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Long-term SMOS soil moisture products: A comprehensive evaluation across scales and methods in the Duero Basin (Spain)

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ABSTRACT

The European Space Agency's Soil Moisture and Ocean Salinity (SMOS) Level 2 soil moisture and the new L3 product from the Barcelona Expert Center (BEC) were validated from January 2010 to June 2014 using two *in situ* networks in Spain. The first network is the Soil Moisture Measurement Stations Network of the University of Salamanca (REMEDHUS), which has been extensively used for validating remotely sensed observations of soil moisture. REMEDHUS can be considered a small-scale network that covers a 1300 km^2 region. The second network is a large-scale network that covers the main part of the Duero Basin (65,000 km^2). At an existing meteorological network in the Castilla y Leon region (Inforiego), soil moisture probes were installed in 2012 to provide data until 2014. Comparisons of the temporal series using different strategies (total average, land use, and soil type) as well as using the collocated data at each location were performed. Additionally, spatial correlations on each date were computed for specific days. Finally, an improved version of the Triple Collocation (TC) method, i.e., the Extended Triple Collocation (ETC), was used to compare satellite and *in situ* soil moisture estimates with outputs of the Soil Water Balance Model Green-Ampt (SWBM-GA). The results of this work showed that SMOS estimates were consistent with *in situ* measurements in the time series comparisons, with Pearson correlation coefficients (R) and an Agreement Index (AI) higher than 0.8 for the total average and the land-use averages and higher than 0.85 for the soil-texture averages. The results obtained at the Inforiego network showed slightly better results than REMEDHUS, which may be related to the larger scale of the former network. Moreover, the best results were obtained when all networks were jointly considered. In contrast, the spatial matching produced worse results for all the cases studied.

These results showed that the recent reprocessing of the L2 products (v5.51) improved the accuracy of soil moisture retrievals such that they are now suitable for developing new L3 products, such as the presented in this work. Additionally, the validation based on comparisons between dense/sparse networks and satellite retrievals at a coarse resolution showed that temporal patterns in the soil moisture are better reproduced than spatial patterns.

1. Introduction

Although soil moisture represents a small portion of the water volume of the planet, it is a key parameter in several hydrologic and atmospheric processes. Soil moisture controls the hydrological interactions between soil, vegetation and climate forcing, and it affects the balance of water and energy between the land surface-atmosphere interface. Moreover, soil moisture is crucial in agriculture because it represents the actual reservoir of the plant available water. In 2010, soil moisture was introduced as one of the Essential Climate Variables established by the World Meteorological Organization (WMO), the Global Climate Observing System and the Committee on Earth Observation Satellites, among others, considering it as "technically and economically feasible for systematic observation" (WMO, 2010). Monitoring soil moisture is critical for improving agricultural productivity, forestry, and ecosystem health. Much effort has been

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focused on measuring soil moisture using diverse approaches, ranging from *in situ* measurement networks and hydrological models to satellite sensors, which are the only practical means of providing global mapping. Data from individual *in situ* networks across the globe are disseminated though the International Soil Moisture Network (Dorigo et al., 2011). A variety of sensors and systems have been used for measuring soil moisture, and several satellite soil moisture data services are currently operational. The microwave spectra has been identified as the most suitable for soil moisture sensing based on the contrast between the dielectric properties of liquid water and soil material. Passive and active techniques have been satisfactorily used (Schmugge et al., 2002; Wagner et al., 2013). Active sensors (radars) have a high spatial resolution (~1 km), whereas passive sensors (radiometers) typically have a low resolution (~40 km). Although synthetic aperture radar can achieve spatial resolutions of meters, its temporal resolution needs considerable improvement; furthermore, its signal is significantly affected by soil roughness and vegetation, which hinders the accuracy of soil moisture retrievals (Jackson et al., 1996). The most common active sensors are the European Remote Sensing satellites, ERS-1 and ERS-2, with a spatial resolution of 50 km for the vertical polarization in the C-band (5.3 GHz), and its successor, the Advanced Scatterometer (ASCAT), which has a spatial resolution of 25 km and a temporal resolution of 1–2 days (Wagner et al., 2007a). In terms of passive sensors, the first microwave radiometer was the Scanning Multichannel Microwave Radiometer (SMMR), which achieved a spatial resolution of 148 km × 95 km in the 6.6 GHz channel (Gloersen and Barath, 1977). Later, the Advanced Microwave Scanning Radiometer, AMSR-E (with six bands ranging from 6.9 to 89 GHz at the HH–VV polarization) operated on board the Aqua satellite from 2002 to 2011. AMSR-E was the first satellite sensor to incorporate soil moisture as a standard product with an accuracy goal of 0.06 m^3/m^3 and a spatial resolution of 74 km × 43 km (Njoku et al., 2003).

