

# Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations

Clement Albergel, Patricia de Rosnay, Claire Gruhier<sup>1</sup>, Joaquin Muñoz-Sabater, Stefan Hasenauer<sup>2</sup>, Lars Isaksen, Yann Kerr<sup>1</sup>, Wolfgang Wagner<sup>2</sup>

Research Department

October 2011

<sup>1</sup> Centre d'Etudes Spatiales de la Biosphère (CESBIO),  
Toulouse, France,

<sup>2</sup> Institute of Photogrammetry and Remote Sensing (I.P.F.),  
Vienna University of Technology, Austria.

Submitted to Remote Sensing of Environment

This paper has not been published and should be regarded as an Internal Report from ECMWF.

Permission to quote from it should be obtained from the ECMWF.



Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:

<http://www.ecmwf.int/publications/>

Contact: [library@ecmwf.int](mailto:library@ecmwf.int)

© Copyright 2011

European Centre for Medium Range Weather Forecasts  
Shinfield Park, Reading, Berkshire RG2 9AX, England

Literary and scientific copyrights belong to ECMWF and are reserved in all countries. This publication is not to be reprinted or translated in whole or in part without the written permission of the Director. Appropriate non-commercial use will normally be granted under the condition that reference is made to ECMWF.

The information within this publication is given in good faith and considered to be true, but ECMWF accepts no liability for error, omission and for loss or damage arising from its use.

## *Abstract*

In situ soil moisture data from more than 200 stations located in Africa, Australia, Europe and United States are used to determine the reliability of three soil moisture products, one analysis from the ECMWF (European Centre for Medium-Range Weather Forecasts) numerical weather prediction system (SM-DAS-2) and two remotely sensed soil moisture products, namely ASCAT (Advanced scatterometers) and SMOS (Soil Moisture Ocean Salinity). SM-DAS-2 is produced offline at ECMWF and relies on an advanced surface data assimilation system (Extended Kalman Filter) used to optimally combine conventional observations with satellite measurements. ASCAT remotely sensed surface soil moisture is provided in near real time by EUMETSAT. At ECMWF, ASCAT is used for soil moisture analyses in SM-DAS-2, also. Finally the SMOS remotely sensed soil moisture data level two product developed at CESBIO is used. Evaluation of the times series as well as of the anomaly values, show good performances of the three products to capture surface soil moisture annual cycle and short term variability. Correlations with in situ data are very satisfactory over most of the investigated sites located in contrasted biomes and climate conditions with averaged values of 0.70 for SM-DAS-2, 0.53 for ASCAT and 0.54 for SMOS. Although radio frequency interference disturbs the natural microwave emission of Earth observed by SMOS in several parts of the world, hence the soil moisture retrieval, performances of SMOS over Australia are very encouraging.

## **1 Introduction**

Soil moisture plays a fundamental role in the partitioning of mass and energy fluxes between the hydrosphere, the biosphere and the atmosphere, as it controls both evaporation and transpiration fluxes from bare soil and vegetated areas, respectively. Many applications require global or continental scale soil moisture, to be used as realistic initial states for the soil moisture variables, from forecasts of weather and seasonal climate variations to models of plant growth and carbon fluxes. A number of studies have been conducted to obtain soil moisture estimates from spaceborne microwave instruments (e.g. Wagner et al., 1999, Kerr et al., 2007, 2010, Njoku et al., 2003). Indeed, quantitative information about the water content of a shallow near surface layer can be obtained from spaceborne microwave instruments (Schmugge, 1983), particularly in the low-frequency microwave region from 1 to 10 GHz. While it was shown that surface soil moisture (SSM) influences the microwave emission of vegetated surfaces from L-band to K-band (~1.42–23.8 GHz, Calvet et al., 2011), L-band is the optimal wavelength range to observe soil moisture (e.g. Wigneron et al, 1995). Higher frequencies are more significantly affected by perturbing factors such as atmospheric effects and vegetation cover (Schmugge, 1983, Kerr et al., 2007). In the last decade microwave remote sensing offered the possibility to obtain soil moisture estimates at global scale with sampling times of few days. However, apart from a few days of L-band radiometric observations on Skylab between June 1973 and January 1974 (Jackson et al., 2004) current or past instruments have been operating at frequencies above 5 GHz. The Soil Moisture and Ocean Salinity mission (SMOS) is a dedicated soil moisture mission launched in November 2009 (Kerr et al., 2007, 2010). It consists of a spaceborne L-band (~1.42 GHz, 21 cm) interferometric radiometer able to provide global SSM estimates at a spatial resolution of about 40 km, with a sampling time of 2–3 days. Previous spaceborne microwave radiometers were the Scanning Multichannel Microwave Radiometer (SMMR) which operated on Nimbus-7 between 1978 and 1987 (6.6 GHz and above), followed by the Special Sensor Microwave Imager (SSM/I starting in 1987 at 19 GHz and above) and the TRMM Microwave Imager (TMI) on the Tropical Rainfall Measuring Mission (TRMM) satellite (1997, at 10.7 GHz and above). The Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E on the Aqua satellite from 6.9 to

89.0 GHz), Windsat (from 6.8 to 37 GHz) and the scatterometer on board the European Remote Sensing Satellite (ERS-1&2, 5.3 GHz) are operating closer to the L-band. A review of these different active and passive microwave products can be found in Rüdiger et al., 2009, Gruhier et al., 2010. Another sensor, the Advanced Scatterometer ASCAT onboard METOP-A (launched 2006), produces SSM estimates with a spatial resolution of 50 km and 25 km (resampled to 25 km and 12.5 km grids in the swath geometry). It is the first sensing satellite to provide SSM product in operation and in Near Real Time (NRT). ASCAT is a C-band radar operating at 5.255 GHz (Wagner et al, 2007; Bartalis et al., 2007a,b; Albergel et al., 2009). Those spatial missions, as well as the upcoming SMAP (Soil Moisture Active/Passive) mission programmed by the National Aeronautics and Space administration (NASA) demonstrate the relevance of the retrieval of SSM from space within the scientific community.

As sensors and their retrieval algorithms continue to improve, users trust more and more in remotely sensed products. By developing and applying statistical methods to make use of soil moisture properties, remotely sensed data are used as input or as validation, sometimes both. These applications highlight the need to assess satellite products accuracy at a global level. This study presents an evaluation of two remotely sensed surface soil moisture data sets, ASCAT and SMOS using in situ observations from more than 200 stations across the world (Australia, Africa, America and Europe) for the 2010 period. Along with those data sets, SM-DAS-2 soil moisture analysis from ECMWF (European Centre for Medium-Range Weather Forecasts) is evaluated. The latter relies on an advanced surface data assimilation system (an Extended Kalman filter, Drusch et al., 2009, de Rosnay et al., 2011) used to optimally combine conventional observations with satellite data sensitive to surface variables such as soil moisture from ASCAT. Firstly, the different SSM products used in this study, ASCAT and SMOS from remote sensing, ECMWF analysis (SM-DAS-2) and in situ data are described. In a second part, the ability of the three products to reproduce the SSM annual cycle is evaluated and then anomaly time-series are calculated to assess their capacity to reproduce the soil moisture short term variability, results are presented and discussed.

## 2 Material and methods

### 2.1 Remotely sensed surface soil moisture

#### 2.1.1 ASCAT

Like its predecessor ERS-1&2 scatterometers, ASCAT is a real-aperture radar instrument measuring radar backscatter with very good radiometric accuracy and stability (Bartalis et al., 2007a). ASCAT uses a VV polarization in the C-band (5.255 GHz) and observes the surface of the Earth with a spatial resolution of circa 50 km or 25 km. Measurements occur on both sides of the subsatellite track, thus two 550 km wide swaths of data are produced. Because ASCAT operates continuously, more than twice of the ERS scatterometer coverage is provided.

On both sides of METOP-A, ASCAT produces a triplet of backscattering coefficients ( $\sigma^0$ ) from the three different antenna beams. A  $\sigma^0$  measurement is the result of averaging several radar echoes. Backscatter is registered at various incidence angles and it is possible to determine the yearly cycle of the backscatter-incidence angle relationship. This is an essential prerequisite for correcting seasonal vegetation effects (Bartalis et al., 2007a, 2007b). The spatial and temporal behaviour of the

scatterometer is affected by land cover and vegetation phenology. It was demonstrated that by using a time series-based approach for the soil moisture retrieval, the influence of the vegetation could be minimized (Wagner et al., 1999). In order to retrieve surface soil moisture from ERS scatterometer, Wagner et al., (1999), proposed a time-series based change-detection approach where the backscattering coefficient extrapolated to a reference angle at 40° is scaled using the lowest and highest backscattering coefficient values measured over a long period. The theoretical background of this method is described in detail in Wagner et al. (1999).

The ASCAT provides a relative measure of the soil moisture content in the first few centimetres of the soil which are sensed by C-band microwaves. According to Schmugge (1983), the depth of this layer is about 0.5 to 2 cm. Thus, ASCAT measurement represents the degree of saturation of the topmost soil layer and is given in percent ranging from 0 (dry) to 100 % (wet). This measure is complemented by an error estimate, derived by error propagation of the backscatter noise (ranging from 0 to 100 %, covering instrument noise, speckle and azimuthal effects). Even if satellite sensors sample the very first centimetres of soil, their derived surface soil moisture related information can be propagated in deeper layers using techniques such as the EKF (Walker et al., 2001, Sabater et al., 2008).

A first ASCAT soil moisture data set was evaluated over southwestern France (Albergel et al., 2009) with encouraging results. This data set used change detection parameters derived from the analysis of multi annual backscatter time series using ERS data over a 15-yr long period. Brocca et al. (2010a) then used a new ASCAT data set developed by deriving the change detection model parameter from the analysis of ASCAT time series of the 2007-2008 period (Wagner et al., 2010, Hahn and Wagner, 2011). This new data set is able to provide reliable soil moisture estimates across different test sites in Europe, with reduced noise with respect to the initial ASCAT soil moisture product. Other findings of evaluating ASCAT-derived soil moisture over Europe, as well as its use in Numerical Weather Prediction (NWP) model and hydrological models through data assimilation can be found in Brocca et al., 2010b, Mahfouf, 2010 and Draper et al., 2011.

