

SOIL MOISTURE FROM SATELLITE: A COMPARISON OF METOP, SMOS AND ASAR PRODUCTS

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Abstract

This paper describes the first outcomes of an activity aiming at validating the H-SAF soil moisture products derived from METOP-ASCAT data. For this purpose, an extensive comparison between SMOS and ASCAT derived soil moisture retrievals has been accomplished by considering the 25 km resolution ASCAT products and the SMOS level 2 products. Both Europe and Northern Africa have been considered and data acquired during 2010 have been used. The procedure that has been followed to accomplish the comparison is described together with the first results. The way the ASCAT soil moisture relative index has been converted into a volumetric moisture content, which represents a critical aspect of the comparison, is also described. Results have demonstrated that, after the conversion of the H-SAF estimates into absolute volumetric soil moisture, the two products show a fairly good degree of correlation. Additional factors, such as spatial property features are also preliminary investigated.

INTRODUCTION

The role of soil moisture as a key variable for the characterization of the global climate is widely recognized within the international scientific community. The importance of its monitoring stems from the fact that it influences the water cycle by controlling the partition of rainfall between land (infiltration, percolation and runoff) and the atmosphere (evaporation and plant transpiration). Its knowledge is therefore essential for several applications, such as drought and flood predictions, meteorology, climatology and agronomy. Moreover, soil moisture maps at different spatial scales are currently used as realistic initial states for the soil moisture predictions performed by hydrological models and numerical weather models (Brocca et al., 2012; Panegrossi et al., 2011), as well as for models of plant growth and carbon fluxes.

Volumetric soil moisture content (*SMC*) data can be directly obtained from in situ measurements, but soil moisture ground stations are generally very sparse so that the spatial variation of soil moisture cannot be retrieved and many geographic areas are unmapped. Alternatively, soil moisture can be measured at a variety of spatial and temporal scales using remote sensing techniques, which offer synoptic view and regular sampling. Although volumetric soil moisture content (*SMC*) can be indirectly measured by looking at the thermal inertia in the thermal infrared spectral band, a direct sensitivity of remote sensing measurements to *SMC* occurs at microwave bands. Basically, the capability of microwave remote sensing sensors to retrieve soil moisture depends on the large difference between the dielectric constant (ϵ) of dry soil ($\sim 3-6$) and of water that, below its relaxation frequency (~ 17 GHz at 20 °C), is approximately in the order of the ϵ in static conditions (when frequency goes to zero the real part of the relative permittivity of water is equal to about 78.3).

Microwave remote sensing encompasses both active and passive forms, depending on the sensor and its mode of operation. Passive sensors (radiometers) detect the naturally emitted microwave radiation within their field of view. In order to detect sufficient energy to record a signal, the field of view of microwave radiometer's antennas should be large, resulting in a coarse spatial resolution (tens of km). Active microwave sensors provide their own source of illumination and basically measure the ratio (in terms of power density) between the transmitted and received electromagnetic radiation (i.e., the radar backscattering). Among active sensors, scatterometers, which are primarily used to obtain information on wind speed and direction over ocean surfaces, offer the opportunity to achieve revisit times consistent with the requirements of a soil moisture product (in the order of five days, or less), although their spatial resolution is similar to that of microwave radiometers. It must be noted that in the near future, even synthetic aperture radars (SARs) will offer revisit times in the order of six days (or less, in Europe and Canada), thanks to the forthcoming Sentinel-1 mission.

Actually, L-band (~1.4 GHz) is the optimal spectral range to observe soil moisture because of its larger penetration into the soil with respect to higher frequencies and because of its low sensitivity to nuisance parameters, such as soil roughness and vegetation canopy. Consequently, the first satellite mission carrying a microwave radiometer designed for soil moisture, i.e., the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) satellite (Kerr et al., 2001), uses an L-band interferometric radiometer (MIRAS). The Aquarius SAC-D instrument and the future Soil Moisture Active and Passive (SMAP) mission use two L-band instruments, i.e., a passive radiometer and an active radar; however SMOS, launched on November 2009, is the first instrument (either active or passive) at L-band dedicated to this application.

Even sensors operating at C or higher frequency bands turned out to be useful for SMC mapping. In particular, sensitivity to SMC was demonstrated by the Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E) aboard the AQUA satellite (Gruhler et al., 2010) and by active instruments, such as the ENVISAT/Advanced Synthetic Aperture Radar (ASAR) (Pathe et al., 2007; Panegrossi et al., 2011), the Airborne Synthetic Aperture Radar (AirSAR) (Pierdicca et al., 2010), the SIR-C radar (Pierdicca et al., 2008) and the scatterometer onboard ERS (Wagner et al., 1999).

