Validation of the SMOS L2 Soil Moisture Data in the REMEDHUS Network (Spain)

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***Abstract*—The Level 2 soil moisture products from the Soil Moisture and Ocean Salinity (SMOS) mission have been released. The data must be validated under different scenarios of biophysical and climatic conditions. For the current study, the data from January to December 2010 from 20 *in situ* soil moisture stations from the REMEDHUS soil moisture measurement station network (Spain) were used. A comparison analysis was carried out in terms of the soil moisture content, its spatial variability, and temporal stability. The results show an acceptable level of agreement ($R = 0.73$, RMSD $= 0.069$ m$^3 \cdot$ m^{-3}, and $bias = 0.053$ m$^3 \cdot$ m^{-3}) between the *in situ* and satellite data. A slight constant underestimation from the SMOS data set was detected. A centered (bias removed) root-mean-square difference was calculated to account for this persistent bias (RMSDc $= 0.044$ m$^3 \cdot$ m^{-3}). This result is close to the SMOS accuracy objective of 0.04 m$^3 \cdot$ m^{-3}. Two conclusions can be drawn: First, SMOS is close to meet the mission accuracy requirements in REMEDHUS, and second, SMOS is able to detect temporal anomalies and the temporal evolution of ground soil moisture, even though the soil moisture was slightly underestimated. Despite a noticeably reduced spatial variability among the SMOS grid cells, the remotely sensed soil moisture shows a spatial pattern of the soil moisture fields on the area scale, in agreement with the site-specific characteristics of REMEDHUS. No differences were found between the use of ascending and descending orbits. In addition, no differences were detected between the use of time-overpass values of *in situ* soil moisture and that of the daily average.**

***Index Terms*—Measurement, passive microwave remote sensing, soil moisture.**

I. Introduction

THERE is a broad consensus regarding the need for an in-depth knowledge of the global distribution of soil moisture. For at least the last three decades, various attempts have been made to make frequent global soil moisture estimates [1], [2]. The first satellite to make passive observations specific to soil moisture retrieval is the Soil Moisture and Ocean Salinity (SMOS) mission launched by the European Space Agency (ESA) in November 2, 2009. The SMOS payload is a novel interferometric L-band radiometer (1.4 GHz) that provides brightness temperature measurements of the soil at different incidence angles, with a spatial resolution of approximately 40 km [3]. The Level 2 (L2) processor ingests the multiangular and multipolarization brightness temperatures as input and, by minimizing a cost function, derives soil moisture estimates as well as other surface parameters such as vegetation opacity. The resulting soil moisture is expected to be 0.04 m$^3 \cdot$ m^{-3}, which is the root-mean-square error (rmse).

To compare the ground measurements and SMOS products, it is necessary to characterize and monitor an area slightly larger than the actual pixel in terms of brightness temperature [4]. The key issue here is the spatial scale. Conventional measurements of soil moisture are made on a point scale, whereas satellite sensor provides an integrated area/volume value for a much larger spatial extent. Satellite measurements represent integrated values over the sensor footprint area, while ground-truth measurements usually consist of point measurements that are not necessarily representative for the whole area. To deal with the spatial issue, the point scale should be enlarged using a dense network of soil moisture measurements in which climatic conditions, soil characteristics, land use, land cover, and topography should be monitored. A wide range of conditions, such as wet and dry periods, temperatures, and land uses, are required. Another critical requirement is the temporal frame. The validation of SMOS L2 soil moisture data requires the maintenance of long-term soil moisture monitoring sites [5], [6]. Regarding the accuracy, it is well known that ground-based sensors have their own errors, but the assumption is that these errors (averaged over the satellite footprint) are significantly smaller than the errors from satellite-based products [7].

Validation strategies of microwave remotely sensed soil moisture can emerge from comparisons with near-surface *in situ* soil moisture data [8]–[10], modeled surface soil moisture data [4], [10]–[13], and satellite data intercomparisons [13]. Currently, similar validation activities of L2 products, such as that presented here, are being undertaken in test sites for SMOS around the world, e.g., Germany [14], France [15], the U.S. [16], and Australia and Africa [17], among others. These long-term networks, including REMEDHUS, provide *in situ* data from only a few stations for an area corresponding to the footprint of SMOS, but currently, no global *in situ* soil moisture monitoring network exists [14].

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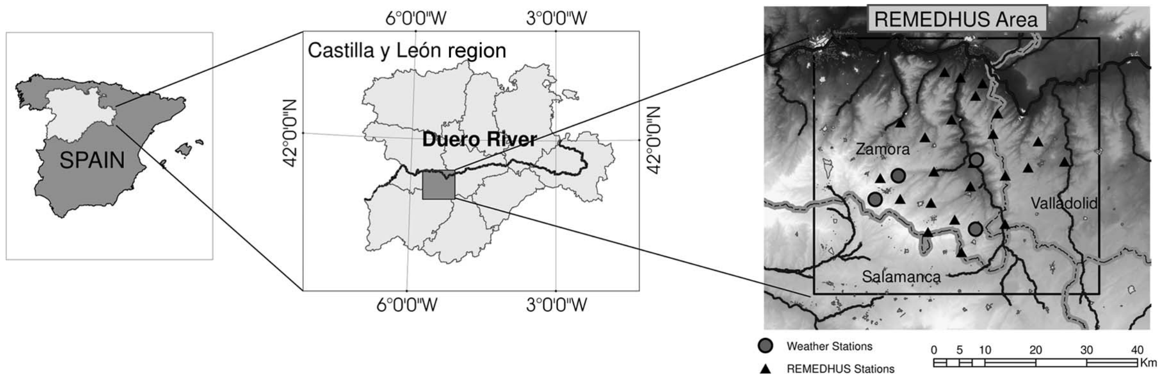

Fig. 1. Location of the REMEDHUS network (Spain).

