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Soil moisture analyses at ECMWF: evaluation using global ground-based in situ observations

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Abstract

In situ soil moisture from 117 stations across the world and under different biome and climate conditions are used to evaluate two soil moisture products from ECMWF, namely the operational analysis and the interim reanalysis (ERA-Interim). The ECMWF's operational Integrated Forecasting System (IFS) is based on a continuous effort to improve the analysis and modelling schemes, resulting in frequent updates of the system (few times a year). The ERA-Interim reanalysis is produced by a fixed IFS version (for the main component of the atmospheric model and data assimilation). It presents the advantage of being consistent over the whole period from 1979 onwards and by design, reanalysis products are more suitable than their operational counterparts for use in climate studies. Although, the two analyses show good skills to capture surface soil moisture variability, they tend to overestimate soil moisture, particularly for dry lands. However, compared to the scheme used in ERA-Interim, the current model used in the IFS has an improved match to soil moisture, attributed to recent changes in the IFS. In particular, major upgrades recently implemented in the operational land surface analysis and modelling system improve the surface soil moisture and the root-zone soil moisture analyses. Additionally, the new soil moisture analysis scheme used within the IFS, based on an Extended Kalman Filter has improved the soil moisture analysis.

1 Introduction

Soil moisture is a crucial variable for numerical weather and climate prediction as it controls the partitioning of energy in latent and sensible heat fluxes at the soil-atmosphere interface. It is a key variable in hydrological processes (runoff, evaporation from bare soil and transpiration from the vegetation cover), impacts plant growth and carbon fluxes (Dirmeyer et al., 1999, Entekhabi et al, 1999). Soil moisture is also important on its own for monitoring land surface conditions that trigger extreme events such as droughts, heat-waves and flood. As a consequence, a significant amount of studies have been conducted to obtain soil moisture estimates. It was shown that, land surface modelling (e.g. Dirmeyer et al., 1999; Georgakakos and Carpenter, 2006) and remote sensing techniques (Wagner et al., 1999, 2007a Kerr et al., 2001, 2007, Njoku et al., 2003) have a great potential to provide reliable estimates of soil moisture.

In recent years, major upgrades have been implemented in the land surface modelling and analysis systems of the European Centre for Medium-Range Weather Forecasts (ECMWF). An improved soil hydrology (Balsamo et al., 2009), a new snow scheme (Dutra et al., 2010) and a multi-year satellite based vegetation climatology (Boussetta et al., 2010) were implemented in the operational Integrated Forecasting System (IFS). A new soil moisture analysis scheme based on a point-wise Extended Kalman Filter (EKF) for the global land surface has been developed and implemented (Drush et al., 2009, de Rosnay et al., 2011). As the previous Optimal Interpolation (OI, Mahfouf, 1991a, Mahfouf et al., 2000a) scheme, it uses proxy observations to analyse soil moisture (temperature and relative humidity at two meters). The EKF is able to make optimal use of satellite based land surface information, while the OI method is not flexible enough to easily account for those new types of observations (Mahfouf et al., 2009).

Quantitative information about the soil 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 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. 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., 2001, 2007). It consists of a spaceborne L-band (~1.42 GHz, 21 cm) interferometric radiometer able to provide global surface soil moisture (SSM) estimates at a spatial resolution of about 40 km. Another sensor, the Advanced Scatterometer ASCAT onboard METOP (launched 2006), also 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). ASCAT is a C-band radar operating at 5.255 GHz (Wagner et al, 2007b; Bartalis et al., 2007a,b; Albergel et al., 2009). Even if satellite sensors sample the very first centimetres of soil, their derived SSM related information can be propagated in deeper layers using analyses techniques such as the EKF (Walker et al., 2001, Sabater et al., 2007, 2008, Albergel et al., 2010a).

This study presents an evaluation of the operational analysis soil moisture product of ECMWF using in situ SSM from more than 100 stations across the world (Australia, Africa, America and Europe) for the 2007- early 2011 period. Along with the operational product, the new ECMWF interim reanalysis product, ERA-Interim (from 1979 onwards, Dee et al., 2011) is evaluated. While the operational analysis is obtained from continously and frequently revised IFS versions, including changes in spatial and vertical resolutions, data assimilation and parameterizations advances, and new data sources, ERA-Interim guarantees a higher level of consistency (e.g. in skill) due to its frozen configuration. After a description of the different soil moisture data set used in this study, ECMWF SSM products are firstly evaluated against the SMOSMANIA (Soil Moisture Observing System – Meteorological Automatic Network Integrated Application) soil moisture network (Calvet et al., 2007, Albergel et al., 2008) and the SMOSREX experimental site (de Rosnay et al., 2006) in southwestern France. In situ data from those sites were already used to assess the quality of several SSM data sets including operational products, from meteorological services as well as remotely sensed product such as ASCAT SSM (Albergel et al., 2009, 2010b). ECMWF operational and reanalysis products are evaluated for a four year period (2007-2010) showing the evolution of the operational product quality. The comparison between ECMWF's analyses and soil moisture observations of the SMOSMANIA network and the SMOSREX experimental site in southwestern France set up the frame of this study. ECMWF's products evaluation is then extended to in situ observation network across the world.

2 Material and methods

In situ soil moisture observations are needed to evaluate soil moisture products derived from either modelling or remote sensing. In this study in situ data from more than 12 networks across four continents were gathered. Some of them were 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/), a new data hosting centre where globally available ground based soil moisture measurements are collected, harmonized and made available to users, was also useful in this study. Others data sets were obtained by request from the concerned organisations such as Météo-France and European the Short-Range Numerical Weather Prediction (SRNWP) Programme. Data at 133 stations were collected, a first visual quality check was performed and when suspicious data were observed, they were discarded leading to 117 stations retained to evaluate ECMWF's products in the first model layer of soil (0-7 cm) and 69 for the second model layer of soil (7-28 cm). Indeed, most of the stations are measuring surface soil moisture, only.

Soil moisture analyses from either the deterministic operational suite or ERA-Interim are available at four depths (0-7, 7-28, 28-100 and 100-289 cm, Balsamo et al., 2009). The first two layers of soil moisture analysis product are evaluated on a period from January 2007 to April 2011. In situ data are collected within this period, however their availability does not necessarily cover the whole period. The different soil moisture data sets used in this study are presented in Table 1.

Table 1: Presentation of the different soil moisture products used in this study. NWP stand for numerical weather prediction. 133 stations with in situ observations are available.

Soil Moisture data set	**Type**	**Soil layer depth (cm)**	**Considered period**	**Spatial resolution**	**Number of stations**
ECMWF operational analysis	NWP analysis	0-7 and 7-28	January 2007 to April 2011	Before 26-01-2010 : 23 km (T799) from 27-01-2010 : 16 km (T1279)	Global product
ECMWF ERA-Interim	NWP reanalysis	0-7 and 7-28	January 2007 to February 2011	80 km (T255)	Global product
SMOSMANIA (France)	In situ observations	5, 10, 20, 30	January 2007 to December 2010	Local scale	12 stations
SWATMEX (France)	In situ observations	5, 10, 20, 30	January 2009 to December 2009	Local scale	9 stations
SMOSREX (France)	In situ observations	0-6, 10, 20, 30, 40, 50, 60, 70, 80, 90	January 2007 to December 2009	Local scale	1 station
OZNET (Australie)	In situ observations	0-5 or 0-8 and 0-30	January 2007 to August 2010	Local scale	38 stations
NCRS-SCAN (US)	In situ observations	5, 20	January 2007 April 2011	Local scale	28 stations
AMMA (West Africa)	In situ observations	5	January 2007 to December 2009	Local scale	10 stations
SRNWP (Germany)	In situ observations	8	January 2007 to December 2009	Local scale	1 station
REMEDHUS (Spain)	In situ observations	5	January 2007 to December 2010	Local scale	21 stations
UMSUOL (Italy)	In situ observations	10	June 2009 to September 2010	Local scale	1 station
SWEXPOLAND (Poland)	In situ observations	5	January 2007 to September 2009	Local scale	1 station
UDC-SMOS (Germany)	In situ observations	5	January 2007 to December 2010	Local scale	10 stations
Sodankyla (North Finland)	In situ observations	10	January 2007 to December 2010	Local scale	1 station

2.1 ECMWF’s Integrated Forecast System (IFS)

Data produced at ECMWF include a large variety of surface parameters, describing atmosphere as well as ocean-wave and land-surface conditions.

2.1.1 Upper-air analysis

The core atmospheric assimilation system at ECMWF relies on the four-dimensional variational (4D-Var) data assimilation scheme (Rabier et al., 2000, Mahfouf et al., 2000b) with an observation time windows of 12 hours (Bouttier, 2001). Data provided by satellite sensors both from microwave and infrared radiometers as well as conventional observations (e.g. radiosonde network) are ingested within the 4D-Var. Surface observations such as surface pressure, humidity and wind enter the 4D-Var, also.

