# Consistent validation of H-SAF soil moisture satellite and model products against ground measurements for selected sites in Europe

Associated Scientist Activity in the framework of the Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF)

Final Report

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The EUMETSAT Network of Satellite Application Facilities

H SAF
Support to Operational Hydrology and Water Management

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# 1 Introduction

The Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF), currently in Development Phase until September 2010, has the objective of prototyping soil moisture products derived from scatterometers (surface soil moisture product) or as model output from data assimilation schemes (volumetric soil moisture product). Before entering the Continuous Development and Operations (CDOP) phase (September 2010 – February 2012), the project would benefit from a harmonized effort to evaluate the data quality of the existing prototype products in a standardized way. Results from this activity could lead to improvements in the product specification/characterization and could give valuable feedback to the product generation entities.

The three soil moisture products, which are currently under development, are as follows:

1. SM-OBS-1 (large-scale surface soil moisture) as the segment of the Global surface soil moisture product covering the area of H-SAF interest;
2. SM-OBS-2 (small-scale surface soil moisture) by disaggregation of SM-OBS-1;
3. SM-ASS-1 (large-scale volumetric soil moisture) as the output of the ECMWF soil moisture assimilation scheme, covering the area of H-SAF interest.

The three products (SM-OBS-1, SM-OBS-2, SM-ASS-1) are provided by representatives of TU-Wien and ECMWF (prototype datasets from the operational product generation chains are already existing now for Europe). Both SM-OBS-2 and SM-ASS-1 result from the use of SM-OBS-1 in a disaggregation model and a land surface data assimilation system, respectively. Moreover, the profile soil moisture, SWI, directly estimated by the SM-OBS-1 product through the exponential filter proposed by Wagner et al. (1999) is also analyzed in this study. Therefore, since all the products basically are derived from SM-OBS-1, a comprehensive validation of this product is conducted in the present work.

SM-OBS-1 is the surface soil moisture product obtained from the ASCAT scatterometer onboard of METOP satellite and operating since 2007 with a spatial resolution of 25/50 km. ASCAT is characterized by a daily time step for mid-latitude regions and is therefore suitable for soil moisture estimation to be used for hydrological applications. This sensor succeeded the ERS-1/2 scatterometers that provide soil moisture estimate at the global scale since 1992 through the algorithm proposed by Wagner et al. (1999) and recently improved by Bartalis et al. (2006) and Naeimi et al. (2009a). Moreover, Naeimi et al. (2009b) have ensured the consistency of migrating soil moisture retrieval from the long term ERS scatterometer to ASCAT measurements successfully coupling the two data sets. An initial qualitative evaluation of the ASCAT soil moisture product was performed by Bartalis et al. (2007a) inferring that recent

cases of drought and excessive rainfall in South Africa and Australia are clearly visible through the ASCAT data. The first validation of the ASCAT soil moisture data was performed by Albergel et al. (2009) who found significant correlations between ASCAT derived surface and root-zone soil moisture products and in situ observations from 11 stations located in south-western France. Moreover, Sinclair and Pegram (2010) compared the soil moisture simulations produced by the rainfall-runoff TOPKAPI model to the exponentially filtered time series of the ASCAT surface soil moisture obtaining a good linear agreement in the dynamic behaviour of the two independent soil moisture estimates. Albergel et al. (2009) and Sinclair and Pegram (2010) used the first version of the ASCAT soil moisture product produced in near-real-time by EUMETSAT, which was based on model parameters derived from the analysis of long-term ERS-1/2 scatterometer time series (Bartalis et al. 2007b). Because the radiometric calibration of the ERS-1/2 scatterometer and METOP ASCAT turned out to be slightly different, the use of ERS SCAT derived model parameters to retrieve soil moisture from METOP ASCAT has led to periodic errors that add to the uncertainty of the ASCAT retrievals (Sinclair and Pegram, 2010). Therefore, the ASCAT surface soil moisture data were retrieved off-line by the Vienna University of Technology based on two years (2007-2008) of only ASCAT observations, but considering the same algorithm as used by EUMETSAT for the near-real-time ASCAT product and by Naeimi et al. (2009a) for the ERS-1/2 scatterometer.

In this report the performance of the different existing soil moisture products (SM-OBS-1, SM-OBS-2, SM-ASS-1) against in-situ measurements/model data over four different climatic conditions in the geographic region of Europe are analyzed. In particular, the performance of all the products is assessed in terms of different statistical scores (root mean square difference, correlation, bias, etc.) by using as benchmark in situ data for six different test sites located in Italy, France, Luxembourg and Spain. This work could support the soil moisture products development and aid the Hydrological Validation Programme of H-SAF.

# 2 Test sites and data sets

In the following, the different test sites used for the validation of the three soil moisture products are described. A total of 13 sites across four different countries (Italy, France, Spain and Luxembourg) are investigated. ***Table 1*** synthesizes the main characteristics of each site in terms of soil texture, vegetation cover, slope, estimated porosity and measurement depth while ***Figure 1*** shows the framework of the study sites along with the Digital Elevation Model (DEM).

For nearly all the investigated sites rainfall and temperature data are also available. Therefore, the comparison both with in-situ observations and also with modeled saturation degree data is carried out.

**Table 1** Main characteristics of the different test sites. For site acronyms see text.

| Location | Site | Soil texture | Land use | Terrain | Meas. depth (cm) | Meas. period | Porosity * |
|---|---|---|---|---|---|---|---|
| **central Italy** | **VAL** | sandy loam | grass | rolling | 10, 20, 40 | 04/07-06/08 | 0.28 |
| | **CER** | loamy sand | grass | flat | 10 | 11/09-04/10 | 0.30 |
| | **SPO** | sandy loam | grass | flat | 10 | 09/07-12/08 | 0.25 |
| **south Italy** | **BAG** | sandy loam | grass | flat | 30 | 01/07-12/09 | 0.30 |
| | **MEL** | sandy clay loam | grass | flat | 30 | 01/07-12/09 | 0.22 |
| | **TOR** | ? | ? | ? | 30 | 01/07-04/10 | 0.20 |
| | **CHI** | ? | ? | ? | 30 | 01/07-04/10 | 0.31 |
| **Luxembourg** | **BIB** | loam | grass | rolling | 5 | 01/07-12/08 | 0.31 |
| **Spain** | **K10** | sand | corn | flat | 5 | 01/07-12/09 | 0.22 |
| | **F11** | loamy sand | grass | flat | 5 | 01/07-12/09 | 0.18 |
| | **I06** | sand | bare soil | flat | 5 | 01/07-12/09 | 0.08 |
| | **VCE** | loam | grass | flat | 20 | 01/07-12/09 | 0.27 |
| **France** | **VSC** | sandy | grass | flat | 30, 50 | 01/07-12/09 | 0.28 |

