Remote Sensing of Environment 205 (2018) 85–99

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Assessment of the impact of spatial heterogeneity on microwave satellite soil moisture periodic error

Fangni Lei[a,b,*], Wade T. Crow[a], Huanfeng Shen[b], Chun-Hsu Su[c], Thomas R.H. Holmes[d], Robert M. Parinussa[e], Guojie Wang[f]

[a] USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA
[b] School of Resource and Environmental Sciences, Wuhan University, Wuhan, Hubei 430072, China
[c] Department of Infrastructure Engineering, University of Melbourne, Parkville, Victoria 3010, Australia
[d] NASA GSFC Hydrological Sciences Laboratory, Greenbelt, MD 20771, USA
[e] Transmissivity B.V./VanderSat B.V., Space Technology Business Park, Huygenstraat 34, Noordwijk 2201, DK, The Netherlands
[f] School of Geography and Remote Sensing, Nanjing University of Information Science and Technology, Nanjing, Jiangsu 210044, China

ARTICLE INFO

Keywords:
Microwave remote sensing
Satellite-derived soil moisture
Spectral analysis
Periodicity
Spatial heterogeneity

ABSTRACT

An accurate temporal and spatial characterization of errors is required for the efficient processing, evaluation, and assimilation of remotely-sensed surface soil moisture retrievals. However, empirical evidence exists that passive microwave soil moisture retrievals are prone to periodic artifacts which may complicate their application in data assimilation systems (which commonly treat observational errors as being temporally white). In this paper, the link between such temporally-periodic errors and spatial land surface heterogeneity is examined. Both the synthetic experiment and site-specified cases reveal that, when combined with strong spatial heterogeneity, temporal periodicity in satellite sampling patterns (associated with exact repeat intervals of the polar-orbiting satellites) can lead to spurious high frequency spectral peaks in soil moisture retrievals. In addition, the global distribution of the most prominent and consistent 8-day spectral peak in the Advanced Microwave Scanning Radiometer – Earth Observing System soil moisture retrievals is revealed via a peak detection method. Three spatial heterogeneity indicators – based on microwave brightness temperature, land cover types, and long-term averaged vegetation index – are proposed to characterize the degree to which the variability of land surface is capable of inducing periodic error into satellite-based soil moisture retrievals. Regions demonstrating 8-day periodic errors are generally consistent with those exhibiting relatively higher heterogeneity indicators. This implies a causal relationship between spatial land surface heterogeneity and temporal periodic error in remotely-sensed surface soil moisture retrievals.

1. Introduction

Within the past two decades, extensive efforts have been aimed at enhancing remote estimation of surface soil moisture. Currently, several global space-borne soil moisture products are available from a series of satellite-based passive and/or active microwave sensors. The accurate characterization of global satellite-derived soil moisture products is crucial for multiple hydrological (Srivastava et al., 2013; Wagner et al., 2007a), meteorological (Koster et al., 2004; Seneviratne et al., 2010), agricultural (Bolten et al., 2010; Engman, 1991; Lakhankar et al., 2009a), and natural hazardous (Lacava et al., 2005) applications. Especially in hydrological data assimilation community, the inclusion of satellite-based soil moisture observations has drawn great attention for the purposes of catchment rainfall-runoff (Alvarez-Garreton et al., 2014; Crow et al., 2009; Komma et al., 2008) and both continental (Crow and Zhan, 2007; Walker and Houser, 2004) and global-scale (Reichle and Koster, 2005; Reichle et al., 2004, 2007) land surface modeling.

Recently, Su et al. (2013a, 2015) presented a spectrally-based approach for evaluating satellite-derived soil moisture retrievals which builds upon a semi-empirical water balance model and operates in the frequency domain. Based on this approach, they identified periodic error components in passive microwave retrieved soil moisture Level 3 (gridded) retrieval products acquired from both the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) and the Soil Moisture and Ocean Salinity (SMOS) missions, suggesting the need to consider the presence of temporally-periodic errors when using and/or evaluating such products. Most land data assimilation approaches

---

* Corresponding author at: USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA.
E-mail address: leifangni@whu.edu.cn (F. Lei).

https://doi.org/10.1016/j.rse.2017.11.002
Received 6 July 2017; Received in revised form 28 September 2017; Accepted 1 November 2017

are based on an assumption of temporally-white and Gaussian-distributed errors forms (Burgers et al., 1998). Therefore, a thorough examination of soil moisture retrieval error structure is crucial for not only properly describing their error characteristics but also their potential implementation within a land data assimilation system (Crow and Van den Berg, 2010).

Gridded satellite-based soil moisture retrievals are based on the sampling of adjacent footprints within the same orbital overpass. Three commonly used interpolation algorithms are: drop-in-bucket, nearest neighbor, and inverse-distance-squared methods (Chan et al., 2012). The choice of interpolation algorithm affects the effective antenna pattern of the spatial support associated with a particular grid box. For the Soil Moisture Active Passive (SMAP) mission, the averaged half-power beam-width field-of-view (FOV) size of the inverse-distance-squared approach is about 40 km. In addition, radiation outside the half-power beam-width can contribute to the signal – suggesting that the gridded signal may include significant radiance contributions from emitters outside the grid (Jackson et al., 2010). For polar-orbiting satellites with an exact repeat cycle there are periodic variations in the spatial support of individual grids (due to day-to-day variations in the exact footprint-averages underlying each grid cell). Over highly heterogeneous regions, the impact of this periodic sampling may become more pronounced and periodic errors may arise which are related to the periodicity of the sampling pattern.