2.1.2 Surface analysis

The model background for land surface analysis is provided by the TESSEL land surface scheme (Van den Hurk et al., 2000) then upgraded to H-TESSEL (Van den Hurk and Viterbo, 2003, Balsamo et al., 2009) with an improved soil hydrology. H-TESSEL development was a response to the TESSEL hydrology weaknesses: a Hortonian runoff scheme hardly producing surface runoff and the choice of a single global soil texture, not able to characterize different soil moisture regimes. Formulation of the soil hydrological conductivity and diffusivity were revised to be spatially variable according to a global soil texture map (FAO/UNESCO Digital Soil Map of the World, DSMW, FAO, 2003). In addition a surface runoff is based on the variable infiltration capacity. H-TESSEL was implemented by Balsamo et al. (2009) and verified from field site to global atmospheric coupled experiments and in data assimilation. However they considered only few selected soil moisture stations. Evaporation processes were revised and monthly Leaf-Area-Index (LAI) climatology (Bousseta et al., 2011) together with a enhanced bare ground evaporation (Balsamo et al., 2011) became operational in November 2010. Bare ground evaporation over dry lands has been enhanced by adopting a lower stress threshold than for the vegetation, it allows a higher evaporation. This is in agreement with the experimental findings of Mahfouf and Noilhan (1991b) and results in more realistic soil moisture values for dry land (Balsamo et al, 2011).

Three different analysis schemes for the surface (and near-surface) variables are currently used in operations. They are based on: the spatial Optimal Interpolation (2D-OI, for snow depth and screen-level analyses), the column Optimal Interpolation (1D-OI, used for soil and snow temperature analysis), and a simplified extended Kalman filter (EKF, used for the soil moisture analysis).

2.1.3 Soil moisture products

For both IFS products (operational analysis and ERA-Interim), the information contained in meteorological observations of screen level parameters such as air temperature and relative humidity (T_{2m} and RH_{2m}) close to the surface is used to analyse the soil moisture. In this section, the major differences between the deterministic operational suite and ERA-Interim, with respect to soil moisture analyses, are described.

The IFS cycles (version of IFS) used in operations at ECMWF within the considered period (from January 2007 to December 2010) span from 31r2 to 36r4 (more information: http://www.ecmwf.int/research/ifsdocs/). The land surface scheme used in operation is TESSEL and its revised version, H-TESSEL was implemented in operation in 9 November 2007. The revised bare ground evaporation and the montly LAI was implemented in November 2010. Before the implementation of cycle 36r4 in November 2010, the assimilation technique used was the optimal interpolation (Mahfouf, 1991a, Mahfouf et al., 2000a). On 9 November 2010, an advanced surface data assimilation scheme was implemented in operations, in order to optimally combine conventional observations with satellite measurements. It is based on an Extended Kalman Filter (EKF), as described in Drusch et al. (2009) and de Rosnay et al. (2011). In its current configuration, the EKF soil moisture analysis uses the T_{2m} and RH_{2m} screen level parameters as input. However it allows assimilating satellites data, such as ASCAT (de Rosnay et al., 2011, Albergel et al., 2010b). The operational IFS soil moisture analysis is produced daily at 00:00, 06:00, 12:00 and 18:00 UTC, at a spatial resolution of about 25 km (T799) until 26 January, 2010 and then at about 16 km (T1279). Analyses at 00:00 UTC are considered in this study. For the 00:00 UTC analysis, the 12 hour 4D-Var analysis is run using observations in the time window 21:00 UTC to 09:00 UTC. A summary of the different improvements implemented in operation between 2007 and 2010, with respect to soil moisture, is specified in Table 2.

ERA-Interim is the latest global atmospheric reanalysis produced by ECMWF (Dee et al., 2011), it uses IFS cycle 31r1. It covers the period from 1 January 1979 onwards, and continues to be extended forward in near-real time (with a delay of approximately one month). Berrisford et al. (2009) provide a detailed description of the ERA-Interim product archive. The land surface scheme used in ERA-Interim is TESSEL for the whole period. Therefore it does not take into account the hydrological improvements discussed in the above section. The assimilation technique used for soil moisture is the optimal interpolation and the spatial resolution is about 80 km (T255).

Table 2: Summary of the different improvements, with respect to soil moisture, implemented in operation at ECMWF over the 2007-2010, period.

Modifications implemented in operation	**Date of modification**
Implementation of H-TESSEL land surface scheme (Balsamo et al., 2009)	November 2007
Spatial resolution enhancement from about 25 km (T799) to about 16 km (T1279)	January 2010
Extended Kalman Filter analysis for soil moisture instead of Optimal Interpolation (Drusch et al., 2009, de Rosnay et al., 2011)	November 2010
Revised bare ground evaporation (Balsamo et al., 2011)	November 2010
Monthly MODIS-based LAI (Boussetta et al., 2010)	November 2010

2.2 In situ soil moisture observations

2.2.1 SMOSMANIA, SWATMEX and SMOSREX

The SMOSMANIA network is a long-term data acquisition effort of profile soil moisture observations in Southwestern France (Calvet et al., 2007; Albergel et al., 2008). With this project, 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). The soil moisture measurements are in units of m^3m^{-3}, they are derived from capacitance probes: ThetaProbe ML2X of Delta-T Devices, easily interfaced with the RADOME stations. A ThetaProbe provides a signal in units of volt and its variations is 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. Since January 2009, 9 additional RADOME stations where equipped with ThetaProbe in south and south eastern France. They form the SWATMEX (Soil Water and Temperature in Mediterranean EXPeriment) network. In situ SSM (5 cm) are compared to the first layer of ECMWF analysis (0-7 cm) and an average of in situ data (10 and 20 cm) is compared to the second layer of ECMWF analysis (7-28 cm). The considered period for the comparison is specified in Table 1. Located along the SMOSMANIA transect, the SMOSREX experimental site (de Rosnay et al., 2006) is also used in this study as it includes profile soil moisture observations since 2001. SSM measurements are performed with a vertically installed ThetaProbe (0–6 cm) and every ten centimetres until almost one meter depth (10, 20, 30, 40, 50, 60, 70, 80 and 90 cm).

2.2.2 OZNET

In situ data at 38 stations of the OZNET network (Young et al., 2008, http://www.oznet.org.au) are used in this study. They are all located within the Murrumbidgee experimental catchment in southern New South Wales, Australia. Each soil moisture site of the Murrumbidgee monitoring network measures the soil moisture at 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 also their moisture content.

2.2.3 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 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. In total, 28 stations presenting continuous measurements of soil moisture between 2007 and April 2011 were randomly selected within the whole US. Data are collected by a dielectric constant measuring device, typical measurements at 2 inches (about 5 cm) and 8 inches (about 20 cm), are used.

2.2.4 AMMA

In the framework of AMMA (African Monsoon Multidisciplinary Analysis), a 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. Among others, soil moisture 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. In this study, data collected at 5 and 20 cm are used from ten stations in Mali, Niger and Benin.

2.2.5 SRNWP

The goal of this program is to support the development of soil-vegetation-atmosphere transfer models within the European Short-Range Numerical Weather Prediction (SRNWP) community, by providing good quality operational data from a limited set of well instrumented and high quality observation sites, including soil moisture. It gathers soil moisture data for several European networks such as the SMOSREX experimental site already used in this study. In addition to SMOSREX, data from one site, the Lindenberg station observations are used. Lindenberg is a small village situated in a rural landscape in the East of Germany about 65 km to the South-East of the centre of Berlin. Soil moisture is measured at the upper level by 4 sensors (TDR) at 8 cm. Soil moisture determination using the gravimetric method is performed regularly during frost-free periods for comparison with the continuous sensors measurements.

2.2.6 ISMN soil moisture: REMEDHUS, UMSUOL, SWEXPOLAND, UDC-SMOS

21 stations from the REMEDHUS network in Spain are available through the ISMN website. This network is located in the central sector of the Duero basin. Each stations has been equipped with capacitance probes (HydraProbes, Stevens) installed horizontally at a depth of 5 cm. Analysis of soil sample were carried out to verify the capacitances probes and to asses soil properties at each station (Martinez-Fernandez and Ceballos, 2005).

The San Pietro Capofiume station belongs to the UMSUOL network located in northern Italy. 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). The Trzebieszow station from the SWEXPOLAND network in western Poland was used, also, data are collected by the mean of a TDR technology based (EasyTest, D-LOG/mpts) at 10 cm depth between January 2007 and September 2009.

10 stations near the city of Munich in Germany from the UDC-SMOS network (Loew et al., 2009) are introduced in this study. Data 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).

The Arctic Research Centre of the Finnish Meteorological Institute (ARC-FMI) monitors soil moisture at Sodankyla. It contains multiple soil moisture measurements at 2 cm and 10 cm with ThetaProbes. Data at 10 cm are used.

2.3 Statistical Comparison between analysis and in situ observations

All the soil moisture products are in units of m^3m^{-3}, but they may correspond to soil surface layers with different thicknesses (0–7 cm for ECMWF products, 5 cm for the SMOSMANIA stations, 8 cm for the OZNET stations). As both ECMWF products (operational analysis and ERA-Interim) use a multilayer soil moisture representation, additionally to SSM, the analysed soil moisture content in the second layer of soil (7–28 cm) can be compared to the in situ observations at deeper layer (an average at 10 and 20 cm for SMOSMANIA, 30 cm for OZNET) when available (69 stations). Data at 00:00 UTC are used for in situ data as well as for analysis. For each of the 117 stations available in this study and for both operational and ERA-Interim (referred as OPER and ERA-I in the following of the paper) analyses, correlation (R, Eq.1), bias (in situ minus analysis) and root mean square difference (RMSD, Eq.2) are computed for each year and for the whole 2008-2010 period (extended to April 2011 when available) between observations and analyses.

$$R = \sqrt{1 - \frac{\left(Analyses - insitu\right)^2}{\left(Analyses - \overline{insitu}\right)}} \tag{1}$$

$$RMSD = \sqrt{\overline{\left(Analyses - insitu\right)^2}} \tag{2}$$

The rational for using root mean square difference instead of root mean square error is that it permits to underline that, as well as model analysis, in situ data contain errors (instrumental and representativeness), so they are not considered as 'true' soil moisture. The year 2007 is removed from the final comparison as the land surface scheme was modified in operation in November 2007 (TESSEL upgraded to H-TESSEL), leading to a potential strong shift in the OPER analysis. Additionally, the normalised standard deviation (SDV) and the centred RMSD analysis and in situ patterns, normalised by the in situ standards deviations (E) are computed. SDV is the ratio between analysed and in situ standard 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.3 and Eq.4, respectively.

$$SDV = \sigma_{analyse} / \sigma_{in\ situ} \tag{3}$$

$$E^2 = \left(RMSD^2 - Bias^2\right)/\sigma^2{}_{in\ situ} \tag{4}$$

R, SDV and E are complementary but not independent as they are related by Eq.5 (Taylor, 2001).

$$E^2 = SDV^2 + 1 - 2 \cdot SDV \cdot R \tag{5}$$

Taylor diagram 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.