When comparing SMC estimates from different instrument for cross-validation purposes, the different quantities measured by active and passive sensors must be accounted for. Radar backscattering, and surface emission are in some way related, being sensitive to soil parameters, as well as to vegetation conditions, but their relationships with SMC are not identical. Considering also the scarcity of in situ measurements previously pointed out, it can be stated that both the validation of remotely sensed soil moisture products and their intercomparison can be considered a fairly hard task.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Satellite Application Facility (SAF) on support to operational hydrology and water management (H-SAF) was established by the EUMETSAT Council in July 2005, with the objectives of providing new satellite-derived products for use in operational hydrology, and performing independent validation of these products. Within the framework of the soil moisture H-SAF product validation activity, a fairly extensive comparison between the H-SAF SMC estimated from the Advanced SCATterometer (ASCAT) onboard the METOP-A satellite, working at C-band (5.255 GHz) and that retrieved from SMOS is carried out in this study. Such a comparison, accomplished also by Parrens et al. (2012), by considering the SMC estimates over France, is extended here to the whole Europe and to North Africa. The comparison, performed for the year 2010, revealed a fairly good correlation (~0.68) between the two different estimates, although it must be underlined that, since the ASCAT retrieval is actually a soil moisture index (relative to a reference range of moisture, i.e. the maximum and minimum value for each site) and not an absolute quantity, to convert the ASCAT soil moisture index (SMI, adimensional) into volumetric Soil Moisture Content (SMC, in m^3/m^3), a sort of normalization has been performed, as described in the next section.

THE DATA SET AND THE METHODOLOGY

As mentioned in the introduction, METOP-ASCAT derived products and MIRAS-SMOS ones have been compared. ASCAT is a radar instrument that measures radar backscatter at C-band in vertical polarization. Measurements are taken on both sides of the sub-satellite track over two 550 km wide swaths, from a 817 km height orbit and with an orbit repetition interval of 5 days. The SM-OBS-1 products, available through the Eumetsat H-SAF project, have been used for the comparison. They are produced by means of the TU-Wien algorithm (Wagner et al., 1999) with a spatial resolution of 25 Km and resampled to a 12.5 km grid; for each SM-OBS-1 map, a pixel *SMI* value represents a relative value (between 0% and 100%) of moisture with respect to the driest conditions and the wettest ones registered for that pixel during the calibration phase of the TU Wien algorithm. As for MIRAS-SMOS, it measures surface emission at 1.427 GHz (L-band) from a 758 height orbit with a repetition time of 3 days and a spatial resolution of 35 km. The reprocessed L2 products that provide an actual volumetric moisture content, have been used; they are sampled over the ISEA4h9 grid, which has a spacing in the order of 15 km.

In order to minimize the temporal mismatch between daily SMOS and ASCAT data over Europe, only the SMOS ascending orbits and the METOP descending orbits have been selected, thus obtaining a time offset in the order of 4÷6 hours, since the SMOS ascending passes over Europe occur between 1.00 and 6.30 UTC, while the METOP descending overpasses occur in the interval 8.00÷12.00 UTC. In order to co-locate ASCAT and SMOS products, for each ASCAT grid point the closest SMOS grid point has been searched for (i.e., a nearest neighbor approach has been adopted). The spatial distance between centers of SMOS and ASCAT grid points has the most probable value of 6.5 km, and 8.8 km as the largest one, whereas the most probable value of the time difference is in the order of 250 min. Figure 1 shows the histograms of the spatial (left panel) and temporal (right panel) distances between co-located ASCAT and SMOS grid points. Considering that METOP has two sub-swaths whose total across track extension is considerably high, larger than the SMOS swath, in the same day more than one METOP pixel might be associated to a ISEA4h9 grid point at the considered latitudes; in this case, the ASCAT measurement closest in time to the SMOS one has been selected.