The objective of this paper is to validate the L2 v4.00 products over the REMEDHUS site in Spain. To accomplish this, an analysis of both data sets is first performed based on different quantitative approaches, such as the study of the temporal evolution of absolute and anomaly values of soil moisture, standard errors, the soil moisture daily index, and the most representative station/grid cell. A matching comparison between the two data sets is performed based on a linear regression over the comprehensive subsets.

II. Materials and Methods

A. REMEDHUS Data and Network

REMEDHUS is composed of 20 soil moisture monitoring stations. There are also four automatic weather stations as well as several other sensors and equipment for hydrological monitoring [18]. These stations are located within an area of 1300 km^2 (41.1° to 41.5°N; 5.1° to 5.7°W) in a central semiarid sector of the Duero basin (Fig. 1). This area is nearly flat (less than 10% slope), and it ranges from 700 to 900 m above sea level. The climate is continental semiarid Mediterranean with an average annual precipitation of 385 mm and a mean temperature of 12 °C. The land use is mainly agricultural, with rainfed cereals grown in winter and spring (78%), irrigated crops in summer (5%), and vineyards (3%). There are also patchy areas of forest and pasture (13%). The growing cycle for rainfed cereals consists of the seeding period in autumn, development in spring, and ripening/harvesting in early summer.

This network provides intensive observations over a 35 km × 35 km area, which allows for the study of the scale changes in the use of *in situ* soil moisture data compared with remotely sensed soil moisture. For SMOS validation purposes, the REMEDHUS network performs a continuous soil moisture measurement in 20 stations with Hydra probes (Stevens Water Monitoring System, Inc.) integrating over a depth of 0–5 cm. This data set provides a continuous measurement of soil moisture each hour. The network and the database are managed and retrieved with a remote data transfer system using General Packet Radio Service (GPRS) modems.

The REMEDHUS soil moisture network has been used for several purposes, including the following: 1) calibration and validation campaigns in support of the SMOS mission [19]; 2) the parameterization and validation of water balance models [20]; 3) the evaluation of remotely sensed soil moisture products [21], [22]; and 4) the performance of soil moisture experiments at different scales and with different methodologies [23]. REMEDHUS is part of the International Soil Moisture Network [24]. This network has been used to validate several satellite products. By comparing REMEDHUS data with Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) data, a previous study [9] found a mean correlation coefficient of $R = 0.83$ ($rmse = 0.06$ m$^3 \cdot$ m^{-3}). Similarly, other authors [21] found a coefficient of determination of $R = 0.75$ ($rmse = 0.022$ m$^3 \cdot$ m^{-3}) when comparing profile-averaged soil moisture against the soil water index obtained using the European Remote Sensing scatterometer.

B. SMOS L2 Data

The selected model for the soil moisture retrievals is the so-called L-band Microwave Emission of the Biosphere model [25]. The processing from the SMOS brightness temperatures to the L2 soil moisture product is described in great detail in [26]. The distribution of L2 soil moisture data began at the end of the summer 2010. As expected, the system underwent many changes, both in terms of the instrument (calibration and polarization modes) and the retrieval algorithms. Thus, the 2010 Level 1 data set has been reprocessed by the ESA and the European Space Astronomy Centre, whereas the Centre d'Etudes Spatiales de la BIOsphère and the Centre National d'Études Spatiales have reprocessed the L2 soil moisture data with the version 4.00 of the L2 algorithms. This L2 data set contains the retrieved geophysical parameters and their associated theoretical uncertainties. The soil moisture product is tested in the present research.

The ECOCLIMAP 2004 [27] is the current reference land cover for L2 products, aggregated into 12 classes. For each class, the radiometric contribution is assumed to be known in the retrieval. For the study area, all of the land cover codes are vegetated soil (nominal land use: low vegetation of grass and crops); thus, the retrieval is only valid for this nominal class. Only a small percentage (less than 10%) of forested areas (Mean_FM0_FFO value for each discrete global grid (DGG) cell) is shown in the cells overlapping the REMEDHUS area. Taking into account the land use percentages presented in the previous section, a realistic retrieval is indicated for the study area.

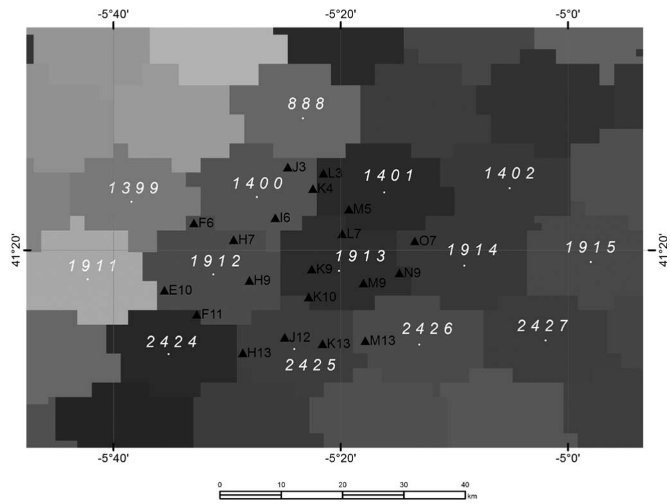

Fig. 2. SMOS grid cell collocation in REMEDHUS. Each ISEA DGG cell (only the four last numbers of the Grid_Point_ID of the DGG are used) is mapped in its hexagonal shape (approximately) by the SMOS tool software program found in http://www.brockmann-consult.de/cms/web/beam/welcome.

