampling depth, and soil temperature can affect the calculation of T_{eff}, based on Lv's scheme. Comparisons with Wigneron's scheme (Wigneron et al., 2008) and Holmes' scheme (Holmes et al., 2006) are presented. In Section 4, a numerical discrete scheme is presented and theoretically formulated as a reference. Subsequently, Lv's scheme is evaluated based on the in-situ observations and its limitations are discussed. Conclusions are drawn in Section 5.

2. Method and materials

2.1. Derivation of the two-layer (Lv's) scheme

A satellite microwave radiometer measures the intensity of microwave radiation emitted from the earth's surface. From the deep point of origin to the soil surface, the intensity is attenuated by the intervening soil, whose absorption is determined by soil water content via the imaginary part of the dielectric constant. The net intensity at the soil surface is, therefore, a superposition of intensities emitted at different depths within the soil layers (Wilheit, 1978). In the absence of vegetation and atmospheric influence, the observed microwave intensity T_B is a product of emissivity (e) and T_{eff}:

$$T_B = eT_{eff} \tag{1}$$

while T_{eff} is expressed as follows (Ulaby, Bradley, and Dobson, 1979; Ulaby et al., 1978):

$$T_{eff} = \int_0^\infty T(x)\alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx \tag{2}$$

where x is the vertical distance (depth) from the surface to the soil layer concerned. $T(x)$ is the physical temperature at depth x and $\alpha(x)$ is an attenuation coefficient determined by dielectric constant ε and wavelength λ. The detailed form of $\alpha(x)$ is (Wilheit, 1978):

$$\alpha(x) = \frac{4\pi}{\lambda}\varepsilon''(x)/2[\varepsilon'(x)]^{\frac{1}{2}}. \tag{3}$$

T_{eff} may be calculated by using Eq. (2) with measured and interpolated soil moisture and temperature profiles. Choudhury et al. (1982) developed a simple two-layer algorithm with one parameter to calculate T_{eff}, based on the microwave radiative transfer equation (Eq. 2) in a plane stratified dielectric layer, which provides a soil temperature profile, and is expressed as (Choudhury et al., 1982):

$$T(x) = T_\infty + (T_1 - T_\infty)f(x) \tag{4}$$

where T_1 and T_∞ are the surface and deep soil temperatures, respectively, and $f(x)$ is a function dependent on depth. T_{eff} can then be described as follows:

$$T_{eff} = T_\infty + (T_1 - T_\infty)C \tag{5}$$

where $C = \int_0^\infty f(x)\alpha(x)\exp[-\int_0^x a(x')d\,x']d\,x$. This well-accepted Eq. (5) has been used in a series of ground calibration experiments, and is further developed by modifying parameter C with soil permittivity (Holmes et al., 2006) and soil moisture information (Wigneron et al., 2001, 2008). The sampling depth of microwave radiation is implicit in Eq. (5) (Escorihuela, Chanzy, Wigneron, and Kerr, 2010). If we suppose that there are 2 homogeneous soil layers, Choudhury's scheme can be re-derived. Assuming that these two layers have the same soil moisture, and texture, the derivation could be further stated as:

$$\begin{aligned}
T_{eff} &= \int_0^\infty [T_\infty + (T_1 - T_\infty)f(x)]\alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx \\
&= \int_0^\infty T_\infty \alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx \\
&\quad + \int_0^\infty (T_1 - T_\infty)f(x)\alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx \\
&= T_\infty \int_0^\infty \alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx \\
&\quad + (T_1 - T_\infty)\int_0^\infty f(x)\alpha(x)\exp\left[-\int_0^x \alpha(x')dx'\right]dx
\end{aligned} \tag{6}$$

where it is assumed that α is constant within each layer. The last term of Eq. (6) may be simplified to $(T_1 - T_\infty)C$, while the first term equals T_∞. Thus presented, the T_{eff} scheme by Choudhury et al. (1982) is a simplified form of Wilheit's (1978) scheme. Empirical Eq. (5) is a simplification of Eq. (2). However, this simplification is derived without a detailed physical explanation. The parameter C is comprised of a series of empirical constants that can only be acquired in a few specified bands. For other bands, it is not possible to infer C by an interpolation method, because C is supposed to be an empirical parameter determined by a least-square method. In practice, this may lead to huge differences (Tian et al., 2012).

Understanding C based on a physical explanation using a soil moisture profile has been investigated in many studies. Wigneron et al. (2001) developed a new algorithm to estimate soil effective temperature using the L band: $T_{eff} = T_\infty + (T_1 - T_\infty)\cdot(w_s/w_0)^b$, where w_s is the 0–3 cm surface soil moisture (this depth interval corresponds well with the effective soil moisture value contributing to soil emission in the L band), and w_0 and b are semi-empirical parameters depending on specific soil characteristics (Wigneron et al., 2001). The algorithm is further improved by considering soil properties when estimating w_0/b, using a range constraint of $\min\left[\left(\frac{w_s}{w_0}\right)\right]^b, 1$ (Wigneron et al., 2008). This scheme is successfully adopted in the SMOS soil moisture retrieval algorithm (Kerr et al., 2012). Holmes et al. (2006) presented a similar algorithm using the L band: $T_{eff} = T_\infty + (T_1 - T_\infty)\cdot((\varepsilon''/\varepsilon')/\varepsilon_0)^b$ with parameters ϵ_0 and b, and where $(\varepsilon''/\varepsilon')$ is calculated from soil moisture according to the dielectric mixing model. All parameters in these two models are retrieved empirically through experiments.

In theory, any integral equation can be numerically expressed by discrete variables and simplified based on certain assumptions. Hypothetically, $x_0 = 0$ represents the soil surface as well as the upper boundary for the first layer; x_{i-1} and x_i are the upper and lower boundaries, respectively, of the i th layer, whereas the