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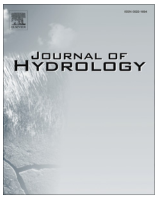

A spatially coherent global soil moisture product with improved temporal resolution

Richard A.M. de Jeu [a,*], Thomas R.H. Holmes [b], Robert M. Parinussa [a], Manfred Owe [c]

[a] *VU University Amsterdam, Department of Earth Sciences, Earth and Climate Cluster, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*
[b] *USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA*
[c] *NASA Goddard Space Flight Center, Greenbelt, MD 20770, USA*

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SUMMARY

Global soil moisture products that are completely independent of any type of ancillary data and solely rely on satellite observations are presented. Additionally, we further develop an existing downscaling technique that enhances the spatial resolution of such products to approximately 11 km. These products are based on internal modules of the Land Parameter Retrieval Model (LPRM), an algorithm that uses the radiative transfer equation to link soil moisture, vegetation optical depth and land surface temperature to observed brightness temperatures.

The soil moisture product that is independent of any type of ancillary data uses the internally calculated dielectric constant as a soil moisture proxy. This data product is not influenced by errors associated with coarse-scale global soil property maps or by any other type of forcing (e.g. re-analysis) data and is therefore solely based on satellite microwave observations. The second step builds upon recent developments to increase the spatial resolution of the LPRM retrievals using a smoothing filter downscaling method. With this method we can attain a spatial resolution that can be more useful at the scale of local and regional hydrological studies as well. The steps presented in this paper were applied to observations from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E). The newly derived data sets were validated using ground-based observations from the International Soil Moisture Network (ISMN).

The internally calculated dielectric constant product results in significantly more days with valid retrievals than the original soil moisture data products, in particular over arid regions. The dielectric constant product resulted in similar correlations with in situ data as the original soil moisture data product. Together, these findings demonstrate the usefulness of this new dielectric constant product for the hydrological modeling community and climate studies. A case study on the Australian Fitzroy catchment demonstrated that the downscaled data product has a more detailed spatial description of soil moisture, especially during wet and dry conditions with more pronounced dry and wet regions within the catchment. The increased resolution data products could therefore improve runoff predictions and this study demonstrated the potential added value of a transitioning from a spatial resolution of 56 km toward a higher resolution of 11 km. The hydrological implications of these newly developed data records are not only linked to AMSR-E satellite data, but also to the next generation Soil Moisture Active and Passive (SMAP) mission where a 9 km spatial resolution is the target resolution for satellite soil moisture products. The new data products will not replace the current LPRM products, but will be added to the existing array of data products and will become publicly available through our data portals.

1. Introduction

The Land Parameter Retrieval Model (LPRM) was developed jointly by researchers from the VU University Amsterdam and the NASA Goddard Space Flight Center over a 10-year period beginning in the mid 1990s (Owe et al., 1999, 2001; de Jeu and Owe, 2003). This retrieval algorithm uses a radiative transfer model (Mo et al., 1982) to convert low frequency brightness temperatures from the satellite microwave radiometers to soil moisture (Owe et al., 2001, 2008). A unique aspect of LPRM is the simultaneous retrieval of vegetation density in combination with soil moisture

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* Corresponding author. Tel.: +31 20 5987287.
E-mail address: r.a.m.de.jeu@vu.nl (R.A.M. de Jeu).

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and surface temperature. A result of this physical parameterization is that any differences in frequency and incidence angle that exist among different satellite platforms are accounted for within the framework of the radiative transfer model based on global constant parameters. LPRM does not require ancillary time varying parameters to characterize the surface biophysical state. LPRM can therefore be adapted to work with any low frequency passive microwave dataset currently available. However the quality of soil moisture retrievals is strongly related to microwave frequency (e.g. Dorigo et al., 2010; Parinussa et al., 2011b). The L-band (i.e. 1.4 GHz) frequency is often considered to be the most ideal frequency for soil moisture retrieval (Schmugge, 1983; Kerr et al., 2001) which is the main reason for the dedicated soil moisture missions, like the European Space Agency (ESA) Soil Moisture Ocean Salinity Mission (SMOS) and the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive Mission (SMAP), to carry a L-band Radiometer.

The first global scale soil moisture products retrieved from a series of satellite sensors using the Land Parameter Retrieval Model (LPRM) became publicly available for the research community in 2008. These data products describe surface soil moisture of the first centimeters and were distributed at both the original satellite swath level and on a 0.25-degree spatial resolution global grid. They were derived from passive microwave observations at low frequencies from the Advanced Microwave Scanning Radiometer (AMSR-E), the Tropical Rainfall Measurement Mission Microwave Imager (TRMM-TMI), the Special Sensor Microwave Imager (SSM/I), and the Scanning Multichannel Microwave Radiometer (SMMR) onboard the Nimbus 7 platform.

