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Testing regression equations to derive long-term global soil moisture datasets from passive microwave observations

A. Al-Yaari [a,*], J.P. Wigneron [a], Y. Kerr [b], R. de Jeu [c,d], N. Rodriguez-Fernandez [b], R. van der Schalie [c,d], A. Al Bitar [b], A. Mialon [b], P. Richaume [b], A. Dolman [c], A. Ducharne [e]

[a] INRA, UMR1391 ISPA, Villenave d'Ornon, France
[b] CESBIO, CNES/CNRS/IRD/UPS, UMR 5126, Toulouse, France
[c] Faculty of Earth and Life Sciences, VU University Amsterdam (VUA), Amsterdam, Netherlands
[d] Transmissivity B.V., Space Technology Center, Noordwijk, Netherlands
[e] Sorbonne Universités, UMR 7619 METIS, UPMC/CNRS/EPHE, Paris, France

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ABSTRACT

Within the framework of the efforts of the European Space Agency (ESA) to develop the most consistent and complete record of surface soil moisture (SSM), this study investigated a statistical approach to retrieve a global and long-term SSM dataset from space-borne observations. More specifically, this study investigated the ability of physically based statistical regressions to retrieve SSM from two passive microwave remote sensing observations: the Advanced Microwave Scanning Radiometer (AMSR-E; 2003–Sept. 2011) and the Soil Moisture and Ocean Salinity (SMOS) satellite. Regression coefficients were calibrated using AMSR-E horizontal and vertical brightness temperature (TB) observations and SMOS level 3 SSM (SMOSL3; as a training dataset). This calibration process was carried out over the June 2010–Sept. 2011 period, over which both SMOS and AMSR-E observations coincide. Based on these calibrated coefficients, a global SSM product (referred here to as AMSR-reg) was computed from the AMSR-E TB observations during the 2003–2011 period. The regression quality was assessed by evaluating the AMSR-reg SSM product against the SMOSL3 SSM product over the period of calibration, in terms of correlation (R) and Root Mean Square Error (RMSE). A good agreement (mean global R = 0.60 and mean global RMSE = 0.057 m^3/m^3), was obtained between the AMSR-reg and SMOSL3 SSM products particularly over Australia, central USA, central Asia, and the Sahel. In a second step, the AMSR-reg SSM retrievals and commonly used AMSR-E SSM retrievals derived from the Land Parameter Retrieval Model (AMSR-LPRM), were evaluated against two kinds of SSM references (i) the global MERRA-Land SSM simulations and (ii) in situ measurements over 2003–2009. The results demonstrated that both AMSR-reg and AMSR-LPRM (better when considering global simulations) successfully captured the temporal dynamics of the references used having comparable correlation values. AMSR-reg was more consistent with MERRA-land than AMSR-LPRM in terms of unbiased RMSE (ubRMSE) with a global average of ubRMSE of 0.055 m^3/m^3 for AMSR-reg and 0.084 m^3/m^3 for AMSR-LPRM. In conclusion, the statistical regression, which is tested here for the first time using long-term spaceborne TB datasets, appears to be a promising approach for retrieving SSM from passive microwave remote sensing TB observations.

1. Introduction

Soil moisture (SM) is one of the key variables in the environment and the climate system as it influences the exchange of heat and water between the land surface and atmosphere (Fischer, Seneviratne, Vidale, Lüthi, & Schär, 2007; Taylor et al., 2011; Western et al., 2004). In 2010, SM was recognized as an Essential Climate Variable (ECV) (http://www.esa-soilmoisture-cci.org/) by the Global Observing Systems Information Center (GOSIC). A complete and consistent record of SM, as an ECV, is required for many environmental applications like flood prediction, drought monitoring and prediction, climate forecasts, etc.