The p-value (Schervish, 1996), a measure of the correlation significance is calculated as well. It indicates the significance of the test, if it is small (e.g. below 0.05), it means that the correlation is not a coincidence.

3 Results

3.1 Using in situ data in southwestern France

The statistical scores for OPER and ERA-I are presented in Table 3 for the SMOSMANIA and SMOSREX stations. Figure 1 presents an illustration of the three different soil moisture products used in this study for three stations of the SMOSMANIA networks (Sabres, Lahas and St Felix) on the 2007-2010 period. The implementation of H-TESSEL land surface scheme within OPER (black line), in November 2007, resulted in a shift in the soil moisture range (shift down for Sabres and up for Lahas station). A simple look at Figure 1 permits to see that after the implementation of H-TESSEL, OPER presents a larger variability than ERA-I (red line) which uses TESSEL for the whole period. Note that OPER and ERA-I are only similar on the period from January to October 2007. After November 2007, OPER presents a larger annual water cycle and is in better agreement with the observations. Statistical scores are computed for 2007, 2008, 2009, 2010 and for the period 2008-2010. The shift induced by the implementation of H-TESSEL in November 2007 is an artifact which decreases the stability of the scores. That is why when considering the whole period, the year 2007 is not used.

Comparison between in situ data and ECMWF products show good temporal correlations for the 2008-2010 period with R ranging from 0.73 to 0.87 with an average of 0.80 for OPER and 0.62 to 0.83 with an average of 0.77 for ERA-I. The SSM temporal dynamic is well captured by both OPER and ERA-I analyses. Biases are ranging from -0.208 m^3m^{-3} to 0.041 m^3m^{-3} with an average value of -0.050 m^3m^{-3} for OPER and from -0.175 m^3m^{-3} to 0.087 m^3m^{-3} with an average of -0.035 m^3m^{-3} for ERA-I. No systematic biases are observed for this group of stations, however most of the stations present negatives values (10 of 13). RMSD are ranging from 0.044 m^3m^{-3} to 0.211 m^3m^{-3} with an average value of 0.088 m^3m^{-3} for OPER and from 0.038 m^3m^{-3} to 0.179 m^3m^{-3} with an average value of 0.097 m^3m^{-3} for ERA-I.

Table 3: Statistical scores for the comparison between ECMWF surface soil moisture analysis (0-7 cm, operational product in bold and ERA-Interim) and in situ SSM (5 cm) for the twelve station of the SMOSMANIA network and for the SMOSREX site for 2007, 2008, 2009, 2010 and 2008-2010. Biases and RMSD are in m^3m^{-3}.

	2007			2008			2009			2010			2008-2010		
	R	Bias	RMSD	R	Bias	RMSD	R	Bias	RMSD	R	Bias	RMSD	R	Bias	RMSD
SBR	**0.55**	**-0.156**	**0.165**	**0.80**	**-0.099**	**0.104**	**0.76**	**-0.068**	**0.081**	**0.83**	**-0.093**	**0.098**	**0.76**	**-0.087**	**0.095**
	0.71	-0.176	0.184	0.74	-0.176	0.180	0.79	-0.169	0.173	0.82	-0.181	0.184	0.77	-0.175	0.179
URG	**0.37**	**0.044**	**0.142**	**0.82**	**0.037**	**0.069**	**0.86**	**0.032**	**0.108**	**0.81**	**0.054**	**0.104**	**0.82**	**0.041**	**0.095**
	0.69	0.047	0.139	0.77	0.097	0.120	0.88	0.072	0.143	0.78	0.092	0.145	0.82	0.087	0.137
CRD	**0.16**	**-0.183**	**0.191**	**0.65**	**-0.233**	**0.235**	**0.83**	**-0.202**	**0.204**	**0.83**	**-0.192**	**0.195**	**0.73**	**-0.208**	**0.211**
	0.66	-0.174	0.179	0.79	-0.166	0.168	0.86	-0.148	0.150	0.80	-0.148	0.152	0.80	-0.153	0.156
PRG	**0.31**	**-0.027**	**0.068**	**0.74**	**-0.037**	**0.053**	**0.90**	**-0.012**	**0.040**	**0.84**	**-0.083**	**0.091**	**0.79**	**-0.043**	**0.065**
	0.67	-0.028	0.060	0.80	0.017	0.045	0.83	-0.003	0.064	0.81	-0.046	0.067	0.78	-0.010	0.060
CDM	**0.51**	**0.018**	**0.072**	**0.80**	**-0.016**	**0.042**	**0.88**	**0.015**	**0.041**	**0.85**	**0.028**	**0.049**	**0.82**	**0.009**	**0.044**
	0.75	0.015	0.070	0.74	0.036	0.061	0.88	0.030	0.063	0.83	0.032	0.059	0.83	0.033	0.061
LHS	**0.31**	**0.008**	**0.075**	**0.79**	**-0.038**	**0.068**	**0.87**	**0.003**	**0.042**	**0.92**	**0.022**	**0.044**	**0.80**	**-0.005**	**0.053**
	0.78	0.024	0.068	0.84	0.026	0.070	0.81	0.029	0.063	0.86	0.039	0.077	0.81	0.031	0.070
SVN	**0.32**	**-0.069**	**0.107**	**0.79**	**-0.112**	**0.126**	**0.87**	**-0.045**	**0.067**	**0.82**	**-0.054**	**0.086**	**0.76**	**-0.071**	**0.096**
	0.74	-0.058	0.094	0.80	-0.060	0.092	0.86	-0.026	0.074	0.79	-0.038	0.096	0.79	-0.041	0.087
MNT	**0.64**	**0.036**	**0.072**	**0.87**	**0.015**	**0.051**	**0.82**	**0.038**	**0.081**	**0.78**	**0.056**	**0.081**	**0.80**	**0.036**	**0.072**
	0.33	0.038	0.084	0.57	0.046	0.095	0.83	0.045	0.108	0.80	0.064	0.095	0.73	0.052	0.099
SFL	**0.39**	**-0.064**	**0.089**	**0.86**	**-0.066**	**0.076**	**0.89**	**-0.045**	**0.058**	**0.89**	**-0.036**	**0.053**	**0.87**	**-0.049**	**0.063**
	0.07	-0.072	0.098	0.72	-0.044	0.073	0.76	-0.040	0.073	0.83	-0.035	0.061	0.75	-0.040	0.069
MTM	**0.73**	**-0.057**	**0.063**	**0.78**	**-0.065**	**0.084**	**0.88**	**-0.065**	**0.077**	**0.84**	**-0.095**	**0.106**	**0.80**	**-0.075**	**0.090**
	0.72	-0.032	0.041	0.71	-0.018	0.032	0.87	-0.024	0.035	0.87	-0.039	0.046	0.82	-0.027	0.038
LZC	**0.73**	**-0.130**	**0.137**	**0.81**	**-0.115**	**0.124**	**0.81**	**-0.089**	**0.101**	**0.53**	**-0.162**	**0.172**	**0.75**	**-0.111**	**0.123**
	0.63	-0.159	0.166	0.79	-0.137	0.144	0.84	-0.101	0.111	0.52	-0.139	0.150	0.73	-0.123	0.133
NBN	**0.68**	**-0.052**	**0.068**	**0.86**	**-0.063**	**0.074**	**0.87**	**-0.025**	**0.046**	**0.87**	**-0.032**	**0.052**	**0.84**	**-0.040**	**0.059**
	0.60	-0.079	0.093	0.76	-0.084	0.097	0.81	-0.046	0.065	0.85	-0.044	0.058	0.76	-0.058	0.075
SMX	**0.38**	**-0.061**	**0.105**	**0.86**	**-0.075**	**0.097**	**0.87**	**-0.024**	**0.067**	**Na**	**Na**	**Na**	**0.80**	**-0.049**	**0.083**
	0.38	-0.061	0.107	0.49	-0.036	0.099	0.73	-0.018	0.101	Na	Na	Na	0.62	-0.027	0.100
average	**0.47**	**-0.053**	**0.104**	**0.80**	**-0.067**	**0.093**	**0.85**	**-0.037**	**0.078**	**0.82**	**-0.049**	**0.094**	**0.80**	**-0.050**	**0.088**
	0.60	-0.055	0.106	0.73	-0.038	0.098	0.83	-0.031	0.094	0.80	-0.037	0.099	0.77	-0.035	0.097

