Journal of Hydrology 557 (2018) 740–752

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Exploiting the synergy between SMAP and SMOS to improve brightness temperature simulations and soil moisture retrievals in arid regions

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A R T I C L E I N F O

Article history:
Received 13 July 2017
Received in revised form 5 December 2017
Accepted 19 December 2017
Available online 26 December 2017
This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief, with the assistance of Viviana Maggioni, Associate Editor

Keywords:
SMAP
SMOS
Synergy
Vegetation optical depth
τ-ω
L-MEB

A B S T R A C T

The objective of this study was to exploit the synergy between SMOS and SMAP based on vegetation optical depth (VOD) to improve brightness temperature (TB) simulations and land surface soil moisture (SM) retrievals in arid regions of the world. In the current operational algorithm of SMAP (level 2), vegetation water content (VWC) is considered as a proxy to compute VOD which is calculated by an empirical conversion function of NDVI. Avoiding the empirical estimation of VOD, the SMOS algorithm is used to retrieve simultaneously SM and VOD from TB observations. The present study attempted to improve SMAP TB simulations and SM retrievals by benefiting from the advantages of the SMOS (L-MEB) algorithm. This was achieved by using a synergy method based on replacing the default value of SMAP VOD with the retrieved value of VOD from the SMOS multi angular and bi-polarization observations of TB. The insitu SM measurements, used as reference SM in this study, were obtained from the International Soil Moisture Network (ISMN) over 180 stations located in arid regions of the world. Furthermore, four stations were randomly selected to analyze the temporal variations in VOD and SM. Results of the synergy method showed that the accuracy of the TB simulations and SM retrievals was respectively improved at 144 and 124 stations (out of a total of 180 stations) in terms of coefficient of determination (R^2) and unbiased root mean squared error (UbRMSE). Analyzing the temporal variations in VOD showed that the SMOS VOD, conversely to the SMAP VOD, can better illustrate the presence of herbaceous plants and may be a better indicator of the seasonal changes in the vegetation density and biomass over the year.

1. Introduction

The surface soil moisture (SM) governs the partitioning of the energy fluxes between the land and the atmosphere (Brocca et al., 2017), thus is of great importance in the hydrological cycle (Brocca et al., 2007; Corradini, 2014; Wagner et al., 2007). SM is an important variable for many applications such as flood modeling (Brocca et al., 2010), landslide prediction (Brocca et al., 2012), drought assessment (Rahmani et al., 2016), agriculture (Korres et al., 2013; Rodríguez-Iturbe and Porporato, 2007), hydrology (Vereecken et al., 2014), land-atmosphere interaction and climate studies (Entekhabi et al., 1996). It plays a critical role in many hydrological processes such as precipitation, runoff, infiltration, and evaporation (Puri et al., 2011).

L-band passive microwave has received much attention over the last two decades to monitor SM from space due to its advantages, such as transparent atmosphere, transmission of signals from the underlying soil, semi-transparent vegetation, strong dependency on the soil dielectric properties which are a function of SM, and being independent of solar illumination in comparison with other remote sensing techniques (Hong and Shin, 2011; Jackson, 1993; Njoku and Entekhabi, 1996; Schmugge, 1998). The NASA Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010) and the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2012) are two recent L-band satellites that measure SM in the top layer of soil.

The L-band passive observations are sensitive to soil moisture and to vegetation optical depth (VOD), a parameter used to estimate the extinction effect of the microwave radiations within the canopy (Wigneron et al., 2017). Therefore, estimating VOD is of

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https://doi.org/10.1016/j.jhydrol.2017.12.051
0022-1694/

great importance in order to accurately retrieve soil moisture (Konings et al., 2016).

Several approaches exist for the estimation of VOD as a necessary input into the L-band algorithms for SM retrievals. The approach used in the SMAP level 2 algorithm is based upon the work described by (Hunt et al., 1996). In this approach, VOD is considered to be proportional to the total vegetation water content (VWC) and stem factor. VWC, as the total water weight in vegetation per unit area expressed in units of kg/m^2, is not a routinely measured quantity and indirect measurement methods have been used for its large-scale mapping. The most common method is to use normalized difference vegetation index (NDVI) as a proxy of VWC. In this method, VWC is considered as the sum of foliage water content which is estimated using NDVI, and stem water content which is estimated using past field observations and leaf area index (LAI) (Chan et al., 2013; Hunt et al., 1996). However, this method is not without challenges and there are several well-known limitations of NDVI to estimate VWC. The stem factor is an input parameter into the conversion function of NDVI into VWC. This parameter is estimated empirically and relies on field observations over specific regions. As a result, there may be large uncertainty associated with extending the calculations globally. Also, NDVI is reported to be prone to saturation effects due to the strong absorption in the red wavelength (Sellers, 1985), as a result, its sensitivity to VWC is decreased as the water content reaches a threshold (Jackson et al., 1999) especially over dense vegetation coverage and high LAI (Chen and Brutsaert, 1998; Gamon et al., 1995). Furthermore, NDVI represents chlorophyll rather than water content (Gamon et al., 1995; Gao, 1996) because it is calculated by using the red and near-infrared bands which is based on the strong absorption and high reflectance of vegetation canopies respectively. Moreover, there are also issues associated with the land cover. The International Geosphere-Biosphere Program (IGBP) global land cover is used by the SMAP algorithm to derive the stem factor which is required to compute VWC. The global land cover maps are always subject to some level of uncertainty and inconsistency due to using different remote sensing sensors and a variety of employed methods for creating the maps (Congalton et al., 2014). In addition, a land-cover dependent method for deriving VWC is sensitive to errors in the land cover classifications, as well as to variations in albedo within a certain land cover type (Konings et al., 2016). Finally, although VOD is dependent on VWC, vegetation structure, incidence angle, frequency and polarization (Wigneron et al., 2007), the baseline approach of the SMAP does not take into account the effect of polarization on VOD.