* computed as the difference between the maximum and minimum soil moisture value observed in the measurement period

? information not available

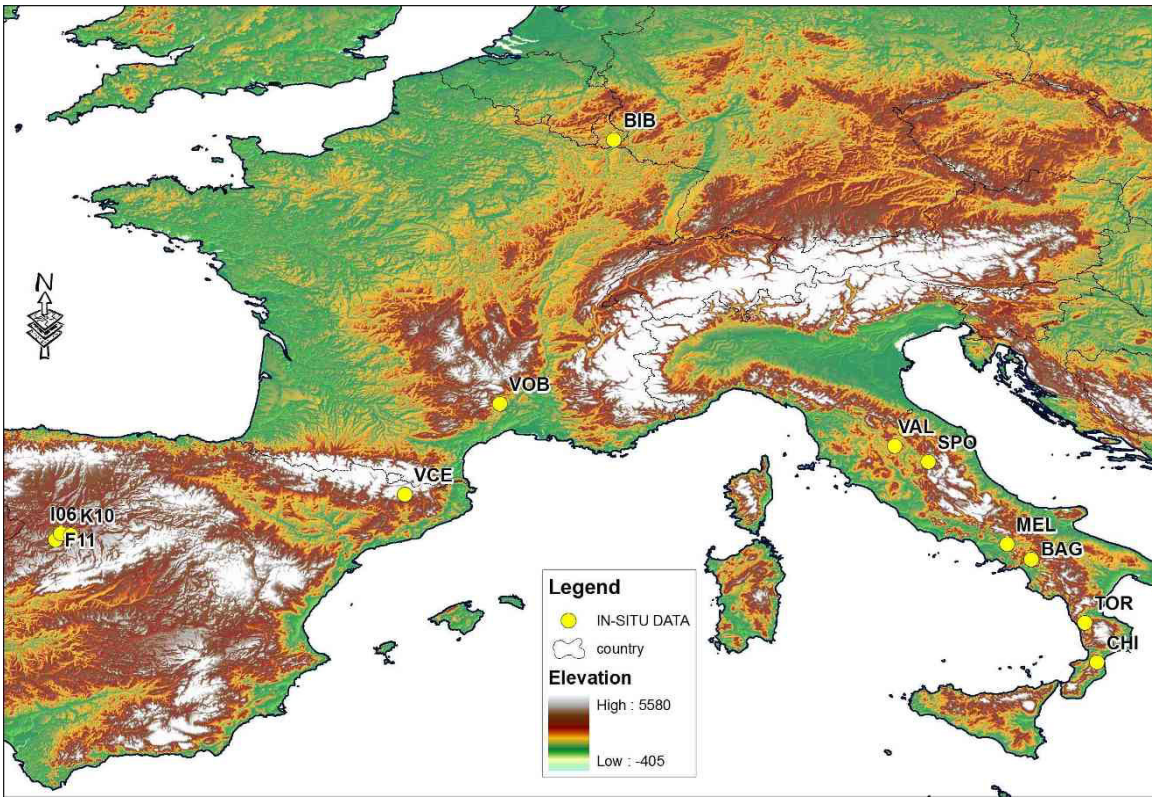


**Figure 1** Location of the study sites.

## 2.1 Italy data set

### *2.1.1 Central Italy*

Ground based surface soil moisture measurements, used for this study, were carried out in three sites located in an inland region of central Italy (Umbria region): the Vallaccia, Cerbara and Spoleto site. ***Figure 2*** shows the framework of the study area along with the location of in situ soil moisture sensors and the centroids of the ASCAT pixels. The area is characterized by a Mediterranean semi-humid climate with average annual precipitation ranging between 900 and 1200 mm (mainly depending on elevation) and mean annual temperature of ~13 °C. Accordingly, the mean annual potential evapotranspiration, computed with the Thornthwaite formula, is almost 850 mm.

The Vallaccia site (hereinafter named VAL) covers an area of ~56 km$^2$ with elevation ranging between 288 and 818 m above sea level (see ***Figure 2b***). In the area, there are four experimental plots where soil moisture measurements are collected automatically with an hourly time step (see ***Figure 2b***). The soil moisture probes are based on the Frequency Domain Reflectometry (FDR) technique (Enviroscan$^{TM}$) and continuously measure volumetric soil moisture in the soil column at 10 cm, 20 cm and 40 cm depth, providing at each depth the average volumetric soil moisture for a layer thickness of nearly 10 cm. The soil moisture data set selected for this study covers a period of 15 months from April 2007 to June 2008. Moreover, surface volumetric soil moisture measurements (0-15 cm) were carried out on seven

additional plots (see ***Figure 2b***) by using a two-wire connector-type Time Domain Reflectometer (TDR) (Brocca et al., 2010a). A good agreement between the two data sets was found allowing to infer that the collected data set can be effectively used for the validation of coarse resolution satellite data.