### 2.1.2 SMOS

The SMOS system is a microwave imaging radiometer with aperture synthesis collecting top of atmosphere full polarized radiances coming from the scene viewed by SMOS antennas through their power patterns. It is a Y-shaped instrument where 69 elementary antennas regularly spaced along the arms provide at each integrations step, a full image (circa 1000x1200 km), at either 2 polarisations or full polarisation, of the Earth's surface (Kerr et al. 2007, 2010). Spatial resolution is about 40 km and the globe is fully imaged at least twice every three days (ascending and descending orbits). Any points at the surface are viewed frequently at different angles and polarisations. The angular information is used to separate the different contributions (soil-vegetation) to the signal (Wigneron et al., 2000). The signal measured at satellite level is a brightness temperature (TB) consisting of four main contributions: (i) the up-welling atmospheric emission, (ii) the Earth's surface emission, attenuated by the atmosphere, (iii) the atmospheric down-welling atmospheric emission reflected at the surface and attenuated along the upward path by the atmosphere; and (iv) the cosmic background emission attenuated by the atmosphere, reflected at the surface and attenuated again along the upward path by the atmosphere. At L-band, up to the first 5 cm of soil are sampled. The principle of the SMOS level 2 product is to find the best-suited set of SSM and vegetation characteristics which minimize a cost function; the differences between modelled direct and measured angular TB data (Waldteufel and

Vergely, 2003, more information available on [http://www.cesbio.ups-tlse.fr/data\\_all/SMOS-doc/atbd/](http://www.cesbio.ups-tlse.fr/data_all/SMOS-doc/atbd/)). The resulting SMOS level 2 product is complemented by a Data Quality index (dqx), an index related to the quality of the retrieved parameter. It takes into account the error in the parameter retrieval as well as the LIC TB accuracy. It is provided in the parameter units (volumetric soil moisture units, usually between 0 and 0.1 for soil moisture for instance). The SMOS level 2 product used in this study was provided by CESBIO (Centre d'Etudes Spatiale de la Biosphere), as for the other products, the year 2010 was considered.

## 2.2 ECMWF soil moisture analysis: SM-DAS-2

The IFS (Integrated Forecast System) cycles used to produce SM-DAS-2 are 36r1, 36r3 and 36r4 (more information: <http://www.ecmwf.int/research/ifsdocs/>). It is produced offline and available at a spatial resolution of about 25 km (T799). The generation of SM-DAS-2 relies on an advanced surface data assimilation system used to optimally combine conventional observations with satellite measurements. It is based on an Extended Kalman Filter (EKF), as described by Drusch et al. (2009) and de Rosnay et al. (2011). In its current configuration, the EKF soil moisture analysis uses the two-metre air temperature and two-metre air relative humidity ( $T_{2m}$  and  $RH_{2m}$ , respectively) screen level parameters as well as ASCAT surface soil moisture as input (de Rosnay et al., 2011). The land surface model used is HTESSEL (Van den Hurk and Viterbo, 2003, Balsamo et al., 2009), a multilayer model where the soil is discretized in four layers of 0.07, 0.28, 0.72, and 2.89 m depths (from top to bottom). The surface analysis is independent from the 4D-VAR atmospheric analysis. SM-DAS-2 analysis is produced daily at 0000, 0600, 1200 and 1800 UTC. In this study, analyses at 00:00 UTC are used. SM-DAS-2 is not the first attempt to use satellite derived SSM at ECMWF. Scipal et al. (2008), examined the potential of ASCAT SSM from its predecessors, ERS-1&2. A nudging scheme (similar to the one in Dharssi et al., 2011) was used to assimilate those data, authors found an increase in correlation and a decrease in root mean square difference when comparing the resulting soil moisture analysis to in situ data of the Oklahoma Mesonet.

## 2.3 In situ soil moisture observations

In situ soil moisture observations are necessary to evaluate both remotely sensed and modelled soil moisture. In the recent years huge efforts were made to make available such observations in contrasting biomes and climate conditions. Some of them are now freely available on the Internet such as data from NCRS-SCAN (Natural Resources Conservation Service - Soil Climate Analysis Network) in the United States (Schaefer and Paetzold 2000, <http://www.wcc.nrcs.usda.gov/scan/>) or the OZNET hydrological monitoring network in Australia (Young et al., 2008, <http://www.oznet.org.au/>). The International Soil Moisture Network (ISMN, Dorigo et al., 2011, <http://www.ipf.tuwien.ac.at/insitu/>), a new data hosting centre where globally available ground based soil moisture measurements are collected, harmonized and made available to users, is also a clear evidence of how relevant the availability of such data is for the scientific community. Other data sets used in this study were obtained by request from the concerned organisations such as Météo-France for the SMOSMANIA and SWATMEX data in southwestern France and the LTHE for the AMMA data in western Africa. The different soil moisture data sets used in this study are described in Table 1 and presented in Figure 1. For each station available, a quality check of the data was performed and suspicious data were eliminated. 229 of 252 available stations were retained for this study, so 23 of them were rejected from this first visual quality check.

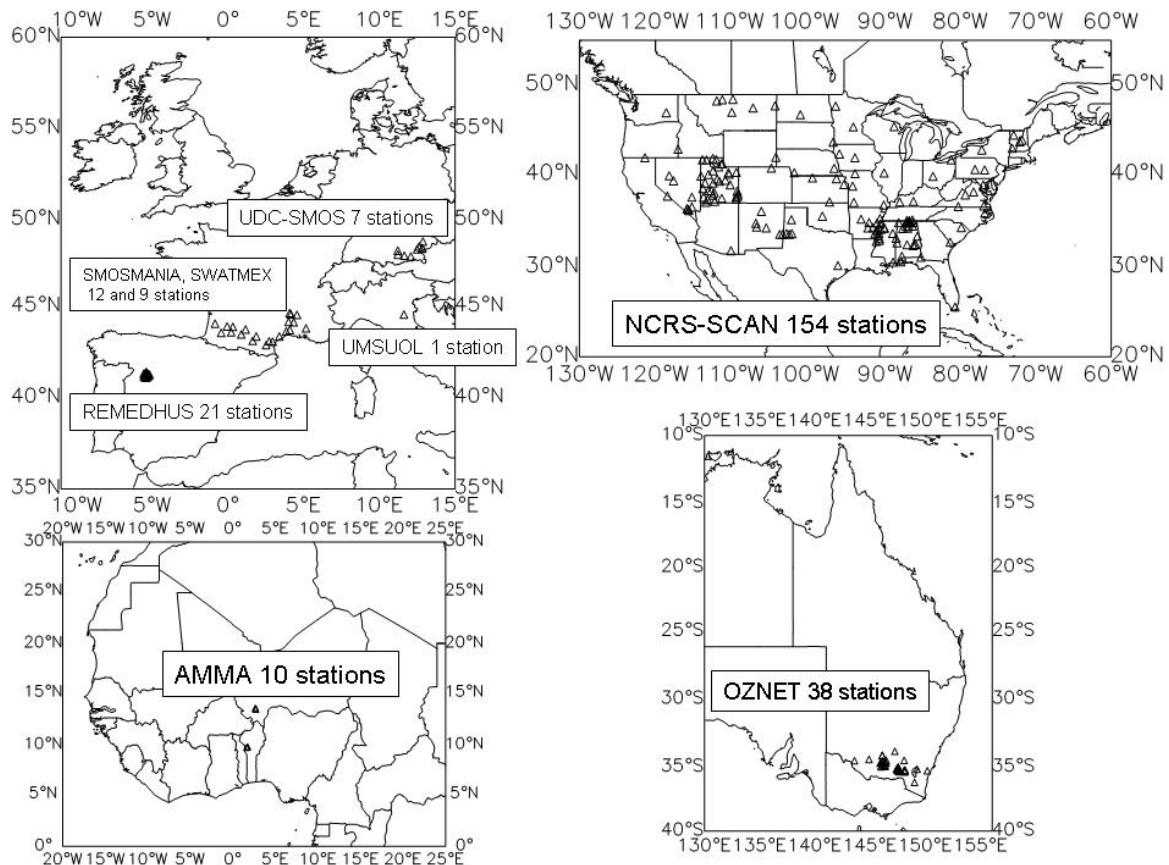


Figure 1: Location of the different in situ soil moisture stations used in this study, 38 in Australia (OZNET network), 154 within the United States (NCRS-SCAN network), 10 in Western Africa (AMMA network), 21 in southwestern France (SMOSMANIA and SWATMEX networks), 7 in Germany (UDC-SMOS network) and 1 in Italy (UMSUOL).

Table 1: Presentation of the different soil moisture data sets used in this study. NWP stands for numerical weather prediction. 252 stations with in situ observations are available.

Soil Moisture data set	Type	Soil layer depth (cm)	Spatial resolution	Number of stations
ECMWF SM-DAS-2	NWP analysis	0-7	~25 km (T799)	Global product
ASCAT	Remotely sensed product	C-band, ~0.5-2	~25 km	Global product
SMOS level 2 product	Remotely sensed product	L-band, ~5	~40 km	Global product
SMOSMANIA (France)	In situ observations	5, 10, 20, 30	Local scale	12 stations
SWATMEX (France)	In situ observations	5, 10, 20, 30	Local scale	9 stations
OZNET (Australia)	In situ observations	0-5 or 0-8 and 0-30	Local scale	38 stations
NCRS-SCAN (US)	In situ observations	~5, ~20	Local scale	154 stations
AMMA (West Africa)	In situ observations	5	Local scale	10 stations
REMEDHUS (Spain)	In situ observations	5	Local scale	21 stations
UMSUOL (Italy)	In situ observations	10	Local scale	1 station
UDC-SMOS (Germany)	In situ observations	5	Local scale	7 stations

### 2.3.1 NCRS-SCAN

The SCAN network (<http://www.wcc.nrcs.usda.gov/scan/>) is a comprehensive, nationwide soil moisture and climate information system designed to provide data to support natural resource assessments and conservation activities. Administered by the United States Department (USDA) of Agriculture Natural Resources Conservation Service (NRCS) through the National Water and Climate Center (NWCC), in cooperation with the NRCS National Soil Survey Centre, the system focuses on agricultural areas of the U.S. monitoring soil temperature and soil moisture content at several depths, soil water level, air temperature, relative humidity, solar radiation, wind, precipitation, barometric pressure, among others. SCAN data are used for various studies from global climate modelling to agricultural studies. Data are collected by a dielectric constant measuring device, typical measurements at 2 inches (about 5 cm) are used. In this study, all the stations of the NCRS-SCAN network presenting data in 2010 network are used (154 stations).