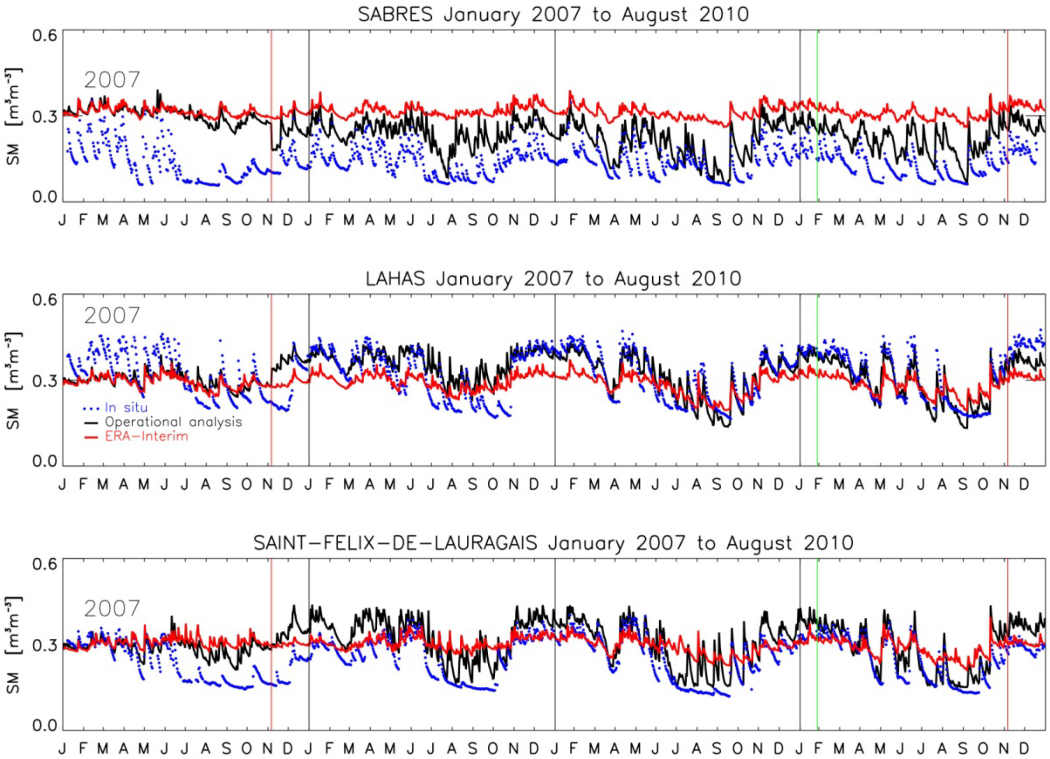

Figure 1: Illustration of soil moisture products time series used in this study, blue dots are for in situ data, black line for the operational ECMWF analysis and the red line for ERA-Interim. Stations belong to the SMOSMANIA network, from top to bottom are Sabres, Lahas and St Felix in southwestern France. Vertical lines indicate major changes in the operational system, with respect to soil moisture: in November 2007 the implementation of H-TESSEL, in January 2010, a change in the spatial resolution from 25 km (T799) to 16 km (T1279) and in November 2010 the implementation of the EKF soil moisture analysis and the bare ground evaporation parameterisation.

Statistics are computed for the second layer of soil, too (not shown). Soil moisture analysis between 7 and 28 cm is compared to averaged in situ data at 10 and 20 cm. Correlations values are ranging from 0.66 to 0.90 with an average of 0.82 for OPER and from 0.60 to 0.84 with an average of 0.78 for ERA-I. Biases are ranging from -0.215 m^3m^{-3} to 0.022 m^3m^{-3} with an average value of -0.056 m^3m^{-3} for OPER and from -0.177 m^3m^{-3} to 0.049 m^3m^{-3} with an average of -0.049 m^3m^{-3} for ERA-I. RMSD are ranging from 0.039 m^3m^{-3} to 0.219 m^3m^{-3} with an average value of 0.081 m^3m^{-3} for OPER while they range from 0.035 m^3m^{-3} to 0.184 m^3m^{-3} with an average value of 0.091 m^3m^{-3} for ERA-I. For the different periods considered (2007, 2008, 2009, 2010 and 2008-2010), OPER presents higher correlations, smaller bias and RMSD than ERA-I. All p-values are below 0.05, indicating that all stations present significant level of correlations.

Figure 2 presents two Taylor diagrams illustrating the statistics of the comparison between ECMWF OPER and ERA-I analyses with in situ data for the twelve stations of the SMOSMANIA network and SMOSREX experimental site for 2007, 2008, 2009 and 2010 (diagram on the left is for the first layer of soil and diagram on the right is for the second layer of soil). These diagrams underline the good range of correlation with most of the values between 0.70 and 0.90. Also, it is shown the smaller variability of ERA-I product (triangles) than the OPER analysis (circles). The dynamical range of ERA-I is most often than not smaller than OPER (in agreement with Figure 1) and systematically smaller than in situ data. Triangles symbols, representing ERA-I analysis are systematically below the SDV value of 1 (blue dashed line on Figure 2). As SDV is the ratio between analysed and in situ standard deviation (see Eq.3) it indicates that the variability of the in situ data is higher than the one of ERA-I. Taylor diagrams of Figure 2 are in line with statistical scores presented in Table 3. They are complementary as they permit to better appreciate the dynamic of the two ECMWF analyses, giving an additional indication on the relative amplitude and the pattern variation. Taylor diagrams provide a global view of the dynamic of ECMWF soil moisture analyses (correlation and SDV). Those results show the added value of the different upgrades within the operational analysis (including the change in spatial resolution in January 2010). The main contribution of the improvement in terms of soil moisture dynamic comes from the revised H-TESSEL land surface scheme. The soil physiographic parameters (wilting point and field capacity) associated to each soil texture in the new analysis produce a larger water holding capacity leading to a better representation of the observed dynamical range of in situ soil moisture.

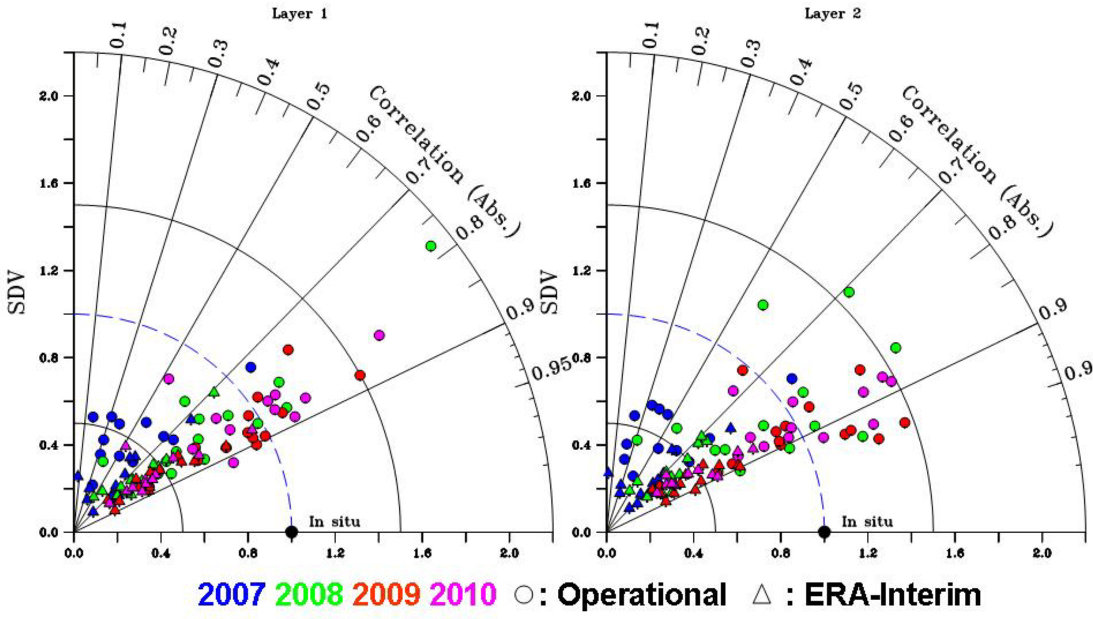

Figure 2: Taylor diagram illustrating the statistics of the comparison between ECMWF soil moisture analyses (left: first layer of soil 0-7 cm, right: second layer of soil, 7-28 cm) and in situ observations of the SMOSMANIA network and SMOSREX experimental site for 2007 (blue), 2008 (green), 2009 (red) and 2010 (pink). Circles are for the operational product and triangles for ERA-Interim. Each symbol indicates: the correlation value (angle), the normalized SDV (radial distance to the origin point), and the normalized centred root mean square error (distance to the point marked "In situ"). (Right) It is the same as the left Taylor diagram, for the second layer of soil.

3.2 Extension to other countries

Additionally to the 12 stations of the SMOSMANIA network and the SMOSREX experimental site, data from other networks across the world are used in this study leading to the number of 117 stations. Results are presented in Table 4. In average, correlation is 0.70 (ranging from 0.52 to 0.84) for OPER and is slightly lower for ERA-I, 0.63 (ranging from 0.47 to 0.81) which presents smaller bias (-0.079 m^3m^{-3} against -0.081 m^3m^{-3}) but higher RMSD (0.121 m^3m^{-3} against 0.113 m^3m^{-3}) than OPER. All p-values are below 0.05, indicating that all correlations are significant.

Presence of strong negatives biases on Table 4 (in situ minus analyses) shows that both ECMWF products tend to overestimate soil moisture. Figure 3 presents an illustration of the three different soil moisture products used in this study for three stations of three different networks: Concejo del Monte in Spain (REMEDHUS network), Ginninderra in Australia (OZNET network) and Uapb_Earl in the United State (NCRS-SCAN network), from top to bottom. The annual water cycle for Ginninderra in Australia (Southern hemisphere), with maximum values in summer, is the opposite of Concejo del Monte in Spain (Northern hemisphere), with low values in summer. Similarly to the SMOSMANIA and SMOSREX results, OPER presents a higher variability than the observations and ERA-I has smaller variability than the in situ data. Figure 4 presents two Taylor diagrams illustrating the statistics of the comparison between either ECMWF (OPER and ERA-I) and in situ data for the 117 above mentioned stations for the 2008-2010 period (for NCRS-SCAN data, the period is extended to April 2011 and for SWATMEX only 2009 is considered, only).