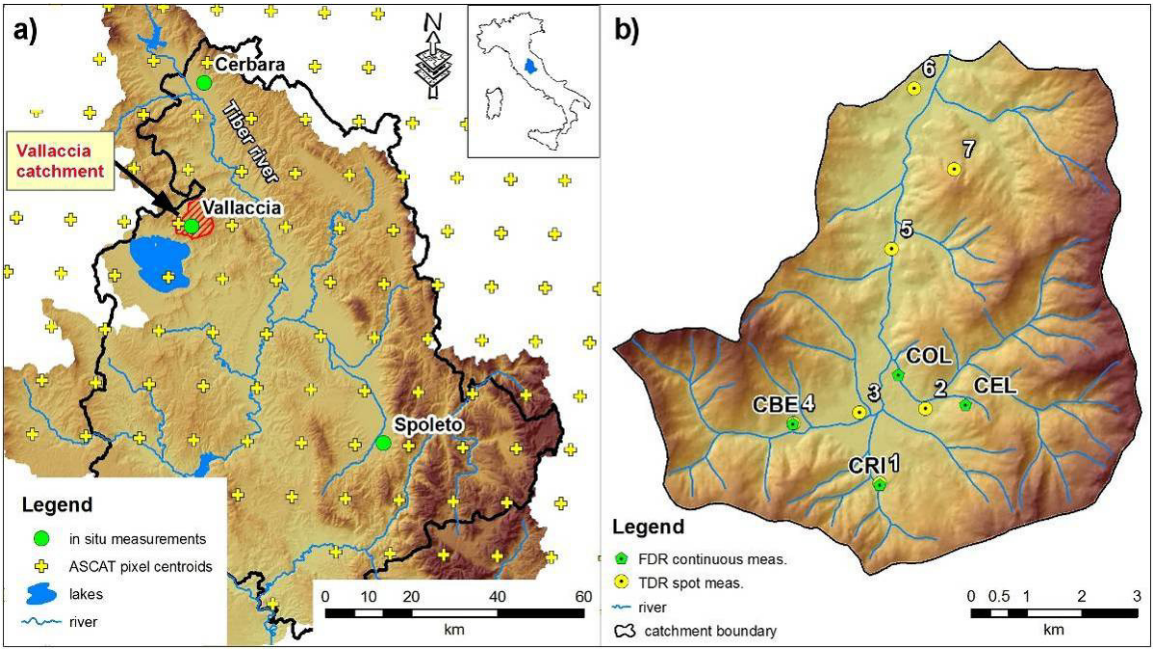


**Figure 2** a) Framework of the study area with the location of the three soil moisture sites (Vallaccia, Cerbara and Spoleto) and of the ASCAT pixel centroids. b) Enlargement for the Vallaccia catchment with the location of the four FDR continuous soil moisture probes and of the spot TDR measurement plots.

The Cerbara site (hereinafter named CER) is one of the new soil moisture probes installed in the Umbria region for Civil Protection activities aimed at flood prediction and forecasting (see ***Figure 2a***). The probe, based on TDR technique (ML2X ThetaProbe), was set up in November 2009 and continuously measures volumetric soil moisture with the same configuration used for the Vallaccia site. For this study, half-hourly volumetric soil moisture data at 10 cm depth from November 2009 to February 2010 are used for the calibration of the soil water balance model (see below) and not directly compared with the different soil moisture products due to the unavailability of these latter in the same period.

The Spoleto site (hereinafter named SPO) was installed by the Department of Applied Biology of the University of Perugia (see ***Figure 2a***) to study the relation between soil moisture conditions and the production of mycorrhized plants used in truffle cultivation (Di Massimo et al., 2008). In the site, eight boreholes were established and weekly FDR soil moisture measurements were carried out in the period September 2007 - December 2008. Measurements were taken every 10 cm depth up to 80 cm. As for CER site, the data at 10 cm depth for one representative location were used for the calibration of the soil water balance model.

### *2.1.2 South Italy*

In south Italy, four more sites were used in this study. In particular, two sites are located in the Campania region (see ***Figure 3a***) and two sites in the Calabria region (see ***Figure 3b***).

For Campania region, the two soil moisture sensors (Melizzano and Bagnoli, hereinafter named MEL and BAG, respectively) were installed by "Centro Funzionale Decentrato della Regione Campania, Settore Programmazione Interventi di Protezione Civile sul Territorio" for Civil Protection activities related to hydrometeorological monitoring for flood and landslide risk mitigation. Specifically, sensors measure the volumetric soil moisture at a depth of 30 cm, with hourly time resolution, since July 2000. For this study, the soil moisture temporal pattern for the period Jan2007-Dec2009 is used.

As it can be seen in ***Figure 3b***, for Calabria region five soil moisture sensors are available; only two of them providing the more reliable soil moisture measurements were selected (Torano and Chiaravalle, hereinafter named TOR and CHI, respectively). These soil moisture sensors were installed by "Centro Funzionale Decentrato della Regione Calabria", again for Civil Protection activities, and measure the volumetric soil moisture at a depth of 30, 60 and 90 cm since 2001 (with hourly time resolution). For this study, the soil moisture temporal pattern for the period Jan2007-Apr2010 is used.

Moreover, for all selected sites, rainfall and temperature data for the application of the soil water balance model are also available.

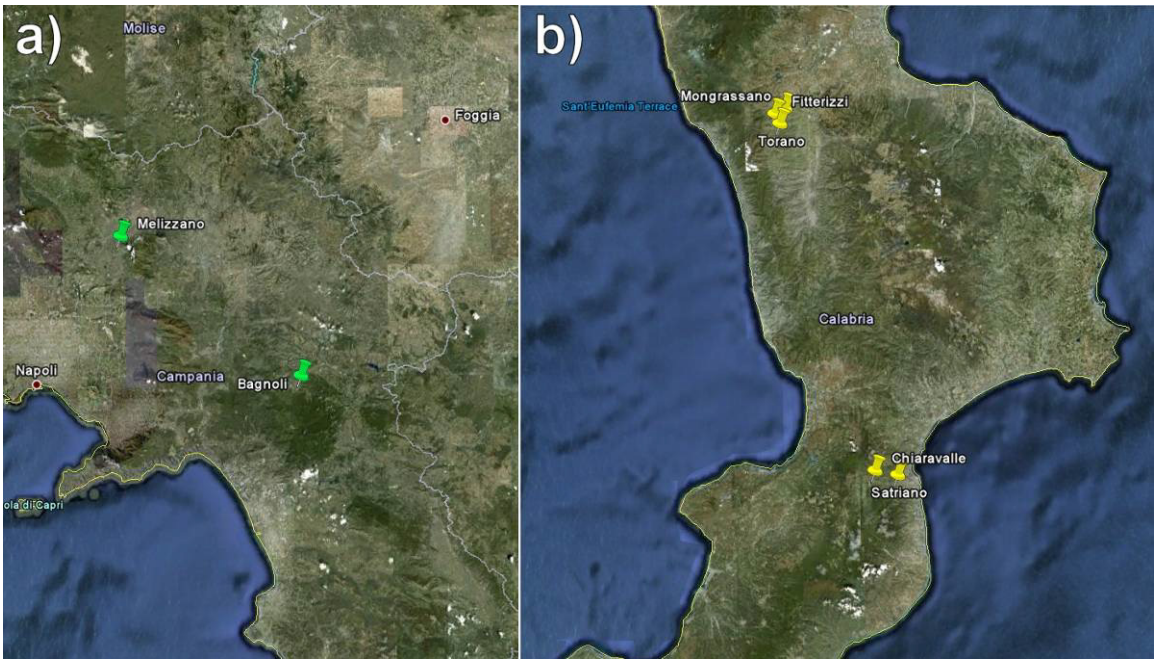


**Figure 3** Location of the study sites located in South Italy: a) Campania region, and b) Calabria region.

## 2.2 Luxembourg data set

The experimental Bibeschbach catchment (10.8 km$^2$), BIB, is located in the southern part of the Alzette River basin, Luxembourg (see ***Figure 4***).

Elevations range between 268 and 350 m a.s.l. with a mean slope of 6.4%. Two rain gauges and one thermometer are operating in the vicinity of the basin which is characterized by a typical humid temperate climate with a mean annual rainfall of about 860 mm. The site is mainly characterized by forest and agriculture (i.e. cropland and pasture) on loamy soils.