### 2.3.2 SMOSMANIA and SWATMEX

The SMOSMANIA project is a long-term data acquisition effort of soil moisture observations in Southwestern France (Calvet et al., 2007; Albergel et al., 2008). Soil moisture profile measurements at 12 automated weather stations of Météo-France from the RADOME network (Réseau d'Acquisition de Données d'Observations Météorologiques Etendu), have been obtained since January 2007 at four different depths (5, 10, 20 and 30 cm) with a 12 minutes time step. Stations span from the Mediterranean Sea to the Atlantic Ocean. The soil moisture measurements are in units of  $\text{m}^3\text{m}^{-3}$ , they are derived from capacitance probes: ThetaProbe ML2X of Delta-T Devices. ThetaProbes provide a signal in units of volt and their variations are virtually proportional to changes in the soil moisture content over a large dynamic range. In order to convert the voltage signal into a volumetric soil moisture content, site-specific calibration curves were developed using in situ gravimetric soil samples, for each station, and each depth (i.e., 48 calibrations curves). In January 2009, 9 additional RADOME stations were equipped with ThetaProbe in south and south eastern France. They form the SWATMEX (Soil Water and Temperature in Mediterranean EXPeriment) network. Data at 5 cm over the year 2010 are used in this study.

### 2.3.3 AMMA

In the framework of AMMA (African Monsoon Multidisciplinary Analysis) project dedicated to improve our understanding and our modelling capabilities of the effect of land surface processes on monsoon intensity, variability and predictability (Redelsperger et al., 2006), West Africa has been extensively instrumented. Three meso-scale sites were implemented in Mali (de Rosnay et al., 2009), Niger (Pellarin et al., 2009a) and Benin (Pellarin et al., 2009b), providing information along the North–South gradient between Sahelian and Soudanian regions. Soil moisture and other data are collected at different stations within the three meso-scale sites. The same installation protocol is used for all the soil moisture stations, where Time Domain Reflectometry sensors are used (Campbell CS616). When they were not suitable (e.g. due to soil texture), Delta-T Theta Probes were used. Three stations in Niger and 3 in Benin are used in this study. Data are collected at 5 cm.



#### 2.3.4 OZNET

The OZNET network (Young et al., 2008, <http://www.oznet.org.au>) is located within the Murrumbidgee experimental catchment in southern New South Wales, Australia. Each soil moisture site of the Murrumbidgee monitoring network (38) measures the soil moisture between 0-5 cm with soil dielectric sensor (Stevens Hydraprobe®) or 0-8 cm, 0-30 cm, 30-60 cm and 60-90 cm with water content reflectometers (Campbell Scientific). Hydraprobes are soil dielectric sensor operating at 50 MHz. At each measurement point, a volumetric soil moisture value is inferred from the real component of the measured relative dielectric constant and the conductivity from the imaginary component. Reflectometers measure the travel time of an output pulse to estimate changes in the bulk soil dielectric constant. Measurement is converted to volumetric water content with a calibration equation parameterised with soil type and soil temperature. As sensor response to soil moisture may vary with soil characteristics such as salinity, density, soil type and temperature, soil moisture sensor calibration was undertaken using both laboratory and field measurements. Reflectometer measurements were compared with both field gravimetric samples and Time-Domain Reflectometry (TDR) measurements. TDR measurements are based on the relationship between the dielectric properties of soils and their moisture content, also. Surface soil moisture observations are used in this study (either 0-5 cm or 0-8 cm).

#### 2.3.5 ISMN soil moisture: REMEDHUS, UDC-SMOS and UMSUOL

Several stations from the 3 different networks were obtained through the ISMN website, 21 from the REMEDHUS network in Spain, 9 from the UDC-SMOS network in Germany and one from UMSUOL in Italy.

REMEDHUS is located in the central sector of the Duero basin. Each station has been equipped with capacitance probes (HydraProbes, Stevens) installed horizontally at a depth of 5 cm. Analysis of soil samples were carried out to verify the capacitance probes and to assess soil properties at each station (Martinez-Fernandez and Ceballos, 2005). Data from UDC-SMOS in Germany (Loew et al., 2010) near the city of Munich are collected with TDR (IMKO-TDR) at 5 cm. This soil moisture network is run in cooperation with the Bavarian State Research Center for Agriculture and is carried out as part of the project SMOSHYD (FKZ 50EE0731) funded by the German Aerospace Centre (DLR). Finally, the San Pietro Capofiume station (Brocca et al., 2011) belonging to the UMSUOL network located in northern Italy it used. It was installed by the Service of Hydrology, Meteorology and Climate of the regional Agency for Environmental Protection in Emilia-Romagna (ARPA-SIMC, <http://www.arpa.emr.it/sim/>). Data are collected at 10 cm with TDR (TDR100, Campbell Scientific Inc).

## 2.4 Data preparation and metrics used for the comparison

ASCAT SSM estimates represent a relative measure of the soil moisture in the first centimetres of soil and it is given in percent, SM-DAS-2 is an index (between [0,1]), SMOS and in situ data are in  $\text{m}^3\text{m}^{-3}$ . Hence, to enable a fair product comparison, all soil moisture data sets (in situ, remotely sensed and modelled) are scaled between [0,1] using their own maximum and minimum values over the year 2010. The nearest neighbour technique is used to make a correspondence between SM-DAS-2, ASCAT, SMOS and in situ SSM. Time steps for in situ data range from 12-min (e.g. SMOSMANIA, SWATMEX) to 1 hour (e.g. NCRS-SCAN). SM-DAS-2, ASCAT, SMOS and in situ SSM are

available at different time of the day, each of them is collocated in time with ground observations. For all stations, correlations ( $R$ , Eq.1), bias (in situ minus analysis), root mean square difference (RMSD, Eq.2) and p-value (a measure of the correlation significance) are calculated for the whole 2010 year. The latter indicates the significance of the test, the 95% confidence interval is used in this study (as in Rüdiger et al., 2009, Albergel et al., 2009); configurations where the p-value is below 0.05 (i.e. the correlation is not a coincidence) are retained.

$$R = \sqrt{1 - \frac{(SSM_{products} - SSM_{insitu})^2}{(SSM_{products} - \overline{SSM_{insitu}})^2}} \quad (1)$$

$$RMSD = \sqrt{(SSM_{products} - SSM_{insitu})^2} \quad (2)$$

In situ data contain errors (instrumental and representativeness), so they are not considered as ‘true’ soil moisture. This is underlined here by using the RMS Difference terminology instead of RMS Error.

In order to avoid seasonal effects, anomaly time-series are also calculated. The difference to the mean is calculated for a sliding window of five weeks (if there are at least five measurements in this period), and the difference is scaled to the standard deviation. For each SSM estimate at day ( $i$ ), a period  $F$  is defined, with  $F=[i-17, i+17]$  (corresponding to a 5-week window). If at least five measurements are available in this period of time, the average SSM value and the standard deviation are calculated. The Anomaly ( $Ano$ ), dimensionless is then given by:

$$Ano(i) = \frac{SSM(i) - \overline{SSM(F)}}{stdev(SSM(F))} \quad (3)$$

The same equation is used to compute in situ anomaly time-series which can be compared with the ASCAT, SMOS and ECMWF soil moisture anomaly time-series.

Additionally, the normalised standard deviation (SDV) and the centred root mean square difference between analysis and in situ patterns, normalised by the in situ standard deviations ( $E$ ) are computed. SDV is the ratio between SSM product and in situ standards deviations; it gives the relative amplitude whilst  $E$  quantifies errors in the pattern variations. It does not include any information on biases since means of the fields are subtracted before computing second order errors. SDV and  $E$  are expressed by Eq.4 and Eq.5, respectively:

$$SDV = \sigma_{SSM_{product}} / \sigma_{SSM_{insitu}} \quad (4)$$

$$E^2 = (RMSD^2 - Bias^2) / \sigma_{insitu}^2 \quad (5)$$

$R$ , SDV and  $E$  are complementary but not independent as they are related by Eq.6 (Taylor, 2001):

$$E^2 = SDV^2 + 1 - 2 \cdot SDV \cdot R \quad (6)$$

Taylor diagrams are used to represent these three different statistics on two dimensional plots. The normalized standard deviation is displayed as a radial distance and the correlation with in situ data as an angle in the polar plot. In situ data are represented by a point located on the x axis at  $R=1$  and  $SDV=1$ . The distance to this point represents the centred normalized RMS difference ( $E$ ) between the analysis and in situ patterns.

### 3 Results and discussion

#### 3.1 Comparison of the normalised times series

The statistical scores for the comparison between SM-DAS-2, ASCAT, SMOS (referred as *ECM*, *ASC* and *SMO* in the following of the paper) and in situ SSM are presented in Table 2. Only the configurations associated to significant correlation values ( $p$ -value  $< 0.05$ ) are considered leading to 219, 208 and 180 stations available for *ECM*, *ASC* and *SMO*, respectively. In average, for all the stations, correlation values are 0.70, 0.53 and 0.54 for *ECM*, *ASC* and *SMO*. SMOSMANIA in southwestern France and OZNET in Australia present the best correlation values for *ECM* (0.83 and 0.82 in average) while AMMA in western Africa presents a correlation value average of 0.45.

