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Title: A Comparison of ASCAT and SMOS Soil Moisture Retrievals Over Europe and Northern Africa from 2010 to 2013

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Abstract: Abstract: A comparison between ASCAT/H-SAF and SMOS soil moisture products was performed in the frame of the EUMETSAT H-SAF project. The analysis was extended to the whole H-SAF region of interest, including Europe and North Africa, and the period between January 2010 and November 2013 was considered. Since SMOS and ASCAT soil moisture data are expressed in terms of absolute and relative values, respectively, different approaches were adopted to scale ASCAT data to use the same volumetric soil moisture unit. Effects of land cover, quality index filtering, season and geographical area on the matching between the two products were also analyzed. The two satellite retrievals were also compared with other independent datasets, namely the NCEP/NCAR volumetric soil moisture content reanalysis developed by NOAA and the ERA-Interim/Land soil moisture produced by ECMWF. In situ data, available through the International Soil Moisture Network, were also considered as benchmark. The results showed to be influenced by the way ASCAT data was scaled. Correlation between the two products can exceed 0.6, while the root mean square difference does not decrease below 8 %. ASCAT generally shows a fairly good degree of correlation with ERA, while, as expected considering the different kinds of measurement, the discrepancies with respect to local in situ data are large for both satellite products.

Opposed Reviewers:

Dear Editor,

we are pleased to submit our manuscript “A Comparison of ASCAT and SMOS Soil Moisture Retrievals Over Europe and Northern Africa from 2010 to 2013” for the *Special Issue: Advances in the Validation and Application of Remotely Sensed Soil Moisture*.of the International Journal of Applied Earth Observation and Geoinformation.

Our paper is focused on the comparison between ASCAT/H-SAF and SMOS soil moisture products in the frame of the EUMETSAT H-SAF project. We have analyzed the effects of quality index filtering, land cover, geographical area and season on the matching between the products; a fairly good degree of correlation between the products has been observed. The two satellite retrievals have been also compared with other independent datasets, namely the NCEP/NCAR volumetric soil moisture content reanalysis developed by NOAA and the ERA-Interim/Land soil moisture produced by ECMWF.

Kind regards

Fabio Fascetti

Reviewers' comments:

Dear Fabio,
I am happy to announce that I accept your manuscript for publication. I'd only suggest to have a final grammar check by a native speaker, especially regarding the use of the past simple and present perfect.
Thank you for choosing our special issue to publish your research,
Best regards,
Wouter Dorigo

Dear Guest Editor,
We would like to thank you and the reviewers for the relevant observations. We have reported our corrections related to the grammar check below.

Paper Implementation:

Page 1 Line 17: “has been performed” has been replaced with “was performed”.
Page 1 Line 18: “has been extended” has been replaced with “was extended”.
Page 1 line 21: “has been considered” has been replaced with “was considered”.
Page 1 line 23: “have been adopted” has been replaced with “were adopted”.
Page 1 line 28: “have been also analyzed” has been replaced with “were also analyzed”.
Page 1 line 28: “have been also compared” has been replaced with “were also compared”.
Page 1 line 32: “have been considered” has been replaced with “were also considered”.
Page 1 line 32: “ Results have turned out to be influenced by the way ASCAT data have been scaled.” has been replaced with “The results showed to be influenced by the way ASCAT data was scaled”.
Page 1 line 38: “for both the satellite” has been replaced with “ for both satellite”.
Page 1 line 58: “dielectrical” has been replaced with “dielectric”.
Page 2 line 6: “From now on, we indicate with ASCAT the product available through H-SAF” has been added into the text.
Page 2 line 7: “ideal one” has been replaced with “ ideal frequency”.
Page 2 line 24: “SMAP is still in commissioning phase, having been launched in January 2015” has been replaced with “SMAP was recently launched”.
Page 2 line 25: “one of” has been deleted.
Page 2 line 25: “derived ones” has been replaced with “derived SMC”.
Page 2 line 27: “several years” has been replaced with “several years ago”.
Page 2 line 31: “performing” has been replaced with “enabling”.
Page 2 line 33: “considered limited areas” has been replaced with “generally considered limited”.
Page 2 lines 36-39: the sentences have been replaced with “In this study, a comparison of ASCAT and SMOS soil moisture products was also performed. The region of interest was extended to the whole H-SAF region, including Europe and Northern Africa, and the period between January 2010 and November 2013 was considered”.
Page 2 line 45: “From now on we indicate with ASCAT the product available through H-SAF” has been deleted.
Page 2 line 48: “501” has been replaced with “ 5.01”.
Page 2 line 55: “allows deriving” has been replaced with “allows at deriving”.
Page 3 line 1: “[22] In this” has been corrected in “[22]. In this”.
Page 3 line 1: “evaluated” has been replaced with “assessed”.
Page 3 lines 8-9: “gives useful indication on the accomplishment of a quality control of the data to select” has been replaced with “gives useful indications for a better quality control of the data to select”.
Page 3 line 15: “are reported and subsequently,” has been replaced with “is presented and finally,”.

Page 3 line 16: "described" has been replaced with "drawn in section 4,".
Page 3 line 31: "a 817" has been replaced with "an 817".
Page 3 line 41: "In the sequel" has been replaced with "Hereafter".
Page 3 line 46: "height of 758 km with a repetition" has been replaced with "height of 758, a repetition".
Page 3 line 49: "an" has been deleted.
Page 3 line 51: "which has a spacing" has been replaced with "which has spacing".
Page 3 line 52: "the processor generating the products is the current" has been replaced with "the processor generating the products was the current".
Page 4 line 26: "grid point center" has been replaced with "grid centers".
Page 4 line 32: "have been co-located" has been replaced with "were co-located".
Page 4 line 42: "has been searched" has been replaced with "was searched".
Page 4 line 44: "have been combined" has been replaced with "were combined".
Page 4 line 45: "has been used to" has been replaced with "was used to".
Page 4 line 47: "have been up-scaled" has been replaced with "were up-scaled".
Page 4 line 53: "have been chosen in order to" has been replaced with "were selected as to".
Page 4 line 56: "SD_{ASCAT} has been converted" has been replaced with "SD_{ASCAT} was converted".
Page 4 line 59: "values have been computed" has been replaced with "were computed".
Page 4 line 60 :"SD_{ASCAT} has been converted to" has been replaced with "was converted".
Page 5 line 1: "It is worth to mention that a similar analysis can be obtained scaling the satellite soil moisture products using different normalizations approach, like linear regression and CDF matching [29]" has been replaced with "It is worth mention that a similar analysis can be obtained by scaling the satellite soil moisture products using different approaches, such as linear regression and CDF matching [29]".
Page 5 line 6: "SD has been transformed" has been replaced with "SD was transformed".
Page 6 line 24: "Commissioning" has been corrected in "commissioning".
Page 6 line27: "we have performed as described in the previous section" has been replaced with "that was performed and described in the previous section"
Page 5 line 51: "red lines are perfect" has been replaced with "red lines point to perfect".
Page 6 line 25: "similar considerations can be done, so that we can state that" has been replaced with "similar considerations were obtained, so one can state that".
Page 6 line 28: "An" has been replaced with "The".
Page 6 line 31: "have been observed" has been replaced with "were observed".
Page 6 lines 31-34: "This is consistent with our finding, that is with a reduced underestimation (i.e., reduce positive bias of version 5.51) of SMOS with respect to ASCAT" has been replaced with "This is consistent with our finding of a reduced positive bias version 5.51 of SMOS with respect to ASCAT".
Page 6 line 37: "as expected with respect of using SMOS" has been replaced with "when compared to the use of SMOS, as expected".
Page 6 line 43: "reported" has been replaced with "presented".
Page 6 line 46: ""slope S " has been replaced "slope S (adimensional)".
Page 7 line 1: "In what follows we analyze some regional and temporal dependence of the comparison between SMOS and ASCAT, " has been replaced with "In what follows, the regional and temporal dependence of the comparison between SMOS and ASCAT is analysed, ".
Page 7 line 1: "for what concerns these aspects," has been replaced with "for the previous aspects,".
Page 7 line 8: "attained" has been replaced with "obtained".
Page 7 line 11: "is achieved when using" has been replaced "holds when considering".
Page 7 line 16: "doesn't match" has been replaced "does not match".
Page 7 line 16: "this is because we have adopted two different thresholds on the longitude" has been replaced with "this is because two different thresholds on the longitude were adopted".
Page 7 line 18: "relevant" has been replaced with "significant".
Page 7 line 18: "is obtained" has been replaced with "was obtained".

