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Improving soil moisture retrievals from a physically-based radiative transfer model

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ABSTRACT

Near surface soil moisture is being estimated from space-borne passive microwave observations through inverting a physically-based radiative transfer model (RTM), the land surface microwave emission model (LSMEM) at Princeton University for the past several years. The existing retrieval scheme utilizes only the horizontal (*H*) polarization measurement from a single channel (10.65 GHz). This physically-based approach requires a relatively large number of parameters, and it generally suffers from large biases/errors due to the difficulty in determining the correct parameters. This study characterizes these errors in order to improve the retrieval performance. Through model sensitivity analysis, this study finds that a dual polarization approach (using both horizontal and vertical polarizations) is needed to infer the correct vegetation opacity and correct polarization mixing measured by the space-borne sensor. Revisions are then made to the LSMEM formulations and soil moisture retrieval algorithm by 1) combining two vegetation parameters and one roughness parameter into one effective vegetation optical depth (VOD) value; and 2) providing an additional model equation that estimates the effective VOD from both polarizations and an initial guess of soil moisture value. The new retrieval algorithm is implemented to produce a daily 0.25° gridded soil moisture dataset based on observations from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E). Validations are performed globally against land surface model simulations and at local/point scale against in-situ data within the continental United States. The new retrievals are shown to have good and robust performance over most parts of the world in terms of reproducing the spatial and temporal dynamics of soil moisture.

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1. Introduction

It is widely recognized that the land surface soil moisture content is a very important state variable for the terrestrial hydrologic system (Entekhabi et al., 2010), but it is both difficult and expensive to measure through ground-based sensor networks at large scales. For this reason, many efforts have been made to estimate the near surface soil moisture from space-borne sensors in microwave frequencies and to provide reliable long-term, global scale estimates. Most efforts have largely focused on passive brightness temperature measurements, for example, the 10.65 GHz channel of both the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (Bindlish et al., 2003; Gao, Wood, Jackson, Drusch, & Bindlish, 2006) and the Advanced Microwave Scanning Radiometer (AMSR-E) have been heavily used for soil moisture retrievals (Bindlish, Jackson, Gasiewski, Klein, & Njoku, 2006; McCabe, Wood, & Gao, 2005; Njoku, Ashcroft, Chan, & Li, 2005; Owe, de Jeu, & Holmes, 2008). Other sensors (including active) have also been used (de Jeu et al., 2008; Parinussa, Holmes, & de Jeu, 2012), including the 1.4 GHz channel of Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2012, 2010). Various global long-term remotely sensed soil moisture datasets have been established through blending estimates from different sensors available (Liu et al., 2011; Liu et al., 2012).

Changes in surface soil moisture content lead to changes in the surface emissivity in microwave frequency, and passive satellite sensors can detect the soil moisture signals by measuring the brightness temperature (Njoku, 1977). The related radiative transfer theory is quite well known, but this physical process is dramatically complicated by factors like strong influence of vegetation phenology and surface properties (Jackson & Schmugge, 1991; Jones, Jones, Kimball, & McDonald, 2011; Owe, de Jeu, & Walker, 2001; Ulaby, Razani, & Dobson, 1983). Different researchers have been using different approaches in their retrievals trying to minimize errors and to simplify the retrieval algorithm. One basic approach would be to invert a physically-based radiative transfer model (RTM). Such a RTM parameterizes a number of physical processes/relationships including the dielectric property of wet soil (Dobson, Ulaby, Hallikainen, & Elrayes, 1985; Wang & Schmugge, 1980), polarization mixing (Choudhury, Schmugge, Chang, & Newton, 1979; Wang & Choudhury, 1981), vegetation emission/scattering, and radiative transfer to the top

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of the atmosphere (TOA). The soil moisture is estimated from satellite measurements by inverting the RTM using a root-finding algorithm. A typical example, which is also our existing approach for estimating soil moisture from AMSR-E measurements, is to invert the Land Surface Microwave Emission Model (LSMEM) (Dobson et al., 1985; Drusch, Wood, Gao, & Thiele, 2004; Drusch, Wood, & Jackson, 2001; Gao, Wood, Drusch, Crow, & Jackson, 2004). Other similar approaches include the retrieval products by the United States Department of Agriculture (USDA) (Jackson, 1993; Jackson & Hsu, 2001; Jackson et al., 1999) and the L-band Microwave Emission of the Biosphere (L-MEB) model (Wigneron et al., 2007) used for SMOS soil moisture retrievals at the European Centre for Medium Range Weather Forecasts (ECMWF). This approach usually solves for one unknown (soil moisture) given the brightness temperature from a single channel/polarization and the inversion is algorithmically simple. Also, since the parameters have clear physical definitions, it is more convenient to perform in-situ parameter validation or to intercompare parameters among different RTMs. However, the challenge of this approach is that it requires many physical parameters, some of which we lack any accurate knowledge of, e.g., the emission/optical properties of the soil surface and vegetation cover in target frequency.