The reprocessed MIR_SMUDP2 (L2 Soil Moisture User Data Product, v4.00) file was used in this study. This file contains the data of the retrieved variables as well as ancillary information about the quality of each parameter [data quality index (DQX)]. The DQX for parameters obtained through the retrieval is expressed in terms of the theoretical standard deviation of the retrieval. The reprocessed MIR_SMDAP2 (L2 Soil Moisture Data Analysis Product, v4.00) files were also provided for each SMUDP2 file containing data for analysis purposes, such as the fraction of land cover code for each DGG cell, the quality parameters, and the overall quality. L2 data are geolocated products, delivered by the ESA on the Icosahedral Snyder Equal Area (ISEA) projection [28]. In particular, the grid used by SMOS processors corresponds to a hexagonal partitioning of aperture 4 at a resolution of 9 km, known as ISEA4H9. The DGG system ISEA 4H9 has fixed latitude and longitude coordinates for the center of each grid cell, which are identified by a Grid_Point_ID and equispaced by 15 km. Fourteen ISEA DGG cells covered the REMEDHUS area, hereafter referred to as the four last numbers of their Grid_Point_ID (Fig. 2). However, the SMOS soil moisture product is derived from multiangular brightness temperature measurements that cover an area on the order of tens of kilometers. The actual radiometer resolution is 43 km on average. This oversampling should be taken into account when working with SMOS data. To perform the validation, collocated *in situ* and SMOS L2 data sets were produced semiautomatically on a daily basis, both with ascending and descending orbits.

The period of study covered the reprocessed SMOS L2 data of 2010 from January 14 to December 22 ($n = 343$ days). Among these dates, the data over the study area were available for 189 days, with similar quantities of data for the ascending and descending orbits. Some data are missing for the first ten days of each month, with several exceptions.

A strong source of error was detected over Spain due to radio-frequency interference (RFI), which created spurious signals of the brightness temperatures during the first weeks of 2010. Notably, some sources of RFI in Cáceres (west of Spain) were identified and switched off on March 16, 2010. The most robust RFI detection algorithms have been used to build maps of frequency of occurrence of RFI for each SMOS grid node. In fact, the study of the RFIs, as well as the corresponding mitigation values for the reprocessed data set, has showed that there has been a clear diminishing effect of the RFIs since the middle of March 2010, from 60 K to 5 K of brightness temperature. Therefore, the period from January to March does not contain much reprocessed data.

C. Methods

1) REMEDHUS and SMOS L2 Soil Moisture Analysis: The first group of methods analyzes the time evolution of the soil moisture series to assess the behavior and variability of both the *in situ* and satellite series. Local conditions, such as soil and climate characteristics and land use distribution, are also considered.

The most efficient way to predict large-scale moisture averages from only a few sensors located at representative sites is through temporal stability analysis [29]. If temporal stability patterns can be established in a watershed, a small number of soil moisture observation sites can be used to predict watershed averages accurately and precisely [5]. In this case, the most representative REMEDHUS station as well as the most representative DGG cell of the SMOS scene over the area can be predicted. The mean relative difference (MRD) [29] represents the ability of a particular soil moisture measurement location to estimate the average over the watershed [5]. The MRD is computed by means of the differences between the sites (in this case, both stations and SMOS grid cells) and the averaged sites during the dates studied. The MRD of each site is then plotted by rank with the error bounds of one standard deviation of the relative differences to determine which station best estimates the average of the watershed [5]. The observation site is most representative when the MRD is close to zero and the standard deviation is low.

The temporal evolution of each data set (stations and grid cells) was studied considering the following: 1) hourly and daily series of soil moisture; 2) averaged values of all stations and all grid cells; and 3) only ascending or descending orbits. The pattern of such an evolution was assessed by the soil moisture daily index

$$SM_{\text{index},i} = (SM_{i+1} - SM_i)/SM_i \qquad (1)$$

where SM_{i+1} is the soil moisture of the day $i+1$ and SM_i is the soil moisture of the day before i. This index allows for the study of daily variations, and it provides an idea of the influence of climatic forcing factors.

The analysis of spatial variability and its evolution in time is based on the coefficient of variation (CV). The variance was also applied to determine which series fluctuates more in time during the period of study. Finally, the internal relationships among the SMOS footprint in REMEDHUS were studied by the correlation analysis of the 14 SMOS DGG cells.

