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A reappraisal of global soil effective temperature schemes

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ABSTRACT

Traditionally, effective soil temperature (T_{eff}) has been considered to be a secondary intermediate variable in microwave radiative transfer theory. However, its impact on microwave radiometry is comparable to that of vegetation cover, soil surface roughness and dielectric constant. T_{eff} is defined as the weighted temperature of the emitting layers, where the weighting involved depends on the soil moisture profile. In this study, we evaluate the suitability of various models for estimating T_{eff} using temperature and moisture profiles obtained from a land surface model. MERRA-Land (the Modern-Era Retrospective analysis for Research and Applications-Land) soil moisture profiles and temperature profiles were used to reproduce global T_{eff} data sets with single parameter schemes (e.g. the Beta Soil Moisture Active Passive, SMAP scheme), two-parameter Choudhury's schemes (e.g. the current SMAP's scheme), two-parameter Wigneron schemes (e.g. the current Soil Moisture and Ocean Salinity scheme, SMOS), and multilayer T_{eff} schemes (e.g. Lv′s scheme). The results show that differences in T_{eff} between these schemes are usually <5 K. The comparison between Wigneron's and Lv′s schemes indicates that, the difference is small (RMSD, root mean squared difference <1 K). In exceptional cases (<1%), the RMSD between Choudhury's T_{eff} scheme and Lv′s scheme can reach around 5 K. The Beta SMAP T_{eff} has a difference of around 5 K, compared to Lv′s scheme. Such a change in T_{eff} could lead to an emissivity difference of around 0.015. The most extreme emissivity difference is only found in desert areas, at 42.5° (the incidence angle used by the SMAP mission is about 40°).

1. Introduction

Soil moisture is an essential variable in terrestrial water and energy budgets. A detailed knowledge of soil moisture has the potential to improve our current knowledge of hydrological processes and of seasonal climate forecasting (Hirschi, Mueller, Dorigo, & Seneviratne, 2014; Su et al., 2014; Wen et al., 2014). Satellite microwave remote sensing is deemed to be the only feasible, direct method for retrieving data on global soil moisture levels. However, the accuracy of this method is heavily dependent on the sensors and retrieval algorithms used. The remote sensing of soil moisture by means of microwaves is based on the theory that the energy emitted from the soil is proportional to the thermodynamic temperature (Ulaby, Razani, & Dobson, 1983). The brightness temperature observed by satellite sensors is expressed as,

$$T_B = \varepsilon T_{eff} \quad (1)$$

where ε is the effective emissivity that corresponds to soil moisture, via the dielectric constant in radiative transfer models, and to vegetation conditions. T_{eff} is the effective soil temperature, which is influenced by soil moisture, wavelength and temperature (Wilheit, 1978). In order to obtain ε from Eq. (1), a T_{eff} value must be known a priori. On the other hand, the T_{eff} used in current global operational processors for SMOS and SMAP was not obtained from direct measurements, but was instead taken from the modelled soil temperature profile. For example, the Soil Moisture and Ocean Salinity (SMOS) retrieval (Kerr et al., 2012) uses ECMWF (European Centre for Medium-Range Weather Forecasting) land surface model data. Similarly, the Soil Moisture Active Passive (SMAP) retrieval uses MERRA-Land, which is a land surface data product of the Modern-Era Retrospective analysis for Research and Applications (SMAP Algorithm Development Team and SMAP Science Team, 2015). The rational for deriving T_{eff} from model simulation results is that the resultant errors are no more significant than those derived using a crude interpolation scheme, and will only have an impact in the case of very dry soils (Kerr et al., 2012).

More specifically, operational SMOS retrieval uses ECMWF simulations of global soil temperatures for the top layer and the deepest layer (or next to deepest layer), as the surface and deep temperatures, respectively. Wigneron's two-layer T_{eff} scheme used these two soil

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Table 1
MERRA-Land soil temperature/moisture data for layers 1–7, prepared as input for Eq. (2). MERRA-Land also provides data on layers 8 and 9, but this was not used in the present study.

<table>
<tr><td colspan="2">Layer</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
<tr><td rowspan="2">Soil Moisture</td><td>Variable Name</td><td colspan="2">DZSF[a]</td><td colspan="4">DZRZ[b]</td><td colspan="3" rowspan="2">None</td></tr>
<tr><td>Depth(m)</td><td colspan="2">0-0.02</td><td colspan="4">0.02-0.3401</td></tr>
<tr><td rowspan="2">Soil Temperature</td><td>Variable Name</td><td>DZTS[c] (TSURF)</td><td colspan="2">DZGT1[d] (TSOIL1)</td><td>DZGT2 (TSOIL2)</td><td>DZGT3 (TSOIL3)</td><td colspan="2">DZGT4</td><td>DZGT5</td><td>DZGT6</td></tr>
<tr><td>Depth(m)</td><td>0 -0.018</td><td colspan="2">0.018 -0.0988</td><td>0.0988 -0.294</td><td>0.294 -0.6799</td><td colspan="2">0.6799 -1.4425</td><td>1.4425 -2.9496</td><td>2.9496 -10</td></tr>
</table>

[a] DZSF: Thickness of soil layer associated with top soil layer soil moisture content.
[b] DZRZ: Thickness of soil layer associated with root zone soil moisture content.
[c] DZTS: Thickness of soil layer associated with non-snow surface temperature components.
[d] DZGT: Thickness of soil layer associated with i^{th} layer.

temperatures as inputs, together with auxiliary information (Kerr et al., 2012). Similarly, the previous Beta SMAP retrieval assumed a homogenous soil temperature and soil moisture profile at 6:00 a.m. and 6:00 p.m. It also used the surface skin temperature and soil temperature at 0–10 cm derived from the MERRA-Land model as the surface and deep temperature, respectively (SMAP Algorithm Development Team and SMAP Science Team, 2015). The arithmetic average of these two temperatures is taken as T_{eff}. Since September 2015, the SMAP team has updated its T_{eff} using Choudhury's two-layer scheme. This was because preliminary analysis showed that a more sophisticated model was required for computing T_{eff}, due to non-uniform soil temperature profiles (O'Neill, Chan, Njoku, Jackson, & Bindlish, 2015).