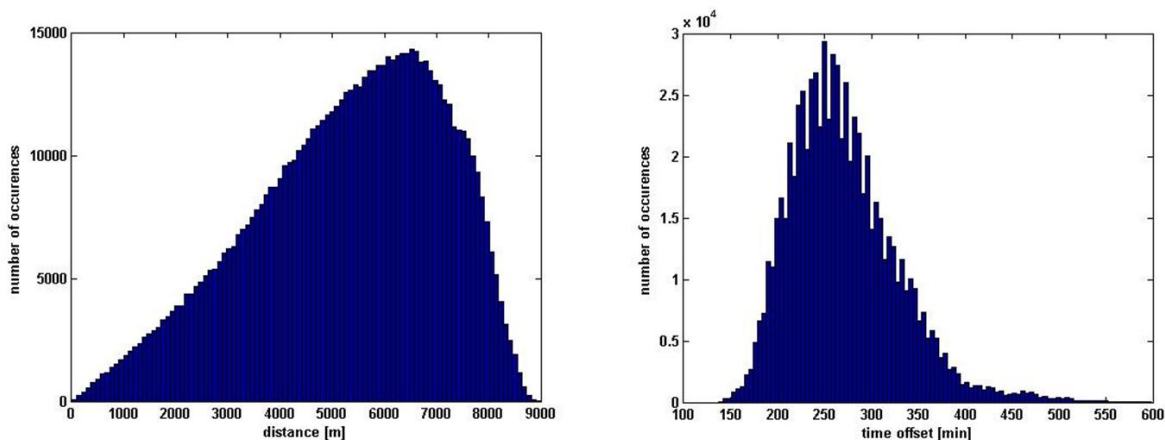


Figure 1: Histograms of the spatial (left panel) and temporal (right panel) distances between co-located ASCAT and SMOS grid points.

The fact that the ASCAT-derived soil moisture product is actually an index, represents a critical aspect for the purpose of a comparison with a SMOS-derived product. In fact, to carry out a reliable comparison, the two moisture products should be expressed by the same unit of measurement; consequently, the ASCAT *SMI*'s have been converted into volumetric moisture in m^3/m^3 . To this end, maps of the maximum and minimum values of SMOS *SMC* have been produced for the year 2010; they are shown in Figure 2. Each pixel of an H-SAF map, according to the definition of *SMI* (between 0 and 100), has been converted into an absolute value of *SMC* through a linear transformation as in the following :

$$\frac{SMC - \min(SMC_{SMOS})}{\max(SMC_{SMOS}) - \min(SMC_{SMOS})} = \frac{SMI}{100} \quad (1)$$

To avoid outliers, $\max(SMC_{SMOS})$ and $\min(SMC_{SMOS})$ have been evaluated by considering values in the interval 1%÷99% of the SMOS SMC histogram. Note that a perfectly equivalent approach could consist in scaling the SMOS absolute SMC into a relative quantity using their own maximum and minimum values over the year 2010 as done in other works comparing H-SAF for instance with ground measurements of soil moisture (e.g. Albergel et al., 2012).

ANALYSIS OF THE RESULTS

Figure 3 shows the result of the comparison in the form of a scatterplot between SMOS and ASCAT SMC values. With respect to the total number of collocations, data points have been filtered using the values of the processing flags reported in both products. SMOS data have been rejected when *DQX* (Data Quality index) was greater than 0.045, whereas H-SAF data have been disregarded when more than 3 bad quality flags were up, thus obtaining a database of 795310 records. The first row of Table 1 reports the main statistical scores describing the matching between the two instruments, namely the correlation coefficient (*R*) between SMOS and ASCAT SMC, the root mean square difference (*RMSD*), the bias, and the slope of the best fit line (red in Figure 3).