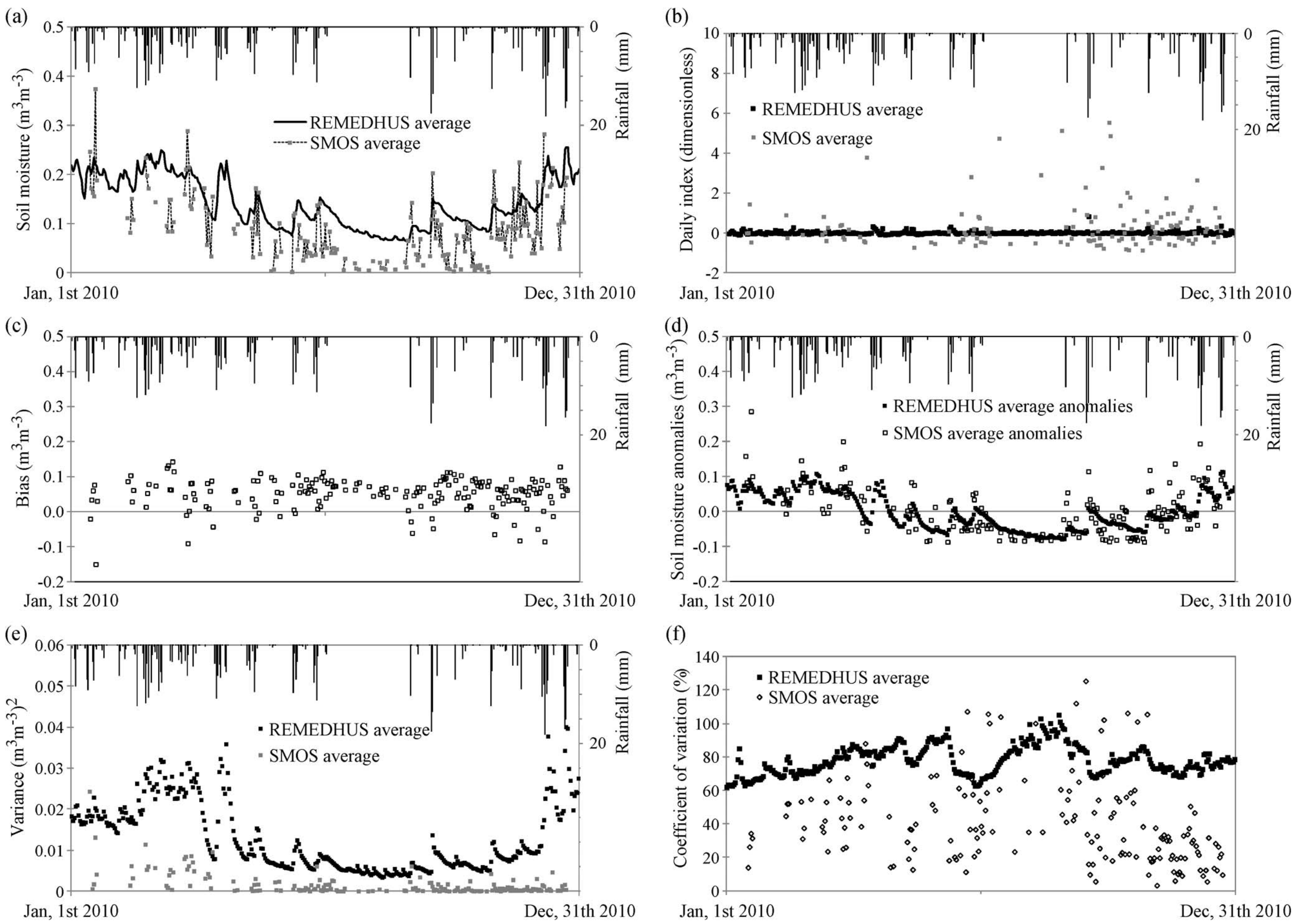

Fig. 3. (a) Averaged REMEDHUS and averaged SMOS soil moisture evolution, (b) daily index, (c) bias, (d) anomalies, (e) variance, and (f) CV.

2) Matching Strategies: The attempt to relate point-scale information to area-averaged information is a complex task. A robust validation program should include as many types of comparisons as possible and must attempt to provide actual spatially representative values for ground-based soil moisture [30]. The comparison was performed at four levels for the selected data sets of both series. The first approach consisted of using the spatial average of both *in situ* and satellite data. The second approach consisted of comparing the average of the REMEDHUS soil moisture data against each grid cell and, inversely, comparing the averaged SMOS soil moisture data against each soil moisture station. This approach can reveal the spatial homogeneity of the SMOS cells and of the field sites. It can also provide an idea of which grid cell better describes the field-averaged soil moisture and, conversely, which point measurement better represents the mean SMOS soil moisture. The third approach compared only the data that coincided spatially (i.e., only the stations coinciding in the same cell). Finally, the most representative station was compared against the most representative SMOS cell.

These approaches considered both the hourly *in situ* data coinciding with the satellite time and the daily averaged values. For the SMOS data, descending and ascending orbits were also considered in each calculation. Linear regression and the correlation coefficient (R) were used to compute the comparisons. The bias and the root-mean-square difference (RMSD), which is typically used to predefine the accuracy requirements of a satellite's soil moisture product [31], [32], were also calculated. Because the RMSD is very sensitive to a bias between *in situ* reference data and the satellite product [14], a debiased or centered RMSD (RMSDc) [33] was also applied to differentiate between the systematic and random error components. The RMSDc removed the overall bias before calculating the RMSD, i.e., isolating the differences in the patterns from differences in the means of both data sets [33]. The series of these anomalies, once the mean values are subtracted from both the SMOS and REMEDHUS time series, were also analyzed.

III. Results

A. Series of REMEDHUS and SMOS Soil Moisture Data

1) Temporal Analysis: The absolute daily values of averaged REMEDHUS stations and averaged SMOS cells have been evaluated [Fig. 3(a)]. Overall, the regional soil moisture content from the REMEDHUS stations for this period ranged from 0.063 to 0.271 $m^3 \cdot m^{-3}$. The averaged SMOS data are much more variable, showing a wider range of values (0.001–0.373 $m^3 \cdot m^{-3}$) as well as a more extreme daily index [Fig. 3(b)].

The general behaviors of the averaged SMOS and *in situ* data are rather similar, although the SMOS values were generally lower, with a dry bias of 0.053 $m^3 \cdot m^{-3}$ on average. This underestimation of SMOS soil moisture is fairly constant during the entire period of study [Fig. 3(c)], except for some rain events, when the SMOS average seems more sensitive than the *in situ* data. The lack of SMOS data at the beginning of 2010, as well as the unreliable nature of the data as a result of the presence of RFI during this period, hampered a complete analysis during the winter season. There is no apparent connection between the bias and both the surface water content conditions and the phenological cycle of the predominant vegetation cover. It could be suspected that there exists a systematic and almost constant bias in the retrieval of data that makes it difficult to analyze the soil moisture contents. Indeed, if anomalies are used instead of the absolute soil moisture values, the comparison improves [Fig. 3(d)]. The SMOS L2 series seems to be able to detect the evolution of the ground soil moisture over time.

The temporal variability of the ground measurements, considered as the standard deviation within each station, ranges between 0.020 (vineyard stations) and 0.170 $m^3 \cdot m^{-3}$ (forest–pasture stations). The standard deviation for each SMOS cell is lower, ranging between 0.050 and 0.090 $m^3 \cdot m^{-3}$. However, for the whole area, the temporal variability of the SMOS seems similar to the temporal variability of the *in situ* measurements (standard deviation of 0.060 $m^3 \cdot m^{-3}$ for the area averaged in both cases).

