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Benchmarking of L-band soil microwave emission models

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ABSTRACT

A first step before assimilating Soil Moisture and Ocean Salinity (SMOS) L-band brightness temperatures (Tb) over land is to couple land surface models (LSMs) to microwave emission models. In this study, the Interactions between Soil Biosphere and Atmosphere (ISBA) LSM is coupled to the Community Microwave Emission Modelling platform (CMEM). Simulations of Tb are performed over a 3-yr period (2003–2005) for a bare soil field in southwestern France, at the Surface Monitoring Of the Soil Reservoir EXperiment (SMOSREX) experimental site. Both ISBA and CMEM present several options for the representation of the soil moisture and soil temperature profiles. Simplified 2-layer simulations are compared with more detailed multilayer simulations. In the 2-layer simulations, the soil is divided into two layers (a thin surface layer and a bulk reservoir), and Fresnel laws are used in CMEM to model the smooth surface emissivity. In the multilayer simulations, the ISBA soil diffusion scheme is used (with 11 soil layers represented) together with either the Wilheit or Fresnel option of CMEM. The Tb simulations are compared to the Tb ground observations available for the SMOSREX site, at H and V polarizations and at different angles, and the impact of soil roughness is assessed. It is shown that taking surface soil moisture into account in the calculation of soil roughness improves the representation of the seasonal cycle and increases the correlation for all the versions of CMEM. The Tb derived from the most complex multilayer simulations correlate slightly better to the observations than the Tb derived from the 2-layer model ($r = 0.84$ and $r = 0.82$, respectively, for the pooled dataset). This is partly due to a better representation of the soil moisture profile. Finally, the multilayer model is used to investigate the L-band sampling depth for contrasting soil texture profiles. For a variety of soil textures, it is found that Tb are mainly driven by the top 15 cm soil layer.

1. Introduction

Soil moisture plays a crucial role in the interactions between the hydrosphere, the biosphere and the atmosphere, as it controls both soil evaporation and plant transpiration. It is a major variable of the continental hydrological cycle (Dirmeyer, Dolman, & Sato, 1999; Entekhabi et al., 1999; Milly & Dunne, 1994). Soil moisture is highly variable both spatially and temporally in the natural environment, as the result of the heterogeneity of soil properties, topography, land cover, rainfall and evapotranspiration. The impact of soil moisture on the atmospheric variables has been shown at the local scale (Seuffert, Gross, Simmer, & Wood, 2002), at the regional scale (Schär, Luethi, Beyerle, & Heisse, 1999) and at the global scale (Koster & the GLACE Team, 2004).

Microwave remote sensing is able to provide quantitative information about the water content of the top soil layer, particularly in the microwave low frequency domain, from 1 to 10 GHz. Many studies have shown that L-band is the optimal wavelength range to observe soil moisture (e.g. Calvet et al., 2011; Schmugge, 1983). With respect to higher frequencies, the signal at L-band is less perturbed by atmospheric effects and by the vegetation cover. Passive microwave remote sensing at L-band measures brightness temperatures (Tb), representing the natural emission of the surface. Over land, Tb is related to the surface soil moisture (SSM) content of the top surface layer of the soil. The sensitivity of Tb to SSM is about 2 K per 0.01 $m^3\ m^{-3}$ over bare soil (Chanzy et al., 1997; Schmugge & Jackson, 1994).

SMOS (Soil Moisture and Ocean Salinity) is the first satellite mission dedicated to the observation of soil moisture (Kerr, 2007; Kerr et al., 2001). It was launched in November 2009. The SMOS instrument is an L-band (21 cm, 1.4 GHz) 2-D interferometric radiometer. Over land, the aim of SMOS is to provide global SSM maps with an accuracy better than 0.04 $m^3\ m^{-3}$, at a spatial resolution better than 50 km, every three days (Kerr et al., 2001). The SSM values are derived from the L-band Tb using retrieval algorithms. The Soil Moisture Active Passive (SMAP) instrument incorporates an L-band radiometer and is scheduled for launch in 2014. These new spaceborne L-band radiometers and the development of soil moisture retrieval algorithms for preexisting active and passive microwave remote sensing missions (Bartalis et al., 2007; Owe, de Jeu, & Walker, 2001; Wagner, Lemoine, & Rott, 1999) offer an opportunity to improve land surface models (LSM).