Since 2005, the basin has been equipped with a set of 40 $ECH_2O$ Decagon™ SM sensors over different sites (***Figure 4***) measuring the volumetric soil water content of the topsoil layer at a depth of 4 to 7 cm. The soil probes were installed at different locations in accordance with land use, geology and pedology. For this study, the temporal patterns of the average soil moisture over all sites are used considering the period Jan2007-Apr2010.

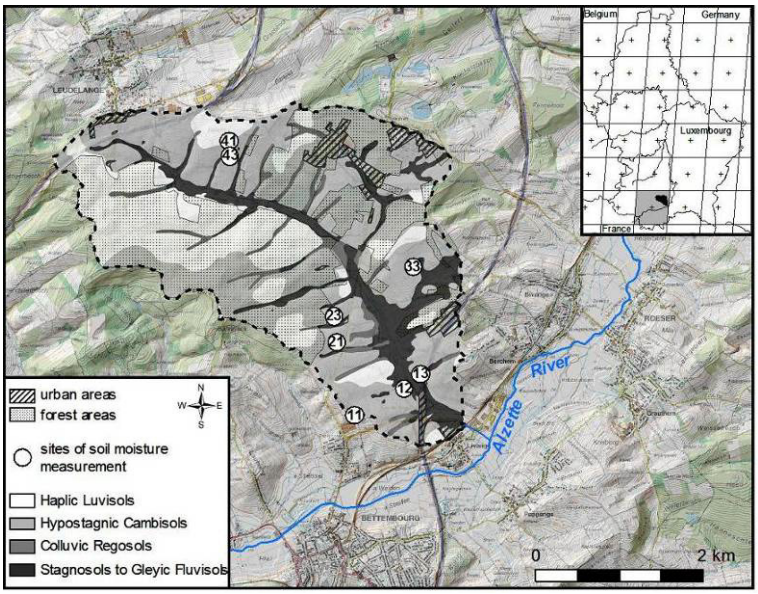


**Figure 4** Framework of the Bibeschbach catchment and location of the soil moisture sensors. On the top-right the ASCAT pixel centroids are also shown.

## 2.3 Spain data set

### *2.3.1 REMEDHUS network*

The REMEDHUS network (~1300 $km^2$) is located in the central sector of the Duero basin (Spain), called La Guareña (***Figure 5***). The climate is continental semi-arid Mediterranean, with a mean annual rainfall of 385 mm, a mean temperature of 12 °C, and an annual potential evapotranspiration (PET) of 908 mm. Maximum monthly precipitation is 47 mm in May and the monthly minimum is 11 mm in August. The main texture is sandy (mean sand content, 71%), above all at the surface horizons, and occasionally there are clayey horizons at the bottom of the profiles. The organic matter content is very low (mean, 0.9%). Throughout almost all the territory the soil is used for agricultural purposes, rainfed crops being the norm (80% cereals).

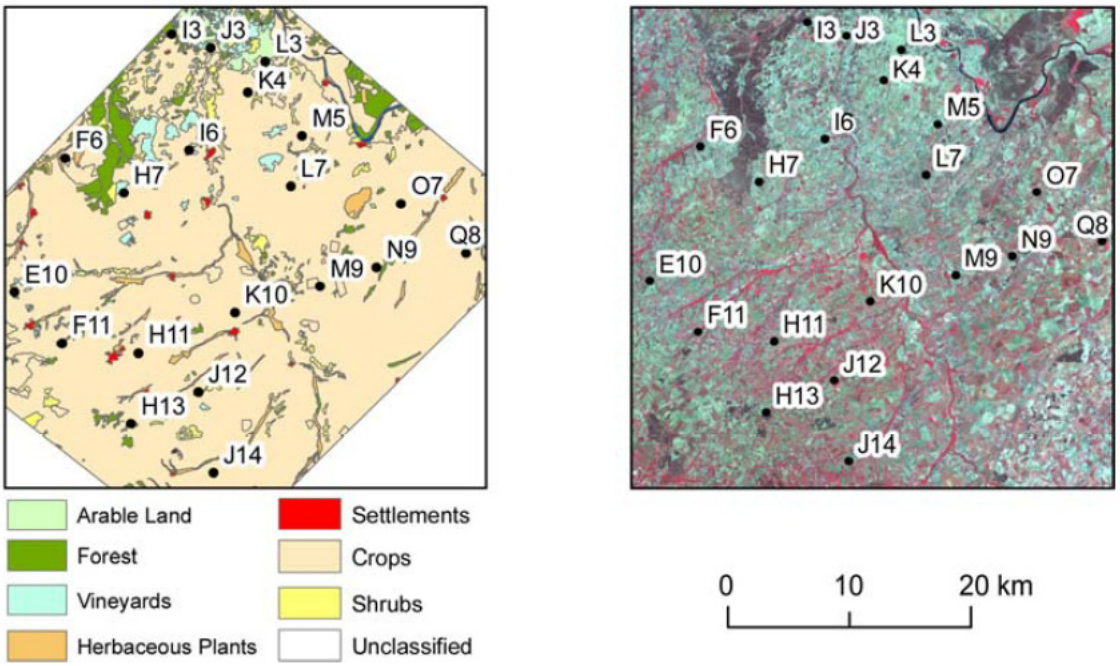


**Figure 5** Framework of the Spain test site. The left map shows the land cover and location of the in-situ soil moisture stations within the REMEDHUS network located in the Duero Basin, Spain. The right map shows a false-colour Landsat image (bands 4, 3, 2) of the area.

In the spring of 1999, a network of 23 soil moisture-measuring stations (REMEDHUS) was set up in the area (Martinez-Fernandez and Ceballos, 2005). The distribution of the stations is irregular and is based on the distribution of the main physiographic and pedological units of the area. Four physiographic units were identified, each corresponding to a topographic type and with characteristic soil types (Hill Tops, Slopes, Fluvial Terraces and Valley Bottoms). The number of stations is proportional to the surface area of each unit and the stations were distributed randomly. With the exception of three stations located at the bottoms of valleys used for grazing, all the rest are located in areas used for non-irrigated crops (cereals and grapevines). The slope angle is low (less than 10%) and the altitude of the stations ranges between 700 and 900 m above sea level. Each station comprises a soil profile equipped with two-wire TDR probes (Tektronix 1512C) measuring 265 mm in length, installed horizontally at depths of 5, 25, 50 and 100 cm. Only the values taken at 5 cm are used in this study. Comprehensive laboratory analyses of soil samples were carried out to calibrate the TDR measurements and to assess soil properties at each station (texture, porosity, etc.). The land cover map and the location of the TDR stations are shown in ***Figure 5***.