Table 2: Comparisons of normalised SSM between in situ observations and products; SM-DAS-2 (*ECM*), ASCAT (*ASC*) and SMOS (*SMO*) for 2010. Mean correlation, bias (in situ minus products) and root mean square difference (RMSD) are given for each network and for each product. Scores are presented for significant correlations with  $p$ -values  $< 0.05$ .

Soil Moisture data set	Number of stations with $p$ -values $<0.05$			Correlation [-]			Bias [-]			RMSD [-]		
	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>
SMOSMANIA (France)	11	11	10	0.83	0.52	0.44	-0.178	-0.037	0.124	0.242	0.254	0.273
SWATMEX (France)	9	8	6	0.79	0.33	0.40	-0.274	-0.140	0.101	0.345	0.284	0.235
OZNET (Australia)	36	34	30	0.82	0.80	0.74	-0.013	-0.021	0.195	0.178	0.184	0.255
NCRS-SCAN (US)	131	125	106	0.65	0.48	0.51	-0.022	-0.078	0.095	0.233	0.266	0.232
AMMA (West Africa)	5	6	6	0.45	0.55	0.42	-0.074	-0.179	0.079	0.531	0.407	0.316
REMEDHUS (Spain)	17	17	17	0.79	0.57	0.52	-0.118	-0.088	0.128	0.243	0.245	0.232
UMSUOL (Italy)	1	1	1	0.76	0.39	0.54	-0.176	0.077	0.167	0.233	0.237	0.240
UDC-SMOS (Germany)	9	6	4	0.59	0.30	0.29	-0.061	0.052	0.267	0.198	0.267	0.344
All stations	219	208	180	0.70	0.53	0.54	-0.050	-0.068	0.120	0.235	0.255	0.243

Considering the use of *ASC* in *ECM* analysis, previous studies (de Rosnay et al., 2011, Albergel et al, 2010) indicated that *ASC* assimilation has a neutral impact on soil moisture analyses. Its use requires that *ASC* data are matched to ECMWF IFS soil moisture using a bias correction method; a Cumulative Distribution Function (CDF) matching as described in Scipal et al., 2008. Coming improvement in the *ASC* soil moisture products and in bias correction at ECMWF are expected to enhance the impact of using *ASC* soil moisture data.

For *ASC*, best correlation values are obtained with OZNET (0.80) and poor values are found in Germany (UDC-SMOS) and southeastern France (SWATMEX), 0.30 and 0.33. Several authors (e.g.

Albergel et al., 2010, Brocca et al., 2010b, Draper et al., 2011) found higher level of correlations, but considered reprocessed *ASC* data set. In this study, near real time (NRT) data from EUMETSAT are used, as in Albergel et al., 2009, who found similar correlations levels over the SMOSMANIA network for a 6 month period in 2007 (0.58 against 0.52 here for a one year period; 2010). This *ASC* data set was retained for this study as it is the official operational *ASC* product available in NRT via EUMETSAT and disseminated to NWP community.

Radio frequency interference (RFI) disturbs the natural microwave emission observed by *SMO*, hence the soil moisture retrieval. Their impact on Western Europe (e.g. in southwestern France, Zribi et al., 2011, Albergel et al., 2011) as well as over the United State (Parinussa et al., 2011) are known. The OZNET network in Australia, which presents the best correlation values for *SMO*, does not seem to be affected by RFI with an averaged correlation value of 0.74. In addition to the RFI issue, *ASC* and *SMO* signals are influenced by the vegetation. A reduced sensitivity to soil moisture is to be expected over dense vegetation canopies. A possible explanation of the good scores obtained with *SMO* and *ASC* over the OZNET network could be the presence of a significant fraction of bare soil and/or of dry vegetation, caused by the crop rotation practice; land use in the Murrumbidgee catchment is predominantly agricultural (Young et al., 2008). Moreover, if the indication given by the *dqx* can only be considered as indicative so far, (according to the guide of Release of SMOS level 2 products to Cal/Val teams) several tests with various *dqx* values permit to set a threshold of  $0.045 \text{ m}^3\text{m}^{-3}$  allowing an increase in the correlation levels for SMOS. Scores obtained in this study with *SMO* data consider this threshold.

Biases are in average of -0.050, -0.068 and 0.120 (in situ minus SSM products, dimensionless) for *ECM*, *ASC* and *SMO*, respectively. Negative biases are found with *ECM*, it concerns all networks used in this study. On the contrary, *SMO* systematically presents positive averaged biases. Averaged RMSD are 0.235, 0.255 and 0.243 for *ECM*, *ASC* and *SMO*, respectively. The RMSD represents the relative error of the soil moisture dynamical range. The average dynamic range observed for each network, associated to the average RMSD values of each network permits to give an estimate of the average error in volumetric soil moisture; about  $0.07 \text{ m}^3\text{m}^{-3}$ ,  $0.08 \text{ m}^3\text{m}^{-3}$  and  $0.08 \text{ m}^3\text{m}^{-3}$  for *ECM*, *ASC* and *SMO*, respectively.

Figure 2 presents three Taylor diagrams illustrating the statistics of the comparison between *ECM*, *ASC* and *SMO* and in situ data. They correspond to three networks used in this study, REMEDHUS in Spain, OZNET in Australia and SMOSMANIA in France. These diagrams underline the good range of correlation obtained for *ECM* with most of the values between 0.70 and 0.90 while *ASC* and *SMO* present lower values. It is particularly clear for SMOSMANIA (Fig. 2C), moreover, for this network, symbols representing *ASC* and *SMO* are most of the time below the SDV value of 1 (red dashed line on Figure 2); as SDV is the ratio between analysed and in situ standard deviation (see Eq.4) it indicates that the variability of the in situ data is higher than the one of *ASC* and *SMO* for this group of stations. For the OZNET network (Fig. 2B) however, the three products present good levels of correlation (most of the time above 0.70). Figure 3 presents three Taylor diagrams illustrating the statistics of the comparison between *ECM*, *ASC* and *SMO* and in situ data for the NCRS-SCAN network. Correlation values are better for *ECM* than for *ASC* and *SMO*, which is in line with Table 2. *SMO* presents better correlation values than *ASC* and a smaller dispersion in term of SDV. However its variability is smaller than in situ data.

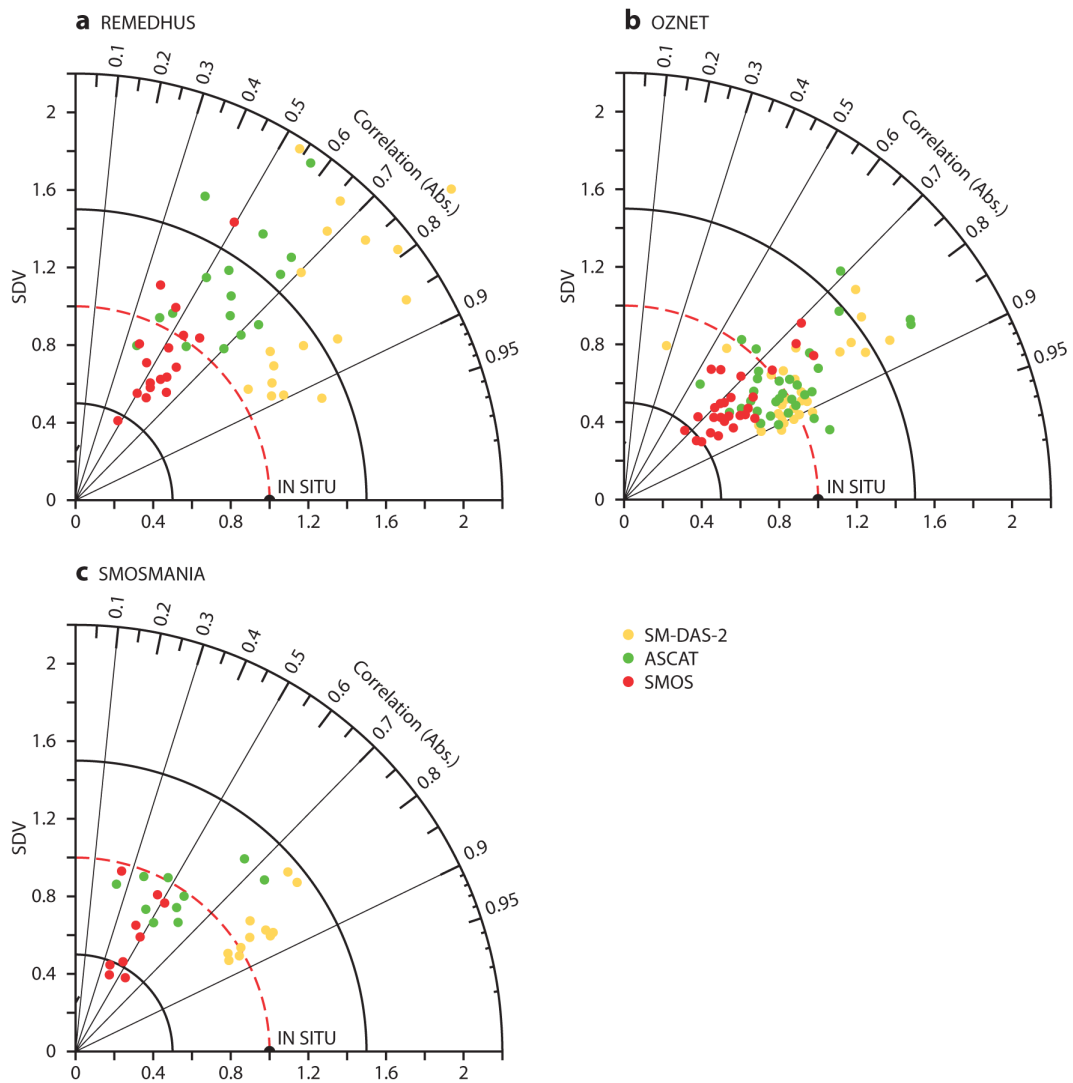


Figure 2: Taylor diagram illustrating the statistics of the comparison between SM-DAS-2, ASCAT, SMOS and in situ SSM for a) the REMEDHUS network in Spain, b) the OZNET network in Australia and c) the SMOSMANIA network in France. Yellow circles are for SM-DAS-2, green circles for ASCAT and red circles for SMOS.