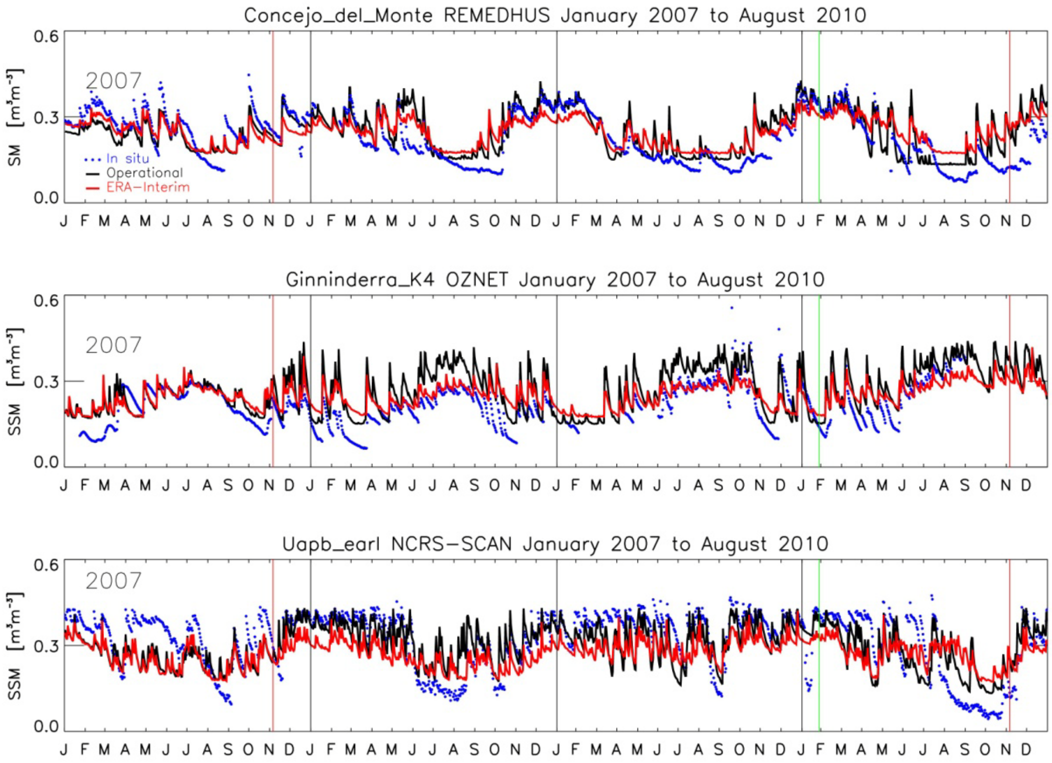

Figure 3: Same as Figure 1 for 3 stations of 3 different networks across the world: Concejo del Monte in Spain (REMEDHUS network), Ginninderra in Australia (OZNET network) and Uapb_Earl in the United State (NCRS-SCAN network), from top to bottom.

Table 4: Statistical scores for the comparison between ECMWF SSM (operational in bold and ERA-interim) and in situ SSM for all the 117 stations available over the 2008-2010 period (extended to April 2011 for NCRS-SCAN and 2009 only for SWATMEX).

2008 to 2010	**R**			**Bias (m^3m^{-3})**			**RMSD (m^3m^{-3})**		
	Min	Average	Max	Min	Average	Max	Min	Average	Max
SMOSMANIA (12 stations)	**0.73**	**0.80**	**0.87**	**-0.208**	**-0.050**	**0.041**	**0.044**	**0.088**	**0.211**
	0.73	0.77	0.83	-0.175	-0.035	0.087	0.038	0.097	0.179
OZNET (35 stations)	**0.57**	**0.74**	**0.85**	**-0.272**	**-0.117**	**-0.033**	**0.065**	**0.132**	**0.276**
	0.62	0.76	0.85	-0.178	-0.094	-0.014	0.064	0.111	0.179
REMEDHUS (17 stations)	**0.59**	**0.77**	**0.88**	**-0.219**	**-0.111**	**0.055**	**0.056**	**0.147**	**0.227**
	0.59	0.76	0.88	-0.202	-0.102	0.052	0.060	0.137	0.205
UDC-SMOS (10 stations)	**0.44**	**0.58**	**0.71**	**-0.093**	**0.012**	**0.131**	**0.051**	**0.085**	**0.157**
	0.33	0.47	0.58	-0.044	0.050	0.180	0.043	0.100	0.200
NCRS-SCAN (24 stations)	**0.40**	**0.63**	**0.79**	**-0.240**	**-0.061**	**0.108**	**0.060**	**0.118**	**0.244**
	0.34	0.56	0.77	-0.134	-0.001	0.080	0.058	0.094	0.138
SWATMEX (8 stations)	**0.60**	**0.74**	**0.91**	**-0.151**	**-0.102**	**-0.024**	**0.083**	**0.127**	**0.172**
	0.61	0.75	0.92	-0.141	-0.086	-0.035	0.084	0.116	0.148
UMSUOL (1 station)	**Na**	**0.77**	**Na**	**Na**	**-0.065**	**Na**	**Na**	**0.081**	**Na**
	Na	0.77	Na	Na	-0.049	Na	Na	0.066	Na
Sodankyla (1 station)	**Na**	**0.54**	**Na**	**Na**	**-0.184**	**Na**	**Na**	**0.190**	**Na**
	Na	-0.07	Na	Na	-0.275	Na	Na	0.282	Na
Lindenberg (1 station)	**Na**	**0.80**	**Na**	**Na**	**-0.170**	**Na**	**Na**	**0.175**	**Na**
	Na	0.87	Na	Na	-0.121	Na	Na	0.129	Na
SMOSREX (1 station)	**Na**	**0.80**	**Na**	**Na**	**-0.049**	**Na**	**Na**	**0.083**	**Na**
	Na	0.62	Na	Na	-0.027	Na	Na	0.100	Na
SWEXPOLAND (1 station)	**Na**	**0.68**	**Na**	**Na**	**-0.003**	**Na**	**Na**	**0.045**	**Na**
	Na	0.75	Na	Na	-0.064	Na	Na	0.077	Na
AMMA (6 stations)	**0.30**	**0.53**	**0.88**	**-0.196**	**-0.075**	**-0.043**	**0.052**	**0.083**	**0.200**
	0.10	0.48	0.81	-0.161	-0.144	-0.088	0.100	0.148	0.162
Average (117 stations)	**0.52**	**0.70**	**0.84**	**-0.197**	**-0.081**	**0.034**	**0.059**	**0.113**	**0.213**
	0.47	0.63	0.81	-0.148	-0.079	0.038	0.064	0.121	0.173

Stations of SMOSMANIA, SWATMEX, SMOSREX, OZNET, NCRS-SCAN and AMMA (Benin) are also used to analyse OPER and ERA-I soil moisture in the second layer of soil (69 stations). Results are illustrated by Figure 5 and presented in Table 5. As well as for SSM, OPER (Figure 5, left) and ERA-I (Figure 5, right) present good level of correlations. Compared to the first layer of soil, the variability of the analysis in the second layer is lower that the variability in the first layer of soil and much closer to the in situ data (blue dashed line, SDV value of 1) with almost the stations with SDV values between 0.5 and 1.5. No systematic tendency is observed. Correlation are better with OPER (0.77 in average) than with ERA-I (0.70 in average) which presents however smaller bias and RMSD (-0.058 m^3m^{-3} and 0.092 m^3m^{-3}) than OPER (-0.094 m^3m^{-3} and 0.116 m^3m^{-3}).

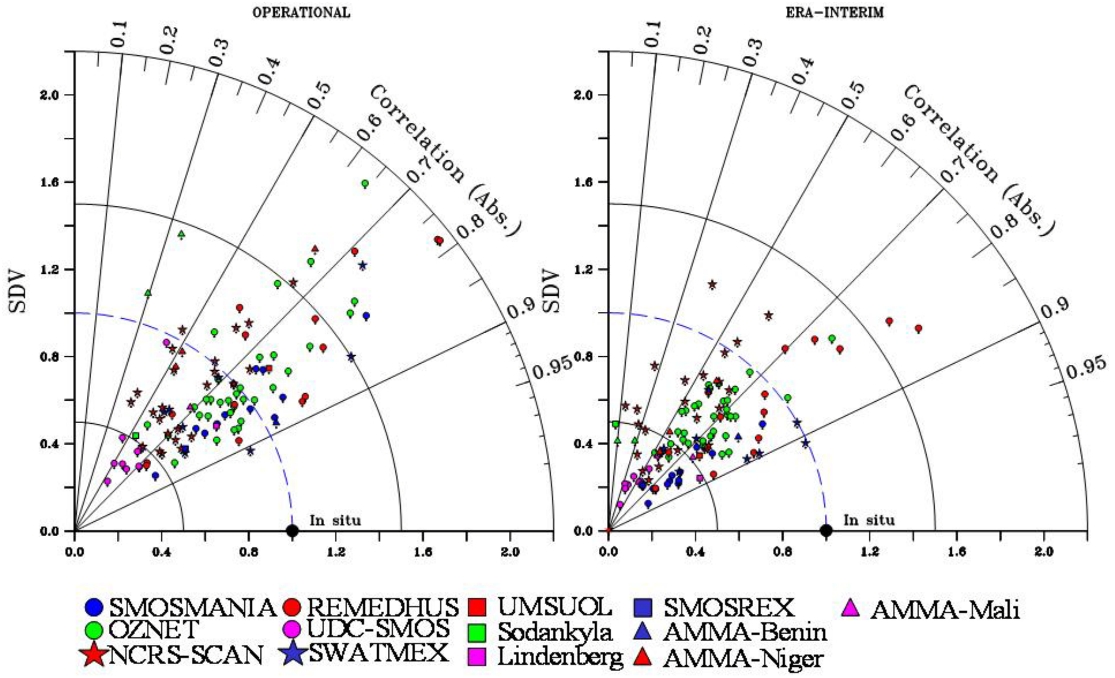

Figure 4: Taylor diagram illustrating the statistics of the comparison between ECMWF soil moisture analyses (left: operational, right: ERA-Interim) and in situ observations for 13 networks (117 stations) across the world, for 2008-2010. Best agreements are obtained for symbols that are closest to the point marked "In situ". Each symbol indicates; the correlation value (angle), the normalized SDV (radial distance to the origin point), and the normalized centred root mean square error (distance to the point marked "In situ")