Finally, in the REMEDHUS area, there are four automatic weather stations with data on the main climatic variables (rainfall, humidity, air temperature, wind velocity and direction and global radiation), recorded every 10 min.

In this report, only the data for three stations are used (K10, F11 and I06).

### *2.3.2 The Vallcebre research catchments*

Research in the Vallcebre catchments started in 1989, with the objective of better understanding the hydrological functioning of Mediterranean mountain basins. Along with the monitoring of weather, precipitation and stream flow variables, several state variables (soil moisture and tensiometry, water table) and processes (rainfall interception, tree transpiration, grass evapotranspiration) are measured all the time or for periods lasting several years. The Vallcebre catchments are located at the headwaters of the Llobregat river, on the southern margin of the Pyrenees (Catalonia, north-east Spain) at an altitude of 1100–1700 m a.s.l. (see ***Figure 1***). The research area (***Figure 6***) consists of two catchment clusters, whose centers are 2.5 km apart. The main cluster (Cal Rodo´ catchment, 4.17 km$^2$) was sub-divided into three sub-catchments, whereas the smaller cluster (Cal Parisa catchment, 0.32 km$^2$) consists of two catchments of similar size. The catchments are covered by pasture and forest, resulting from spontaneous forestation by Pinus sylvestris after land abandonment. The bedrock comprises red clayey smectite-rich mudstones with massive limestone beds of continental facies attributed to the Palaeocene. The soft mudstones are prone to landsliding and erosion by water, leading to the occurrence of intensely dissected landscapes with poor vegetation cover (badlands), that occupy only 2.8% of the catchments area but play a dominant role in sediment production. Soil thickness varies greatly, depending on lithology, geomorphology and the changes induced by terracing. Badland areas exhibit regoliths whose thickness varies throughout the year, but which rarely reach 15 cm; limestone areas are overlain by discontinuous soils up to about 40 cm thick; soils on hillslopes over clayey rocks are up to 80 cm thick and agricultural terraces can have soils thicker than 3 m. Topsoils are loamy and show high infiltration capacities due to their good structure. Nevertheless, hydraulic conductivity drops in the deeper horizons, inducing shallow semi-permanent aquifers.

Climate is humid Mediterranean, with a marked water deficit in summer. Mean annual temperature at 1260 m a.s.l. is 9.1 ºC and long-term (1983–2006) mean annual precipitation is 862 ± 206 mm, with a mean of 90 rainy days per year. Snowfall accounts for less than 5% in volume over the period. The rainiest seasons are autumn and spring and winter is the season with least precipitation. In summer, convective storms may provide significant precipitation input. Long-term (1989–2006) mean annual reference evapotranspiration, calculated by the method of Hargreaves and Samani (1982) is 823 ± 26 mm. A complete overview of general hydrological findings in the Vallcebre research area can be found, for instance, in Gallart et al. (2002) and Latron et al. (2009).

Soil water content has been measured in the Vallcebre catchments since 1993 using the Time-Domain Reflectometry (TDR) method at nine profiles distributed in the main geo-ecological units (seven in the Cal Parisa catchment and two in Can Vila sub-catchment). These profiles consisted of sets of four vertical 20 cm-long probes permanently installed in the ground at 0–20, 20–40, 40–60 and 60–80 cm depth. These were read every week with a Tektronix 1502-C cable tester. Moreover, spot soil moisture measurements were also carried out through several field campaigns.

For this study, hourly soil moisture data collected by an automatic station at a depth of 20 cm are used considering the period 2007-2009.

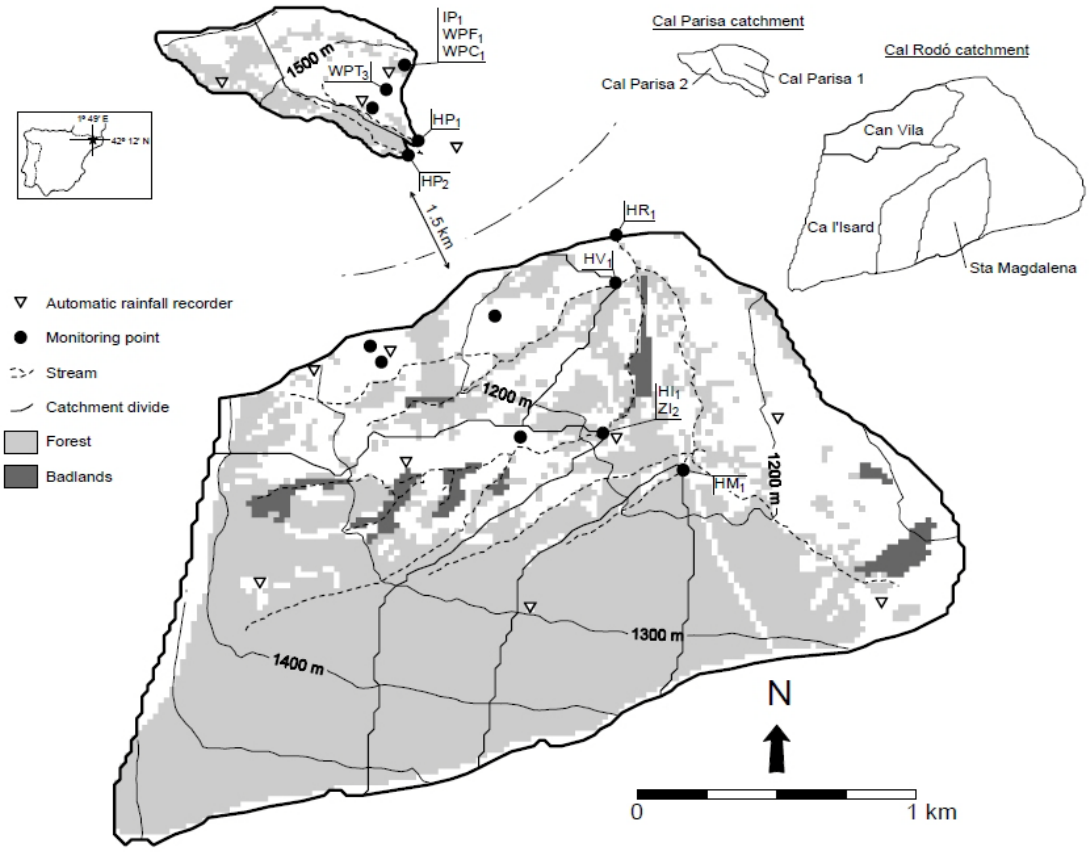


**Figure 6** Map of the Vallcebre catchments, showing the location of the instruments.

## 2.4 France data set

The Valescure catchment (Tramblay et al., 2010) is a small headwater catchment of 3.83 km$^2$ located in the South of France, at the southern boundary of the Cevennes mountain area (see ***Figure 7***). The Valescure catchment is mainly forested, with an altitude ranging from 244 m to 815 m a.s.l. The hillslopes are steep with an average slope of 56%. The geology mainly consists in granite and gneiss rocks, and the soils are relatively thin, generally not exceeding 1 m in depth. Floods occur mostly in autumn, driven by very intense rainy events that can exceed several hundred millimetres in 24 h. In spite of these high rainfall intensities, field surveys have shown that runoff is caused by soil saturation, because of very high hydraulic conductivities. Soils can thus store up to dozens or even hundreds of rainfall millimetres before runoff occurs, depending on porosity, depth and initial soil moisture.