2) Spatial Analysis: The homogeneity of the SMOS spatially averaged soil moisture is expected to be greater than the REMEDHUS spatially averaged data, because of its broad resolution. This homogeneity is expressed by a much smaller variance that remained close to null values throughout the entire cycle [Fig. 3(e)] and a smaller value for the standard deviation of the SMOS average (0.032 $m^3 \cdot m^{-3}$) than for the ground measurement average (0.108 $m^3 \cdot m^{-3}$).

The CVs of the spatially averaged SMOS data were lower [Fig. 3(f)], ranging between 3% and 125%, whereas the CV for the averaged REMEDHUS data ranged between 62% and 105%. The lower CV of the L2 indicated that these data are less scattered than the *in situ* data, as indicated before. It also indicated that a higher signal-to-noise ratio was randomly maintained throughout the entire cycle, with no relationship with specific soil water content conditions. The high variability of the SMOS CV indicates that the SMOS average is much more variable, while the standard deviation remains constant. This fact is in agreement with the higher daily index observed in Fig. 3(b). Despite the expected overlapping and averaging of SMOS observations and the detected low variance among grid cells, SMOS responds to soil moisture variations over time.

To study the variability of inter-SMOS cells, a correlation analysis was applied. Although a spatial analysis is not the aim of the present work, the correlation analysis between cells could help to understand the behavior of the SMOS soil moisture in this area. Although there was a low variance among the cells [Fig. 3(e)], a slightly different water content was detected between the east side (DGG cells 1402, 2427, 1914, and 1915) and west side (DGG cells 2424, 1911, and 1399) of the working area. This pattern has been detected by considering two facts. First, there is a smaller correlation $(0.50 < R < 0.60)$ between the east and west cells compared to the general correlation values between cells $(0.60 < R < 0.90)$. Second, lower soil moisture contents (0.061 $m^3 m^{-3}$) on average were observed in the eastern cells relative to the western ones, over 68% of the entire time series. A subtle spatial pattern is discernible, although the variance analysis did not reach statistical significance (at $\alpha = 0.05$, p-value > 0.005 in all cases). Note that, despite the fact that the footprint of SMOS is approximately 40 km, SMOS imaging is not conducted along discrete directions, as in real aperture radiometers, in which the antenna scans the scene and data are acquired at specific times. In SMOS, a full image is obtained during every snapshot, and the value at every particular direction is exactly obtained by means of an exact inverse discrete Fourier transform of the Fourier components of the brightness temperature image obtained after the inversion of the G-matrix [34].

This spatial pattern is in agreement with the edaphoclimatic characteristics of the REMEDHUS area. Due to the slightly higher altitude of the western part of the working area, a similar rainfall drift was observed. This fact, in addition to the presence of several areas of clay-rich soils (soil erosion has left argillic horizons on the surface), causes the soil water content in the western part of this area to be greater than that of the eastern part.

3) Land Uses and Most Representative Station/Grid Cell: With regard to the influence of land use on the water content dynamics, the highest soil water content was found in the soils of the forest–pasture stations (H9, K9, and M13). These stations are located at the bottoms of valleys where the water table is shallow in winter, where occasional flooding occurs, and where there is a higher content of clay in the soil. The lowest water content levels were found at the vineyard stations (E10, F6, H7, I6, J3, K4, and L3), where the soils contain more sand (always more than 80% sand in the topmost layer). Thus, these soils have a lower water retention capacity [35]. Finally, the rainfed cereal soils (F11, H13, J12, J14, K10, L7, M5, M9, N9, and O7) had an intermediate water content.

The study of the most representative station [Fig. 4(a)] by means of the temporal stability analysis showed that the minimum value of the MRD is -0.86. The maximum value reached 1.29, indicating that the distribution of the stations is balanced, although the wetter areas had a slightly higher temporal variability. The most representative station for the REMEDHUS area during this period was M5 $(MRD = 0.06 \pm 0.19)$, which was covered by rainfed cereals. The M5 series explains 83% of the variability of the estimated mean of the REMEDHUS area.

The homogeneity among the SMOS cells is evident if the temporal stability analysis is performed for the grid cells of the REMEDHUS area [Fig. 4(b)]. The MRD in this case ranged between -0.12 and 0.20, which was a smaller interval compared with the range of the MRDs of the *in situ* data. The most representative SMOS cell of the area average was 2426 $(MRD = -0.02 \pm 0.36)$, which showed no spatial relationship with the most representative station M5 (Fig. 2).

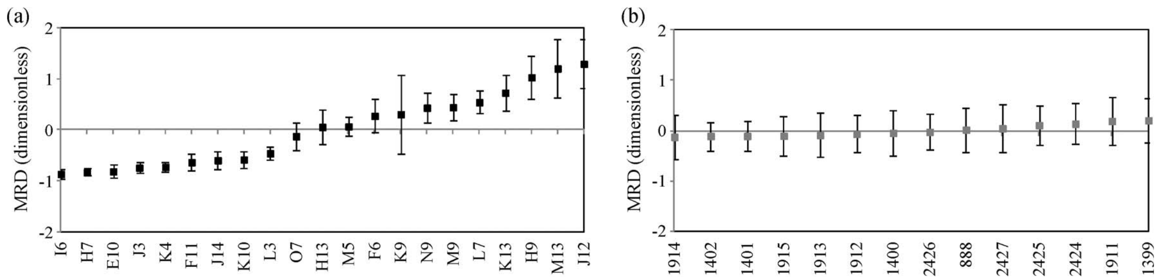

Fig. 4. (a) MRDs of the REMEDHUS stations and (b) the SMOS DGG cells.