Several studies have demonstrated that the modeled root-zone soil moisture can be improved by assimilating remotely sensed SSM data (Calvet & Noilhan, 2000; Crow & Wood, 2003; Drusch, 2007; Entekhabi, Nakamura, & Njoku, 1994; Houser et al., 1998; Ragab,

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1995; Reichle et al., 2007; Sabater, Jarlan, Calvet, Bouyssel, & de Rosnay, 2007; Walker & Houser, 2001; Walker, Willgoose, & Kalma, 2001 among others). Assimilating Tb instead of SSM in a LSM permits using a more direct geophysical observation and preserving the consistency with the model parameters (e.g. soil texture) and model variables (e.g. soil temperature profile) (Crow & Wood, 2003; Reichle, Entekhabi, & McLaughlin, 2001; Seuffert, Wilker, Viterbo, Drusch, & Mahfouf, 2004). Moreover, Tb can be assimilated in order to provide timely soil moisture initial conditions for Numerical Weather Prediction systems (Fisher, Seneviratne, Vidale, Lüthi, & Schär, 2007). From an operational point of view, producing the SMOS SSM product takes more than 24 h, while the SMOS Tb are available in near-real time, within 3 h of sensing (Sabater, Fouilloux, & de Rosnay, 2011). Consequently, a land surface microwave emission model is needed to transfer the model state variables (e.g. soil moisture and soil temperature profiles) into the observation space (Tb) (Drusch, Holmes, de Rosnay, & Balsamo, 2009). A number of studies have addressed the modeling of the L-band soil emission such as Wigneron et al. (2007), de Rosnay et al. (2009), Drusch et al. (2009), Sabater, de Rosnay, et al. (2011). They showed the strong sensitivity of Tb to the soil roughness. The soil roughness impact on Tb is complex at it implies 3-D geometric soil surface features as well as soil moisture heterogeneity. The Tb derived from smooth soil emission models usually differ from Tb observations and they can be corrected using soil roughness models. Soil roughness can be represented by a roughness height parameter h, related to the wave number and to the standard deviation in surface height (σ) (Choudhury, Schmugge, Chang, & Newton, 1979; Wegmüller & Matzler, 1999) or σ together with the surface height correlation length (L_C) (Wigneron, Laguerre, & Kerr, 2001). A number of studies have shown that h may depend on SSM (Escorihuela et al., 2007; Mo & Schmugge, 1987; Saleh et al., 2007; Wigneron et al., 2001). Lawrence, Wigneron, Demontoux, Mialon, and Kerr (2013) have proposed a parameterization of h using the Portos-93 data (Wigneron, Chanzy, Calvet, & Bruguier, 1995). An increase in soil roughness tends to increase Tb (Engman & Chauhan, 1995; Njoku & Entekhabi, 1996) and to decrease the sensitivity of Tb to soil moisture (Choudhury et al., 1979; Wang & Choudhury, 1981). The Wilheit (1978) multilayer smooth soil emission model was used in Raju et al. (1995) to assess the microwave sampling depth to be used in the Fresnel smooth soil emission model, using the Portos-93 data. For the same purpose, Escorihuela, Chanzy, Wigneron, and Kerr (2010) used a soil multilayer model to interpolate the soil profile measurements performed at the bare soil plot of the Surface Monitoring Of the Soil Reservoir EXperiment (SMOSREX) site in southwestern France. From April 2003 to August 2012, an L-band radiometer performed Tb measurements over bare soil and fallow plots of the SMOSREX site. In addition, the infrared surface temperature, and the soil moisture and soil temperature profiles were measured, together with meteorological observations (de Rosnay et al., 2006). Raju et al. (1995) and Escorihuela et al. (2010) indicated that a shallow surface soil layer (1 cm to 2 cm thick) governs the response of the L-band Tb to soil moisture as simulated with the Fresnel approach.

de Rosnay et al. (2009) have developed the current version of the ECMWF Community Microwave Emission Modelling platform (CMEM) that simulates low frequency microwave Tb from LSM variables and parameters. CMEM has a modular structure for the parameterization of soil, vegetation, snow and atmosphere. For each component of the emission model, a choice of parameterizations is available, which facilitates benchmarking studies.