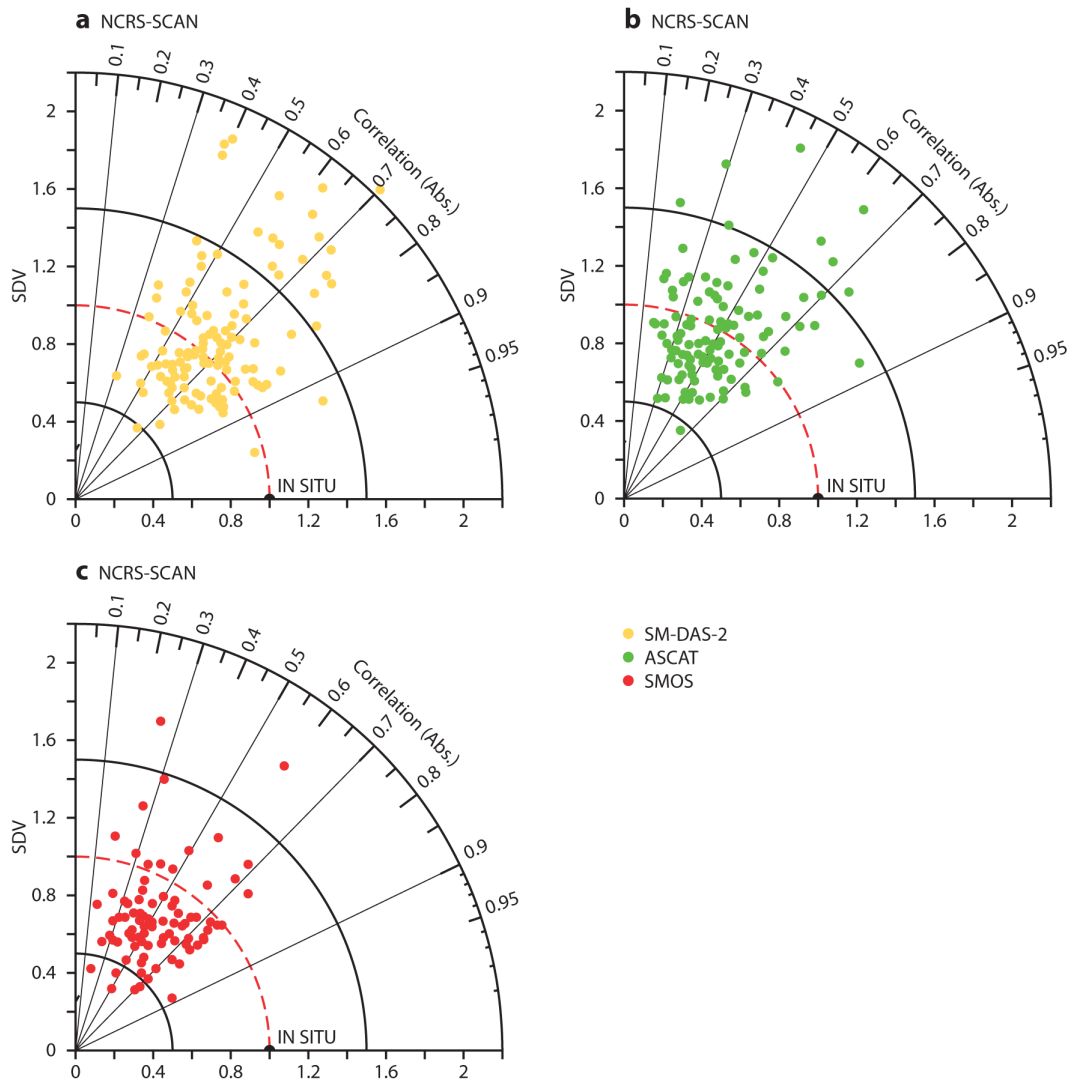


Figure 3: Taylor diagram illustrating the statistics of the comparison between a) SM-DAS-2, b) ASCAT, c) SMOS and in situ SSM for the NCRS-SCAN network. Yellow circles are for SM-DAS-2, green circles for ASCAT and red circles for SMOS.

Table 3 presents for each network and each product the count (in %) of significant R values ranked as: Inadequate ( $R < 0.2$ ), Poor ( $0.2 < R < 0.5$ ), Fair ( $0.5 < R < 0.7$ ) and Good ( $R > 0.7$ ). Considering the NCRS-SCAN network, *ECM* presents 34% of good, 50% of fair, 14% of poor and only 2% of inadequate R. *ASC* and *SMO* present 7% and 17% of good correlations. Figure 4 presents correlation values for *ECM*, *ASC* and *SMO*, for the NCRS-SCAN network, values are ranked using the same intervals above-mentioned. For this network, most stations present better correlation values when in situ data are compared to *SMO* data than with *ASC* data (57%).

For *ECM*, more than 80% of good correlation values are found for 5 networks out of 8 (OZNET, REMEDHUS, SMOSMANIA and SWATMEX) and even 100% for 2 (SMOSMANIA and SWATMEX networks). For all the stations, *ECM* presents 52% of good correlation values, *ASC* 20% and *SMO* 23%. Most of the correlations for *ECM* are above 0.70 while the main parts for *ASC* and *SMO* are between 0.2 and 0.5 (38% and 44%, respectively). For the OZNET network (38 stations) most of the correlation values are above 0.70; with 94%, 88% and 80% for *ECM*, *ASC* and *SMO*, respectively.

Table 3: Correlations between in situ SSM and each product; SM-DAS-2 (*ECM*), ASCAT (*ASC*) and SMOS (*SMO*) for 2010. For each network, number of significant correlation values ( $p$ -value  $< 0.05$ ) between in situ SSM and each product are ranked as; Inadequate ( $R < 0.2$ ), Poor ( $0.2 < R < 0.5$ ), Fair ( $0.5 < R < 0.7$ ), Good ( $R > 0.7$ ).

Soil Moisture data set	Inadequate (%) $R < 0.2$			Poor (%) $0.2 < R < 0.5$			Fair (%) $0.5 < R < 0.7$			Good (%) $R > 0.7$		
	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>	<i>ECM</i>	<i>ASC</i>	<i>SMO</i>
SMOSMANIA (France)	0	0	0	0	45	80	0	46	20	100	9	0
SWATMEX (France)	0	25	0	0	50	83	0	25	17	100	0	0
OZNET (Australia)	0	0	0	3	0	0	3	12	20	94	88	80
NCRS-SCAN (US)	2	7	3	14	47	48	50	39	32	34	7	17
AMMA (West Africa)	20	0	0	20	17	83	60	83	17	0	0	0
REMEDHUS (Spain)	0	0	0	0	23	41	18	65	59	82	12	0
UMSUOL (Italy)	0	0	0	0	100	100	0	0	0	100	0	0
UDC-SMOS (Germany)	0	17	0	11	83	100	89	0	0	0	0	0
All stations	1	6	2	10	38	44	37	36	31	52	20	23

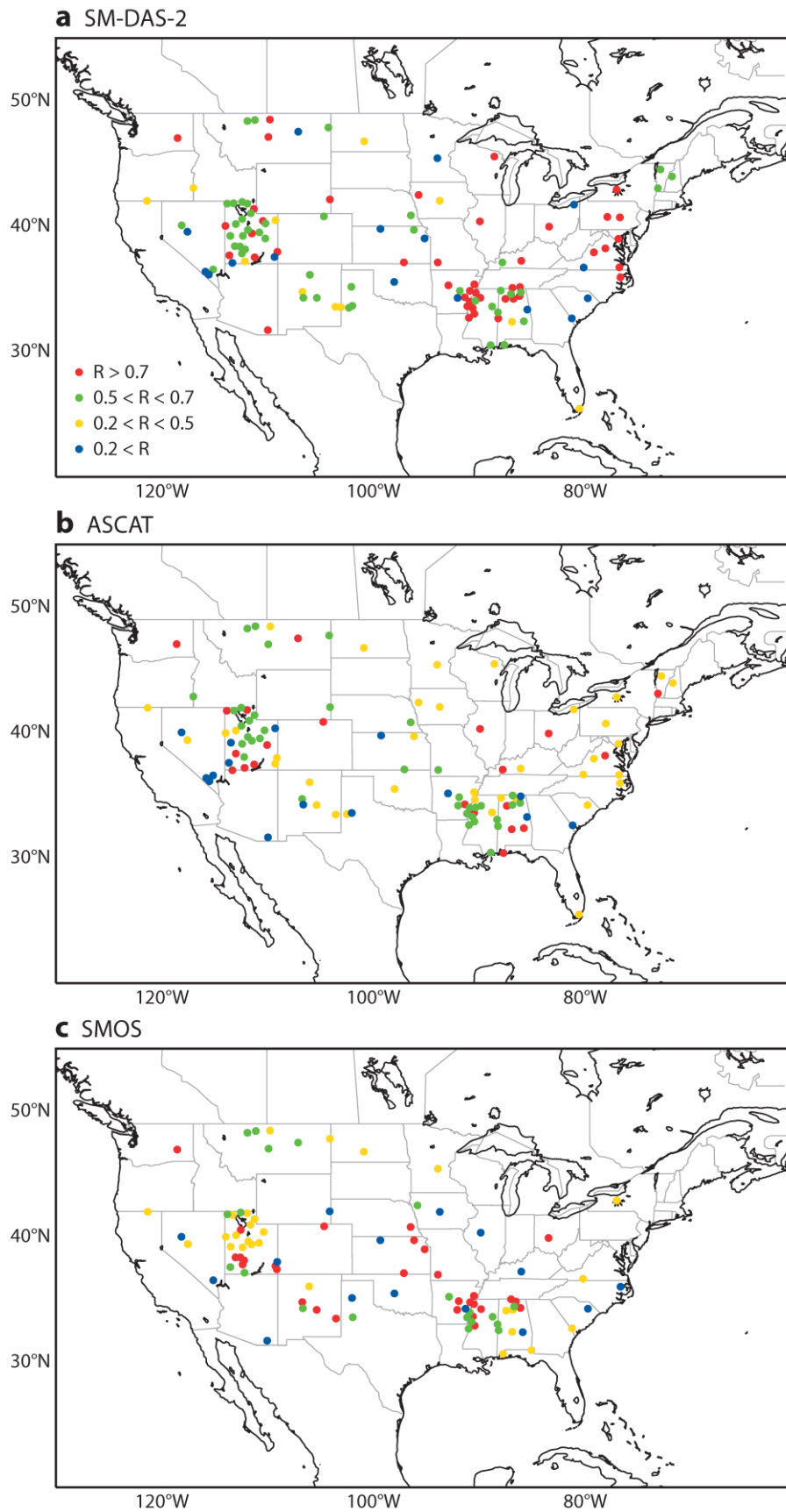


Figure 4: Correlation values between in situ SSM and (from top to bottom) ECMWF SM-DAS-2 product, ASCAT and SMOS for the stations of the NCRS-SCAN network.