Both discharge and rainfall have been monitored in the catchment since 2003. There is a large inter annual variation in the total amount of rainfall from year to year: 1092 mm in 2005, 1642 mm in 2006, 920 mm in 2006 and 2400

mm in 2008, the wettest year. The Château and Valescure sites have a very similar seasonal pattern typical of the region, with most of the precipitations occurring between the months of September and December. In 2005, 12 TDR soil moisture probes TRIME®-PICO IPH/T3 (IMKO company) were installed in the Château site. The TDR probes were buried in the soil at different depths to account for the vertical variability of the soil moisture profile. The sampling site is located in the immediate vicinity of the river stream, on a set of terraces covered by grass. The TDR probes were installed in five plots (***Figure 7***) with the plots G1, G2 distant 20 m from the plots G3, G4 and G5. Soil moisture has been derived from TDR measurements by using the standard calibration given for mineral soils by IMKO. The measurements were scheduled at 15-min time steps for the whole 2005–2008 period. The TDR measurements showed similar variations at different depths and in the different plots, but higher variations in the upper soil zone. When considering averaged values for each depth, the volumetric soil moisture exhibited a typical Mediterranean seasonal pattern. The lowest soil moisture was observed at the end of summer and the highest soil moisture was observed during winter and spring. It must be noted that soil moisture decreases quickly (in less then 24 h) after a rainfall event back to the initial value before the beginning of the rainy event.

For this study, 15 min soil moisture data collected by the automatic station G4 at a depth of 30 and 50 cm are used considering the period 2007-2009.

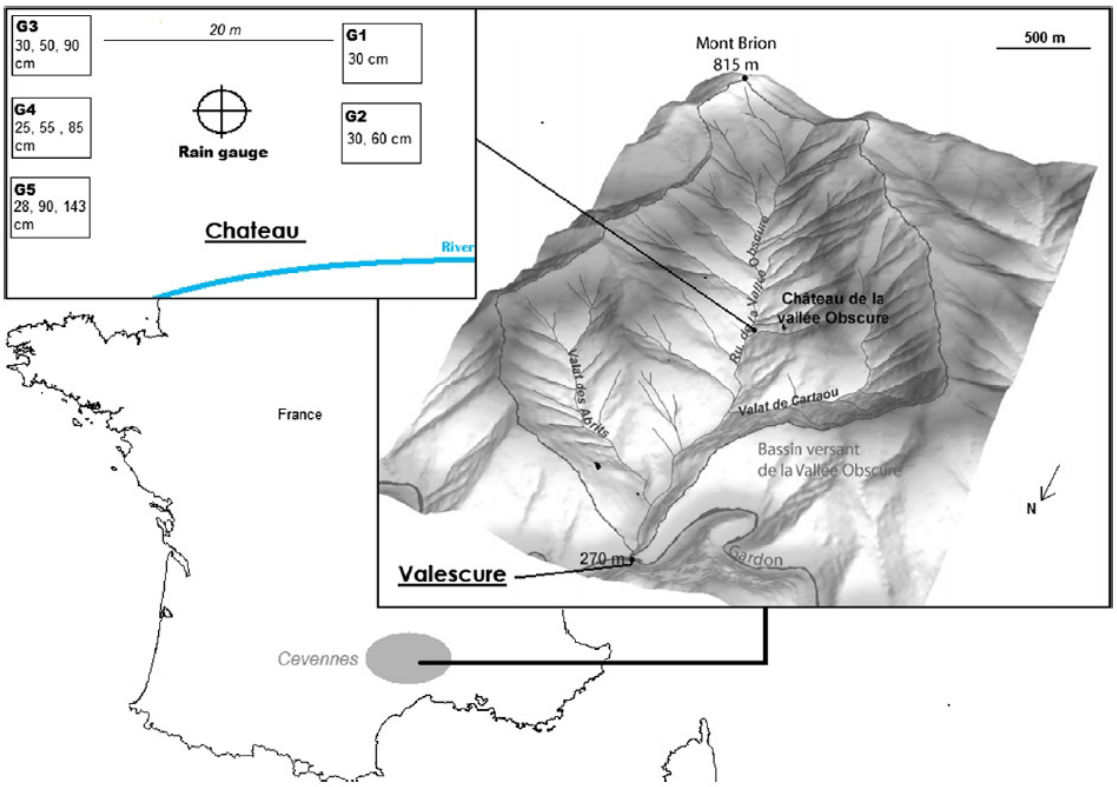


**Figure 7** Valescure catchment. The experimental device consists in two rain gauges (Valescure and Château), one water level recorder (Valescure), five TDR probes plots (near Château).

## 2.5 ASCAT data set

In this study, ASCAT scatterometer data in several versions and formats are used, provided originally from EUMETSAT and processed within the operational H-SAF generation chains and TU-Wien.

The product SM-OBS-1 is the large scale surface soil moisture product, available globally. Based on the radar scatterometer ASCAT mounted on the METOP satellite, the instrument scans the globe in a push-broom mode by six side-looking antennae (three left-hand and three right-hand beams). Each antenna provides three views of the earth under different viewing angles measuring three backscattering coefficients ($\sigma_0$) in triplets for each beam (fore-, mid-, and aft-beam). The swath width is approximately 550 km and there are 14 orbit revolutions per day resulting in a global coverage achieved in ~1.5 days. The basic instrument sampling distance is 12.5 km. For soil moisture, the processing is performed at 50 km (operational) and 25 km (research) resolution. The product is giving relative soil moisture values ranging between 0% and 100% and represent the soil moisture content in the first few centimetres of the soil in relative units between totally dry conditions and saturation. The product SM-OBS-1 is the European sector of the global EUMETSAT product, available in near real-time (within 120 minutes of sensing). The product format is BUFR (Binary Universal Form for the Representation of meteorological data), a WMO standard for binary data. An example of SM-OBS-1 is given in ***Figure 8***.