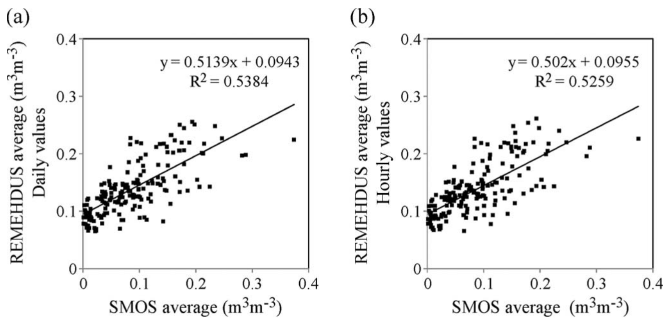

Fig. 5. Scatter plot and linear regression between SMOS and *in situ* soil moisture both (a) daily averaged and (b) at the SMOS acquisition time.

B. Matching In Situ and Satellite Data

Hourly and daily averaged data, as well as the ascending and descending data sets, were considered in the matching analysis. The first analysis consisted of a comparison between the area-averaged series. The comparison of the averaged REMEDHUS stations versus the averaged SMOS cells showed a reasonable agreement ($R = 0.73$, $\mathrm{RMSD} = 0.069\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.044\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.053\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$) when considering the stations' mean daily data [Fig. 5(a)] as well as the *in situ* data at the SMOS acquisition time (Fig. 5(b); $R = 0.72$, $\mathrm{RMSD} = 0.069\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.045\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.053\ \mathrm{m}^3\mathrm{m}^{-3}$). Thus, no improvement was found with the hourly data instead of the daily mean data. In turn, when the ascending and descending orbits were analyzed separately, the mean of the descending orbits ($R = 0.72$, $\mathrm{RMSD} = 0.073\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.043\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.058\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$) did not have a different correlation compared to the mean of the ascending orbits ($R = 0.70$, $\mathrm{RMSD} = 0.065\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.042\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.044\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$).

A second correlation analysis was performed to compare the averaged SMOS data with the daily averaged *in situ* data and to compare the hourly *in situ* soil moisture at the same time as the SMOS overpass [Table I(a)]. Similar results were obtained in both cases, and this similarity was particularly clear when comparing the bias values. This bias spanned between -0.119 and $0.168\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$. The higher bias and RMSD values were found at the forest–pasture areas because of the higher variability and soil water content in these stations. In contrast, the smallest values were obtained from the rainfed cereal sites, and the stations at the vineyards showed a negative bias.

The third correlation analysis between the averaged REMEDHUS soil moisture and the data from each SMOS cell showed weak but different results for each cell [Table I(b)]. The best correlated cells were 1399, 1911, and 2424, which correspond to the higher SMOS values. This result underlines the fact that SMOS underestimates the averaged REMEDHUS soil moisture. Based on the ISEA grid distribution, another correlation analysis was performed using only the soil moisture stations located inside a single cell. The data from these stations were averaged and compared to the corresponding cell (Table II). Only daily values are shown in the table because the same conclusions (similar values for daily/hourly values and orbits) were obtained. The highest RMSD and bias values were found for cell 2426 where the only station is located at the bottom of a valley and it is affected by the previously mentioned factors.

Finally, the use of the most representative station and the most representative grid cell provides a general idea of the SMOS estimations with a reduced data set consisting of one cell and one station. The results of the comparison between 2426 and M5 ($R = 0.52$, $\mathrm{RMSD} = 0.075\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.057\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.049\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$) were not better than the results obtained for the other cells and stations.

IV. Discussion

One critical issue regarding the validation of remotely sensed soil moisture via *in situ* observations is the conflicting representativeness of both data sets. While the soil moisture at the DGG cell represents an area-averaged value where the assumptions of the mean values of many variables should be decided, the single *in situ* measurement represents an isolated data point. Thus, the use of field data sets should be used as long as these data sets are representative of the global area. The use of the temporal stability analysis method is a way to predict large-scale moisture averages from only a few sensors located at representative sites [5]. By performing an analysis of temporal stability on REMEDHUS [18], a considerable degree of temporal persistence for the spatial structure in that area was found. In the present study, one station showed attributes representative of the analyzed period in soils that hosted rainfed cereals. The comparison of this station with the L2 series does not result in an improvement of the matching results, and it was showed that the simple average of the stations was sufficiently useful. The temporal stability analysis performed in [18] led to a different representative station than that described here, indicating that the results depend on the period of study, the sensor type, and the temporal sampling strategy. Nevertheless, this analysis, applied comparatively to both the remotely sensed and the ground series, has an added value when analyzing the spatial variability of both data sets, detecting, in this case, the small spatial

TABLE I
(a) Comparison of the REMEDHUS Stations (Daily and Hourly Data) Versus Averaged SMOS Soil Moisture. Land Uses: (V) Vineyard, (R) Rainfed Cereals, and (F–P) Forest–Pasture. (b) SMOS Cells Versus Averaged REMEDHUS Stations (Daily and Hourly Data). (R) Correlation Coefficient, (RMSD) RMSD, and (RMSDcent) RMSDc