Page 7 line 19: “labelled” has been replaced with “labeled”.
Pge 7 line 23-26 : ”Considering the other methods to rescale SDASCAT, the results are substantially the same for what concerns the differentiation in terms of geographical areas, seasons and land cover, so that in the sequel of section 3.1 only the scaling using SMOS will be considered.” has been replaced with ”Considering the alternative methods to rescale SDASCAT, the results are substantially the same in terms of considering different geographical areas, seasons and land cover. Therefore, in what follows in this section only the scaling using SMOS will be considered”.
Page 7 line 32: “In particular, we found” has been replaced with “In particular, it was found”.
Page 7 line 39: “has not improved” has been replaced with “did not improve”.
Page 7 line 40: “has” has been deleted.
Page 7 line 45: “Moreover, as far as the probability of” has been replaced with “Concerning”.
Page 7 line 46: “is concerned” has been deleted.
Page 7 line 47: “are discarded” has been replaced with “were discarded”.
Page 7 line 49: “are selected” has been replaced with “were selected”.
Page 7 line 49: “Point with very” has been replaced with “Using only points with very”.
Page 8 line 14: “is rescaled” has been replaced with “was rescaled”.
Page 8 line 20: “a much higher correlation is observed in Winter” has been replaced with “ a larger correlation is observed in winter”.
Page 8 line 23: “Summer” has been replaced with “summer”.
Page 8 line 23: “The presence of smaller scale” has been replaced with “This result could be explained by the presence in summer of smaller scale”.
Page 8 line 24: “in Summer could be an explanation of this finding” has been deleted.
Page 8 line 26: “ Autumn and Winter” has been replaced with “autumn and winter too”.
Page 8 line 27: “higher” has been replaced with “larger”.
Page 8 line 28: “ A larger agreement when discarding forested targets, less influenced by the season, is also apparent from the figure” has been replaced with “Figure 3 also shows a better agreement in the comparison when discarding forested targets, less influenced by thee season”.
Page 8 line 57: “A summary” has been replaced with “Table 3 presents a summary”.
Page 8 line 57: “is presented in Table 3” has been deleted.
Page 8 line 60: “have been calculated on the common period” has been replaced with “were calculated for the common”.
Page 8 line 61: “is obtained” has been replaced with “was obtained”.
Page 9 line 1: “is also obtained” has been replaced with “was also obtained”.
Page 9 line 1: “has been found also in” has been replaced with “was also found”.
Page 9 line 26: “have been independently investigated” has been replaced “were investigated independently”.
Page 9 line 27: “has been computed” has been replaced with “was computed”.
Page 9 line 28: “correlation is not dependent on” has been replaced with “correlation coefficient is independent on”.
Page 9 line 31: “We can see” has been replaced with “It can be obsverved”.
Page 9 line 32: “ASCAT is compared” has been replaced with “ASCAT was compared”.
Page 9 line 33: “has been found” has been replaced with “was found”.
Page 9 line 37: “However, such behavior is already known in literature, and could be addressed to the different operating principle of the two sensors.” has been deleted.
Page 9 line 39: “ it leads to” has been deleted.
Page 9 line 40: “considered region, retaining a positive” has been replaced with “considered region were obtained, whereas positive”
Page 9 line 41: “over desert, as shown in Fig.4” has been replaced with “over desert were observed (see Fig.4)”.

Page 9 line 41: "The different behavior of SMOS and ASCAT over desert is already know in literature, and could be addressed to the different operating principle of the two sensors" has been added into the text.
Page 9 line 46: "the extreme Northern areas" has been replaced with "the northernmost areas".
Page 10 line 22: "has been scaled" has been replaced with "was scaled".
Page 10 line 28: "we have computed" has been deleted.
Page 10 line 28: "correlation coefficient among collocated data collected during the same day" has been replaced with "correlation coefficients among collocated data collected during the same day were computed".
Page 10 line 29-34: "The SD relative index form ASCAT has been converted into the absolute SMC trhough the porosity map, in order to avoid introducing any kind of correlation between SMOS and ASCAT respect to the other data used for the comparison" has been replaced with "In order to avoid introducing any kind of correlation between SMOS and ASCAT respect to the other data used for the comparison, the SD relative index from ASCAT was converted into the absolute SMC through the porosity map".
Page 10 line 34: "We can see that" has been replaced with "It can be observed that".
Page 10 line 39: "substantially constant during the year (slightly better in Spring)" has been replaced with "and it quite stable during the whole year (slightly better in spring)".
Page 10 line 41: "Winter" has been replaced with "winter".
Page 11 line 34: ""the several networks" has been replaced with "the different networks".
Page 11 line 36: "The figure" has been replaced with "This figure".
Page 11 line 45: "(bias and gain), which is considered of no interest when looking at the temporal variability of soil moisture, so that in each site the satellite retrievals are standardized" has been replaced with "(bias and gain). This can be considered irrelevant when looking at the temporal variability of soil moisture. Hence, at each site the satellite retrievals were standardized".
Page 11 line 48: "The lower panel in Figure 6" has been replaced with "The lower panel of Figure 6".
Page 12 line 36: "performance are basically" has been replaced with "performance is basically".
Page 12 line 36: "we have considered together" has been deleted.
Page 12 line 37: "Table 6" has been replaced with "Table 6 were considered together".
Page 12 line 38: "according to the need of the final user" has been replaced with "according to the end user needs".
Page 12 line 38; " For instance if the user is interested just to monitor the temporal variability," has been replaced with "For instance, if the end user is interested at just monitoring the temporal variability".
Page 12 line 40: "its mean value it may" has been replaced with "its mean value, then it may".
Page 12 line 43: "requires to know" has been replaced to "requires knowing".
Page 12 line 17: "colocations" has been replaced with "collocations".
Page 13 line 7: "Restricting to the period January 2010 – March 2012, it has been possible observe the improvements brought by the new processor version" has been replaced with "The improvements brought by the new processor version were possible to observe by limiting the period from January 2010 to March 2012".
Page 13 line 11: "and bias (from 11.85 to 7.75) has been observed" has been replaced with "mainly associated to a decrease of the bias (from 11.85 to 7.5) were observed".
Page 13 line 14: "are analysed" has been replaced with "were analysed".
Page 13 line 21: "(European Organization for the Exploitation of Meteorological Satellites" has been deleted.
Page 13 line 22: "(Hydrology-Satellite Application Facility)" has been deleted.
Page 13 line 23: "has been carried out" has been replaced with "was carried out".
Page 13 line 27: " has been performed" has been replaced with "was performed".
Page 13 line 29: "As a first outcome, we did not find substantial changes in the results of the comparison between SMS and ASCAT products due to the change the SMOS processor (from version 5.01 to verison 5.51)." has been replaced with "As a first results, substantial changes in the comparison between SMOS and

ASCAT products due to the change the SMOS processor (from version 5.501 to version 5.51) were not found”.

Page 13 line 31: “ When using SMOS data to scale ASCAT ones” has been replaced with “If SMOS data was used to scale ASCAT data”.

Page 13 line 31: “show” has been replaced with “showed”.

Page 13 line 32: “reaches” has been replaced with “reached”.

Page 13 line 33: “difference is in the” has been replaced with “difference was in the”.

Page 13 line 34: “where processor 501 SMOS data and a short temporal period have been considered” has been replaced with “where SMOS processor version 5.01 and a short temporal period was considered”.

Page 13 line 38: “has been quantitatively” has been replaced with “was quantitatively”.

Page 13 line 39: “increases” has been replaced with “increased”.

Page 13 line 40: “ERA-LAND for the” has been replaced with “ERA-LAND data for the”.

Page 13 line 42: “Another outcome” has been replaced with “Another result”.

Page 13 line 43: “has been analysed” has been replaced with “was analysed”.

Page 13 line 46: “It has been found” has been replaced with “It was found”.

Page 13 line 51: “has been proposed” has been replaced with “was proposed”.

Page 13 line 51: “this relative DQX has significantly improved the scores” has been replaced with “the relative DQX significantly improved the scores”.

Page 13 line 53: “model derived” has been replaced with “model-derived”.

Page 13 line 54: “have shown a good” has been replaced with “showed a good”.

Page 13 line 56: “difference has never fallen below” has been replaced with “difference never fell below”.

Page 13 line 56: “have been found for SMOS in agreement” has been replaced with “were found for SMOS, which is in agreement”.

Page 13 line 59: “between different datasets we have found some inconsistencies, for instance” has been replaced with “between different datasets some inconsistencies were obtained, for instance”.

Page 14 line 1: “ have been obtained” has been replaced with “were obtained”.

Page 14 line 1: “different kinds of scaling” has been replaced with “different approaches of scaling”.

Page 14 line 1: “ERA-LAND has provided the” has been replaced “ERA-LAND provided the best”.