The alternative to parameter-intensive approaches is to solve for more parameters altogether. The initial production of the official NASA AMSR-E soil moisture product (Njoku, Jackson, Lakshmi, Chan, & Nghiem, 2003) takes a multi-channel and multi-polarization approach (Njoku & Li, 1999) where the vegetation properties and soil moisture (as well as the surface temperature) are solved simultaneously. Later this approach was revised such that the combined vegetation-roughness effect is modeled as a function of the Microwave Polarization Difference Index (MPDI) and the soil moisture is estimated as a deviation relative to a reference dry moisture condition (Njoku & Chan, 2006). The Land Parameter Retrieval Model (LPRM) (Owe et al., 2001) provides another alternative based on the concept of the MPDI and it solves for the soil moisture and other parameters through an iterative optimization procedure (de Jeu et al., 2008).

The research group at Princeton has been producing global soil moisture retrieval dataset (Gao et al., 2006) by inverting the physically-based LSMEM. For the past few years, this approach has suffered from the lack of suitable parameters that produce accurate vegetation opacity and polarization mixing measured by the satellite sensors, and consequently large errors and biases exist in both the forward model and soil moisture retrievals. The goal of this study is to first characterize the errors in the existing LSMEM model, then propose revisions to the model formulations for improving soil moisture retrievals, and finally test and validate the improved retrieval approach. In the sections to follow, a thorough description of the existing LSMEM and its inversion are given first, then an error/bias diagnosis study is performed for two typical types of model errors, followed by a model sensitivity analysis to identify ways to reduce such errors/biases, then improvements are proposed, and finally the retrieval tests and validations are carried out with discussions and summaries.

2. LSMEM forward and inverse models

LSMEM is designed as a forward RTM that predicts the brightness temperature measured at TOA given all surface and atmospheric conditions. An important purpose of such a RTM is to work in conjunction with a general circulation model (GCM) or land surface model (LSM) (Crow, Drusch, & Wood, 2001). Therefore, LSMEM starts from the

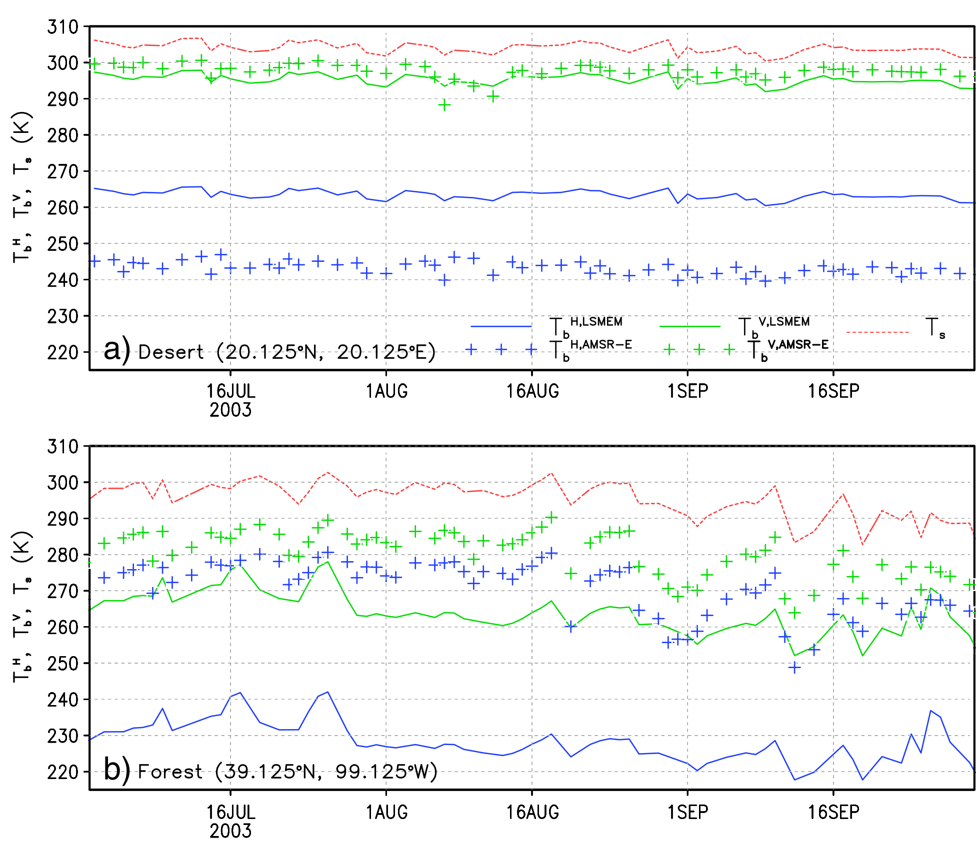

Fig. 1. LSMEM forward model prediction errors in July–September of 2003 forced with VIC soil moisture inputs. The first test point shown in panel (a) is located in the Sahara desert, and the second point shown in panel (b) is located in a forested area in Kansas, United States. Solid lines are LSMEM predictions and plus marks are AMSR-E measurements. T_b^H is drawn in blue color and T_b^V in green. The red dashed line is T_s.

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