Additionally, passive microwave observations are potentially contaminated by man-made radio frequency interference (RFI). RFI can obscure (relatively weaker) geophysical emission associated with land source variables like soil moisture (Daganzo-Eusebio et al., 2013; Njoku et al., 2005). In addition to the spatial heterogeneity in natural land surface signals, RFI sources observed over land areas are typically fixed in space (Njoku et al., 2005) which may lead to periodic errors in satellite-based retrievals as these sources are re-sampled periodically. From this point of view, a satellite-derived soil moisture product with consideration of the contributing factor of RFI should be analyzed to expose the origins of periodic errors.

In practice, a simple ad hoc low pass filter (i.e., a 5-day moving average) adopted by Wagner et al. (2007b) and Draper et al. (2009) has been shown to slightly improve the quality of satellite-based soil moisture retrievals. Nonetheless, this empirical method is arbitrary and only effective for dampening very short-term fluctuations (i.e., 2-day periodic errors). Recent experimental studies have shown that analyzing the soil moisture time series in the frequency domain can provide supplementary insights with regard to its conjugate time domain (Katul et al., 2007). For example, Du (2012) used the high-pass Fourier filter to keep small temporal scale soil moisture signals in the directly observed emissivity time series, while filtering out the mixture signals of vegetation phenology in the low frequency component (Moody and Johnson, 2001; Scharlemann et al., 2008) and long-term soil moisture trends. However, such a method requires not only the accurate extraction of high-frequency soil moisture signals from sensor direct observations, but also the availability of an accurate long-term climatology from land surface models or existing satellite-based soil moisture product. On the other hand, Su et al. (2013a) applied a band-stop filter to remove the identifiable stochastic and systematic errors in high-frequency regime and then a low-pass Wiener filter for preserving the long-term temporal mean and variance. This approach is more physically realistic and based on the rationale that small time scale soil moisture dynamics can be simplified into incoming precipitation and water loss process with brown-like spectrum (Katul et al., 2007; Su et al., 2013a).

However, the application of any filter comes at the risk of information loss. For example, when blindly applying the band-stop filter, high-frequency signal components related to rapid soil moisture changes following intense rainfall events can also be attenuated. Therefore, the accurate a priori identification of land surface conditions associated with spurious high frequency resonances is beneficial for efficient and flexible application of the band-stop filter.

To examine the plausible reasons behind the existence of high-frequency peaks and improve our understanding of errors in the satellite-derived soil moisture time series, this study will focus primarily on the most prominent and consistent periodicity (8-day) existing in an AMSR-E soil moisture retrieval product. The spatial distribution of such a periodic error will be inter-compared to measures of land surface spatial heterogeneity. Section 2 presents the satellite-derived soil moisture product from the passive microwave AMSR-E sensor via the Land Parameter Retrieval Model (LPRM) retrieval algorithm, the spectral analysis of soil moisture, and our peak detection method. Three straightforward heterogeneity indicators, based on: microwave brightness temperature, land cover types, and long-term averaged Normalized Difference Vegetation Index (NDVI), are then proposed for characterizing spatial variability along the land surface. Section 3 evaluates the spectral characteristics of soil moisture retrievals and explains their relationship with these heterogeneity indicators. Further discussion of concerns and potential implications is provided in Section 4, and final conclusions are presented in Section 5.

2. Materials and methods

A long-term soil moisture product is necessary in order to robustly investigate periodic errors in satellite-derived soil moisture time series. Among various microwave sensors and missions, the AMSR-E sensor onboard the National Aeronautics and Space Administration (NASA) Aqua provides the longest currently-available source of soil moisture data (i.e., from June 2002 to October 2011) from a single sensor and is therefore the primary focus of this study.

2.1. AMSR-E soil moisture product and LPRM retrieval model

2.1.1. AMSR-E basic information

The AMSR-E sensor was a six-frequency dual-polarized passive microwave radiometer, onboard the NASA Aqua satellite with a 16-day exact repeat cycle. With a sun-synchronous orbit at an altitude of 705 km, AMSR-E scans the Earth's surface at 1:30 a.m. (descending)/ 1:30 p.m. (ascending) local equator overpass time and an incidence angle of 55°. AMSR-E provided a nearly nine-and-a-half-years long-term measurement time series from June 2002 to October 2011. Among its six microwave frequency bands, the spatial resolutions of footprint measurements at 6.9 GHz (C-band), 10.7 GHz (X-band), and 36.5 GHz (Ka-band) were 74 × 43 km, 51 × 30 km, and 14 × 8 km, respectively (Njoku et al., 2003).

Several soil moisture retrieval algorithms have been developed for AMSR-E brightness temperature (T_B) data. Here, surface soil moisture (~2 cm) and vegetation optical depth are retrieved simultaneously from C-band T_B via the LPRM (see below for further details). In areas with significant RFI such as the contiguous United States (CONUS), Japan, and India, LPRM switches to X-band. Fig. 1a and b shows the distribution maps of bands that have been utilized for soil moisture retrieval. Regardless of the band used, AMSR-E ascending and descending half-orbits are separately re-sampled from their original footprint resolution to a regular quarter degree grid and then processed through LPRM to retrieve soil moisture (see below).

2.1.2. Land parameter retrieval model

LPRM uses a forward modeling optimization procedure to solve a radiative transfer equation without the need for parameter calibration and other biophysical measurements. The physically-based LPRM (De Jeu and Owe, 2003; Meesters et al., 2005; Owe et al., 2001) has been successfully applied to retrieve surface soil moisture from space-borne passive microwave observations including AMSR-E (Owe et al., 2008) and SMOS (De Jeu et al., 2009; Van der Schalie et al., 2015; Van der Schalie et al., 2016). Moreover, the AMSR-E LPRM product has been well-validated with in situ campaigns (Brocca et al., 2011; De Jeu et al.,