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SMOS soil moisture product evaluation over West-Africa from local to regional scale

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ABSTRACT

This paper assessed the SMOS soil moisture values from Level 3 (SMOS L3SM) product provided by the French CNES-CATDS. The evaluation was conducted at the local scale through comparison with ground-based soil moisture measurements acquired in Mali, Niger and Benin from 2010 to 2012. The SMOS L3SM product was compared to three other satellite-based soil moisture products. It was found that, in average over the three sites, the SMOS L3SM product provided the best coefficients of correlation and the lowest root mean square errors (RMSE). The second part of the paper is devoted to retrieve soil moisture estimates between successive SMOS soil moisture measurements in order to increase the temporal resolution. The result of the methodology allows obtaining 3-hour soil moisture mapping over West Africa with a coefficient of correlation greater than 0.82, and an RMSE lower than 0.030 $m^3 m^{-3}$ in Niger and Mali and lower than 0.044 $m^3 m^{-3}$ in Benin.

1. Introduction

Soil moisture is known to potentially influence atmospheric conditions through its impact on evaporation and other surface energy fluxes (Eltahir, 1998; Fischer, Seneviratne, Vidale, Luthi, & Schar, 2007; Taylor et al., 2011). Land-atmosphere feedbacks were found to be particularly strong in the central Great Plains of North America, the Sahel, equatorial Africa, and India (Koster et al., 2004). The reason is relatively simple: regions with strong land-atmosphere feedbacks require a sufficiently abundant evaporation to act on rainfall but low enough to be controlled by soil moisture, which excludes humid climates as well as too dry climates. Best candidates are regions of transition between wet and dry climates such as the Sahel region. Recent studies investigated the land-atmosphere feedbacks in West Africa (Adler, Kalthoff, & Gantner, 2011; Klupfel, Kalthoff, Gantner, & Kottmeier, 2011) but the complex relationship between soil moisture and atmospheric conditions, and particularly the precipitation, is still to investigate and is probably one reason that explains the current uncertainty of atmospheric general circulation models from IPCC (The Intergovernmental Panel on Climate Change) to predict the evolution of the precipitation regime in West Africa by the end of the century.

In this context, satellite-based soil moisture products are of great interest for providing regularly regional soil moisture maps at the global scale. In November 2009, ESA (European Space Agency) launched the first satellite specifically dedicated to measuring surface soil moisture and ocean salinity. The SMOS (Soil Moisture and Ocean Salinity) mission is a passive interferometric radiometer operating at L-band (1.4 GHz) since passive microwaves remote sensing was shown to be the most efficient approach to provide soil moisture information at the global scale (Kerr, 2007). Although SMOS is the first mission operating at L-band, another significant difference with previous microwave missions is the multi-angular acquisition capability which is used to separate the different contributions (soil and vegetation) to the signal (Kerr, 2007; Wigneron et al., 2007).

Since SMOS launch, several papers were devoted to assess the accuracy of the new SMOS soil moisture retrievals at the global scale (Albergel et al., 2012; Al-Yaari et al., 2014; Leroux, Kerr, Richaume, & Fieuzal, 2013) or in various geographic areas such as over US (Al Bitar et al., 2012; Collow, Robock, Basara, & Illston, 2012; Jackson et al., 2012; Leroux et al., 2014), Europe (Bircher, Skou, Jensen, Walker, & Rasmussen, 2012; dall'Amico, Schlenz, Loew, & Mauser, 2012; Lacava et al., 2012; Montzka et al., 2013; Parrens et al., 2012; Schlenz,

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dall'Amico, Mauser, & Loew, 2012), Australia (Peischl et al., 2012) or Spain (Wigneron et al., 2012). No evaluation of the SMOS soil moisture product was done over Africa except on the extreme North of Africa (Pierdicca, Pulvirenti, Fascetti, Crapolicchio, & Talone, 2013). All these studies were useful to analyze SMOS retrievals accuracy and improve the retrieval algorithm. The principle of the retrieval algorithm is to exploit multi-angular L-band measurements in order to retrieve simultaneously several surface parameters including soil moisture and vegetation characteristics. Regularly, some improvements are made on the retrieval algorithm and are implemented in the operational algorithm. Thus, a complete reprocessing of the SMOS data is done to obtain improved soil moisture and vegetation characteristics time-series. At the moment (January 2014), only one complete reprocess of the SMOS level 3 data was done.

The first objective of this paper is to evaluate the SMOS Level 3 data over West Africa using local measurements from the AMMA-CATCH (African Monsoon Multi-disciplinary Analysis (AMMA)–Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique) observatory (Lebel et al., 2009). The soil moisture network installed between 2005 and 2006 in Mali, Niger and Benin (about 120 soil moisture sensors at various depths) has the advantage to represent a variety of bio-climatic conditions with a strong vegetation gradient (from bare soil to deciduous tropical forest). The use of surface soil moisture measurements (5 cm depth) allows estimating the capability of SMOS to retrieve soil moisture value against a large vegetation optical depth gradient. The study is conducted over West Africa from January 2010 to December 2012. This period allows observing a range of seasonal conditions and contrasted years (2010 and 2011 were respectively abnormally wet and dry on the major part of West-African region). Additionally, an intercomparison with three other existing satellite-based soil moisture products is done. Two of them are based on AMSR-E (Advanced Microwave Scanning Radiometer) sensor onboard the AQUA satellite platform (AMSR-VUA from the University of Amsterdam (Owe, de Jeu, & Holmes, 2008) and AMSR-NSIDC (Njoku, Jackson, Lakshmi, Chan, & Nghiem, 2003)). The last soil moisture product is based on the ASCAT sensor (Advanced SCATterometer) onboard the MetOP satellite platform (Bartalis et al., 2007).