An alternative approach exists and consists in simultaneous retrievals of VOD and SM by using information from observations at both horizontal (H) and vertical (V) polarizations (Jackson et al., 2002; Meesters et al., 2005). However, this retrieval approach is sensitive to noise due to the high correlation of the observations made at the two H and V polarizations (Konings et al., 2016). If multi-angular data are available, such as in the case of SMOS, this type of noise can be reduced (Wigneron et al., 1998). The SMOS algorithm uses the inversion of the L-band Microwave Emission of the Biosphere (L-MEB) model to retrieve simultaneously SM and VOD from multi angular and bi-polarization of TB observations (Wigneron et al., 2007). Direct VOD retrievals from inversion of the L-MEB model are interesting, because this approach avoids the empirical estimation of VOD which is made in the SMAP algorithm and takes into account the effects of some important factors such as polarization, standing vegetation, litter and rainfall (Wigneron et al., 2007). Also, this model is independent of land cover and therefore does not suffer from the limitations related to the land cover as mentioned earlier. Furthermore, the accuracy and robustness of the L-MEB model has been proved theoretically (Wigneron et al., 2000), and has been validated over many sites with a variety of soil and vegetation conditions against in situ measurements (Cano et al., 2010; Panciera et al., 2009; Pardé et al., 2004; Wigneron et al., 1995; Wigneron et al., 2007).

The present paper aims to exploit a possible synergy approach between the SMOS and SMAP algorithms with the emphasis on VOD, and to find whether the SMAP algorithm (level 2) can benefit from the SMOS VOD product in order to improve the accuracy of TB simulations and SM retrievals in arid regions of the globe. The paper is organized as follows. Section 2 describes the study area, used data sets, algorithms and methodology of this paper. Obtained results are shown and discussed in Section 3 and concluded in Section 4.

2. Materials and methods

2.1. Study area

Arid regions of the world were selected as the study area in an attempt to address an additional crucial limitation to estimate NDVI in these regions. The NDVI is very sensitive to the soil background reflectance in sparse vegetated areas (Elvidge and Lyon, 1985; Huete et al., 1985) and the error in estimating NDVI is increased in these regions because of the strong effect of the reflectance from the background soil (Ishiyama et al., 1997). In regions where there are considerable soil brightness variations, the soil effect on the vegetation index values is considerable (Huete, 1988).

In this study, the arid regions were selected as the study area according to the updated world climate map of Koppen-Geiger climate classification (Kottek et al., 2006). Four selected climate classes for this study are: i) arid-desert-hot (BWh) ii) arid-desert-cold (BWk) iii) arid-steppe-hot (BSh) and iv) arid-steppe-cold (BSk) (Fig. 1).

2.2. Data sets

2.2.1. SMOS level 3 products

Multi-angular and dual-polarization TB observations are acquired by the SMOS satellite (launched in November 2009) to retrieve SM and VOD simultaneously. The SMOS satellite orbits the earth at a local overpass time of 06:00 AM/PM for ascending/descending passes with temporal resolution of 3 days. The SMOS mission aims to monitor SM at a depth of about 3–5 cm and an accuracy of 0.04 cm^3/cm^3 (Kerr et al., 2012). The global SMOS level 3 daily products (SMOS-L3) are provided by the Centre Aval de Traitement des Données (CATDS) in the NetCDF format projected on a global EASE (Equal Area Scalable Earth) grid (Version 2) 25 km. In this study, we used the SM products, retrieved VOD (τ_nadir), radio frequency interferences (RFI) and data quality index (DQX) flags which are associated with this level of SMOS products. The SMOS TB observations were not used in this study.

2.2.2. SMAP level 3 radiometer products

The NASA SMAP satellite (launched in January 2015) is the most recent satellite for SM monitoring. The passive sensor of SMAP is dedicated to estimate SM in the top 0–5 cm layer with an average ubRMSE of no more than 0.04 cm^3/cm^3 over areas where VWC $\leq$5 kg/m^2 at the footprint measurement scale of 36 km (Entekhabi et al., 2010). In this study, the passive global level 3 daily products of SMAP (SMAP-L3) were obtained from NASA Reverb metadata and service discovery tool in the NetCDF format. All required input parameters for SM retrievals including: VOD, single scattering albedo (ω), VWC, land cover, roughness parameters, surface temperature, freeze-thaw fraction, vertical and horizontal polarization of TB observations, were obtained from the ancillary information