Active and passive microwave sensors offer the opportunity to retrieve surface SM (SSM) from the measured surface backscatter and brightness temperature (TB) signals, respectively, which are mainly determined by the soil dielectric constant (Njoku et al., 2002; Ulaby, Dubois, & van Zyl, 1996). Both active and passive microwave sensors, particularly at low frequencies, have been shown to provide useful SSM datasets (Bartalis et al., 2007; Kerr et al., 2012; Njoku, Jackson, Lakshmi, Chan, & Nghiem, 2003) with global coverage and daily temporal resolution and hence, to be suitable for SSM monitoring at the global

* Corresponding author.
E-mail address: amen.alyaari@bordeaux.inra.fr (A. Al-Yaari).

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scale (de Jeu et al., 2008; Owe, de Jeu, & Holmes, 2008). The European Space Agency's Water Cycle Multi-mission Observation Strategy (WACMOS) was set up in 2010–2012 and supported by the Support To Science Element (STSE) program. Within WACMOS first long term SSM data records from passive and active microwave data have been developed. In January 2012, the Climate Change Initiative (CCI) soil moisture program, initiated by the European Space Agency (ESA), refined the process made during the first steps of the WACMOS project. In June 2012 the first long term datasets have been made publicly available through the ESA CCI portal (Su et al., 2010) and in July 2014 the second version was available also on the same portal. This CCI product was retrieved by merging different observations acquired by several microwave sensors in an attempt to produce the most complete and consistent long-term time series of SSM over 1978–2013. The used microwave sensors include (Liu et al., 2011): the Scanning Multichannel Microwave Radiometer (SMMR; 6.6, 10.7, 18.0, 21, and 37 GHz channels; Gloersen & Barath, 1977), the Special Sensor Microwave Imager (SSM/I; 19.4, 22.2, 37.0, and 85.0 GHz channels) of the Defense Meteorological Satellite Program, the Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E; from 6.9 to 89.0 GHz; Ashcroft & Wentz, 2000), and the Advanced Scatterometer (ASCAT; Figa-saldan et al., 2002). The long-term availability of the CCI product has attracted researchers to study the long-term trends of SSM (e.g., Albergel et al., 2013). Two dedicated SSM satellites, the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active/Passive (SMAP) satellites were launched recently and therefore not yet considered for the CCI product.

SMOS is an innovative mission in space technology that has been providing multi-angular microwave TB observations at L-band since 2010 (Kerr et al., 2012). The SMOS satellite, launched in November 2009, is the first-ever satellite specifically dedicated to monitoring SSM with an accuracy of 0.04 m^3/m^3 over continental surfaces (Kerr et al., 2010; Kerr et al., 2012). Several studies (e.g., Al-Yaari et al., 2014a; Al-Yaari et al., 2014b; Al Bitar et al., 2012; Albergel et al., 2012; Collow, Robock, Basara, & Illston, 2012; Dall'Amico, Schlenz, Loew, & Mauser, 2012; Wigneron et al., 2012) evaluated the SMOS SSM products and demonstrated that SMOS is skillful compared to other passive and active sensors in retrieving SSM at both global and local scales. The ESA established a passive microwave SSM fusion study to investigate the inclusion of the SMOS SSM product in a long-term SSM datasets. For this purpose, three approaches have been selected: the Land Parameter Retrieval Model (LPRM) algorithm (Owe, de Jeu, & Walker, 2001; Owe et al., 2008; van der Schalie et al., 2015), neural networks (Rodriguez-Fernandez et al., 2014; Rodríguez-Fernández et al., 2015), and statistical regressions (Wigneron et al., 2004).

The present study evaluates the statistical regression method, while the other methods are evaluated in separate studies (Rodríguez-Fernández et al., 2015; van der Schalie et al., 2015). The principle of using the regression method in this SSM fusion project is the following: as we used SMOS SSM data as a reference for the calibration of the regression method applied to the AMSR-E TB data, it is expected that the SSM product retrieved from AMSR-E is coherent with the SMOS SSM time series.