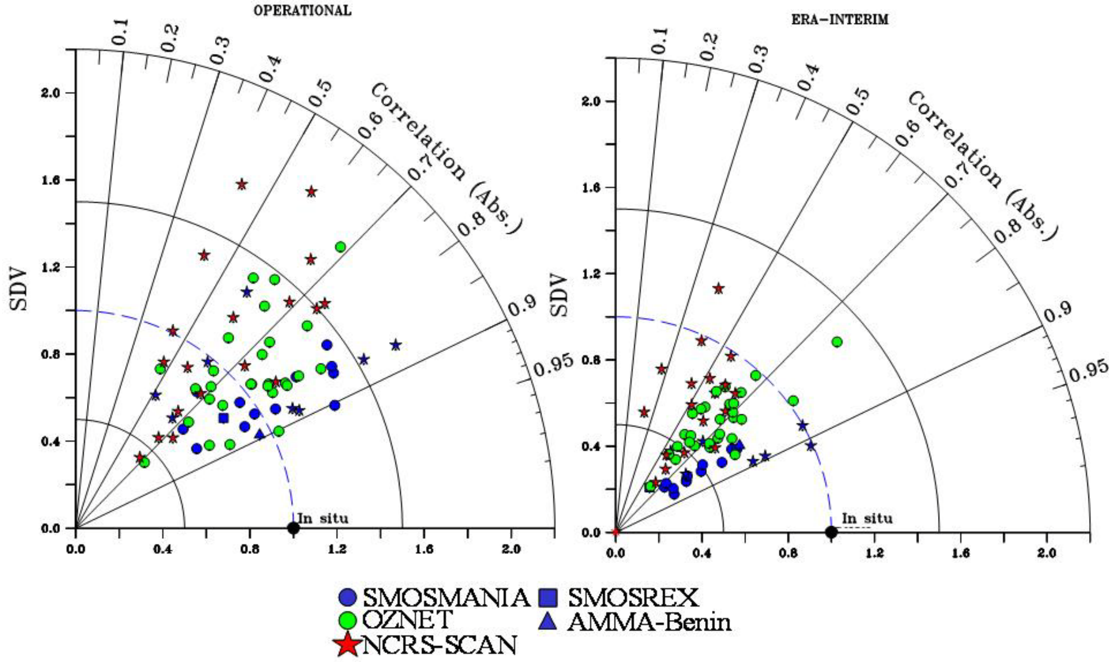

Figure 5: Same as Figure 4 for the second layer of soil. Note that a smaller amount of stations (69) are available for the second layer than for the first layer of soil.

Table 5: Same as Table 3 for the second layer of soil. Note that a smaller number of stations (69) is available for the second layer of soil than for the first layer of soil.

2008 to 2010	**R**			**Bias (m^3m^{-3})**			**RMSD (m^3m^{-3})**		
	Min	Average	Max	Min	Average	Max	Min	Average	Max
SMOSMANIA (12 stations)	**0.66**	**0.82**	**0.90**	**-0.215**	**-0.050**	**0.022**	**0.039**	**0.076**	**0.219**
	0.72	0.80	0.84	-0.177	-0.044	0.049	0.035	0.088	0.184
OZNET (29 stations)	**0.47**	**0.73**	**0.90**	**-0.192**	**-0.054**	**0.107**	**0.042**	**0.091**	**0.196**
	0.54	0.67	0.84	-0.125	-0.050	0.093	0.026	0.083	0.145
SMOSREX (1 station)	**Na**	**0.80**	**Na**	**Na**	**-0.123**	**Na**	**Na**	**0.132**	**Na**
	Na	0.60	Na	Na	-0.106	Na	Na	0.126	Na
SWATMEX (8 stations)	**0.51**	**0.73**	**0.88**	**-0.148**	**-0.101**	**-0.053**	**0.078**	**0.120**	**0.172**
	0.56	0.77	0.91	-0.122	-0.089	-0.049	0.077	0.104	0.146
NCRS-SCAN (18 stations)	**0.43**	**0.62**	**0.81**	**-0.278**	**-0.063**	**0.076**	**0.059**	**0.104**	**0.280**
	0.39	0.57	0.76	-0.137	0.002	0.080	0.034	0.074	0.143
AMMA (1 station)	**Na**	**0.89**	**Na**	**Na**	**-0.170**	**Na**	**Na**	**0.173**	**Na**
	Na	0.82	Na	Na	-0.061	Na	Na	0.075	Na
Average (69 stations)	**0.52**	**0.77**	**0.87**	**-0.208**	**-0.094**	**0.038**	**0.055**	**0.116**	**0.217**
	0.55	0.70	0.84	-0.140	-0.058	0.043	0.043	0.092	0.154

4 Discussions

In general, both OPER and ERA-I analyses captured well the temporal dynamic of the observed soil moisture. Better scores are found for the SMOSMANIA network and the SMOSREX experimental site than for the other networks. Information contained in meteorological observations of air temperature and air humidity close to the surface is used to analyse soil moisture. Therefore, this analysis is more efficient in data-rich areas like southwestern France which presents higher level of correlations and smaller RMSD than in other areas.

4.1 Soil moisture range

Results presented in the previous section show that both ECMWF's OPER and ERA-I tend to overestimate soil moisture. It is particularly clear in dry areas such as in Australia where all the stations used for the comparison present negatives biases (from -0.272 m^3m^{-3} to 0.033 m^3m^{-3} and -0.178 m^3m^{-3} to -0.014 m^3m^{-3} for for OPER and ERA-I, respectively). The improved bare ground evaporation over dry lands implemented in 2010 in operations (Balsamo et al., 2011) reduces biases. Its impact is illustrated by Figure 6 with observed soil moisture time series at two stations of the NSCR-SCAN network between January 2010 and 15 May 2011. Enterprise station (in Utah) and Pine Nut station (Nevada) are located in areas with less than 400 mm of rain according to the PRISM (Parameter-elevation Regressions on Independent Slopes Model, http://www.prism.oregonstate.edu) annual climatology computed over the 1971-2000 period. Before 9 November 2010, the operational SSM minimum values were limited by the dominant low and high vegetation types wilting point parameter values, however ground data indicate much drier conditions, as is clearly observed from May to September 2010 on Figure 6. In spring 2011, the new bare ground evaporation allows the model to go below this wilting point parameter value so the operational analysis is now in better agreement with the observations. Longer term evaluation will be necessary to consolidate this result, however the first 6 months of operational analysis with the improved model are very encouraging. Albergel et al., 2010, already highlighted that the biases observed for ECMWF's OPER might be caused by shortcomings in the employed soil characteristics and pedotransfer functions, as well as by the difficulty to represent the spatial heterogeneity of these properties. Further improvements might be obtained by a better representation of soil texture. The soil texture map currently used at ECMWF is from the Food and Agricultural Organization (FAO) dataset (FAO, 2003) and the implementation of a new map such as the new comprehensive Harmonized World Soil Database (HWSD) (FAO, 2009) could lead to better results.