The second objective of the paper is devoted to apply a methodology to derive 3-hour soil moisture mapping based on SMOS daily retrievals. Initially developed for AMSR-E passive microwave measurements (onboard the AQUA satellite platform, C-band, 6.9 GHz), the methodology is applied for the first time to the SMOS soil moisture retrievals. High temporal resolution soil moisture mapping is potentially of great interest for operational applications in West Africa, particularly for flood forecasting, drought monitoring and yield forecasts or to better understand the complex land-atmosphere feedbacks observed in the West Africa region.

2. Study area and data set

2.1. West Africa

The study area spans over 16° in latitude from 4° N to 20° N and 40° in longitude from 20° W to 20° E (Fig. 1). The region exhibits a strong north-south bio-climatic gradient with less than 100 mm of annual precipitation at the North and 1200 to 2000 mm on the coast. To better understand the geophysical processes which govern the evolution of the monsoon and the associated continental water cycle, the AMMA-CATCH long term observing system (www.amma-catch.org) is based on three mesoscale sites sampling the West-African eco-climatic gradient (Cappelaere et al., 2009; Lebel et al., 2009; Mougin et al., 2009; Seguis et al., 2011). Observations started in 1999 (in Benin) and were intensified during the AMMA project in 2005 which enhanced the in situ observing system network.

The three meso-scale sites located in Mali, Niger, and Benin sample the north–south latitudinal gradient and the main vegetation types. During the AMMA project, about 120 soil moisture sensors were installed in Mali, Niger and Benin in 2005–2006. Among these, numerous soil moisture sensors were installed at 5 cm depth for satellite products assessment. The evaluation of the SMOS product will be conducted on the three 0.25° pixels belonging to the super sites in Mali, Niger and Benin (Fig. 1).

Both the Mali and Niger sites are located in the Sahel region characterized by a single rainy season between June and October. The Mali site is located in the Gourma region near the Agoufou village (1.48° W–15.34° N). The vegetation is mainly composed by open woody savannah (Mougin et al., 2009) and the observed annual rainfall in Agoufou was 400 mm in 2010, 482 mm in 2011 and 393 mm in 2012. The Niger site is typical of a large fraction of the cultivated Sahel area. This site is close to the Wankama village centered on 13.645° N–2.632° E. The annual rainfall amount observed in the Wankama region was 401 mm in 2010, 362 mm in 2011 and 511 mm in 2012. Niger site is mainly composed of tiger bush on the plateaus, fallow savannah and pearl millet crop fields on the sandy slopes (Cappelaere et al., 2009). The Benin site is located 400 km south of the Niger site and differs from the two previous sites. It belongs to the Ouémé catchment (1.5–2.8° E; 9–10.2° N) which covers about 15,000 km^2 (Seguis et al., 2011). Most of ground-based instruments are located in the North–West part of the Ouémé catchment (9.745° N–1.653° E). At such latitudes the climate is no longer Sahelian but Soudanian. The observed annual rainfall amount was 1578 mm in 2010, 1093 mm in 2011 and 1512 mm in 2012. With more water available, the vegetation is significantly denser than at higher latitudes. Woody savannah and tropical forest are typical vegetation of this site.

2.2. Ground-based soil moisture measurements

Most of ground-based soil moisture sensors were installed through a vertical sampling to capture the rooting zone profile. In the present study, only soil moisture probes located at 5 cm depth are considered according to the assumed penetration depth of 0–2 cm or 0–3 cm at L-band (Escorihuela, Chanzy, Wigneron, & Kerr, 2010). Geographical coordinates of soil moisture stations as well as land-cover type and depth of available soil moisture probes are presented in Table 1 and localization of soil moisture stations within satellite 0.25° pixels is illustrated in Fig. 1. In the Benin site, soil moisture stations were installed at various locations along three hill slopes (catena) covered with forest, crops and savanna respectively. In Niger, three sites were installed and each of them includes 2 soil moisture probes at 5 cm depth. In Mali, due to geo-political events which occurred in 2011 and 2012 in North Mali, we only use the Agoufou station where two soil moisture profiles were installed on top and bottom of a hill slope. To resume, we used 2 sensors in the Mali site and 6 sensors in both Niger and Benin sites respectively. Note that the AMMA-CATCH soil moisture network was previously used for various studies related to satellite product assessment (Baup, Mougin, de Rosnay, Timouk, & Chenerie, 2007; Baup et al., 2007, 2011; de Rosnay et al., 2009; Fatras, Frappart, Mougin, Grippa, & Hiernaux, 2012; Gruhier et al., 2008, 2010; Pellarin, Louvet, Gruhier, Quantin, & Legout, 2013; Pellarin et al., 2009a; Pellarin et al., 2009b; Zribi et al., 2009).

The evaluation of satellite surface soil moisture products can be done using comparisons between point-scale ground observations and footprint-scale (40×40 km^2) retrievals. However, since the majority of the available ground-based soil moisture observations are from low-density networks in which one or two measurements are available per satellite footprint, various authors investigated the spatial sampling errors in coarse-scale soil moisture estimates derived from point-scale observations (Brocca, Tullo, Melone, Moramarco, & Morbidelli, 2012; Cosh, Jackson, Bindlish, & Prueger, 2004; Loew & Schlenz, 2011; Miralles, Crow, & Cosh, 2010). Different approaches were assessed to