The first data distributer of the LPRM products was the Atmospheric Data Access for the Geospatial User Community (ADAGUC) portal (http://adaguc.knmi.nl) followed by numerous other portals such as NASA's Reverb portal (http://reverb.echo.nasa.gov) and through the ESA Climate Change Initiative program (http://www.esa-soilmoisture-cci.org/). Recently, the collection of satellites included in the LPRM dataset was expanded with soil moisture observations from the WindSat sensor onboard the Coriolis satellite (Parinussa et al., 2012). Together these soil moisture data products span a time record of 35 years, from October 1978 to the present. Currently, new LPRM retrievals from the Chinese satellite FengYun 3b and AMSR-2 are being developed. This considerably long observation period makes the LPRM database increasingly attractive for climate, hydrological and meteorological studies (e.g. De Jeu et al., 2012; Miralles et al., 2014). The number of operational satellite missions with (multi-frequency) microwave radiometers has increased steadily over the last two decades resulting in an improved temporal sampling of the LPRM-derived soil moisture, especially in the most recent decade with often more than 4 observations a day. This increased temporal sampling, roughly since 2003, allows for more detailed hydrological and meteorological modeling than would be possibly with any single satellite source (Parinussa et al., 2012).

Over the years, LPRM soil moisture products have been validated extensively with models (e.g. Reichle et al., 2007; Rüdiger et al., 2009; Rebel et al., 2012), in situ data (e.g. Owe et al., 2001, 2008; De Jeu and Owe 2003; Draper et al., 2009; Gruhier et al., 2010) and other satellite products (e.g. Scipal et al., 2008; De Jeu et al., 2008; Brocca et al., 2011). These studies indicate a high skill of the LPRM in capturing the temporal variability in observed soil moisture, if not absolute accuracy. In the calibration of a physical based retrieval model there often is a tradeoff between temporal skill, or precision, and absolute accuracy. In the development of the LPRM the priority has always been on temporal skill because that is often the most important consideration in applied studies (e.g. Liu et al., 2011a; Bolten and Crow, 2012)

Complementary studies (e.g. Crow et al., 2010; Dorigo et al., 2010; Parinussa et al., 2011a; Draper et al., 2013) confirmed theoretically predicted increases of uncertainties in LPRM soil moisture products as a function of observation frequency and level of vegetation attenuation. These studies revealed that the LPRM data products give the highest performance over sparse to moderate vegetated regions (i.e. regions with average Leaf Area Index values between 1 and 2) but that it loses its skill when transitioning to denser vegetated regions. Over these more vegetated regions other satellite soil moisture products (e.g. the Advanced Scatterometer (ASCAT) soil moisture data product as developed by TU Wien (Bartalis et al., 2007)) and modeled soil moisture products (e.g. the Global Land Data Assimilation System soil moisture products from the land surface model Noah) outperform the LPRM data products.

The combination of public and timely access to the LPRM data products, an extensive body of independent validation studies, clear documentation of the methods, and the uniquely long and consistent data record have made the LPRM data sets one of the most intensively used soil moisture products currently available. Examples of studies in which LPRM soil moisture products showed a significant added value are listed in Table 1, as divided in four main disciplines. In hydrological research the most significant contribution of satellite soil moisture products can be found in improved spatial estimation of several components of the water balance, for example evaporation (e.g. Miralles et al., 2011), rainfall (e.g. Chen et al., 2012) and runoff (e.g. Beck et al., 2009). In fact, this finding was not limited to the LPRM soil moisture products but was also found for other soil moisture datasets like the ASCAT dataset by TU Wien (Bartalis et al., 2007) and recently developed products of ESA's SMOS Mission (Kerr et al., 2012). For example, Brocca et al. (2010) demonstrated a significant improvement in river discharge in Italian catchments when ASCAT soil moisture was included in the modeling scheme and Srivastava et al., 2013 showed the potential of SMOS data to determine soil moisture deficits in a catchment in the UK.

For climate research and weather prediction studies, the availability of satellite soil moisture played an important role to enhance our understanding of land atmosphere processes at different temporal scales (see Table 1). These studies used the relative temporal changes of LPRM soil moisture rather than the absolute soil moisture values. For example, when LPRM soil moisture was used in a data assimilation scheme, the original LPRM soil moisture was first converted to the modeling range using cumulative distribution functions (CDF) before it was used in a land surface model (Liu et al., 2011a; Reichle et al., 2007). In these studies the temporal dynamics of satellite soil moisture is the essential component and the absolute values are considered to be less important.

The LPRM is based on a forward model that estimates the dielectric constant of the water and soil mixture that needs additional soil information such as porosity and wilting point (e.g. Wang and Schmugge, 1980). The dielectric constant is an electric property of matter and is a measure of the response of a medium to an applied electric field (Ulaby et al., 1986). The dielectric constant is a complex number, containing a real and imaginary part ($\varepsilon = \varepsilon' + \varepsilon''\, i$). To simplify the mathematics the complex dielectric constant is often represented by its absolute value, that is $k = |\varepsilon|$ (De Jeu, 2003). Because of the dipolar property of water molecules there is a strong linear relationship between the dielectric constant and soil moisture. However, laboratory experiments have shown that this increase is not constant over the entire moisture range. This is because part of the water is tightly bound to the soil particles and cannot freely respond to an electrical field (Wang and Schmugge, 1980). Soils with smaller particles such as irregular fine sands, silts and clays have a higher surface area-to-volume ratio