Page 14 lines 1-2: “but correlation has not exceeded 0.55 and root mean square difference has exceeded 9%” has been replaced with “but the correlation did not exceeded 0.55 and the root mean square difference did not exceeded 9%”.

Page 14 line 3-4: “ASCAT scaled using the porosity has yielded the worst performances and SMOS has shown and intermediate behavior (correlation of 0.46 and rms difference of 12.6%)” has been replaced with “The worst performances were obtained with ASCAT scaled using the porosity maps, whereas SMOS showed an intermediate behavior (correlation of 0.46 and RMSD of 12.6%)”.

Page 14 line 15: “This work has been accomplished” has been replaced with “This work was accomplished”.

Page 14 line 17: “We thank Dr Silvia Puca from DPC for her support.” has been added into the text.

Page 14 line 17: “have been acquired” has been replaced with “were acquired”.

Highlights:

- Comparison of SMOS, ASCAT, NOAA NCEP/NCAR, ERA-Interim LAND and in situ soil moisture products;
- Data selection based on SMOS Radio Frequency Index and Data Quality index;
- Different ways to transform ASCAT index in volumetric moisture are compared;
- Temporal and Spatial correlation between the datasets are analyzed.

*Manuscript
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A Comparison of ASCAT and SMOS Soil Moisture Retrievals Over Europe and Northern Africa from 2010 to 2013

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Abstract: A comparison between ASCAT/H-SAF and SMOS soil moisture products was performed in the frame of the EUMETSAT H-SAF project. The analysis was extended to the whole H-SAF region of interest, including Europe and North Africa, and the period between January 2010 and November 2013 was considered. Since SMOS and ASCAT soil moisture data are expressed in terms of absolute and relative values, respectively, different approaches were adopted to scale ASCAT data to use the same volumetric soil moisture unit. Effects of land cover, quality index filtering, season and geographical area on the matching between the two products were also analyzed. The two satellite retrievals were also compared with other independent datasets, namely the NCEP/NCAR volumetric soil moisture content reanalysis developed by NOAA and the ERA-Interim/Land soil moisture produced by ECMWF. In situ data, available through the International Soil Moisture Network, were also considered as benchmark. The results showed to be influenced by the way ASCAT data was scaled. Correlation between the two products can exceed 0.6, while the root mean square difference does not decrease below 8 %. ASCAT generally shows a fairly good degree of correlation with ERA, while, as expected considering the different kinds of measurement, the discrepancies with respect to local in situ data are large for both satellite products.

Keywords: Remote sensing; SMOS; ASCAT; soil moisture

1. 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. Its knowledge is essential for several applications [1], such as drought and flood prediction, weather forecast, climatology and agronomy. Soil moisture maps from satellites are currently assimilated within hydrological models [2], or used as realistic initial states by numerical weather prediction (NWP) models [3].

Remote sensing represents a very useful tool to monitor soil moisture at different spatial and temporal scales; a direct sensitivity to the volumetric moisture content (in m^3m^{-3}, hereafter denoted as *SMC*) can be exploited at microwave bands, where *SMC* influences the soil dielectric permittivity and the atmosphere can be considered fairly transparent. The use of soil moisture maps derived from satellite microwave remote sensing measurements in operational applications is currently limited to instruments providing low spatial resolution data (scatterometers, microwave radiometers), because only these sensors offer a suitable temporal resolution (revisit time shorter than one week, [4]). For instance, within the framework of the EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) H-SAF (Hydrology-Satellite Application Facility) project, soil moisture maps derived from the C-band ASCAT scatterometer, on board the MetOp satellites are routinely produced at present. From now on, we indicate with ASCAT the product available through H-SAF.

Although C-band is not the ideal frequency for soil moisture retrieval applications, being sensitive also to soil roughness and to the presence of vegetation, literature studies demonstrated that both C-band radiometers [5] and scatterometers [6] can be useful for *SMC* mapping [7,8]. Even high resolution of C-band SAR's were exploited to estimate *SMC* by relying on proper retrieval techniques, such as change detection [9], multitemporal methods [10,11], as well as polarimetric measurements [12]. Because of L-band's large capability to penetrate soil and its reduced sensitivity to vegetation, satellites instruments specifically dedicated to soil moisture, as the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission [13], and the Soil Moisture Active Passive (SMAP) one [14,15], operate at this frequency range.

From the previous considerations, it can be deduced that it is worthwhile to perform a mutual assessment of a product derived from an instrument specifically built for soil moisture applications as SMOS (SMAP was recently launched) and an operational product such as the ASCAT derived SMC. Moreover, ASCAT and SMOS are in orbit since several years ago (Metop-A was launched in 2006 and SMOS in 2009) and this allows for building large datasets of co-located data useful for cross-validation purposes. These products can be further assessed taking advantage of other sources of soil moisture data such as land surface or numerical weather prediction models, and/or in situ data, thus enabling a very detailed comparison. Studies regarding a comparison between ASCAT and SMOS [16] generally considered limited areas [17] and/or limited periods of time [18]. In this study, a comparison of ASCAT and SMOS soil moisture products was also performed. The region of interest was extended to the whole H-SAF region, including Europe and North Africa, and the period between January 2010 and November 2013 was considered. This 4-years period, which includes several seasonal cycles, overpasses many previous analyses, thus representing a significant time and spatial extent.

A comparison between SMOS and ASCAT/H-SAF products over the same area of interest was already undertaken in a previous paper [19] for the period from January 2010 until March 2012. Besides the extension of the period of analysis, the present paper introduces the following new aspects: 1) a completely different dataset is considered, since SMOS products in [19] were from processor release 5.01, whereas in this paper they are from release 551; 2) a comparison with additional soil moisture datasets is introduced; 3) the impact of quality indices included in the SMOS products, such as Radio Frequency Interference (RFI) probability, on the matching between SMOS and ASCAT is analysed; 4) different techniques to relate ASCAT index to soil moisture are considered.

As for point 1), the analysis of a new SMOS dataset allows at deriving some indications on the impact of the change of the processor on the agreement with other soil moisture products. Regarding point 2), the satellite retrievals are also compared with the NCEP/NCAR volumetric soil moisture content reanalysis [20], developed by the National Oceanic and Atmospheric Administration (NOAA), the ERA-Interim/Land soil moisture, produced by ECMWF [21], and in situ data derived from the International Soil Moisture Network (ISMN) [22]. In this way some discrepancies between the satellite products already emerged in [19] and in other literature papers [23] can be assessed. In addition the comparison with other sources of data represents a more reliable cross-validation of satellite soil moisture products permitting a better identification of the areas where a product is likely more reliable than the other one. As for point 3), an evaluation of the impact of parameters like the RFI, which is known to be particularly critical for SMOS derived moisture data, gives useful indications for a better quality control of the data to select reliable moisture estimates. Note that a new Data Quality Index with respect to that included in the SMOS product is also proposed for this purpose.

The paper is organized as follows. Section 2 describes the available data and the applied pre-processing methods. In section 3, the comparison of data sources pairs is presented and finally the conclusions are drawn in section 4, including the comparison with the results reported in the literature.

2. Data and Methods

2.1 Data Sets

A short description of the data sets used in this work and their most relevant features is provided in this section, starting with satellite products.

The Advanced SCATterometer (ASCAT) is a real aperture radar sensor that operates at C-band in vertical polarization and measures the backscatter coefficient. Measurements are taken on both sides of the sub-satellite track over two 550 km wide swaths, from an 817 km height orbit. The H07 SM-OBS-1 product, available through the EUMETSAT H-SAF project, has been used for the comparison. The data are sampled on a 25 km grid and the product is generated by means of an algorithm originally conceived for the ERS-1/2 scatterometer, by the Technical University of Wien [6] and successively updated [24]. Each pixel value represents a relative value of moisture with respect to the driest and wettest conditions registered for that pixel during the calibration phase of the algorithm; this index is equal to the saturation degree *SD*, i.e., the soil moisture content expressed in percent of porosity. Hereafter we will refer to this product as SD_{ASCAT}.

The Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) interferometric radiometer on board the SMOS satellite measures the cross correlation between pairs of receivers to derive a visibility function [5] at L-band (1.427 GHz) from an orbit height at 758 km with a repetition time of 3 days and a horizontal spatial resolution between 35 and 50 km. The reprocessed ESA L2 product, that provides actual volumetric soil moisture content (hereafter denoted as SMC_{SMOS}), has been considered in this work. L2 data are sampled over the ISEA4h9 grid, which has spacing in the order of 15 km. It is worth to underline that the processor generating the products is the current 5.51 version.