### 3.2 Comparison of the anomaly time-series

Results presented above give an overview of the products comparison at the annual scale. They are driven to a large extent by the seasonal cycle. To address the ability of the product to capture the short term scale SSM variations, anomaly time-series were calculated (sect 2.5) and statistics are computed on the anomaly time-series. Only the configurations associated to significant correlation values ( $p$ -value $<0.05$ ) are considered, leading to 209, 217 and 178 stations retained for *ECM*, *ASC* and *SMO* respectively. Scores were computed in four different periods in 2010 defined as follows: (i) winter (January, February and December), (ii), spring (March to May), (iii) summer (June to August), (iv) autumn (September to November). These periods were used to study the seasonal variation of the scores. The statistical scores for the comparison between *ECM*, *ASC* and *SMO* and in situ SSM anomaly time-series are presented in Table 4. On average, for all the stations and considering the two first periods (winter and spring) correlation values are: 0.70 for *ECM*, 0.71 for *ASC* and 0.55 for *SMO*, 0.65 for *ECM*, 0.56 for *ASC* and 0.51 for *SMO*, respectively. However in summer, they are lower, 0.53 for *ECM*, 0.46 for *ASC* and 0.46 for *SMO*. The three products evaluated in this study better capture the soil moisture short term variability in winter and spring than in summer. Correlation values for autumn are 0.62, 0.50 and 0.45 for *ECM*, *ASC* and *SMO*, respectively. Figure 5 presents anomaly time series derived from, *ECM*, *ASC*, *SMO* and in situ observations for a randomly chosen station; the Creon d'Armagnac station of the SMOSMANIA network in southwestern France. Most peaks and troughs are well represented for the three soil moisture products. However, in summer *ECM* (Fig 5, top) represents two peaks (first days of June and August) that are not presented in the observations. Representativeness of local rainfall (the main driver of soil moisture temporal pattern) locally observed could induce discrepancies when compared to coarse resolution products, particularly in summer where local storm events may occur in southwestern France. *ECM* analysis does not assimilate rainfall, the information contained in observations of air temperature and humidity close to the surface as well as ASCAT SSM are used to analyse soil moisture. The use of precipitation data in the analysis is ongoing work at ECMWF; Lopez (2011) has demonstrated a positive impact on model performance of the direct 4D-Var assimilation of 6-hourly radar and rain-gauge rainfall accumulations. However, additionally to this representativeness issue, the two precipitations events highlighted by Fig. 5 in *ECM* are not spotted by the two remotely sensed products which are in line with the observations.

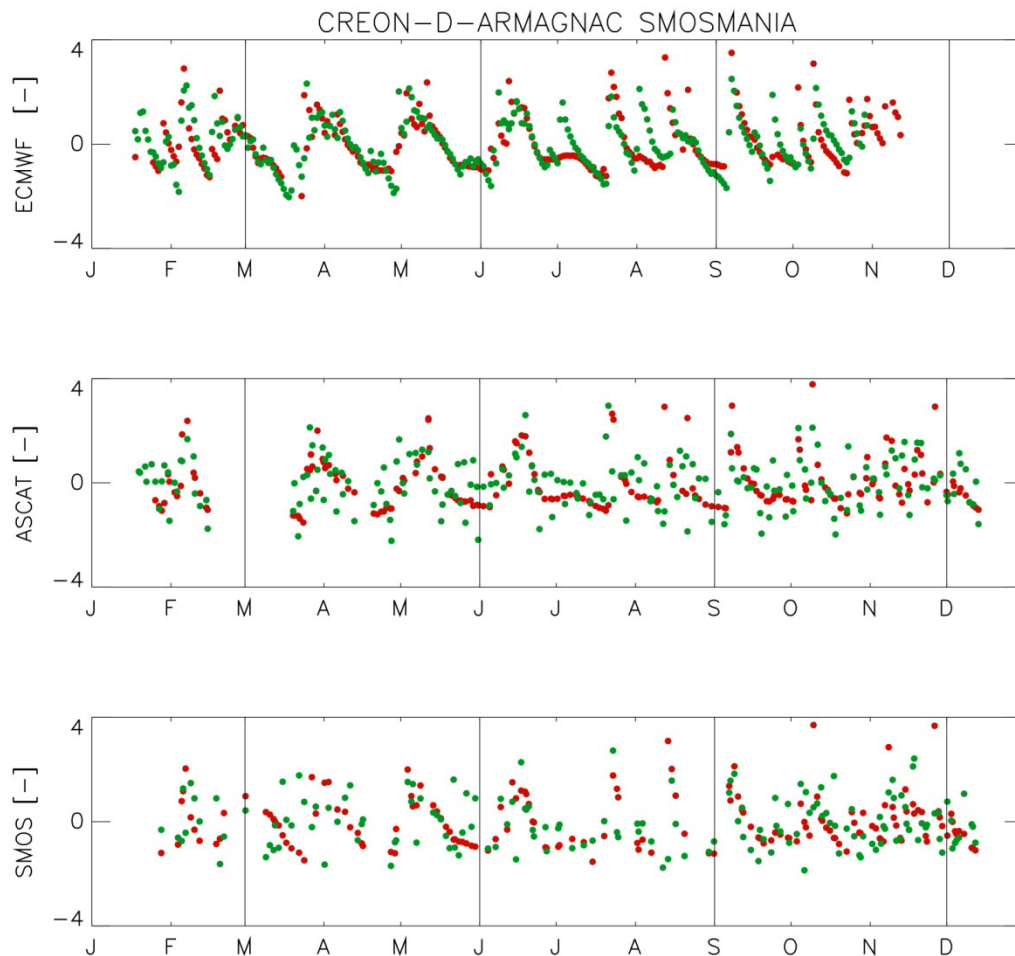


Figure 5: Temporal evolution of SSM anomaly time-series at the Creon d'Armagnac station of the SMOSMANIA network in southwestern France for 2010, from top to bottom; ECMWF (SM-DAS-2), ASCAT and SMOS (green dots). In situ anomaly time-series are in red.

Figure 6 presents scatter plots of the three products correlation performances compared by pairs of two. The top panel shows correlation values for the normalised time series and the bottom panel shows the anomaly correlations values. Normalised time-series correlation values scatter plots permit to see that *ECM* presents better correlation values than *ASC* and *SMO* (most of the correlations below the first diagonal), anomaly correlation values show the same tendency but at a lower degree. Table 5 presents comparisons between *ECM*, *ASC*, *SMO* and in situ observations for the stations presenting significant levels of correlations ( $p$ -values $<0.05$ ) for all the 3 products. Comparisons for normalised times-series as well as for anomaly time-series are presented. 168 and 165 stations for normalised and anomaly times-series, respectively, are available in this configuration. Evaluation of normalised time-series presents better scores than anomaly time series,  $R$  are 0.71, 0.55, 0.55 and 0.57, 0.45, 0.43 for *ECM*, *ASC* and *SMO*, respectively.

Table 4: Comparisons between in situ SSM and the three products; SM-DAS-2 (ECM), ASCAT (ASC) and SMOS (SMO) SSM anomaly time-series for 2010. Mean correlation, bias (in situ minus analyses) and root mean square difference (RMSD) are given for each network and for each product. Scores are presented for significant correlation values with  $p$ -values  $< 0.05$ . Four periods are distinguished: (i) winter, (ii) spring, (iii) summer and (iv) autumn.

Soil Moisture data set	Correlation [-]			Bias [-]			RMSD [-]		
	ECM	ASC	SMO	ECM	ASC	SMO	ECM	ASC	SMO
Winter	0.70	0.71	0.55	-0.023	0.031	-0.014	0.674	0.686	0.865
Spring	0.65	0.56	0.51	-0.004	0.042	$8.10^{-4}$	0.766	0.889	0.928
Summer	0.53	0.46	0.46	-0.014	-0.052	$3.10^{-4}$	0.857	0.964	0.962
Autumn	0.62	0.50	0.45	-0.008	-0.013	-0.017	0.761	0.916	0.967

Table 5: Comparisons between in situ SSM observations and products; SM-DAS-2 (ECM), ASCAT (ASC) and SMOS (SMO) for 2010. For normalised and anomaly time-series, mean correlation, bias (in situ minus analyses) and root mean square difference (RMSD) are given for each network and for each product. Scores are presented for stations presenting significant correlation levels ( $p$ -values  $< 0.05$ ) for all the three products. 168 and 165 stations for normalised and anomaly time-series, respectively, are available in this configuration.