In this study, CMEM is used to simulate Tb over the bare soil plot of SMOSREX for a 3-yr period (2003–2005) at 0530–0540 Local Standard Time (LST). We investigate the simulation of the L-band soil emission and its sensitivity to various representations of the soil moisture and soil temperature profiles in relation to the surface soil roughness. Several soil roughness models are compared and the L-band sampling depth is assessed. This work is also a preliminary investigation before the assimilation of Tb in the Interactions between Soil Biosphere and Atmosphere (ISBA) LSM. In order to assess the impact of the representation of the soil profiles on Tb, two versions of the soil module of the ISBA LSM are used: the original force-restore two-layer scheme of ISBA (Noilhan & Mahfouf, 1996) and the more complex diffusion scheme (Boone, Masson, Meyers, & Noilhan, 2000; Decharme, Boone, Delire, & Noilhan, 2011). Hereafter, the two ISBA versions are referred to as ISBA-2L and ISBA-DF, respectively. The Tb are modeled using different configurations of CMEM, based on the soil variables produced by either ISBA-2L or ISBA-DF: (1) ISBA-2L or ISBA-DF together with the CMEM Fresnel smooth soil emission model; (2) ISBA-DF together with the CMEM Wilheit (Wilheit, 1978) multilayer smooth soil emission model. The modeled Tb is compared to the SMOSREX Tb observations. As this study focuses on the representation of the L-band soil emission, the bare soil spot of SMOSREX is considered, only.

The SMOSREX data are presented in Section 2. The ISBA-2L, ISBA-DF models and the CMEM platform are described in Section 3. The results are presented in Section 4, and discussed in Section 5.

2. SMOSREX data

The SMOSREX long-term experiment (2001–2012) aimed at improving the modeling of the terrestrial microwave L-band emission in the context of the SMOS mission (de Rosnay et al., 2006). The SMOSREX site (43°23′N, 1°17′E) was located in southwestern France. The site was divided into two parts: a bare soil plot and a fallow plot. The L-band radiometer for Estimating Water in Soils (LEWIS; Lemaître et al., 2004) was installed at about 15 m above the soil surface, and measured Tb from April 2003 to August 2012 at incidence angles (θ) of 20°, 30°, 40°, 50° and 60°, at both horizontal and vertical polarizations (H and V, respectively). Over bare soil, this set of 10 Tb measurements was performed twice at regular 10-min time slots (every 3 h): 0230–0240 UTC, 0530–0540 UTC, 0830–0840 UTC, 1130–1140 UTC, 1430–1440 UTC, 1730–1740 UTC, 2030–2040 UTC, and 2330–2340 UTC. The LEWIS beamwidth was 13.5° at −3 dB and its accuracy was 0.2 K. Lemaître et al. (2004) gave a full description of the LEWIS radiometer.

Atmospheric variables and soil profiles were measured from January 2001 to August 2012, on a half-hourly basis. Soil moisture was measured at depths of 0–0.06, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80 and 0.90 m. Soil moisture probes were calibrated from gravimetric measurements (Schmugge, Jackson, & McKim, 1980), from which soil density was derived. Soil temperature was measured at depths of 0.01, 0.05, 0.20, 0.50 and 0.90 m close to the location of the soil moisture probes. The soil properties observed over the bare soil plot are listed in Table 1. A weather station measured precipitation, 2 m air temperature and air humidity, 10 m wind speed, atmospheric pressure, solar and atmospheric incoming radiation.

The SMOSREX data over the fallow plot were analyzed in numerous studies such as Albergel et al. (2010, 2008), Sabater et al. (2007) and Escorihuela et al. (2009). In this study, we focus on the bare soil plot. Only years 2003, 2004 and 2005 are considered as for the bare soil plot, the soil moisture data at depths ranging from 0.20 m to 0.90 m are missing from 2006 onward.

It must be noted that soil roughness was much higher in 2003 than in 2004 and 2005 as the bare soil plot of SMOSREX was artificially crushed and compressed at the end of 2003. While in 2004 rainfall and air temperature were close to the 1981–2010 climatology derived from a nearby ground weather station (Lherm, 43°27′N, 1°16′E), southwestern France was affected by a summer drought in 2003 and in 2005 (Lafont et al., 2012). Exceptionally dry conditions were observed in summer 2003, in relation to a heat wave that affected western Europe (Fisher et al., 2007). At the SMOSREX site, the average spring and summer air temperature of 2003 exceeded the 1981–2010 mean by 3.0 °C. During the same period, rainfall was 50% lower than the 1981–2010 mean.