Some additional comparisons have been also done using the 5.01 version (the one used in [19]). The main difference between the 5.51 and 5.01 processor versions is the change of the dielectric constant model. The latter uses the Dobson dielectric constant model [25], whereas the former adopts the Mironov model [26]. A detailed description of the two dielectric constant models can be found in [27].

The soil porosity map, used to convert SD_{ASCAT} into absolute *SMC*, is based on the Food And Agriculture (FAO) Soil Map of the World and it is available from the Global Land Data Assimilation System (GLDAS) website (http://ldas.gsfc.nasa.gov/gldas/).

The ERA-Interim/Land, produced by ECMWF, is a global atmospheric reanalysis combined with an ocean and a land surface model (LSM) available until 2012. Soil moisture is provided at different layers and time steps, every six hours over a grid with a spatial sampling of 0.75*0.75 degrees [28].

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis volumetric soil moisture content is available from the NOAA website (http://www.ngdc.noaa.gov/). These data represent a daily analysis/estimate of the volumetric soil moisture within a depth between 0 and 10 cm, available four times a day and sampled over a T62 Gaussian grid with 192*94 points.

The International Soil Moisture Network (ISMN) is an international cooperation coordinated by the Global Energy and Water Exchanges Project (GEWEX) in collaboration with the Group of Earth Observation (GEO) and the Committee on Earth Observation Satellites (CEOS), with the task of maintaining a global in situ soil moisture database (see http://ismn.geo.tuwien.ac.at) [22]. For our study, data collected at 0-5 cm depth in Denmark (HOBE), France (SMOSMANIA), Germany (TERENO, COSMOS and UDC_SMOS), Italy (Hydrol-Net_PERUGIA), Poland (SWEX_POLAND) and Spain (REMEDHUS and VAS) were used, where the terms into the parenthesis indicate the employed networks. The number of the available probes changes depending on the considered network and their own distance from the satellite grid centers.

2.2 Data Collocation and ASCAT rescaling

As a first step, ASCAT and SMOS data were co-located in time and space, retaining only data fulfilling the following conditions: SMOS retrievals with Data Quality Index (DQX) less than 0.045; ASCAT retrievals with less than 4 bad quality flags up; SD_{ASCAT} with value between 0 and 100% (values outside this range can be found and we assume them as unreliable); SMOS and ASCAT *SMC* retrievals below 0.7 m^3/m^3 (as greater values are not plausible). To minimize the temporal mismatch between ASCAT and SMOS observations, ascending MetOp orbits and descending SMOS orbits and vice versa were combined.

For each SMOS grid point, the closest ASCAT gridded observation was searched using the nearest neighbour approach. Once SMOS and ASCAT retrievals were combined on the ISEA4h9 grid, the nearest neighbour approach was used to resample ERA-LAND, NOAA and the porosity information on the same grid. As for the ISMN probes, the data were up-scaled to the satellite resolution, through averaging of the in situ measurements at 0-5cm depth within the satellite field of view. Only satellite values with at least one station closer than 10 km were retained in order to gather in situ measurements sufficiently representative of the satellite field of view. Since the ISMN probes are sampled every hour when available, the data were selected as to minimize the temporal matching with the satellite data (in the worst case the temporal mismatching is around 30 minutes).

SD_{ASCAT} was converted into volumetric moisture in m^3/m^3 (denoted as SMC_{ASCAT}) considering that, by definition, it represents the distance of each resolution cell from its driest and wettest soil conditions. Consequently, maps of the maximum and minimum *SMC* values were computed using different datasets. Namely, SD_{ASCAT} was converted to SMC_{ASCAT} using the SMOS L2 data and the other independent sources, i.e., the ERA-LAND and NOAA data collected throughout the period from 1990 to 2012 (a timeframe comparable to the period of calibration of the ASCAT retrieval algorithm). It is worth mention that a similar analysis can be obtained by scaling the satellite soil moisture products using different normalizations approaches, such as linear regression and CDF matching [29]. As an alternative, taking advantage of the availability of a soil porosity (ϕ) map, *SD* was transformed into *SMC* by multiplying it by ϕ, i.e., $SMC_{ASCAT} = \phi \cdot SD_{ASCAT}/100$. More details about the data collocation approach and the linear transformation adopted to scale the ASCAT product can be found in [19].

3. Comparison of data sources pairs: results and discussion

3.1 SMOS/ASCAT

Figure 1 shows the result of the comparison between SMC_{ASCAT} (scaled using SMOS) and SMC_{SMOS} values in the form of a scatterplot, considering the whole period from 2010 to 2013. We have included the beginning of 2010 in the comparison, which could be affected by MIRAS instrument stability problems not fully compensated by the on-ground calibration during the commissioning phase of the SMOS mission [30]. Removing that period does not change the results, also because of the data quality check that was performed and described in the previous section. Table 1 presents the correlation coefficient (*R*), the root mean square difference (*RMSD*), the bias (*B*), and the slope (*S*) of the best fit line (red in Figure 1) describing the matching between the two products.

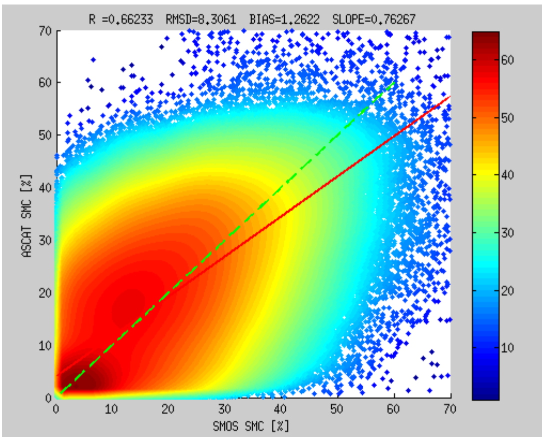

Figure 1: Scatterplot of *SMC* derived from ASCAT (using SMOS for scaling the *SD*) and SMOS using the whole set of data over the H-SAF region (years 2010-2013). The colour code indicates the density of points. Dashed green and red lines point to perfect agreement and best fitting lines, respectively.

Table 1: Correlation coefficient (*R*), root mean square difference (*RMSD*, %), *bias* (%), *slope* of the best fitting line between SMOS and ASCAT derived *SMC*. The number of colocations is included (last column) and different geographic regions within the H-SAF area and land cover categories are considered.

	R [#]	RMSD [%]	BIAS [%]	SLOPE [#]	nRecord
All Data	0.66	8.3	1.26	0.76	5973750
North Africa	0.63	5.5	-1.99	0.50	2098288

Western Europe	0.47	9.4	1.23	0.48	1517652
Eastern Europe	0.47	10.3	5.60	0.48	1730197
no forest	0.72	8.0	-0.07	0.81	4012575

A fairly good correlation (*R*=0.66) between the two products can be observed, although the points are quite scattered, so that the *RMSD* exceeds 8% m^3m^{-3}. The large value of the slope *S* (0.76 compared to an ideal 1:1 matching) demonstrates that, in general, the variations of SMC_{SMOS} are detected by SMC_{ASCAT} (and vice versa). The change from SMOS processing versions from 5.01 to 5.51 and the consideration of a longer timeframe slightly change the results with respect to those reported in [13]. In particular, while *R*, bias and slope are similar to those reported in the previous reference (*R*=0.67, *bias*=1.6% m^3m^{-3}, *S*=0.78), the worsening in terms of *RMSD* (7.3% m^3m^{-3} in [19]) is quite significant. Note that even by restricting the comparison between ASCAT and SMOS to the period January 2010 – March 2012 (the same considered in [19]), similar considerations were obtained, so one can state that the use of the new processor 5.51 implies that the comparison between ASCAT and SMOS derived *SMC* presents an overall larger *RMSD*, slightly less *R* and *S*, but a smaller bias. The effect of the new processor on the SMOS retrieval was also discussed in [27], where higher soil moisture values were observed with the Mironov model with respect to the Dobson one. This is consistent with our finding of a reduced positive bias of version 5.51 of SMOS with respect to ASCAT.

If the ASCAT *SD* is scaled using an independent dataset or the porosity map, the comparison with SMOS generally worsens when compared to the use of SMOS minimum and maximum maps, as expected. The overall correlation goes down to about 0.57 or less (when using porosity), with *RMSD* and bias significantly increasing, the latter reaching almost 12% m^3m^{-3} when considering NOAA, due to the much higher values of soil moisture predicted by that model. The results considering the whole 4-year dataset are presented in Table 2.

Table 2: Correlation coefficient (*R*), root mean square difference (*RMSD* in %), bias (%), slope *S* (adimensional) of the best fitting line and number of colocations between SMOS and ASCAT *SMC* using different approaches to scale *SD* to absolute *SMC*.