Soil Moisture data set	Correlation [-]			Bias [-]			RMSD [-]		
	ECM	ASC	SMO	ECM	ASC	SMO	ECM	ASC	SMO
Normalised time series	0.71	0.55	0.55	-0.036	0.056	0.122	0.232	0.247	0.243
Anomaly time-series	0.57	0.45	0.43	-0.013	0.007	-0.013	0.824	0.967	1.001

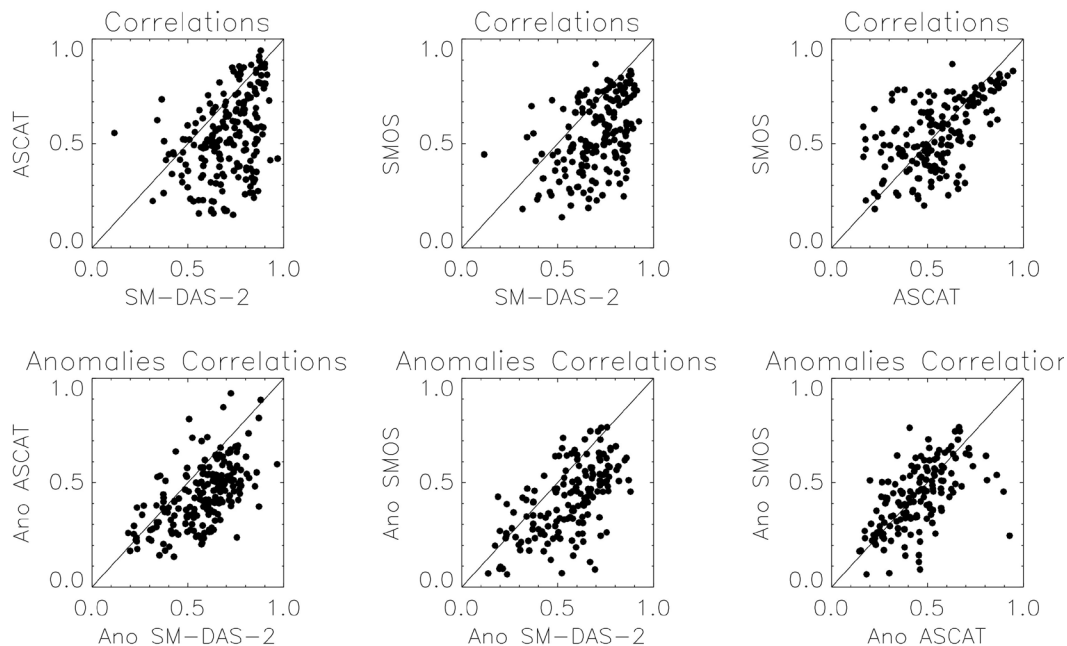


Figure 6: (top) correlations between ASCAT and in situ data against correlations between ECMWF SM-DAS-2 and in situ data, then same for SMOS and SM-DAS-2, SMOS and ASCAT. (Bottom) Same as top but for anomaly correlation values instead of normalised time series.

## 4 Conclusions

The validation activity conducted in this study used in situ surface soil moisture data sets from more than 200 stations located in Africa, Australia, Europe and United States to determine the reliability of three soil moisture products:

- SM-DAS-2, produced by ECMWF numerical weather prediction system and relying on an advanced surface data assimilation system used to optimally combine conventional observations ( $RH_{2m}$ ,  $TH_{2m}$ ) with satellite measurements (ASCAT surface soil moisture),
- ASCAT remotely sensed relative measure of the soil moisture in the first centimetres of soil, provided in near real time by EUMETSAT,
- SMOS soil moisture level 2 product obtained by minimizing the differences between modelled direct and measured brightness temperature data provided by CESBIO.

In general results show good performances of the three products to capture surface soil moisture annual cycle as well as short term variability. Correlation values between the data sets are very satisfactory over most of the investigated sites located in contrasted biomes and climate conditions with averaged values of 0.70 for SM-DAS-2, 0.53 for ASCAT and 0.54 for SMOS. SM-DAS-2 soil moisture analyses performances were found rather similar across the different studied sites with the exception of Western Africa presenting lower correlations. For this product, an estimate of the average error is about  $0.07 \text{ m}^3\text{m}^{-3}$ . SM-DAS-2 is produced at ECMWF in the framework of the Hydrological Satellite Application Facilities (H-SAF) project. It provides, for the first time, a global daily product of consistent quality of surface soil moisture index, available in near real time. Such product is required for many applications to be used as realistic initial states for the soil moisture variables, from forecasts of weather and seasonal climate variations to models of plant growth and carbon fluxes. ASCAT and SMOS present similar performances with an estimated error of  $0.08 \text{ m}^3\text{m}^{-3}$  on average for all the considered stations. While new reprocessed ASCAT data sets were shown to have better correlations with in situ data in Europe, the one used in this study presents the advantage of being available in near real time (operational product delivered by EUMETSAT). In the same way, maturity of the SMOS level 2 product does not reach the one ASCAT yet (first year of data) and improvements in algorithms for both are expected. For the three products, even if in situ data of SSM do not measure the same quantity as coarse resolution SSM (remotely sensed and modelled) due to the high spatial variability of soil moisture, significant correlation values were obtained between in situ and products. In situ data can be used to monitor the quality of SSM from either remote sensing or modelling. These results highlight the complementarities between remotely sensed products and ECMWF soil moisture analysis as well as the potential of using satellite data for NWP soil moisture analysis. The flexibility of the ECMWF soil moisture analysis opens a wide range of development possibilities. Additionally to the use of satellite based soil moisture information from both active and passive microwave sensors like ASCAT, SMOS and the upcoming SMAP (Soil Moisture Active/Passive) mission, an extension of the EKF to analyse other variables such as snow mass and vegetation parameters is under development at ECMWF.

## Acknowledgment

Authors would like to acknowledge J.-C. Calvet from Météo-France for giving access to the SMOSMANIA and SWATMEX soil moisture data as well as T. Pellarin from LTHE for giving access to AMMA soil moisture data and T. Kral from ECMWF for his help in handling the NCRS-SCAN data. Authors thank the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management “(H-SAF)” for their funding support.

## Bibliography

- Albergel, C., Rüdiger, C., Pellarin, T., Calvet, J.-C., Fritz, N., Froissard, F., Suquia, D., Petitpa, D., Pignat, B. & Martin E. (2008). From near-surface to root-zone soil moisture using an exponential filter: an assessment of the method based on in situ observations and model simulations, *Hydrol. Earth Syst. Sci.*, **12**, 1323–1337, doi:10.5194/hess-12-1323-2008.
- Albergel, C., Rüdiger, C., Carrer, D., Calvet, J.-C., Fritz, N., Naeimi, V., Bartalis, Z., & Hasenauer, S. (2009). An evaluation of ASCAT surface soil moisture products with in situ observations in Southwestern France, *Hydrol. Earth Syst. Sci.*, **13**, 115–124, doi:10.5194/hess-13-115-2009.
- Albergel, C., Calvet, J.-C., de Rosnay, P., Balsamo, G., Wagner, W., Hasenauer, S., Naemi, V., Martin, E., Bazile, E., Bouyssel, F. & Mahfouf, J.-F. (2010). Cross-evaluation of modelled and remotely sensed surface soil moisture with in situ data in southwestern France, *Hydrol. Earth Syst. Sci.*, **14**, 2177-2191, doi:10.5194/hess-14-2177-2010.
- Albergel, C., Zakharova, E., Calvet, J.-C., Zribi, M., Pardé, M., Wigneron, J.-P., Novello, N., Kerr, Y., Mialon A. & Fritz, N (2011). A first assessment of the SMOS data in southwestern France using in situ and airborne soil moisture estimates: the CAROLS airborne campaign. *Remote sensing of environment*, **115**, 2718-2728, doi:10.1016/j.rse.2011.06.012.
- Balsamo, G., Viterbo, P., Beljaars, A.C.M., van den Hurk, B.J.J.M., Hirschi, M., Betts, A.K. & Scipal K. (2009). A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the ECMWF-IFS, *J. Hydrometeor.*, **10**, 623–643, doi:10.1175/2008JHM1068.1.
- Bartalis, Z., Wagner, W., Naeimi, V., Hasenauer, S., Scipal, K., Bonekamp, H., Figa, J. & Anderson, C. (2007). Initial soil moisture retrievals from the METOP-A advanced Scatterometer (ASCAT), *Geophys. Res. Lett.*, **34**, L20401, doi:10.1029/2007GL031088.
- Bartalis, Z., Hasenauer, S., Naeimi, V. & Wagner, W. (2007b). WARP-NRT 2.0 Reference Manual, *ASCAT Soil Moisture Report Series*, No. 14, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Austria, 26.
- Broca, L., Melone, F., Moramarco, T., Wagner, W. & Hasenauer, S. (2010a). ASCAT soil wetness index validation through in situ and modelled soil moisture data in central Italy. *Remote Sens. Environ.*, **114**(11), 2745-2755, doi:10.1016/j.rse.2010.06.009.