(a)

		daily				hourly			
			RMSD	BIAS	RMSD cent		RMSD	BIAS	RMSD cent
STATION	LAND USE	R	(m^3m^{-3})	(m^3m^{-3})	(m^3m^{-3})	R	(m^3m^{-3})	(m^3m^{-3})	(m^3m^{-3})
E10	V	0.7	0.112	-0.109	0.025	0.75	0.112	-0.109	0.025
F6	V	0.5	0.047	0.015	0.044	0.51	0.047	0.015	0.045
F11	R	0.3	0.092	-0.086	0.032	0.23	0.091	-0.084	0.036
H7	V	0.5	0.122	-0.115	0.040	0.47	0.121	-0.114	0.041
H9	F-P	0.6	0.171	0.135	0.104	0.63	0.171	0.135	0.104
H13	R	0.5	0.047	0.014	0.046	0.46	0.049	0.013	0.047
I6	V	0.2	0.127	-0.118	0.045	0.2	0.128	-0.119	0.045
J3	V	0.7	0.107	-0.104	0.025	0.64	0.108	-0.105	0.025
J12	R	0.7	0.171	0.167	0.035	0.66	0.171	0.168	0.035
K4	V	0.7	0.104	-0.100	0.029	0.66	0.104	-0.100	0.030
K9	F-P	0.4	0.064	0.016	0.062	0.4	0.063	0.016	0.061
K10	R	0.5	0.085	-0.082	0.025	0.49	0.085	-0.081	0.026
K13	R	0.6	0.104	0.096	0.039	0.62	0.105	0.097	0.041
L3	V	0.5	0.071	-0.064	0.030	0.53	0.071	-0.065	0.030
L7	R	0.7	0.087	0.078	0.040	0.67	0.087	0.077	0.040
M5	R	0.6	0.023	0.000	0.023	0.62	0.025	0.001	0.025
M9	R	0.6	0.068	0.059	0.034	0.65	0.068	0.059	0.035
M13	F-P	0.6	0.188	0.147	0.117	0.65	0.188	0.146	0.118
N9	R	0.6	0.064	0.046	0.046	0.58	0.065	0.046	0.046
O7	R	0.6	0.031	-0.009	0.030	0.63	0.032	-0.009	0.031

(b)

	daily				hourly			
		RMSD	BIAS	RMSD cent		RMSD	BIAS	RMSD cent
DGG CELL	R	(m^3m^{-3})	(m^3m^{-3})	(m^3m^{-3})	R	(m^3m^{-3})	(m^3m^{-3})	(m^3m^{-3})
888	0.63	0.078	0.054	0.056	0.65	0.077	0.055	0.055
1399	0.64	0.068	0.036	0.057	0.64	0.068	0.037	0.057
1400	0.6	0.083	0.047	0.068	0.6	0.082	0.047	0.068
1401	0.59	0.079	0.055	0.057	0.6	0.078	0.055	0.056
1402	0.59	0.076	0.060	0.047	0.59	0.076	0.060	0.047
1911	0.64	0.068	0.029	0.062	0.64	0.068	0.029	0.062
1912	0.55	0.071	0.042	0.058	0.55	0.071	0.042	0.058
1913	0.57	0.073	0.042	0.059	0.56	0.073	0.042	0.060
1914	0.52	0.075	0.053	0.053	0.51	0.075	0.053	0.053
1915	0.62	0.071	0.052	0.049	0.62	0.07	0.051	0.049
2424	0.65	0.066	0.035	0.056	0.66	0.065	0.035	0.055
2425	0.53	0.073	0.047	0.056	0.53	0.072	0.047	0.055
2426	0.59	0.072	0.048	0.054	0.6	0.071	0.047	0.053
2427	0.58	0.071	0.048	0.052	0.57	0.071	0.048	0.052

variability of the SMOS cells among the area expressed in the homogeneity of MRD and the standard deviation values comparing the REMEDHUS stations (Fig. 4). Despite the low variability of the grid cells, one can see [Fig. 4(b)] that several of them (1914, 1402, 1915, and 1401) give values below the mean, and others (1399, 1911, and 2424) give values above the mean. These two groups coincide with the areas where soil moisture is always below or above the REMEDHUS mean, respectively.

A promising approach for understanding the soil moisture spatiotemporal patterns is through the use of passive microwave remote sensing [36]. In the REMEDHUS area, the advantage of the L2 retrieval may arise from the following: 1) the sparse and homogeneous vegetation cover, fitting the nominal class proposed in the algorithm, and 2) the limited topographic effects in this area. Overall, the spatially averaged values of SMOS cells versus the stations (Fig. 5) showed a good correlation ($R = 0.73$ for daily scale and $R = 0.72$ for hourly scale). The correlation coefficient obtained in other works [9], [22] that compared satellite products with soil moisture measured in REMEDHUS is similar to those obtained in this paper. Nevertheless, in the upper Danube, the study of dall'Amico [14] did not find a clear agreement between the time series of SMOS L2 and that of *in situ* data. In the REMEDHUS site, an underestimation of the soil water content was found using the SMOS series (RMSD $= 0.069\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$ and $bias = 0.053\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$). Smaller values of SMOS soil moisture were detected throughout the whole year without indicating any influence by the wet/dry periods. Overall, the L2 series reproduced well the relative soil moisture dynamics, as shown with respect to the use of anomalies [Fig. 3(d)] instead of the absolute values [Fig. 3(a)], but the RMSD would be masked due to the

TABLE II
Comparison of the Soil Moisture of the SMOS Cells and the Mean Soil Moisture of the Stations Belonging to Each Cell. (R) Correlation Coefficient, (RMSD) RMSD, and (RMSDcent) RMSDc

DGG CELL	STATIONS	R	RMSD (m^3m^{-3})	BIAS (m^3m^{-3})	RMSDcent
888	J3	0.56	0.082	-0.055	0.062
1400	F6, J3, K4,I6	0.52	0.083	-0.037	0.074
1401	L3, M5	0.48	0.065	0.049	0.062
1912	E10, F6, H7, H9	0.48	0.068	0.019	0.064
1913	K9, K10, L7, M9	0.52	0.085	0.057	0.062
1914	N9, O7	0.47	0.091	0.070	0.059
2424	F11	0.26	0.096	-0.061	0.075
2425	H13, J12, K13	0.54	0.154	0.145	0.056
2426	M13	0.54	0.236	0.184	0.135

persistence of this bias over time [Fig. 3(c)]. Thus, a debiased rmdsc would nearly meet the SMOS mission requirements, as observed in the averaged series ($rmdsc = 0.044\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$) as well as in the stations and cell series (Table I).