	R [#]	**RMSD [%]**	**BIAS [%]**	**SLOPE [#]**	**nRecord**
$\textbf{ASCAT}_{\textbf{ERA}}$	0.57	13.73	8.14	0.82	5831273
$\textbf{ASCAT}_{\textbf{NOAA}}$	0.57	15.03	11.90	0.65	5974009
$\textbf{ASCAT}_{\textbf{porosity}}$	0.49	17.49	9.00	0.91	5973190

In what follows, the regional and temporal dependence of the comparison between SMOS and ASCAT is analysed, as well as the effectiveness of a modified quality index for SMOS. Note that for the previous aspects, the processor version do not show any significant difference.

3.1.1 Regional SMOS/ASCAT comparison

The previous outcomes are quite general since the data were considered all together. However, it is also interesting to analyse the result obtained in different regions of the continent and in different seasons when cross-validating different products over a continental scale. Table 1 also shows that a better agreement between ASCAT and SMOS holds when considering data only over North Africa, mainly because of the stable contrast between the moist regions close to the coastline and the desert. Elsewhere the matching is worse, especially over Eastern Europe. The number of samples of Northern Africa, West and East Europe does not match the total sample number exactly; this is because two different thresholds on the longitude were adopted, i.e., <14° West and >=18.6° West for West and East Europe, respectively. Indeed, a significant improvement of all the scores was obtained when removing from the comparison pixels labeled as forest, as extensively discussed for instance in [31]. Note from Table 1 the large amount of colocations over Africa, which explains the high density of points with low *SMC* in Figure 1. Considering the alternative methods to rescale SD_{ASCAT}, the results are substantially the same in terms of considering different geographical areas, seasons and land cover. Therefore, in what follows in this section only the scaling using SMOS will be considered.

3.1.2 Sensitivity to DQX threshold

The capability of some of the quality indices reported in the SMOS product to actually predict the quality of the data was analysed. In particular, it was found that the Data Quality Index (DQX) available from the SMOS L2 product, which should represent the theoretical retrieval a posteriori standard deviation, provides a better prediction of the quality when divided by the retrieved soil moisture itself, multiplied by 100 (i.e., computing a relative DQX). Reducing the DQX threshold and flagging the data above that threshold, did not improve the matching between ASCAT and SMOS. Conversely, using the relative DQX, the improvement turned out to be significant. In fact, the DQX tends to be proportional to the estimated *SMC*, so that a threshold on the DQX alone would mask lower values of moisture, despite of their actual reliability. A threshold of 12 % on the *relative* DQX significantly improves the scores, although it almost halves the number of retrievals. Concerning Radio Frequency Interference (RFI), Figure 2 (right panel) shows how the matching score parameter improves when data with larger probabilities were discarded, and a significant improved matching is observed when values below 0.4 were selected. Using only points with very low RFI (<0.2) were not enough to compute reliable statistics.

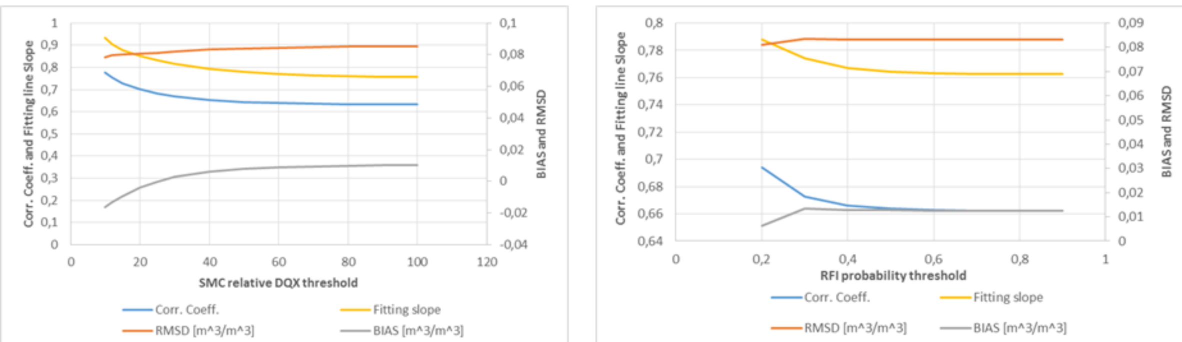

Figure 2: Analysis of the impact of quality indices within the SMOS products on the matching between SMOS and ASCAT. *R*, *RMSD*, bias and slope as function of (left panel) threshold on the *relative DQX* and (right panel) RFI probability index. ASCAT was rescaled using SMOS.

3.1.3 Seasonality of the statistics

Figure 3 shows seasonal *R* and *RMSD* scores. Regarding the seasonal dependence, a larger correlation is observed in winter, whereas the lowest agreement between SMOS and ASCAT is observed in summer. This result could be explained by the presence in summer of smaller scale meteorological systems highly variable in space and time, although one could expect that snow cover and extreme events can affect the comparison in autumn and winter too, for which in fact *RMSD* is larger. Figure 3 also shows a better agreement in the comparison when discarding forested targets, less influenced by the season.

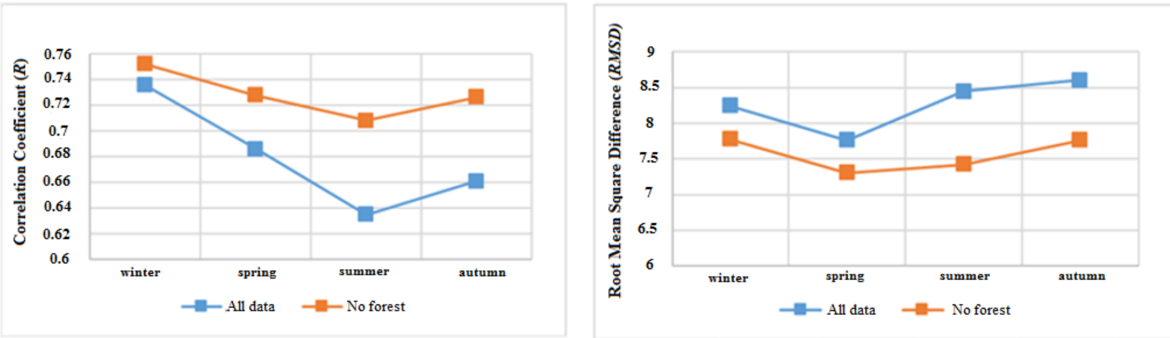

Figure 3: Correlation coefficient *R* (left) and root mean square difference *RMSD* (right) between SMOS and ASCAT *SMC* (the latter scaled using SMOS) computed for different seasons during the whole comparison period and with and without forest cover.

3.2 Analysis for other selected pairs

Table 3 presents a summary of the results, in terms of correlation coefficient *R* and *RMSD*, when comparing all the different pairs of data. It is important to underline that the statistics were calculated for the common period of the four datasets, i.e. from 2010 to 2012. The best agreement was obtained between model data, but good correlation was also obtained between ASCAT (scaled using the independent porosity map) and model data, although with high *RMSD*. The correlation and *RMSD* between SMOS and model data are slightly worse. A similar trend was also found in [32], where ASCAT and SMOS were compared with a hydrological model over two catchments in West Germany.

Table 3: Correlation coefficient (cells above the diagonal) and *RMSD* (cells below the diagonal) between different sources (ASCAT scaled using independent porosity maps).

	SMOS	ASCAT	ERA	NOAA
SMOS		0.48	0.61	0.58
ASCAT	17.08%		0.70	0.70
ERA	13.96%	12.64%		0.89

NOAA	13.05%	12.33%	8.57%

3.2.1 Temporal correlation analysis

As soil moisture encompasses both spatial and temporal variability, the two factors were investigated independently. As for the latter, the correlation coefficient was computed in each point of the ISEA4H9–grid and the results are shown in Figure 4. Note that the correlation coefficient is independent on a linear transformation, so that the ASCAT data can be considered without any scaling. It can be observed that the temporal correlation between ASCAT and ERA is large in most of Central Europe. There are some exceptions, like for example when ASCAT was compared over the desert area, where the correlation becomes negative. A similar result was found in [23] where ASCAT exhibits a negative correlation over desert areas if compared with MERRA-Land (Modern-ERA Retrospective analysis for Research and Applications) data. As for SMOS, low values of the correlation in the extreme North of the considered region were obtained, whereas positive correlation values with the model data over desert were observed (see Fig.4). The different behavior of SMOS and ASCAT over desert is already know in literature, and coul be addressed to the different operating principle of the two sensors. A very similar spatial variability of temporal correlation is observed when considering the NOAA soil moisture estimates, which are shown in the same figure. The LSM predictions are quite well correlated, apart from a few areas of low correlation over the desert and the northernmost areas.