Recent proposals for dedicated soil-moisture missions have chiefly relied on passive microwave techniques in the frequency band from 1 to 2 GHz (L-band) (Jackson et al., 2012) due to its high soil-penetration depth, considering that vegetation is semi-transparent up to moderate densities (Jackson and Schmugge, 1991). Thus, the Soil Moisture and Ocean Salinity (SMOS) mission launched in 2009 by the European Space Agency (ESA). The baseline SMOS payload is an L-Band (1.413 GHz) Y-shaped two-dimensional interferometric radiometer, with multi-angular and full-polarimetric capabilities. SMOS is in a sun-synchronous polar orbit, and it provides global measurements of the Earth's brightness temperature (T_B) with a spatial resolution of 43 km (Kerr et al., 2010). Another mission is scheduled to launch in January 2015, the National Aeronautics and Space Administration (NASA)'s Soil Moisture Active Passive (SMAP) mission, which aims to retrieve soil moisture and the freeze/thaw state. The satellite includes an L-band radiometer and a synthetic aperture radar to improve the spatial resolution of soil moisture estimates at 36, 9 and 3 km spatial resolutions (Entekhabi et al., 2010). Another instrument launched on board the international Aquarius/SAC-D mission by NASA and Argentina's space agency is primarily designed to retrieve ocean salinity. Aquarius uses an L-band radiometer and a real aperture radar (Lagerloef et al., 2008) that acquires measurements at a very coarse resolution (~100 km^2). Recently, the National Snow & Ice Data Center (NSIDC) released the Aquarius soil moisture products (http://nsidc.org/data/aquarius/).

Remotely sensed soil moisture has the advantage of covering large areas and identifying large-scale events, but it aggregates heterogeneities from local to regional scales, which renders validation difficult (Ochsner et al., 2013). The point scale of *in situ*-based measurements contrasts with the footprint-scale of remote soil moisture estimates. Establishing credible ground validation approaches for soil moisture requires bridging the gap between the two resolutions (Crow et al., 2012). An increasing number of permanent *in situ* soil moisture measurement networks have provided data for potential validation activities from the large scale to the regional/local scale (Crow et al., 2012; Ochsner et al., 2013). As the data increases (from both satellite and ground-based networks), the need to optimize and standardize the comparisons to reference measurements are more critical. Additionally, upscaling strategies from point measurements to the satellite footprint must be developed.

Following the classification of Crow et al. (2012), two types of networks used for the validation of remote sensing products can be found: the large scale (>10,000 km^2 extent) and the small scale (between 100 km^2 and 10,000 km^2). The first type has the advantage of covering large areas and a larger range of land cover soil types, but it typically lacks sampling densities that provide multiple measurements per footprint. Conversely, small-scale networks have the advantage of higher spatial densities that provide multiple measurements within a single footprint and that allow for the examination of the sub-footprint scale. A large number of dedicated studies have validated products of soil moisture from different remote sensors worldwide, i.e., AMSR-E products (Njoku et al., 2003; Sahoo et al., 2008; Draper et al., 2009; Gruhier et al., 2010; Jackson et al., 2010; Xie et al., 2014), ERS soil moisture products (Wang et al., 2009; Reimer et al., 2012), ASCAT (Wagner et al., 2013; Paulik et al., 2014) and SMOS (Albergel et al., 2012a,b; Bircher et al., 2012; Dall'Amico et al., 2012; Dente et al., 2012; Jackson et al., 2012; Sánchez et al., 2012a; Petropoulos et al., 2014; Rötzer et al., 2014), among others. The validations based on ground-based networks show that the temporal soil moisture patterns of ground observations are well reproduced by satellite data in terms of the error estimates. However, the instantaneous spatial matching at a particular time step is still an unresolved issue, particularly for passive observations. The coarse resolution of these observations hinders a proper spatial comparison with scattered ground data, including for large networks in which the low-density sampling results in less than one observation within each grid cell. This issue is also apparent for small networks in which a small number of cells should be compared.

This work aims to thoroughly test the latest version of SMOS L2 (v.5.51) and a new SMOS BEC L3 v.001 data, obtained by quality-filtering and re-gridding of SMOS L2 v.551 data from ISEA to the 25 km EASE grid (details are given in Section 2.2.2) over the Duero Basin in Spain from January 2010 to June 2014. ESA L2 and BEC L3 series were compared with *in situ* soil moisture series from two networks in Spain. Considering the different spatial scales of each network, another objective was to study the influence of using different sets of stations with very different spatial distributions. Owing the very different observations compared, the validation methods were discussed. Then, a newly extended version of the Triple Collocation (TC) methodology was applied. Spatio-temporal correlations of the L2 and L3 soil moisture series were analyzed through a comparison with point-scale measurements at the two networks and area-averaged, land-use-averaged and soil-texture-averaged data.

2. Data sets

2.1. In situ soil moisture data set

For the remotely sensed data set validation, two networks were used, so-called "small-scale" and "large-scale" networks. The first network provided multiple measurements within a single