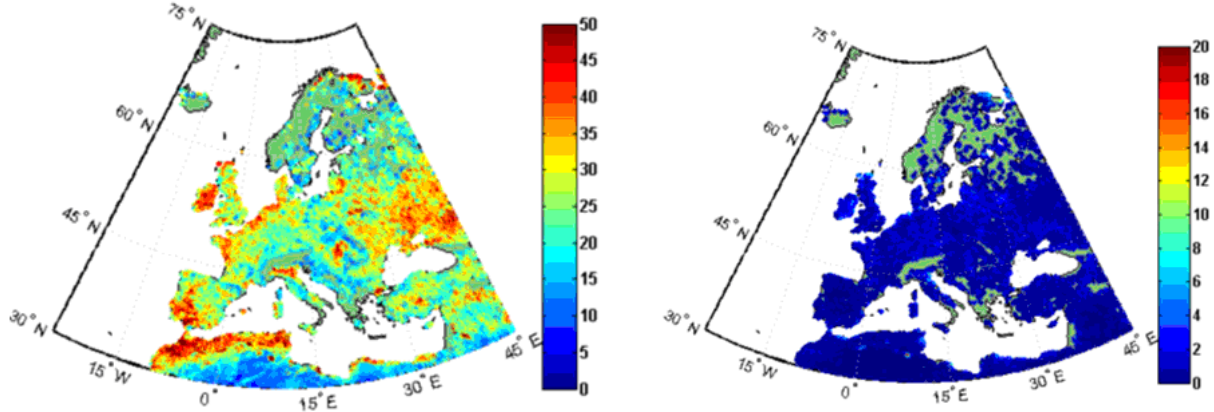


Figure 2: Maps of maximum (left) and minimum (right) SMOS SMC (expressed in percentage of volumetric soil moisture, $100 \cdot m^3/m^3$) for year 2010 in the study area over Central Europe and Northern Africa.

Note that the number of collocations is limited by the fact that not all the daily orbits of the two instruments have been processed yet. Another limitation to the number of collocations originates by the Radio Frequency Interferences (RFI) affecting SMOS. Moreover, the combination of a descending and ascending orbit implies that most of the combined points are located in the African continent, especially in the driest zone, as indicated by the large density of points in Figure 3 close to the origin of the plot (dark red). Nevertheless, a fairly good correlation ($R=0.68$) between the two products can be observed, although the points are quite scattered so that the *RMSD* overcomes 6%. The contribution to the observed discrepancies of the time and space mismatches should be better analyzed, but, at a first glance, at least the space mismatch does not seem to be a problem and by selecting only the closest pairs the scores do not change significantly. Better results are expected from a smarter selection of the data to be compared, based on surface conditions (latitude, season, and/or land cover).

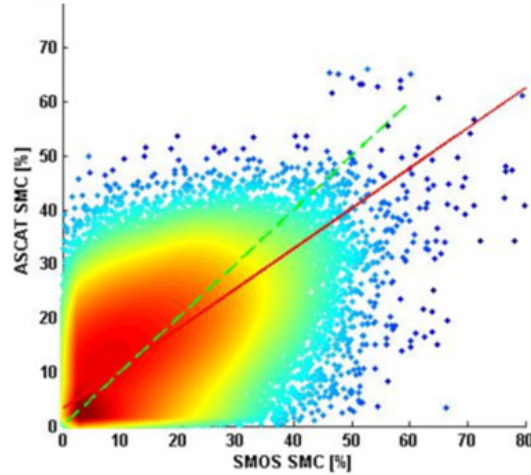


Figure 3: SMOS SMC versus co-located H-SAF SMC (after the conversion of the latter into absolute volumetric soil moisture). The red line represents the best fit, while the different colors represent the points density in the scatterplot (i.e., blue; few points; red: many points).

In Table 1 the statistical scores obtained by separately considering three different regions (Western Europe, Eastern and Northern Africa) are also reported. In addition, the results obtained by analyzing two periods of the year (Winter and Autumn as opposed to Spring and Summer) are shown. Data points characterized by forest cover have been also filtered out. It can be noted that the best results are obtained by considering the Northern Africa. However, this outcome is mainly related to the presence of the steady and very dry desert as opposed to the Mediterranean coast that presents a large moisture dynamic. We also observe that the Winter/Autumn comparison exhibits a larger value of R due to the higher dynamic range of moisture values. Finally, it must be noted that the rejection of forested areas has significantly improved the results, as expected.

	All Data	W Europe	E Europe	N Africa	Winter & Autumn	Spring & Summer	without forest
Corr. Coeff.	0,68	0,54	0,54	0,67	0,71	0,65	0,73
RMSD [%]	6,6	7,3	8,2	4,3	6,3	6,7	6,0
Bias [%]	1,1	1,8	4,1	-1,6	0,6	1,6	-0,2
Slope	0,74	0,47	0,49	0,50	0,77	0,71	0,78
nRecord [#]	795310	162939	265922	272553	412504	382806	537100

Table 1: Statistical scores (Root Mean Square Difference, Correlation Coefficient, Bias, Slope of Fitting line) of the comparison between ASCAT and SMOS derived SMC products.