On the contrary, the SMOS-derived soil moisture revealed an overestimation of the soil water content after some rain events, which was clear both in the soil moisture [Fig. 3(a)] and in the anomalies [Fig. 3(d)] curves, although it is hard to find a pattern when comparing with the daily index [Fig. 3(b)]. It is also difficult to determine if there is any relationship between the response of SMOS to rain events and the actual soil water content because of the limited data gathered at the beginning of 2010. This effect is weaker in the REMEDHUS series, where the station-averaged daily index exhibited flat values. One can speculate that the daily average would smooth out the index of the *in situ* series, but when soil moisture data coinciding with the SMOS observations were chosen, similar results were obtained.

As mentioned before, the SMOS L2 product has a nominal spatial resolution of 43 km in the footprint, which can lead to an oversampled area even though the ISEA grid exhibits a finer scale. Moreover, the L2 processor applies several assumptions and averages regarding soil properties, roughness, and vegetation. Thus, a low variability among DGG cells would be expected relative to the spatial variability of the *in situ* soil moisture stations, which was detected as a lower variance [Fig. 3(e)], a lower standard deviation ($0.032\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$ comparing to $0.108\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$ for the ground measurements), and the homogeneity of the MRD and standard deviation values in the most representative grid cell analysis [Fig. 4(b)]. This fact is also proven by the similarity of the behavior of each SMOS cell regarding the REMEDHUS average [Table I(b)] in terms of the correlation coefficient ($0.51 < R < 0.65$), RMSD ($0.065\ \mathrm{m}^3 \cdot \mathrm{m}^{-3} < \mathrm{RMSD} < 0.083\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$), and bias ($0.029\ \mathrm{m}^3 \cdot \mathrm{m}^{-3} < bias < 0.060\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$). Thus, as it was expected, due to the area-averaged nature of the SMOS data, the comparison performed better with the average of the stations than when comparing individual cells with stations (Tables I(b) and II). It would be desirable to conduct a wider area analysis of at least several footprints, but there is a lack of soil moisture networks of such extent that have a high density of stations.

In spite of this behavior and the mismatch of resolution, the SMOS data showed a certain capability of tracking the spatial pattern of the REMEDHUS area soil moisture, which was detected after an analysis of correlation between the DGG cells and comparing the averaged water content of the eastern and western cells. Although there was an identical nominal class for all of the grid cells, a slightly smaller water content was systematically observed in the eastern areas. Indeed, SMOS detected the east–west spatial trend of the actual soil moisture contents related to the specific topographic and edaphoclimatic characteristics. This behavior may be explained by the different brightness temperature distribution along the footprint and by the specific way the SMOS instrument images the scene, as opposed to the method employed by classical real-aperture radiometers [37]. As expected, the brightness temperature over land can have important variations when strong rain events are present [38]. Thus, it may be possible that the smooth rainfall gradient observed along the east–west direction is being detected from the satellite. During the period of study, this gradient ranged from 480 mm of average precipitation for the eastern weather stations to 590 mm of average precipitation for the western stations.

With respect to the influence of land use, the forest–pasture stations were characterized by a larger error, exhibiting soil moisture contents above the average because of their specific site characteristics and soils. Two comments can be made at this point. First, all of the area is considered to be a nominal class in the retrieval algorithm for REMEDHUS; hence, there is no information about soil moisture over other land uses, i.e., forested areas. Second, due to the reduced spatial variability of the L2 soil moisture data, the best match occurs for averaged values of soil moisture. For the same reason, the stations that best fit the SMOS soil moisture data and exhibited a lower bias and RMSD values are in the most common land use areas and have intermediate values of soil water content. Because all of the DGG cells were considered to be within the same nominal class and that the percentage of forested/pasture cover is low (approximately 13%), the correlation analysis was repeated by discarding the forested/pasture stations. The results improved ($R = 0.72$, $\mathrm{RMSD} = 0.057\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, $\mathrm{RMSDc} = 0.047\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$, and $bias = 0.032\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$). Nevertheless, it is preferable to maintain the stations of all of the land cover classes because it is a more realistic scenario of the ground conditions in the area.

V. Conclusion

The *in situ* soil moisture series and the SMOS L2 data have been compared for the first time in the REMEDHUS network located in the semiarid central part of the Duero basin (Spain). The first results showed an acceptable correlation between SMOS L2 data and the observed *in situ* soil moisture. For the average data of both series, the correlation coefficient was $R = 0.73$. Similar results have been obtained when the averaged soil moisture at the stations was compared with each SMOS cell or, inversely, when the averaged data of the SMOS cells were compared with each station. No differences were found when daily values were chosen instead of the time-overpass data nor between the results of the descending and ascending orbits.

Overall, an underestimation of $0.053\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$ was found between the SMOS and the *in situ* soil moisture data. If a debiased RMSD is calculated, it can be concluded that the SMOS L2 data are close to meeting the mission requirements in the REMEDHUS test site, with an overall RMSDc of $0.044\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$. In other words, the system detected soil moisture anomalies within the expected accuracy, and it was able to detect the ground soil moisture evolution over time at the REMEDHUS site. Likewise, even though there is no statistical evidence, SMOS systematically detects a spatial soil moisture pattern in this area.

Due to the overall homogeneity of the area, the averaged network soil moisture value performed in a similar manner as the most representative station, as well as most of the stations when analyzed individually. This average properly describes the large-scale values of SMOS. We must investigate in greater detail the impact of the scale of the retrieval and, hence, the probably oversampled L2 data. More research concerning the down/up scaling strategies seems necessary using current monitoring sites such as REMEDHUS, which roughly cover the SMOS footprint.

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