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SMOS soil moisture retrievals using the land parameter retrieval model: Evaluation over the Murrumbidgee Catchment, southeast Australia

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ABSTRACT

The land parameter retrieval model (LPRM) is a methodology that retrieves soil moisture from low frequency dual polarized microwave measurements and has been extensively tested on C-, X- and Ku-band frequencies. Its performance on L-band is tested here by using observations from the Soil Moisture and Ocean Salinity (SMOS) satellite. These observations have potential advantages compared to higher frequencies: a low sensitivity to cloud and vegetation contamination, an increased thermal sampling depth and a greater sensitivity to soil moisture fluctuations. These features make it desirable to add SMOS-derived soil moisture retrievals to the existing European Space Agency (ESA) long-term climatological soil moisture data record, to be harmonized with other passive microwave soil moisture estimates from the LPRM. For multi-channel observations, LPRM infers the effective soil temperature (T_{eff}) from higher frequency channels. This is not possible for a single channel mission like SMOS and therefore two alternative sources for T_{eff} were tested: (1) MERRA-Land and (2) ECMWF numerical weather prediction systems, respectively. SMOS measures brightness temperature at a range of incidence angles, different incidence angle bins (45°, 52.5° and 60°) were tested for both ascending and descending swaths. Three LPRM algorithm parameters were optimized to match remotely sensed soil moisture with ground based observations: the single scattering albedo, roughness and polarization mixing factor. The soil moisture retrievals were optimized and evaluated against ground-based data from the Murrumbidgee Soil Moisture Monitoring Network (OzNet) in southeast Australia. The agreement with single-angle SMOS LPRM retrievals was close to the official SMOS L3 product, provided the three parameters were optimized for the OzNet dataset, with linear correlation of 0.70–0.75 (0.75–0.77 for SMOS L3), root-mean-square error of 0.069–0.085 m^3 m^{-3} (0.084–0.106 m^3 m^{-3} for SMOS L3) and small bias of -0.02–0.01 m^3 m^{-3} (0.03–0.06 m^3 m^{-3} for SMOS L3). These results suggest that the LPRM can be applied successfully to single-angle SMOS L-band observations, but further testing is required to determine if the same set of parameters can be used in other geographic areas.

1. Introduction

A better understanding of the dynamics of near-surface soil moisture (θ, m^3 m^{-3} for a top soil layer of defined thickness) with increased spatial and temporal details can be expected to improve the knowledge of energy and water fluxes between the Earth surface and the atmosphere. Evidence suggests that several important practical applications can benefit from satellite-derived θ estimates, including flood forecasting, drought monitoring and weather and climate modeling (Bisselink, Van Meijgaard, Dolman, & De Jeu, 2011; Bolten, Crow, Zhan, Jackson, & Reynold, 2010; Brocca et al., 2010). Space-borne microwave observations at low frequencies (i.e. L-band, C-band, X-band) have the potential to fulfill this need. Over the years several algorithms have been developed to derive θ from passive microwave observations, resulting in numerous data products developed from 1978 onwards (Owe, De Jeu, & Holmes, 2008, and references therein). The datasets have proven their value in research applications (e.g., Jung et al., 2010; Liu, De Jeu, Van Dijk, and Owe, 2007; Taylor, De Jeu, Guichard, Harris, & Dorigo, 2012). They become even more valuable once estimates from subsequent satellite missions are combined into one consistent multi-decadal data record (De Jeu et al., 2012). This was addressed by the European Space Agency (ESA) through the Water Cycle MultiMission Observation Strategy (WACMOS) project and the Climate Change Initiative Program

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(CCI), in which a single consistent 32 year data record was produced by harmonizing soil moisture estimates from historical passive- and active microwave and observations (Liu et al., 2012a). This data record makes use of the land parameter retrieval model (LPRM) (Owe, De Jeu, & Walker, 2001) to derive soil moisture from the passive microwave sensors and the change detection algorithm to derive θ from the active microwave observations (Wagner, Lemoine, & Rott, 1999) as baseline algorithms to develop the long-term soil moisture record.

The LPRM is one of several methods for inferring θ from passive microwave observations. This method has been applied to observations from multiple passive microwave sensors, such as the Scanning Multichannel Microwave Radiometer (SMMR), the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission's Microwave Imager (TRMM-TMI), the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) and WindSat (Owe et al., 2008; Parinussa, Holmes, & De Jeu, 2011a), and has been demonstrated to generate good quality θ estimates (Gruhier et al., 2010; Rossato, De Jeu, Alvala, & Souza, 2011; Rudiger et al., 2009; Su, Ryu, Young, Western, & Wagner, 2013; Wagner, Naeimi, Scipal, De Jeu, & Martinez-Fernandez, 2007). Unlike other θ retrieval methods, the LPRM simultaneously retrieves both θ and vegetation optical depth (τ_v, dimensionless) from microwave brightness temperatures (T_b in K) via inversion of the radiative transfer model. It therefore does not require prior external information on vegetation (Huilin, Wood, Drusch, Crow, & Jackson, 2004; Kerr et al., 2012; Meesters, De Jeu, & Owe, 2005).