Wigneron et al. (2004) and Saleh, Wigneron, de Rosnay, Calvet, and Kerr (2006) have developed and evaluated semi-empirical regression equations between the SSM and microwave reflectivity (i.e. one minus emissivity) derived analytically from the radiative transfer model (tau–omega model; Mo, Choudhury, Schmugge, Wang, & Jackson, 1982; Wigneron, Chanzy, Calvet, & Bruguier, 1995). These regression methods, based on multiple configurations of dual-polarized and multiangular microwave TB observations, have been used in several studies based on in situ, airborne, or space-borne (SMOS) observations (Calvet et al., 2011; Mattar et al., 2012; Parrens et al., 2012). Several studies (Albergel et al., 2011; Calvet et al., 2011; Parrens et al., 2012; Saleh et al., 2006) demonstrated that the regression equations are efficient for retrieving SSM. For instance these methods have been applied successfully to SMOS data over some sites in France by Albergel et al. (2011), and over the whole French country by Parrens et al. (2012). To date, to our knowledge, no study has been performed to assess the potential of the regression methods to retrieve SSM from AMSR-E TBs at the global scale. The main objectives of this study are to:

(i) test a physically based multiple-linear regression method to retrieve SSM from the AMSR-E TB observations at the global scale
(ii) develop and extend into the past (2003–2009) a SSM product based on AMSR-E (henceforth referred to as AMSR-reg) that is consistent with SMOS SSM (2010–2015)
(iii) compare the quality of this product with that of AMSR-LPRM, with reference to modeled SSM datasets and in situ measurements at both global and local scales.

The following section describes the datasets, the regression method, and the metrics used for the evaluation. Section 3 presents the results. Finally, Section 4 provides discussion and conclusions.

2. Materials and methods

2.1. Datasets

2.1.1. SMOS level 3 SM products

The SMOS satellite provides global SSM datasets with a 3-day revisit at the equator with ascending and descending orbits at 0600 and 1800 h local time, respectively, and a spatial resolution of 35–50 km (Kerr et al., 2010).

CATDS (Centre Aval de Traitement des Données) recently provided daily re-processed global gridded SSM products, projected on a global (Equal Area Scalable Earth) EASE grid 25 km, namely the SMOS level 3 (SMOSL3, R02_Version 2.72) product. SMOSL3 has an enhanced accuracy in the SSM data by using several revisits simultaneously and multi-orbit retrievals (Jacquette et al., 2010; Kerr et al., 2013). SMOSL3 retrievals at dawn, corresponding to SMOS ascending overpass-time at 0600 h local time, were selected in this study for a better consistency with the AMSR-E night-time data (Al-Yaari et al., 2014b).

The SMOSL3 SSM product is provided as the volumetric soil water content (m^3/m^3) of the ~0–5 cm top soil layer. It is available since 16 January 2010 and can be freely obtained from the CATDS website (http://catds.fr). The SMOS SSM product is generally impacted by Radio Frequency Interferences (RFI) (Oliva et al., 2012), which originate from man-made emissions. Therefore, it has to be filtered before any use. SMOSL3 SSM values were excluded when the RFI probability is higher than 10% and when the Data Quality index (DQX) is higher than 0.06 m^3/m^3. DQX is an indicator of SMOS SSM retrievals uncertainty, given in the same unit as SSM (ranging from 0 to 0.1 m^3/m^3). The higher the DQX value, the more uncertain the SSM retrievals. We used 0.06 m^3/m^3 as a threshold to ensure that there are no outliers but also to keep as much SSM data as possible for the calibration. More information about the SMOSL3 algorithm can be found in the Algorithm Theoretical Based Document (Kerr et al., 2013).

2.1.2. AMSR-E datasets

The passive microwave AMSR-E sensor, onboard the EOS/Aqua satellite, measures dual-polarized TB at C-band (6.925 GHz), X-band (10.7 GHz), Ku-band (18.7 GHz), K-band (23.8 GHz), Ka-band (36.5 GHz), and W-band (89.0 GHz) vertically and horizontally with a spatial resolution of ~56 km. In this study, the AMSR-E L2A global daily gridded TBs (version 3) product, which has been recently released (Ashcroft & Wentz, 2013), was used. The product was provided and re-gridded to the global EASE grid at a spatial resolution of 25 km by the VU University Amsterdam (VUA).

In the present study, AMSR-E TB observations at C-band (night-time) were used to calibrate the regression equations over 2010–2011