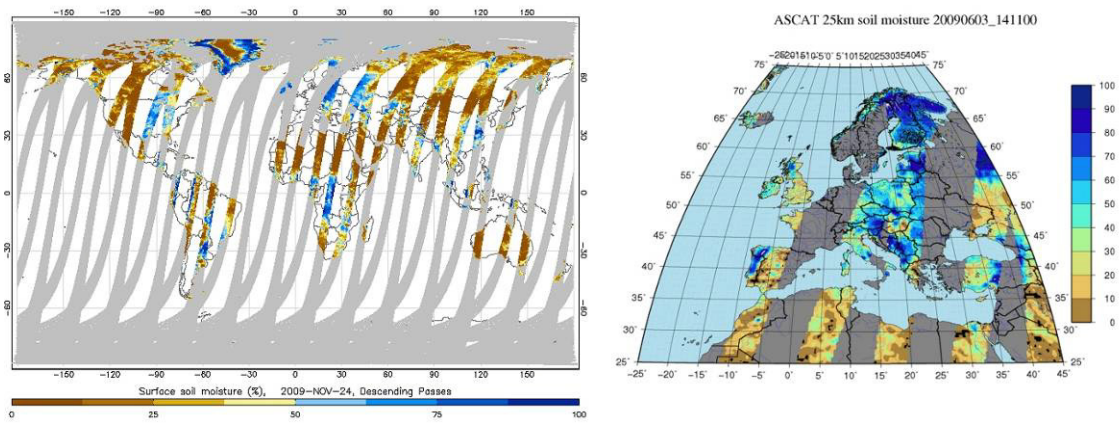


**Figure 8** Composite of descending passes of ASCAT instrument for 24 November 2009 (left) and SM-OBS-1 composite example for 03 June 2009 over Europe (right). Units are given in %vol.

The second product, SM-OBS-2, denotes the small-scale surface soil moisture for Europe at 1 km resolution. It is the result of a subsequent processing of the SM-OBS-1 product performed by the operational processing chain at the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). The 25 km resolution SM-OBS-1 product is first re-sampled at 1 km intervals and then downscaled using statistical parameters from a pre-computed fine-mesh information of downscaling parameters, provided by TU-Wien (Wagner et al., 2008). This parameter database information includes backscatter and scaling characteristics derived from a multi-annual period of

Envisat ASAR (Advanced Synthetic Aperture Radar) operating in the ScanSAR Global monitoring mode. Besides the increased resolution, the main product characteristics are similar to SM-OBS-1 (timeliness, coverage, format). ***Figure 9*** gives an example of the SM-OBS-2 product. ***Table 2*** gives an overview about the versions of datasets used in this study. For more information concerning the products SM-OBS-1 and SM-OBS-2 the reader is referred to Algorithm Theoretical Definition Documents of the H-SAF project.

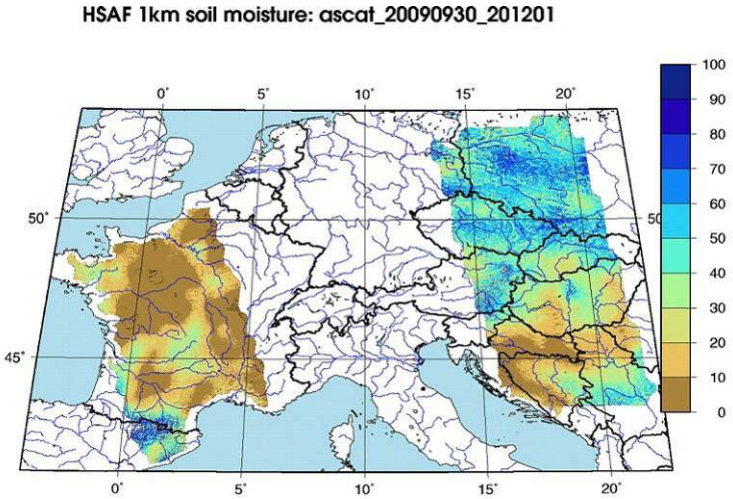


**Figure 9** SM-OBS-2 product of 30 September 2009 (20:12 UTC) given as 3-minute strip file.

## 2.6 ECMWF data set

The volumetric root zone soil moisture product SM-ASS-1 is produced by ECMWF for the H-SAF. Its production chain is documented in the H-SAF Product Users Manual. SM-ASS-1 is produced offline by an early delivery suite of the ECMWF Integrated Forecasting System (IFS), at 25km resolution (T799) using an EKF (Extended Kalman Filter) surface analysis in which screen level parameters and ASCAT SM-OBS-1 data are assimilated (de Rosnay et al., 2009; Drusch et al., 2009; Albergel et al., 2010). SM-ASS-1 data has been produced using the IFS cycle 35r2, for July 2008-August 2009. From September 2009, it is using IFS cycle 36r1. The experiments that produce SM-ASS-1 were set up in July 2009 and are running continuously since then, with a pace of about 2 months of SM-ASS-1 produced every month (July 2010 currently running).

For more information concerning the SM-ASS-1 production chain the reader is referred to documents from the H-SAF web page with the ATDD: Algorithm Theoretical Definition Document, Part-3 - Algorithms for soil moisture products generation. Detailed information can also been found at: http://www.ecmwf.int/research/EUMETSAT_projects/SAF/HSAF/ecmwf-hsaf/index.html

An overview of the SM-ASS-1 product is shown in ***Table 2*** while ***Figure 10*** gives an example of the SM-ASS-1 product for the four layers. Finally, it has to be underlined that the SM-ASS-1 product is available for four layers for

which the corresponding depths are: 0-7 cm, 7-28 cm, 28-100 cm, 100-289 cm.