The use of soil temperatures from the various layers and models used for SMOS and SMAP may lead to differences in the values of T_{eff} calculated by the two global processors. Recent investigations by Lv, Wen, Zeng, Tian, and Su (2014) indicated that the use of different sampling depths can result in a large deviation in T_{eff} (around 7 K at Maqu Network (Su et al., 2011)). This uncertainty may ultimately affect the final soil moisture product. One study (Sabater, De Rosnay, & Balsamo, 2011) reported that, in extreme cases, an error of 5 K in T_{eff} can lead to a 5% error in the soil moisture product. Even when using the *C*-band, which is less sensitive to T_{eff} parameterization than the *L*-band, accurate estimates of T_{eff} are still essential for converting modelled emissivity into brightness temperature (Dente, Ferrazzoli, Su, van der Velde, & Guerriero, 2014).

Thus, the primary objective of the current study is to compare the T_{eff} results from the current SMOS and the SMAP schemes (both the Beta version and Choudhury's), and to examine their influence on emissivity (the intermediate variable directly related to soil moisture). The method and data discussed here will hopefully complement the SMAP mission that was launched in January 2015, thereby enhancing its ability to deliver global soil moisture products.

Table 2
Different schemes used for calculating T_{eff}.

Name	Parameterization	Layers
T1	$T_{eff} = (T_1 + T_\infty)/2$	$T_1 = TSURF$ $T_\infty = TSOIL1$
T2C	$T_{eff} = T_\infty + (T_1 - T_\infty)C, C = 0.246$	$T_1 = TSOIL1$ $T_\infty = TSOIL2$
T2W	$T_{eff} = T_\infty + (T_1 - T_\infty)(\frac{W_s}{W_0})^b, \quad ,\min[(\frac{W_s}{W_0})^b, 1], \begin{cases} W_0 = 0.3 \\ b = 0.3 \end{cases}$	$T_1 = TSOIL1$ $T_\infty = TSOIL3$ $W_s = DZSF$
TM	$T_{eff} = T_1(1-e^{-B_1}) + \sum_{i=2}^{n-1} T_i(1-e^{-B_i}) \prod_{j=1}^{i-1} e^{-B_j} + T_n \prod_{j=1}^{n-1} e^{-B_j}$	All

2. Method and data

2.1. MERRA-land data

The Modern-Era Retrospective analysis for Research and Applications (MERRA) was a global atmospheric reanalysis undertaken by NASA/GMAO (Suarez et al., 2008). With the updated catchment land surface model and precipitation data, MERRA-Land provides a globally integrated, coherent estimate of soil moisture and temperature from 1979 to the present (Rienecker et al., 2011). In this study, hourly global soil moisture and temperature profiles were taken in 2013 to reproduce T_{eff}, using Lv's multilayer scheme (hereafter referred to as TM), the current SMOS scheme (e.g. a two-layer scheme, hereafter referred to as T2W), the SMAP scheme (hereafter referred to as T2C), and the Beta SMAP scheme (e.g. one layer scheme, hereafter referred to as T1). MERRA-Land has a spatial resolution of 0.67 × 0.50°. This product makes it possible to create daily global T_{eff} maps at 6:00 a.m. (ascending/descending for SMOS/SMAP) and 6:00 p.m. (descending/ascending for SMOS/SMAP) local solar time for all time zones. To enable soil moisture and temperature values to be acquired at the exact local solar time, all pixels are temporally interpolated according to their longitudes.

2.2. SMOS brightness temperature

The CATDS Centre (Centre Aval de Traitement des Données; http://catds.ifremer.fr/) SMOS level 3 brightness temperature T_B products (SMOS L3c) were used to assess the influence of T_{eff} on emissivity. It offers mean daily brightness temperature intensities set out in a grid with a resolution of 0.25 × 0.3125°. SMOS L3c includes V and H full polarimetry T_B at nadir incidence angles of between 0 and 65°. This study was restricted to an incidence angle of 42.5°, as this is close to the incidence angle of 40° used by the SMAP mission. As horizontal polarization is primarily used in the context of soil moisture retrieval, this paper uses only H brightness temperature.

2.3. Effective temperature models

As indicated above, the T1, T2C, T2W and TM schemes will be used to reproduce T_{eff}. The Beta SMAP T_{eff} scheme (SMAP Algorithm Development Team and SMAP Science Team, 2015), referred to here as T1, is interpreted as a single layer T_{eff} scheme. This is because it addresses neither sensing depth nor the weighting between a surface layer and a deeper layer. Theoretically, for the SMAP soil moisture retrieval algorithms, T_{eff} is considered to be the average (or effective) temperature of the top 5 cm layer of soil. The T_{eff} is obtained from MERRA-Land data by