In November 2009, ESA launched the Soil Moisture and Oceans Salinity (SMOS) satellite (Kerr et al., 2010); the first mission dedicated to soil moisture. It observes at the 1.4 GHz (L-band) frequency which is considered to be optimal for θ retrievals because of the low sensitivity to cloud and vegetation contamination, a thermal sampling depth of several centimeters, and a high sensitivity to soil moisture fluctuations (Njoku & Entekhabi, 1996). SMOS is the first of several satellite missions measuring at L-band; in 2011 Aquarius (Le Vine, Lagerloef, Colomb, Yueh, & Pellerano, 2007b) was launched, and the Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2010) is launched in 2015. The spatial resolution of the current SMOS Level 3 soil moisture product (SMOS L3) is 43 km. The unique capabilities of SMOS make it desirable to include retrievals from the sensor in ESAs long-term soil moisture climate record. To maintain consistency in the CCI data record, arguably application of the LPRM algorithm to derive θ from SMOS may be more preferable than to use the SMOS L3 product produced by alternative algorithms. In particular, (a) the other passive microwave θ retrievals in the long-term record are derived by the LPRM, (b) the SMOS L3 produces soil moisture for the dominant land type rather than an area-averaged soil moisture estimate for the entire footprint, which introduces conceptual differences and (c) LPRM uses as little as possible ancillary data, which is highly desired for the CCI θ dataset (De Jeu et al., 2014).

LPRM has not yet been thoroughly tested in combination with L-band measurements. De Jeu, Holmes, Panciera, and Walker (2009) showed promising results applying LPRM to L-band observations and ground data from the National Airborne Field Experiment 2005 (NAFE05) over southeast Australia, but stressed that verification with satellite observations was needed, especially because of the lesser incidence angles (up to 40°) and the higher radiometric accuracy (<0.7 K) of the airborne data, when compared to SMOS observations (up to 65°and 2.5–3 K, respectively). LPRM has typically been applied to incidence angles between 50–55° and the applicability of LPRM for a wider range of incidence angles, such as those available from SMOS, has not yet been tested. Like most θ retrieval methods, LPRM requires an estimate of the effective soil temperature (T_{eff} in K) as input to the retrieval scheme. For multi-channel observations, T_{eff} may be inferred from higher frequency channels (e.g. AMSR-E 37 GHz vertical polarized brightness temperature; Holmes, De Jeu, Owe, & Dolman, 2009). However the SMOS (and SMAP) sensors only have a single frequency radiometer at 1.4 GHz, and therefore ancillary temperature data are needed for θ estimation. To address this, two methods to estimate T_{eff} from model simulated land surface temperature have been proposed: (1) by applying a phase-shift and amplitude reduction to a temperature dataset (Holmes, Jackson, Reichle, & Basara, 2012; Parinussa, Holmes, Yilmaz, & Crow, 2011b) and (2) as a function of the surface skin temperature (T_{surf}), deep soil temperature (T_{deep}) and θ (De Rosnay, Wigneron, Holmes, & Calvet, 2006; De Rosnay et al., 2006; Wigneron, Laguerre, & Kerr, 2001), which is in line with the SMOS L3 product. In this study, two objectives are addressed:

1. Establish the quality of LPRM θ retrievals from SMOS L-band observations over the Murrumbidgee catchment and compare this with SMOS L3 θ retrievals;
2. Understand the dependence of retrieval quality on incidence angles of 45° to 60° and on the time of overpass.

To test the parameterization of the LPRM and to evaluate its retrieval outputs ground-based data of the Murrumbidgee Soil Moisture Monitoring Network (OzNet) in southeast Australia was used, because of its dense ground observation network, the variety in land cover types and its applicability to remote sensing studies (Smith et al., 2012).

2. Data and preprocessing

2.1. SMOS

The SMOS satellite carries the Microwave Imaging Radiometer with Aperture Synthesis (MIRAS); a two-dimensional interferometric radiometer that measures the passive radiation emitted by the Earth's surface at the L-band frequency (1.4 GHz). The satellite is in a polar sun-synchronous orbit with a distance of around 758 km from the Earth. The measurements are made for incidence angles between 0° and 65° (Kerr et al., 2010), have an average ground resolution of 43 km and a swath width of 1000 km in the alias-free field of view (Camps, Vall-llossera, Corbella, Duffo, & Torres, 2008). One full measurement is made every 1.2 s, in X, Y or XY polarization in the instrument's reference frame, which differs from horizontal (H) and vertical (V) polarization at surface level. The satellite has a maximum revisit time of 3 days for a fixed point at the ground in case radiometric error is not considered for filtering, with a 6:00 a.m. (local time) ascending and 18:00 p.m. descending overpass (Kerr et al., 2012).

In this study brightness temperatures from the SMOS Level 1C Full-polarization (SCLF1C) data product version 505 for January 2010 until December 2011 were used. The level 1C land product contains multi-angular brightness temperatures at the top of the atmosphere, is geo-referenced and provided in the ISEA-4H9 grid format, with an average ground sampling interval of 15 km. The data is organized in files that contain half an orbit and are still in X/Y/XY polarization.

The measurements with incidence angles within ±0.4° of 45°, 52.5° and 60° were extracted from the data. These were selected to test the performance of LPRM for different incidence angles, with 52.5° being a value extensively tested for LPRM (Owe et al., 2008). The incidence angles are kept above 40° due to the higher sensitivity of H-polarized measurements to soil moisture while V-polarized measurements are strongly affected by T_{eff} at high incidence angles. The data were transformed from X/Y/XY to H/V/HV measurements by correcting for Faraday and geometric rotations following Le Vine, Jacob, Dinnat, de Matthaeis, and Abraham (2007a). This method theoretically needs measurements that are made at the same time and incidence angle, which is practically impossible since each SMOS observations cover a unique area only in one polarization. To solve this and minimize the introduced error, only a full set of measurements (X, Y and XY polarized) made within 3 s for the same grid point were selected, ensuring that the measurements were near coincident in time with a maximum difference in incidence angle of 0.7° for the transformations (Le Vine et al., 2007a).

The data in ISEA-4H9 grid format were resampled to a regular 0.25° grid using area-weighted averaging to allow comparison to field data