- Brocca, L., Melone, F., Moramarco, T., Wagner, W., Naeimi, V., Bartalis, Z. & Hasenauer, S. (2010b). Improving runoff prediction through the assimilation of the ASCAT soil moisture product, *Hydrol. Earth Syst. Sci.*, **14**, 2745-2755.
- Brocca, L., Hasenauer, S., Lacava, T., Melone, F., Moramarco, T., Wagner, W., Dorigo, W., Matgen, P., Martínez-Fernández, J., Llorens, P., Latron, J., Martin, C., Bittelli, M. (2011). Soil moisture estimation through ASCAT and AMSR-E: An intercomparison and validation study across Europe. *Remote Sensing of Environment*, doi: 10.1016/j.rse.2011.08.003
- Calvet, J.-C., Wigneron, J.-P., Walker, J.P., Karbou, F., Chanzy, A. & Albergel, C. (2011). Sensitivity of passive microwave observations to soil moisture and vegetation water content: L-band to W band, *IEEE Trans. Geosci. Remote. Sens.*, **49**, 4, 1190-1199 doi: 10.1109/TGRS.2010.2050488.
- Dharssi, I, Bovis, K., Macpherson, B. & Jones C. (2011). Operational assimilation of ASCAT surface soil wetness at the Met Office, *Hydrol. Earth Syst. Sci. Discuss.*, **8**, 4313-4354, doi:10.5194/hessd-8-4313-2011.
- Draper, C., Mahfouf, J.-F., Calvet, J.-C., Martin, E. & Wagner, W. (2011). Assimilation of ASCAT near-surface soil moisture into the French SIM hydrological model, *Hydrol. Earth Syst. Sci. Disc.*, **8**, 5427-5464, doi:10.5194/hessd-8-5427-2011.
- de Rosnay, P., Gruhier, C., Timouk, F., Baup, F., Mougín, E., Hiernaux, P., Kergoat, L. & V. LeDantec, (2009). Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali. *J. Hydrol.*, **375**, 241–252, doi:10.1016/j.jhydrol.2009.01.015.
- de Rosnay, P., Drusch, M., Balsamo, G., Isaksen L. & Albergel, C. (2011). Extended Kalman Filter soil moisture analysis in the IFS. *ECMWF Newsletter*, n127, 12-16.
- Dorigo, W.A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A. and Jackson, T. (2011). The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, *Hydrol. Earth Syst. Sci.*, **15**, 1675-1698, doi:10.5194/hess-15-1675-2011.
- Drusch, M., Scipal, K., de Rosnay, P., Balsamo, G., Anderson, E., Bougeault, P. & Viterbo, P. (2009). Towards a Kalman Filter based soil moisture analysis system for the operational ECMWF integrated forecast system, *Geophys. Res. Lett.*, **36**, L10401, doi:10.1029/2009GL037716.
- Gruhier, C., de Rosnay, P., Hasenauer, S., Holmes, T., de Jeu, R., Kerr, Y., Mougín, E., Njoku, E., Timouk, F., Wagner, W. & M. Zribi (2010). Soil moisture active and passive microwave products: intercomparison and evaluation over a Sahelian site, *Hydrol. Earth Syst. Sci.*, **14**, 141–156, 2010
- Hahn, S. & Wagner, W. (2011). Characterisation of calibration-related errors on the initial METOP ASCAT soil moisture product, *Geophysical Research Abstract*, **13**, EGU2011-3178.
- Jackson, T.J., Hsu, A.Y., van de Griend, A. & Eagleman, J.R. (2004). Skylab L band microwave radiometer observations of soil moisture revisited, *Int. J. Remote Sens.*, **25**, 2585–2606.

- Kerr, Y. (2007): Soil moisture from space: where are we?, *Hydrogeol. J.*, **15**(1), 117–120.
- Kerr, Y.H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., Escorihuela, M.-J., Font, J., Reul, N., Gruhier, C., Juglea, S.E., Drinkwater, M.R. -Neira, M. & Mecklenburg, S., (2010). The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle. *Proceedings of the IEEE*, **98** (5), 666 - 687.
- Loew, A., Dall'Amico, J.T., Schlenz, F. & Mauser, W. (2010). The Upper Danube soil moisture validation site: measurements and activities, paper presented at Earth Observation and Water Cycle conference, Frascati (Rome), 18-20 November 2009, *ESA Special Publication SP-674*.
- Lopez, P., (2011). Direct 4D-Var Assimilation of NCEP Stage IV Radar and Gauge Precipitation Data at ECMWF, *Monthly Weather Rev.*, **139**, 2098-2116 DOI: 10.1175/2010MWR3565.1.
- Mahfouf, J.-F. (2010). Assimilation of satellite-derived soil moisture from ASCAT in a limited-area NWP model, *Q. J. R. Meteorol. Soc.*, **136**, 784-198, doi:10.1002/qj602.
- Martínez-Fernández, J. & Ceballos, A. (2005). Mean soil moisture estimation using temporal stability analysis, *J. Hydrol.*, **312** (1-4), 28–38, doi :10.1016/j.jhydrol.2005.02.007.
- Njoku, E.G., Jackson, T.J., Lakshmi, V., Chan, T.K. & Nghiem, S.V. (2003). Soil moisture retrieval from AMSR-E, *IEEE T. Geosci. Remote*, **41**(2), 215–123.
- Parinussa, R. M., Holmes, T. R. H. & Crow, W. T. (2011). The impact of land surface temperature on soil moisture anomaly detection from passive microwave observations, *Hydrol. Earth Syst. Sci. Discuss.*, **8**, 6683-6719, doi:10.5194/hessd-8-6683-2011.
- Pellarin T., Laurent, J.P., Cappelaere, B., Decharme, B., Descroix L. & Ramier, D. (2009a). Hydrological modelling and associated microwave emission of a semi-arid region in South-western Niger, *J. Hydrol.*, **375**, 1-2, 262-272.
- Pellarin T., Tran, T., Cohard, J.-M., Galle, S., Laurent, J.-P., de Rosnay, P. & Vischel, T. (2009b). Soil moisture mapping over West Africa with a 30-min temporal resolution using AMSR-E observations and a satellite-based rainfall product, *Hydrol. Earth Syst. Sci.*, **13**, 1887–1896.
- Redelsperger, J.-L., Thorncroft, C., Diedhiou, A., Lebel, T., Parker, D. & Polcher, J. (2006). African monsoon multidisciplinary analysis (AMMA): an international research project and field campaign., *Bull. Am. Meteorol. Soc.*, **87** (12), 1739–1746.
- Rüdiger, C., Calvet, J.-C., Gruhier, C., Holmes, T., De Jeu, R. & Wagner, W. (2009). An intercomparison of ERS-Scat and AMSR-E soil moisture observations with model simulations over France, *J. Hydrometeorol.*, **10**(2), 431–447, doi:10.1175/2008JHM997.1.
- Sabater, J.M., Rüdiger, C., Calvet, J.-C., Fritz, N., Jarlan, L. & Kerr, Y. (2008). Joint assimilation of surface soil moisture and LAI observations into land surface model. *Agricultural and Forest Meteorology*, **148**, 1362-1373, doi:10.1016/j.agrformet.2008.04.003.

- Scipal, K., Drusch, M. & Wagner, W. (2008). Assimilation of ERS scatterometer derived soil moisture index in the ECMWF numerical weather prediction system, *Adv. Water Res.*, **31**, 1101-1112, doi:10.1016/j.adcwatres.2008.04.013.
- Schaefer, G.L. & Paetzold, R.F. (2000). SNOTEL (SNOWpack TELemetry) and SCAN (Soil Climate Analysis Network) *Presented at the Automated Weather Station (AWS) workshop*. March 6-10. Lincoln, NE.
- Schmugge, T. J. (1983). Remote sensing of soil moisture: recent advances, *IEEE T. Geosci. Remote Sens.*, **GE21**, 145–146.
- Taylor, K.E. (2001). Summarizing multiple aspects of model performance in a single diagram, *J. Geophys. Res.*, **106**, 7183-7192.
- van den Hurk, B. & Viterbo, P. (2003). The Torne-Kalix PILPS 2(e) experiment as a test bed for modifications to the ECMWF land surface scheme. *Global and Planetary Change*, **38**, 165–173.
- Waldteufel P. & Vergely, J.-L. (2003). Soil moisture retrieval for the SMOS mission, Retrieval Algorithm Document, ACRI-ST, Sophia antipolis, *Technical note* SMOS-TN-ACR-SA-002, 25/03/2003 2003.
- Wagner, W., Lemoine, G. & Rott, H. (1999). A method for estimating soil moisture from ERS scatterometer and soil data, *Remote Sens. Environ.*, **70**, 191-207.
- Wagner, W., Blöschl, G., Pampaloni, P., Calvet, J.-C., Bizzarri, B., Wigneron, J.-P. & Kerr, Y. (2007). Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, *Nord. Hydrol.*, **38**(1), 1–20, doi:10.2166/nh2007.029.
- Wagner, W., Bartalis, Z., Naeimi, V., Park, S.-E., Figa-Saldaña, J. & Bonekamp, H. (2010). Status of the METOP ASCAT soil moisture product, *Geoscience and Remote Sensing Symposium 2010* (IGARSS2010), 25-30 July 2010, Honolulu, Hawaii, U.S.A., pp. 276-279.
- Walker, J.P., Willgoose, G.R. & Kalma, J.D. (2001). One-dimensional soil moisture profile retrieval by assimilation of near-surface measurements: A simplified soil moisture model and field application, *J. Hydrometeorol.*, **2**, 356-373.
- Wigneron, J.-P., Chanzy, A., Calvet, J.-C & Bruguier, N. (1995). A simple algorithm to retrieve soil moisture and vegetation biomass using passive microwave measurements over crop fields, *Rem. Sens. of Environ.*, **51**(3), 331-341.
- Wigneron, J.-P., Waldteufel, P., Chanzy, A., Calvet, J.-C & Kerr, Y. (2000). Two -D microwave interferometer retrieval capabilities over land surfaces (SMOS mission), *Rem. Sens. of Environ.*, **73**(3), 270-282.
- Young, R., Walker, J.P., Yeoh, N., Smith, A., Ellett, K., Merlin O. & Western, A. (2008) Soil Moisture and Meteorological Observations From the Murrumbidgee Catchment, Department of



Civil and Environmental Engineering, The University of Melbourne.  
(<http://www.oznet.org.au/mdbdata/document.html>, last access, 10/05/2011).

Zribi, M., Pardé, M., Boutin, J., Fanise, P., Hauser, D., Dechambre, M., Kerr, Y., Leduc-Leballeur, M., Skou, M., Søbjaerg, S.S., Albergel, C., Calvet, J.-C., Wigneron, J.-P., Lopez-Baeza, E., Saleh, K., Ruis, A. & Tenerelli, J. (2011). Land and ocean calibration and validation of SMOS: the CAROLS airborne campaigns, *Sensors*, **11**, 719-742, doi:10.3390/s110100719, 2011.