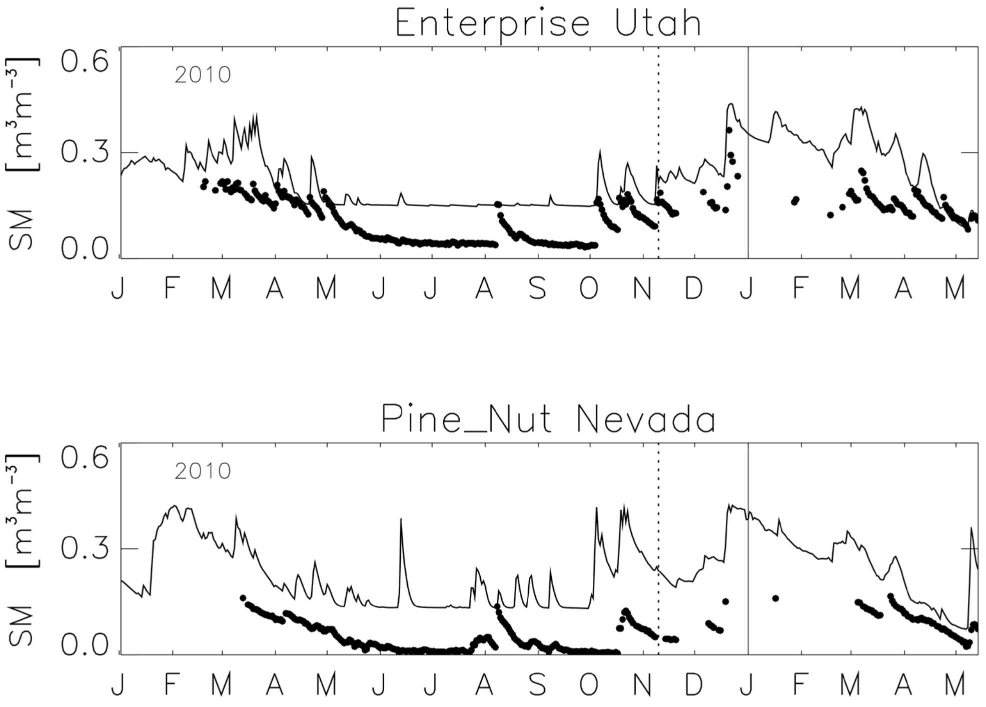

Figure 6: Soil moisture at two stations of the NCSR-SCAN soil moisture network, Enterprise in Utah and Pine Nut in Nevada over a period from January 2010 to 15 May 2010. Observations are represented with black dots and ECMWF's IFS with a black line. The vertical dashed line in 9 November 2010 indicates the implementation of the EKF soil moisture and the new bare ground evaporation.

4.2 Soil moisture variability

In this study local point scale observations are compared with model output at either 16 km or 25 km and even 80 km scale. Several authors demonstrated that local measurements could be used to validate model output as well as remotely sensed surface soil moisture at different scale (e.g. Albergel et al, 2009, 2010b, Rüdiger et al., 2009, Broca et al., 2010). However, surface soil moisture spatial variability is very high and can differ from centimetres to meters. Precipitation, evapotranspiration, soil texture, topography, vegetation and land use could either enhance or reduce the spatial variability of soil moisture depending on how it is spatially distributed and combined with other factors (Famiglietti et al., 2008). Differences in soil properties could imply important differences in the mean and variance on soil moisture, even over small distances. Whilst comparisons between ECMWF products and in situ data present good correlations, they still have high RMSD as discussed above. These findings are in agreement with suggestion of Saleem and Salvucci (2002), Koster et al. (2009, 2010), stating that the true information content in modelled soil moisture not necessarily relies in their absolute magnitudes but in their time variation. The latter representing the time-integrated impacts of antecedent meteorological forcing on the hydrological state of the soil system within the considered model.

The good levels of correlations of ECMWF's product are hence supportive of the development of a root zone soil moisture index which could be of first interest for potential users. In the framework of the H-SAF (Satellite Application Facility on Support to Operational Hydrology and Water Management) EUMETSAT project, an advanced surface data assimilation system is being developed at ECMWF to retrieve root zone soil moisture profile index from satellite data. It is based on the new EKF soil moisture analysis as well as on the ASCAT surface soil moisture data and results in the first global product of consistent surface and root zone soil moisture available in near real time for the numerical weather prediction, climate and hydrological communities.

5 Conclusions

In this study, soil moisture observations from various countries, under different biome and climate conditions, were used to evaluate two ECMWF soil moisture products, the one used in operations and the interim reanalysis, ERA-Interim. Data sets from 133 available stations of which 117 retained for this study, located in Africa, Australia, Europe and United States were used to evaluate ECMWF analyses in the first soil layer. Among them, 69 stations also provide data that was used to verify performance of soil moisture products in the second layer of soil. The operational product is produced by an analysis and model system that is revised on a regular basis, while ERA-Interim remains produced by a fixed analysis and model system. It is shown that a major difference between the two products with respect to soil moisture is the use of an improved soil hydrology (H-TESSEL) in operations from November 2007 as well as new bares ground evaporation and an Extended Kalman Filter soil moisture analysis from November 2010. In addition, the spatial resolution of the operational product increased from 25 km to 16 km in January 2010, leading to a general improvement of the atmospheric forecast. In general, both operational and ERA-Interim analyses captured well the temporal dynamic of the observed soil moisture, with averaged correlations of 0.70 for the operational product and 0.63 for ERA-Interim (in the first layer of soil, for the 2008-2010 period against 117 stations). However ECMWF soil moisture products present large RMSD (average of 0.113 m^3m^{-3} and 0.121 m^3m^{-3} for the operational product and ERA-Interim, respectively) and tend to overestimate soil moisture with negative biases of -0.081 m^3m^{-3} and -0.079 m^3m^{-3} respectively for the operational product and ERA-Interim.

Strong negatives biases (in situ minus analysis) and high RMSD are especially obtained over dry areas (OZNET network in Australia, REMEDHUS in Spain, AMMA in West Africa). The improvements introduced in November 2010 discussed above have overcome this weakness. The first six months of operational analysis with the new bare ground evaporation is shown to decrease bias and RMSD. The added value of the EKF analysis at ECMWF was already demonstrated in previous study (Albergel et al., 2010, de Rosnay et al., 2011). The flexibility of the EKF soil moisture analysis compared to the former OI 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. In recent years, the Operationnal IFS is shown to have better performance than the ERA-Interim soil moisture analysis, for most of the stations. However, ERA-Interim product has consistent and good performance over the considered period of time (2007-2010) with average correlation of 0.70 on the 117 sites. This result adds to the robustness of ERA-Interim for climate study applications as shown in Simmons et al. (2010). At the same time it highlights the potential of future reanalyses, stemming from the EU-funded ERA-Clim project, which will include recent model and data assimilation advances. Finally the root zone soil moisture developed at ECMWF in the framework of the H-SAF project, combining satellite derived soil moisture information through the EKF analysis (ASCAT SSM) will provide, for the first time, a global product of consistent surface and root zone soil moisture index available in near real time. Many applications required such data 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.

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References

Albergel, C., C. Rüdiger, T. Pellarin, J.-C. Calvet, N. Fritz, F. Froissard, D. Suquia, A. Petitpa, B. Piguet, and E. Martin, 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., C. Rüdiger, D. Carrer, J.-C. Calvet, N. Fritz, V. Naeimi, Z. Bartalis, and S. Hasenauer, 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., J.-C. Calvet, J.-F. Mahfouf, C. Rüdiger, A.L. Barbu, S. Lafont, J.-L. Roujean, J.P. Walker, M. Crapeau, J.-P. Wigneron, 2010a: Monitoring of water and carbon fluxes using a land data assimilation system: a case study for southwestern France. *Hydrol. Earth Syst. Sci.*, **14**, 1109-1124, doi:10.5194/hess-14-1109-2010.

Albergel, C., J.-C. Calvet, P. de Rosnay, G. Balsamo, W. Wagner, S. Hasenauer, V. Naemi, E. Martin, E. Bazile F. Bouyssel, and Mahfouf, J.-F., 2010b: 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.

Balsamo, G., P. Viterbo, A.C.M Beljaars, B.J.J.M. van den Hurk, M. Hirschi, A.K. Betts, and 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.

Balsamo, G., S. Boussetta, E. Dutra, A.C.M. Beljaars, P. Viterbo and B.J.J.M. Van de Hurk, 2011: Evolution of land surface processes in the IFS. *ECMWF Newsletter*, no.127, 17-22.

Bartalis, Z., W. Wagner, V. Naeimi, S. Hasenauer, K. Scipal, H. Bonekamp, J. Figa, and C. Anderson, 2007a: Initial soil moisture retrievals from the METOP-A advanced Scatterometer (ASCAT), *Geophys. Res. Lett.*, **34**, L20401, doi:10.1029/2007GL031088.

Bartalis, Z., S. Hasenauer, V. Naeimi and W. Wagner 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.

Berrisford, P., D.P. Dee, K. Fielding, M. Fuentes, P. Kallberg, S. Kobayashi and SM Uppala, 2009: The ERA-Interim Archive. *ERA Report Series*, No.1. ECMWF: Reading, UK.

Boussetta, S., G. Balsamo, A. Beljaars & J. Jarlan, 2010: Impact of a satellite-derived Leaf Area Index monthly climatology in a global Numerical Weather Prediction model. *ECMWF Tech. Memo*. No. 640.

Bouttier, F., 2001, The development of 12-hourly 4D-Var. *ECMWF Tech. Memo* 348, pp21.

Broca, L., F. Melone, T. Moramarco, W. Wagner and S. Hasenauer, 2010: 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.

Calvet, J.-C., N. Fritz, F. Froissard, D. Suquia, A. Petitpa, and B. Piguet, 2007: in situ soil moisture observations for the CAL/VAL of SMOS: the SMOSMANIA network, *International Geoscience and Remote Sensing Symposium*, IGARSS, Barcelona, Spain, doi:10.1109/IGARSS.2007.4423019.

Calvet, J.-C., J.-P. Wigneron, J. Walker, F. Karbou, A. Chanzy, and C. Albergel, 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.

Dee, D.P., S.M. Uppala, A.J. Simmons, P. Berrisford, P. Poli, S obayashi, U. Andrae, M.A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A.C.M. Beljaar, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A.J. Geer, L. Haimberger, S.B. Healy, H. Hersbach, E.V. Holm, L. Isaksen, P. Kallberg, M. Kohler, M. Matricardi, A.P. McNally, B.M. Monge-Sanz , J.-J.Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thépaut and F. Vitart, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **137**, 553–597. DOI:10.1002/qj.828.

de Rosnay, P., J.-C. Calvet, Y. Kerr, J.-P.Wigneron, F. Lemaitre et al. 2006: SMOSREX: a long term field campaign experiment for soil moisture and land surface processes remote sensing, *Remote Sens. Environ.*, **102**, 377–389.

de Rosnay, P., C. Gruhier, F. Timouk, F. Baup, E. Mougin, P. Hiernaux, L. Kergoat and 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., M. Drusch, G. Balsamo, L. Isaksen and C. Albergel, 2011: Extended Kalman Filter soil moisture analysis in the IFS. *ECMWF Newsletter*, n127, 12-16.