We have preliminarily analyzed the capability of the quality indices and flags included in the product to provide a reliable indication to the users about the quality of the SMC estimates. At the moment, we have focused our attention on the SMC DQX available from SMOS. For details on how this index is computed the reader may refer to the SMOS documentation. We have found that filtering data with SMC DQX below a given threshold does not substantially change the results of the comparison, whatever the threshold is. Conversely, filtering data according to smaller thresholds on the ratio between DQX and the value of retrieved SMC (i.e., a sort of relative SMC DQX) certainly improves the comparison with ASCAT products. It produces lower $RMSD$ and higher correlation, as displayed in Figure 4, where the statistical scores are plotted as function of the threshold.

Considering that the transformation that has been carried out for comparing SMOS and ASCAT SMCs influences both bias and $RMSD$, the most reliable parameter to evaluate the results of the comparison is represented by R . For this reason, it may be interesting to see where the two products are correlated or not, so that sites exhibiting a suspicious behavior can be identified. A map of R has been therefore produced and is shown in Figure 5. Smaller correlation (even negative) has been obtained in the desert area, where the range of moisture variability is very small and the behavior of the two instruments is quite

incoherent. Some problems can be also observed in the Northern regions. However, it is required to complete the data collection and processing in order to ensure a suitable number of data in each grid point for a better estimation of R (note the voids in the figure, which are due to a few number of colocations).

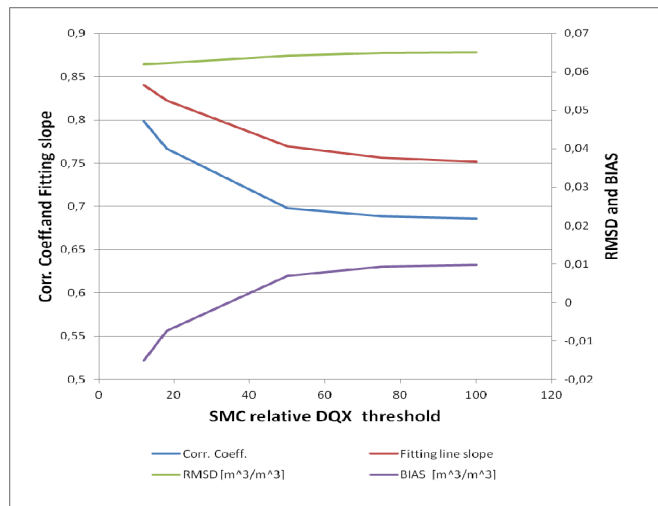


Figure 4: Statistical scores (R , $RMSD$, slope of the fitting line and bias) of the comparison between SMOS and H-SAF products as function of the threshold applied to the relative SMC DQX to filter the data.

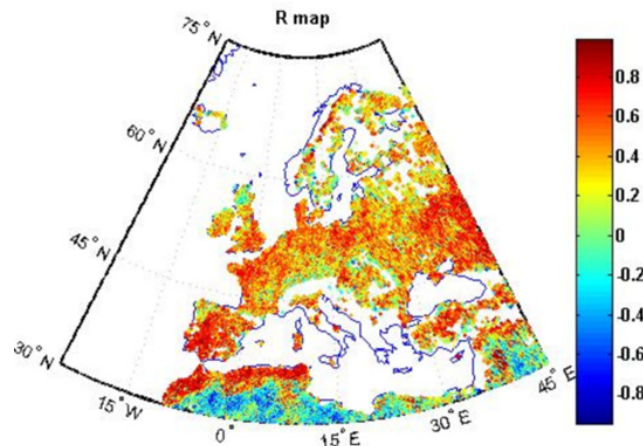


Figure 5: Map of the correlation coefficient (R) between ASCAT and SMOS SMC..

CONCLUSIONS

Within the framework of the H-SAF products validation activity, an extensive comparison between SMOS and ASCAT derived soil moisture retrievals is presently accomplished by considering the 25 km resolution ASCAT products and the SMOS L2 products. Both Europe and Northern Africa are considered and data acquired during 2010 are used at the moment. The most critical aspect of this study consists of the transformation of the ASCAT soil moisture relative index into a volumetric moisture, which implies that the correlation coefficient represents the most reliable statistical score to evaluate the results of the comparison. Results have demonstrated that the two products show a fairly good degree of correlation; some conditions affecting the comparison (geographical area, season, land cover) can be pointed out for a better characterization of the quality the final user should expect. Future work will concern the assessment of the estimates by widening the database, considering also the years 2011 and 2012 and the use of ground data, as those belonging to the International Soil Moisture network.

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