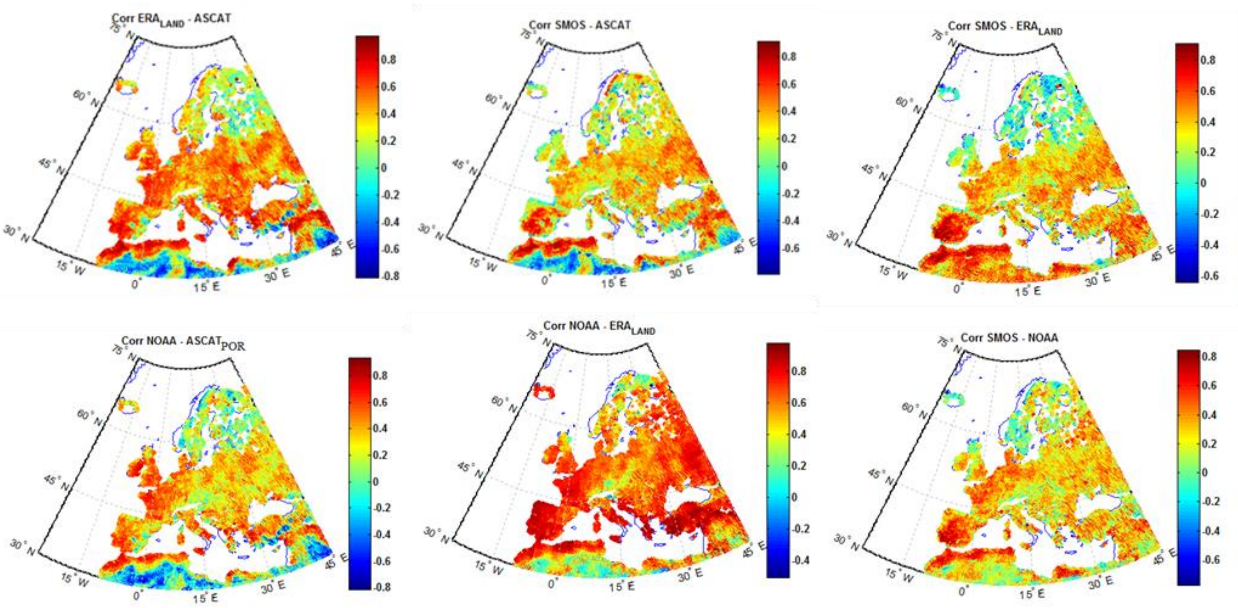

Figure 4: Temporal correlation coefficients between ERA and ASCAT (upper-left), SMOS and ASCAT (upper-middle), SMOS and ERA (upper-right), NOAA and ASCAT (lower-left), NOAA and ERA (lower-middle) and SMOS and NOAA (lower-right).

3.2.2 Spatial correlation analysis

Regarding the matching of the spatial patterns, the correlation coefficient among collocated data collected during the same day were computed. In order to avoid introducing any kind of correlation between SMOS and ASCAT respect to the other data used for the comparison, the *SD* relative index from ASCAT was converted into the absolute *SMC* through the porosity map, Figure 5 shows the results as function of time for three different years. It can be observed that the spatial correlation between satellite retrievals is generally low in Summer (around 0.4), a result which confirms the same trend shown in Figure 3 (which however accounts for both spatial and temporal variability). The spatial correlation between SMOS estimates and LSM predictions is around 0.6, and it quite stable during the whole year (slightly better in spring). The ASCAT product (scaled with porosity) exhibits a much higher spatial correlation with LSM in winter (around 0.8). As expected, the behaviour of the two models is similar.

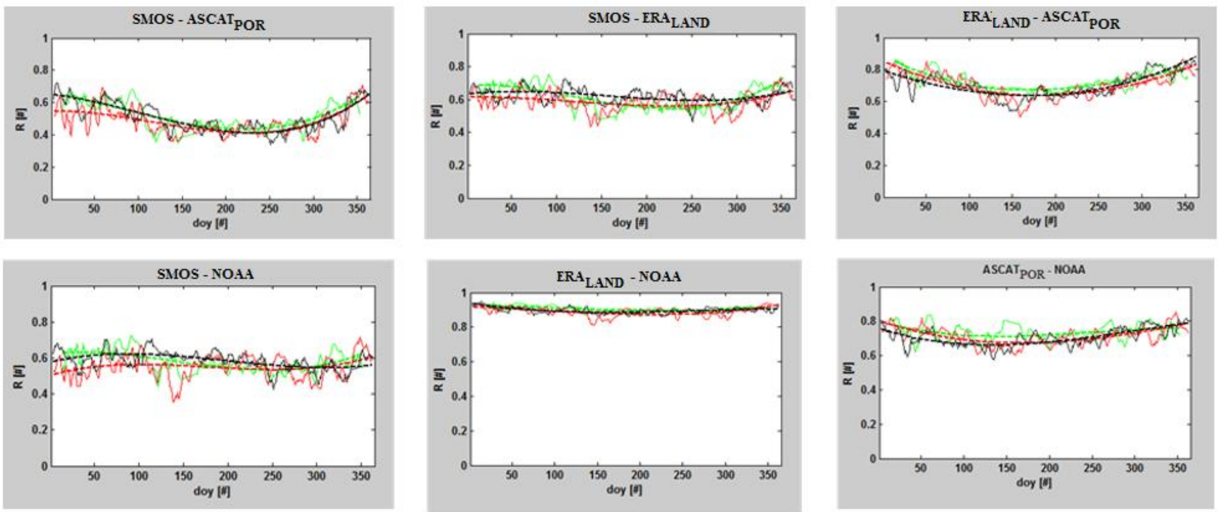

Figure 5: Spatial correlation coefficient between SMOS and ASCAT (upper-left), SMOS and ERA (upper-middle) and ERA and ASCAT (upper-right), SMOS and NOAA (lower-left), ERA and NOAA (lower-middle) and ASCAT and NOAA (lower-right) as function of time (continuous lines) with superimposed polynomial best fitting (dashed lines). Different colours refer to year 2010 (green), 2011 (red), 2012 (black). ASCAT was scaled using porosity.

3.3 Comparison with in–situ data

The upper panel of Figure 6 shows the comparison between SMOS and ASCAT absolute soil moisture products (using different scaling approaches) and ISMN measurements. The different colours in the figure symbolize the different networks used for the analysis: Denmark [blue], France [black], Germany [yellow], Italy [red], Poland [magenta] and Spain [green]. This figure presents the crude comparison of the data, without any standardization, which results in relatively poor comparison scores, as resumed in the first four rows of Table 6. However, the ASCAT product provides the best performances overall when scaled using ERA-LAND, and the worst when scaled using the porosity, whilst SMOS exhibits an intermediate behaviour.

In some literature papers [29], it is assumed that each network probe is characterized by an unknown calibration (bias and gain). This can be considered irrelevant when looking at the temporal variability of soil moisture. Hence, at each site the satellite retrievals were standardized in order to match locally the probe's mean and standard deviation. The lower panel of Figure 6 shows the scatterplot using this approach.