Dirmeyer, P.A., A.J. Dolman, and N. Sato 1999: The pilot phase of the global soil wetness project, *B. Am. Meteorol. Soc.*, **80**, 851–878.

Dorigo, W.A., W. Wagner, R. Hohensinn, S. Hahn, C. Paulik, M. Drusch, S. Mecklenburg, P. van Oevelen, A. Robock, and T. Jackson, 2011: The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, *Hydrol. Earth Syst. Sci. Discuss.*, **8**, 1609-1663, doi:10.5194/hessd-8-1609-2011.

Drusch, M., K. Scipal, P.de Rosnay, G. Balsamo, E. Anderson, P. Bougeault and P. Viterbo, 2009: Towards a Kalman Filter based soil moisure analysis system for the operational ECMWF integrated forecst system, *Geophys. Res. Lett.*, **36**, L10401, doi:10.1029/2009GL037716.

Dutra, E., G. Balsamo, P. Viterbo, P.M.A. Miranda, A. Beljaars, C. Schär and K. Elder, 2010: An improved snow scheme for the ECMWF land surface model: description and offline validation. *J. Hydrometeor.*, **11**, 899-916.

Entekhabi D., G.R. Asrar, A.K. Betts, K.J. Beven, R.L. Bras, C.J. Duffy, T. Dunne, R.D. Koster, D.P. Lettenmaier, D.B. McLaughlin, W.J. Shuttleworth, M.T. van Genuchten, M.Y. Wei and E.F. Wood, 1999: An agenda for land surface hydrology research and a call for the second international hydrological decade. *Bull. Am. Meteorol. Soc.*, **10**, 2043-2058.

Famiglietti, J.S., D. Ryu, A.A. Berg, M. Rodell and T.J. Jackson 2008 : Field observations of soil moisture variability across scales, *Water Resour. Res.*, **44**, W01423, doi:10.1029/2006WR005804.

FAO, 2003: “Digital soil map of the world (DSMW)”. *Technical report*, Food and Agriculture Organization of the United Nations, re-issued version.

FAO/IIASA/ISRIC/ISSCAS/JRC: Harmonized World Soil Database (version 1.1), FAO, Rome, Italy and IIASA, Laxenburg, Austria, 2009.

Georgakakos, K.P. and M. Carpenter 2006: Potential value of operationally available and spatially distributed ensemble soil water estimates for agriculture, *J. Hydrol.*, **328**, 177–191.

Jackson, T.J., A. Y. Hsu, A. van de Griend, and J.R. Eagleman, 2004: Skylab L band microwave radiometer observations of soil moisture revisited, *Int. J. Remote Sens.*, **25**, 2585–2606.

Kerr, Y., P. Waldteufel, J.-P.Wigneron, J.-M. Martinuzzi, J. Font and M. Berger, 2001: Soil moisture retrieval from space: the soil moisture and ocean salinity (SMOS) mission, *IEEE T. Geosci. Remote*, **39**, 1729–1736.

Kerr, Y., 2007: Soil moisture from space : where are we?, *Hydrogeol. J.*, **15**(1), 117–120.

Koster R.D., Z. Guo, R. Yang, P.A. Dirmeyer, K. Mitchell and M.J. Puma 2009 : On the nature of soil moisture in Land Surface Model, *Journal of Climate*, **22**, 4322-4334, doi:10.1175/2009JCLI2832.1.

R. D. Koster, S. P. P. Mahanama, T. J. Yamada, G. Balsamo, A. A. Berg, M. Boisserie, P. A. Dirmeyer, F. J. Doblas-Reyes, G. Drewitt, C. T. Gordon, Z. Guo, J.-H. Jeong, W.-S. Lee, Z. Li, L. Luo, S. Malyshev, W. J. Merryfield, S. I. Seneviratne, T. Stanelle, B. J. J. M. van den Hurk, F. Vitart, and E. F. Wood, 2010: The Second Phase of the Global Land-Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill, *J. Hydrometeor.*, doi: 10.1175/2011JHM1365.1

Loew, A., J. T. Dall'Amico, F. Schlenz, W. Mauser, 2009: 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.

Mahfouf, J.-F., 1991a: Analysis of soil moisture from near surface parameters: A feasibility study, *J. Appl. Meteorol.*, **30**, 506–526.

Mahfouf, J.-F., and J. Noilhan, 1991b: Comparative study of various formulations of evaporation from bare soil using in situ data. *J. Appl. Meteor.*, **30**, 351-362.

Mahfouf, J.-F., P.Viterbo, H. Douville,A.C.M. Beljaars and S. Saarinen, 2000a: A revised land-surface analysis scheme in the Integrated Forecasting System. *ECMWF newsletter*, No 88 – Summer / Autumn 2000, 8-13.

Mahfouf, J.-F. and Rabier, F., 2000b: The ECMWF operational implementation of four dimensional variational assimilation. Part II: Experimental results with improved physics. *Q. J. R. Meteorol. Soc.*, **126**, 1171-1190.

Mahfouf, J.-F., K. Bergaoui, C. Draper, F. Bouyssel, F. Taillefer and L. Taseva, 2009: A comparison of two off-line soil analysis schemes for assimilation of screen level observations, *J. Geophys. Res.*, **114**, D08105, doi:10.1029/2008JD011077.

Martínez-Fernández, J. and A. Ceballos, 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., T.J. Jackson, V. Lakshmi, T.K. Chan, and S.V. Nghiem, 2003: Soil moisture retrieval from AMSER-E, *IEEE T. Geosci. Remote*, **41**(2), 215–123.

Pellarin T., J.P. Laurent, B. Cappelaere, B. Decharme, L. Descroix and D. Ramier, 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., T. Tran, J.-M. Cohard, S. Galle, J.-P. Laurent, P. de Rosnay, and T. Vischel, 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.

Rabier, F., H. Järvinen, E. Klinker, J.-F. Mahfouf and A. Simmons, 2000: The ECMWF operational implementation of four dimensional variational assimilation. Part I: Experimental results with simplified physics. *Q. J. R. Meteorol. Soc.*, **126**, 1143-1170.

Redelsperger, J.-L., C. Thorncroft, , A. Diedhiou, T. Lebel, D. Parker and J. Polcher, 2006: African monsoon multidisciplinary analysis (AMMA): an international research project and field campaign. *Bull. Am. Meteorol. Soc.*, **87** (12), 1739–1746.

Rüdiger, C., J.-C. Calvet, C. Gruhier, T. Holmes, R. De Jeu, and W. Wagner, 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., C. Rüdiger, J.-C. Calvet, N. Fritz, L. Jarlan and Y. Kerr, 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.

Sabater, J.M., L. Jarlan, J.-C Calvet, F. Bouyssel and P. de Rosnay, 2007: From near surface to root zone soil moisture using different assimilation techniques, *J. Hydrometeor.*, **8**(2), 94-206.

Saleem, J.A., and G.D. Salvucci, 2002: Comparison of soil wetness indices for inducing functional similarity of hydrologic response across sites in Illinois. *J. Hydrometeor.*, **3**, 80–91.

Schaefer, G.L. and R.F. Paetzold 2000: SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network) Presented at the *Automated Weather Station (AWS) workshop*. March 6-10. Lincoln, NE.

Schervish, M.J., 1996: P Values: What They Are and What They Are Not. *The American Statistician*, **50** (3): 203–206. doi:10.2307/2684655.

Schmugge, T. J. 1983: Remote sensing of soil moisture: recent advances, *IEEE T. Geosci. Remote Sens.*, **GE21**, 145–146.

Simmon, A.J., K.M. Willet, P.D. Jones, P.W. Thorne and D.P. Dee, 2010: Low-frequency variations in surface atmospheric humidity, temperature and precipitation: Interferences from reanalyses and monthly gridded observational datasets. *J. Geophys. Res.*, **115**, D01110.

Taylor, K.E., 2001: Summarizeing multiple aspects of model performance in a single diagram, *J. Geophys. Res.*, **106**, 7183-7192.

van den Hurk B.J.J.M., P. Viterbo, A.C.M. Beljaars, and A.K. Betts, 2000: Offline validation of the ERA-40 surface scheme. *ECMWF Tech. Memo.*, 295, 43 pp.

van den Hurk, B. and P. Viterbo, 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.

Wagner, W., G.Lemoine and H. Rott, 1999: A method for estimating soil moisture from ERS scatterometer and soil data, *Remote Sens. Environ.*, **70**, 191–207.

Wagner, W., V. Naeimi, K. Scipal, R. de Jeu and J. Martinez-Fernandez, 2007a: Soil moisture from operational meteorological satellites, *Hydrogeol. J.*, **15**, 121–131.

Wagner, W., G. Blöschl, P. Pampaloni, J.-C. Calvet, B. Bizzarri, J.-P. Wigneron and Y. Kerr, 2007b: Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, *Nord. Hydrol.*, **38**(1), 1–20, doi:10.2166/nh2007.029.

Walker, J.P., G.R. Willgoose and J.D. Kalma, 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.

Young, R., J.P. Walker, N. Yeoh, A. Smith, K. Ellett, O. Merlin and A. Western, 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).