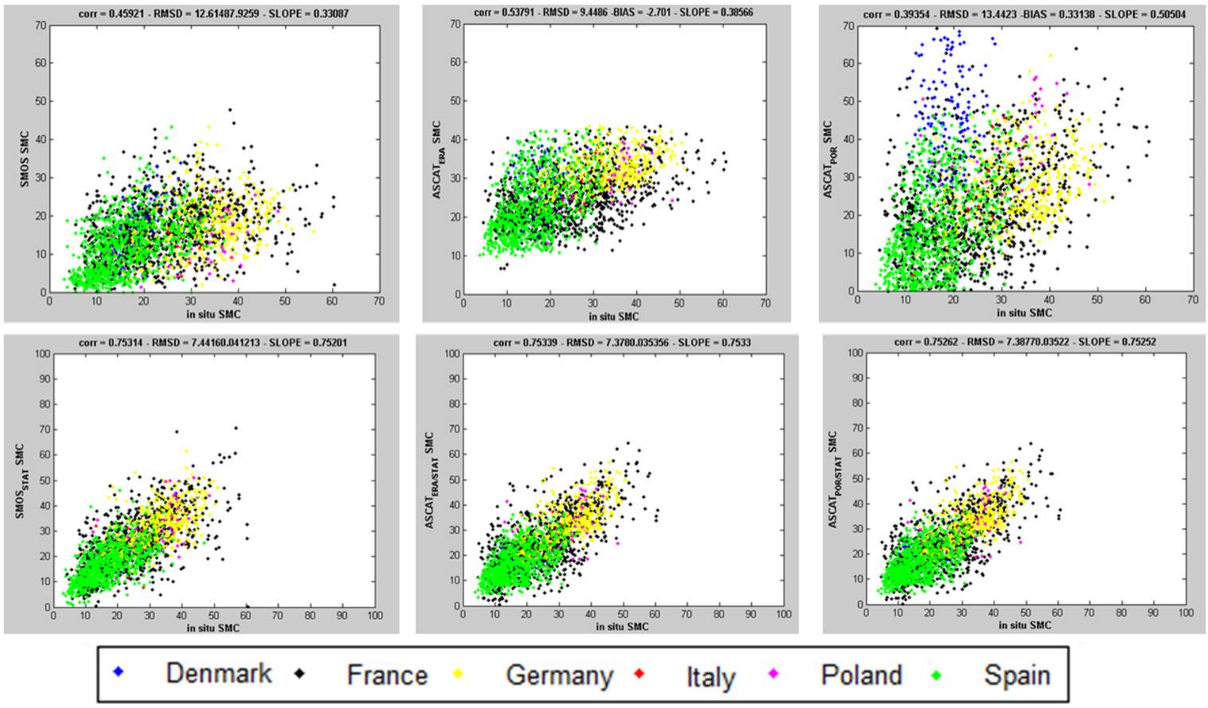

Figure 6: Scatterplot of satellite retrievals as function of ISMN in situ soil moisture (upscaled to the satellite resolution). From left to right: SMOS, ASCAT scaled with ERA-LAND, and ASCAT scaled with porosity. Upper panel refers to the crude comparison, whereas in the lower panel the satellite retrieval are locally rescaled to the in situ observations mean and standard deviation.

It can be observed that the matching scores improve significantly, as confirmed by the last row of Table 6, i.e., the correlation with ISMN improves up to 0.75 and the RMSD decreases to 7%. Note that in this case the previous scaling of ASCAT is not relevant on the resulting scores and the performance is basically identical for both satellite products. This is the reason why the satellite products in the last row of Table 6 were considered together. However, when this kind of normalization is adopted, the results should be taken with care, according to the end user needs. For instance, if the end user is interested at just monitoring the temporal variability in each point of the earth around its mean value, then it may be significant to quantify the RMSD and correlation after such normalization step. Conversely, if the final application requires knowing the absolute value of the soil moisture, applying this normalization before computing the RMSD may lead to too optimistic conclusions.

Table 6: Matching scores (*R*, *RMSD*, bias and *S*) and number of collocations of satellite retrievals as function of ISMN in situ soil moisture (upscaled to the satellite resolution). ASCAT products are scaled using SMOS ($ASCAT_{SMOS}$), ERA-LAND ($ASCAT_{ERA}$), NOAA ($ASCAT_{NOAA}$) or porosity

($ASCAT_{porosity}$). In the last row both satellite retrievals are standardized locally to the observations mean and standard deviation, leading to almost equal results (ASCAT scaling becomes meaningless).

	R [#]	RMSD [% m^3m^{-3}]	BIAS [% m^3m^{-3}]	SLOPE [#]	nRecord
$ASCAT_{SMOS}$	0.48	12.35	7.67	0.36	2606
$ASCAT_{ERA}$	0.54	9.45	-2.70	0.39	2596
$ASCAT_{NOAA}$	0.52	10.24	-4.69	0.36	2606
$ASCAT_{porosity}$	0.39	13.44	0.33	0.51	2606
SMOS	0.46	12.61	7.93	0.33	2606
Satellite scaled	0.75	7.4	0	0.75	

The improvements brought by the new processor version were possible to observe by limiting the period from January 2010 to March 2012. Indeed, while the correlation coefficient between SMOS and in situ data slightly decreases from 0.47 (version 5.01) to 0.46 (version 5.51), a decrease of RMSD (from 15.43 to 12.68) mainly associated to a decrease of the bias (from 11.85 to 7.75) were observed with the new version. Such results are consistent with [33], where many processor versions were analysed and with [27], being associated to the higher retrieval produced by the Mironov model.

4. Conclusions

An in depth and extensive comparison of soil moisture retrievals over the area of interest of the EUMETSAT H-SAF project (Europe and North Africa) was carried out considering the H-SAF SM-OBS-1 and the SMOS L2 products (5.51 processor version), as well as in situ measurements and different land surface model predictions (ERA-LAND and NOAA). The analysis was performed for a period of 4 years (2010-2013).

As a first results, substantial changes in the comparison between SMOS and ASCAT products due to the change the SMOS processor (from version 5.01 to version 5.51) were not found. If SMOS data was used to scale ASCAT data, the two products showed a degree of correlation that reached 0.66, while the root mean square difference was in the order of 8%. These results are similar to those obtained in a previous work [19], where SMOS processor version 5.01 and a short temporal period was considered. The change of the results of the comparison due to the rescaling of ASCAT data using independent datasets was quantitatively evaluated finding that, especially when using a porosity map, the root mean square difference significantly increased. The worsening of the results can be partially mitigated by using ERA-LAND data for the rescaling.

Another result is represented by a more accurate selection of the data used for the comparison. The behavior of the satellite comparison was analysed with respect to DQX (Data Quality indeX) and RFI (Radio Frequency Interference) SMOS values, which can be related to the SMOS quality. It was found that a significant improvement of the statistical scores used to evaluate the comparison between satellite products can be obtained by fixing a threshold of about 0.4 on the RFI probability. In addition, a new quality index obtained by dividing DQX by the retrieved soil moisture itself was proposed. A threshold of 12% on the relative DQX significantly improved the scores.

As for the comparison with model-derived data, using the products derived from land models as reference, ASCAT and ERA showed a good degree of correlation (0.70, even higher in winter), although the root mean square difference never fell below 10%. Worst results were found for SMOS, which is in agreement with other literature papers [32]. Considering the temporal correlation between the different datasets some inconsistencies were obtained, for instance over desert areas, confirming the observed trend in other literature work [23].

When compared with in situ stations, different results were obtained for ASCAT considering different approaches of scaling. Namely, the ASCAT product scaled with ERA-LAND provided the best performances, but the correlation did not exceeded 0.55 and the root mean square difference did not exceeded 9%. The worst performances were obtained with ASCAT scaled using the porosity maps, whereas SMOS showed an intermediate behavior (correlation of 0.46 and *RMSD* of 12.6%).

Other ways to compare satellite products with independent data sets are currently under investigation. An example is represented by the new Quadruple Colocation technique to evaluate the standard deviation of the random errors affecting different data sources related to a target parameter.

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References

1. Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J., Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, **2010**, 99, 125-161.
2. Brocca, L.; Moramarco, T.; Melone, F.; Wagner, W.; Hasenauer, S. and Hahn S. Assimilation of Surface- and Root-Zone ASCAT Soil Moisture Products Into Rainfall–Runoff Modeling, *IEEE Transactions on Geoscience and Remote Sensing*, **2012,** pp. 2542-2555, doi: http://dx.doi.org/10.1109/TGRS.2011.2177468.
3. Panegrossi, G.; Ferretti, R.; Pulvirenti, L.; and Pierdicca, N. Impact of ASAR soil moisture data on the MM5 precipitation forecast for the Tanaro flood event of April 2009, *Nat. Hazards Earth Syst. Sci.* **2011**, vol. 11, pp. 3135–3149.
4. Pierdicca, N.; Pulvirenti, L. and Pace G. A Prototype Software Package to Retrieve Soil Moisture From Sentinel-1 Data by Using a Bayesian Multitemporal Algorithm, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **2014**, 7, pp. 153-166, DOI:10.1109/JSTARS.2013.2257698.
5. Gruhier, C.; de Rosnay, P.; Hasenauer, S.; Holmes, T.; de Jeu, R.; Kerr, Y.; Mougin, E.; Njoku, E.; Timouk, F.; Wagner, W.; Zribi, M. Soil moisture active and passive microwave products: intercomparison and evaluation over a Sahelian site. *Hydrol. Earth Syst. Sci.* **2010**, vol. 14, pp. 141–156.

6. Wagner, W.; Lemoine, G.; Rott, H. A method for estimating soil moisture from ERS scatterometer and soil data—Empirical data and model results. *Remote Sens. Environ.* **1999**, vol. 70, no. 2, pp. 191–207.
7. Luo, Y., Feng, X., Houser, P., Anantharaj, V., Fan, X. De Lannoy, G., Zhan, X., Dabbiru, L., Potential soil moisture products from the acquarius radiometer and scatterometer using an observing system simulation experiment, *Geosci. Instrum. Method. Data Syst.,* **2013**, 2, 113-120.
8. de Jeu, R.A.M., Wagner, W., Holmes, T.R.H., Dolma, A.J., van de Giesen, N.C., Friesen, J., Global Soil Moisture Patternss Observed by Space Borne Microwave Radiometers and Scatterometers, *Surv Geophys*., **2008**, 29, 399-420, doi: 10.1007/s10712-008-9044-0.
9. Hornáček M. ; Wagner, W.; Sabel, D.; Truong, H. L.; Snoeij, P.; Hahmann, T.; Diedrich, E.; Doubková, M. Potential for High Resolution Systematic Global Surface Soil Moisture Retrieval via Change Detection Using Sentinel-1. *IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing* **2012**, Vol. 5, no. 4, pp. 1303-1311.
10. Pierdicca, N.; Pulvirenti, L.; and Bignami, C. Soil moisture estimation over vegetated terrains using multitemporal remote sensing data. *Remote Sens. Environ.* **2010**, vol. 114, pp. 440-448.
11. Pierdicca, N.; Pulvirenti, L.; Bignami, C.; Ticconi, F. Monitoring Soil Moisture in an Agricultural Test Site Using SAR Data: Design and Test of a Pre-Operational Procedure. *IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing* **2013**, vol.6, no.3, pp.1199-1210.
12. Pierdicca, N. ; Castracane, P.; Pulvirenti, L. Inversion of Electromagnetic Models for Bare Soil Parameter Estimation from Multifrequency Polarimetric SAR Data. *Sensors* **2008**, vol. 8, pp. 8181-8200.
13. Kerr, Y.; Waldteufel, P.; Wigneron, J.-P.; Martinuzzi, J.-M.; Font, J.; Berger, M. Soil Moisture retrieval from space: the Soil Moisture and Ocean Salinity (SMOS) mission. *IEEE Trans. Geosci. Remote Sensing*, **2001**, vol. 39, pp. 1729–1736.
14. Entekhabi, D., S. Yueh, P. O'Neill, K. Kellogg et al., 2014. SMAP Handbook, JPL Publication JPL 400-1567, Jet Propulsion Laboratory, Pasadena, California, 182 pp.
15. Entekhabi, D., Njoku, E.G., O'Neill, P.E., Kellog K.H, "The Soil Moisture Active Passive (SMAP) Mission," *Proccedings of the IEEE*, **2010**, 98, issue 5, 704-716.
16. Wagner, W., Brocca, L., Naeimi, V., Reichle, R., Draper, C., de Jeu, R., Ryu, D., Su, C.-H., Western, A., Calvet, J.-C., Kerr, Y., Leroux, D., Drusch, M., Jackson, T., Hahn, S., Dorigo, W., Paulik, C., Clarifications on the "Comparison between SMOS, VUA, ASCAT, and ECMWF soil moisture products over four watersheds in U.S., *IEEE Transactions on Geoscience and Remote Sensing*, 52, **2014**, 1901-1906, doi:10.1109/TGRS.2013.2282172.
17. Parrens, M., Zakharova, E., Lafont, S., Calvet, J.-C., Kerr, Y., Wagner, W., Wigneron, J.-P., Comparing soil moisture retrievals from SMOS and ASCAT over France, *Hydrol. Earth Syst. Sci.*, **2012**, 166, 423-440, doi: 10.5194/hess-16-423-2012.
18. Leroux, D.J., Kerr, Y.H., Al Bitar, A., Bindlish, R., Jackson, T.J., Berthelot, B., Portet, G., Comparison Between SMOS, VUA, ASCAT, and ECMWF Soil Moisture Products Over Four Watersheds in U.S., *Geoscience and Remote Sensing*, **2013**, IEEE Transactions on 52 (3): 1562-71. doi:10.1109/TGRS.2013.2252468.

19. Pierdicca, N.; Pulvirenti, L.; Fascetti, F.; Crapolicchio, R.; Talone M. Analysis of two years of ASCAT- and SMOS-derived soil moisture estimates over Europe and North Africa. *European Journal of Remote Sensing* **2013**, vol. 46, pp. 759-773.
20. Kalnay, E., Kanamitsu, M., Kistler R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen,, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jenne, R., Joseph,, D., The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, **1996**, 77, 437-470.
21. Balsamo, G., Albergel, C., Beljaars, A., Boussetta, S., Brun, E., Cloke, H., Dee, D., Dutra, E., Muñoz-Sabater, J., Pappenberger, F., de Rosnay, P., Stockdale, T., and Vitart, F. ERA-Interim/Land: a global land surface reanalysis data set, *Hydrol. Earth Syst. Sci.*, **2015**, 19, 389-407, doi:10.5194/hess-19-389-2015.
22. Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., and Jackson, T., The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements. *Hydrol. Earth Syst. Sci*., **2011**, 15 1675-1698, doi:10.5194/hess-15-1675-2011.
23. Al-Yaari, A., Wigneron, J.-P., Ducharne, A., Kerr, Y.H., Wagner, W., De Lannoyf, G., Reichle, R., Al Bitar, A., Dorigo, W., Richaume, P., Mialon, A., Global-scale comparison of passive (SMOS) and active (ASCAT) satellite based microwave soil moisture retrievals with soil moisture simulations (MERRA-Land), *Remote Sensing of Environment*, **2014**, vol. 152, pp. 614-626.
24. Naeimi, V.; Scipal, K.; Bartalis, K.; Hasenauer, S.; Wagner, W. An Improved Soil Moisture Retrieval Algorithm for ERS and METOP Scatterometer Observations. *IEEE Trans. Geosci. Rem. Sens.* **2009**, vol 47, pp. 1999-2013.
25. Dobson, M., Ulaby, F., Hallikainen, M., El-Raye, M. Microwave dielectric behavior of wet soil-Part II: Dielectric mixing models, *IEEE Trans. Geosci. Remote Sens*., **1985**, 23, 35-46.
26. Mironov, V.L., Kosolapova, L.G., Fomin, S.V., Physically and mineralogically based spectroscopic dielectric model for moist soils, *IEEE Trans. Geosci. Remote Sens.*, **2009**, 47, 2059-2070.
27. Mialon, A., Richaume, P., Leroux, D., Bircher, S., Al Bitar, A., Pellarin, T., Wigneron J.-P., Kerr, Y.H. Comparison of Dobson and Mironov Dielectric Models in the SMOS soil moisture retrieval algorithm, *IEEE Transactions on Geoscience and Remote Sensing*, **2015**, 53, 3084-3094.
28. Balsamo G.; Albergel, C.; Beljaars, A.; Boussetta, S; Brun, E; Cloke, H; Dee, D.; Dutra, E; Pappenberger, F.; de Rosnay, P.; Muñoz-Sabater, J; Stockdale, T; Vitart, F. ERA-Interim/Land: A global land-surface reanalysis based on ERA-Interim meteorological forcing. *Hydrology and Earth System Sciences*, **2014**, 19, 389-407, doi: 10.194/hess-19-389-2015.
29. Brocca, L., Hasenauer, S., Lacava, T., Melone, F., Moramarco T., Wagner,W., Matgen P., Martinez-Fernandez J., Llorens, P., Latron, J., Martin, C., Bittelli M., Soil moisture estimation trhough ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe, *Remote Sensing of Enviroment*, **2011**, 115, 3390-3408.

30. Corbella, I., Torres, F., Duffo, N., Gonzalez-Gambau, V., MIRAS Calibration and Performance: Results From the SMOS In-Orbit Commissioning Phase, *Goscience and Remote Sensing*, **2010**, IEEE Transactions on 49, 3147-3155, doi: 10.1109/TGRS.2010.2102769.
31. Al-Yaari, A..; Wigneron, J. P; Ducharne, A.; Kerr, Y.; de Rosnay, P.; de Jeue, R.; Govind, A.; Al Bitar, A.; Albergel, C.; Muñoz-Sabater, J.; Richaume, P.; Mialonc, A. Global-scale evaluation of two satellite-based passive microwave soil moisture datasets (SMOS and AMSR-E) with respect to Land Data Assimilation System estimates. *Rem. Sens. Env.* **2014**, 149, 181-195.
32. Rotzer K., Montzka C., Bogena H., Wagner W., Kerr Yann, Kidd R., Vereecken H. Catchment scale validation of SMOS and ASCAT soil moisture products using hydrological modeling and temporal stability analysis. *Journal of Hydrology.* **2014**, 519, 934-946.
33. Djamai, N., Magagi, R., Goita, K., Hosseini, M., Cosh, M.H., Berg, A., Toth, B. Evaluation of SMOS soil moisture products over the CanEx-SM10 area. *Journal of Hydrology*. **2015**, 520, 254-267.