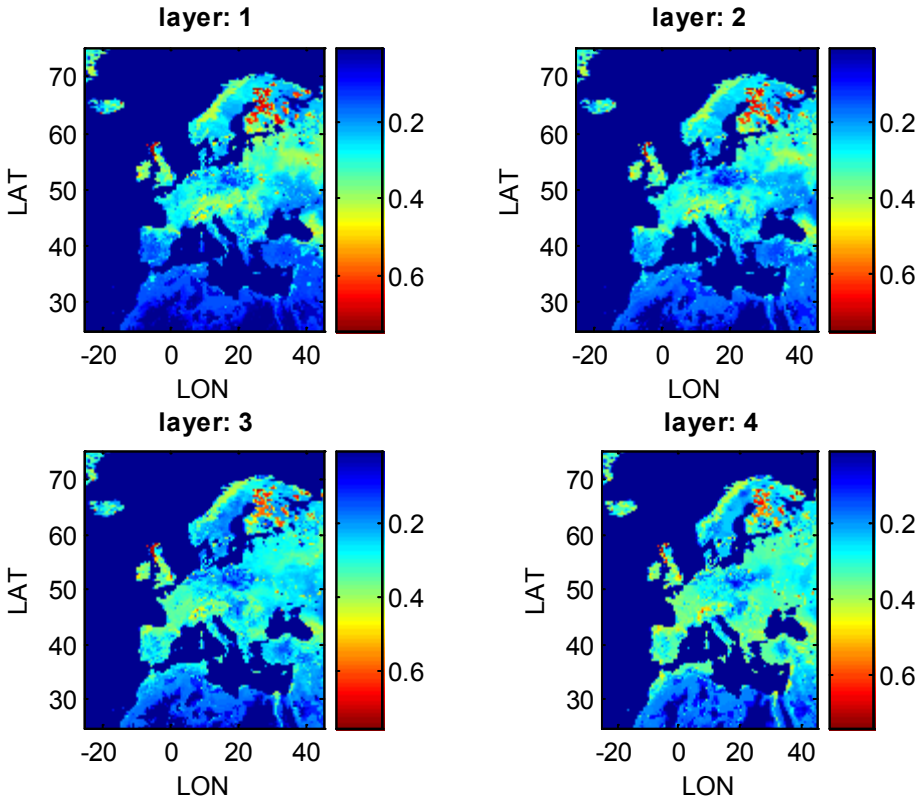


**Figure 10** SM-ASS-1 product of 01 July 2008 for the four layer depth.

**Table 2** Scatterometer and ECMWF data versions (in bold the version used for validation in this study).

| Product | Version | Validity/ Release date | Description |
|---|---|---|---|
| SM-OBS-1 | **v1*** | **May 2007** | **WARP5.0 processor (TU-Wien), time-series format** |
| | **v2** | **Dec 2008** | **WARP5.2 processor (TU-Wien), time-series format, only 2 years of data (2007/2008), new calibration** |
| | v3 | Jun 2009 | SM-OBS-1 prototype, image format (BUFR) |
| SM-OBS-2 | v1 | Mar 2009 | Prototype version, Eastern Europe only, image format (GeoTIFF) |
| | v2 | Dec 2009 | Improved version, whole Europe (with limits over Italy, Benelux countries), image format (BUFR) |
| | v3 | Mar 2010 | Increased geographic coverage, some gaps closed, image format (BUFR) |
| | **v3a** | **Apr 2010** | **Offline-generation at TU-Wien, image format (GeoTiff)** |
| SM-ASS-1 | **IFS cycles 35r2, 36r1** | **Jul 2009, Jul 2010** | **Soil moisture product obtained after the assimilation of SM-OBS-1 (v2) product into ECMWF Integrated Forecasting System** |

* only for demonstration in the analysis of the SM-OBS-2 product.

# 3 Methods

The SM-OBS-1 and SM-OBS-2 products, representative of a layer depth of 0.5-3 cm, are compared with both in situ observations at a depth of 5, 10, 20 and 40 cm and modeled data for a layer depth of 5 and 15 cm. It has to be noted that the two soil moisture products derived from ASCAT represent a relative and dimensionless index between 0 and 1. Therefore, to be consistent, the more appropriate term "saturation degree" is used for them. Accordingly, both in situ observations and modeled data are converted in terms of saturation degree (see below) before their comparison with these two products.

As far as SM-ASS-1 product is concerned, it is directly compared with in situ/modeled data considering the layer depth more close to ground observations. However, in the present study, only the first two layers are investigated.

In this report, a semi-empirical approach, based on an exponential filter, is used to convert the surface saturation degree, SM-OBS-1, into profile saturation degree, the so-called Soil Wetness Index, SWI. However, the exponential filter has the effect to smooth (and retard) the SM-OBS-1 time series and consequently the variability range of SWI is not more limited by 0 and 1 (as the saturation degree) but varies in a narrower range. Therefore, in order to visually and numerically compare the SWI and the ground based (in situ and modeled) saturation degree data, the SWI is linearly rescaled to match the range of variability of observations, yielding SWI*.

In the following, the exponential filter, the linear rescaling and the soil water balance model used in the study are briefly described.

## 3.1 Exponential filter and linear rescaling

The exponential filter proposed by Wagner et al. (1999) is adopted to obtain average profile saturation degree, $\overline{\Theta}(t)$, from surface measurements, $\Theta_s(t)$. For a detailed description of the method the reader may refer to Wagner et al. (1999) and Ceballos et al. (2005). In short, in the method the variation of the average profile saturation degree, $d\overline{\Theta}(t)/dt$, is assumed linearly related to the difference between $\Theta_s(t)$ and $\overline{\Theta}(t)$. For that, $\overline{\Theta}(t)$ can be obtained by the knowledge of $\Theta_s(t)$ and a parameter T, named characteristic time length and representing the time scale of saturation degree variation. The discrete formulation of the method relies on (Wagner et al., 1999):

$$SWI(t) = \frac{\sum_i [SM - OBS(t_i)] exp\left(-\frac{t - t_i}{T}\right)}{\sum_i exp\left(-\frac{t - t_i}{T}\right)} \quad (1)$$

where t is the time, SM-OBS($t_i$) is the discrete analogues of the quantity $\Theta_s(t)$ (SM-OBS-1 and SM-OBS-2), SWI(t) is an estimation of $\overline{\Theta}(t)$ and $t_i$ is the acquisition time of SM-OBS ($t_i$).

The linearly rescaled SWI(t), SWI*(t), is simply computed through the following equation:

$$SWI^*(t) = \left\{ \frac{SWI(t) - \overline{SWI(t)}}{\sigma[SWI(t)]} \right\} \sigma[SD_{ground}(t)] + \overline{SD_{ground}(t)} \tag{2}$$

where $\overline{\phantom{x}}$ and $\sigma$ are the mean and standard deviation operators and $SD_{ground}(t)$ is the ground observed saturation degree (in situ observations or modeled data). The same linear rescaling is also applied to SM-ASS-1 product.

In the remainder, for sake of simplicity, the dependence on time of the different quantities compared in this study is omitted.

### 3.2 Soil water balance model

In addition to in situ observations, modeled saturation degree data for layer depths of both 5 cm and 15 cm are used. It has to be noticed that the modeled data for the 5 cm layer depth are particularly useful because they represent, approximately, the same layer depth investigated by the ASCAT sensor. The structure of the soil water balance model used in this study was derived by using soil moisture observations carried out in an experimental catchment located in the study area. In particular, different expressions were considered for the different components of the model: i.e. infiltration, percolation and evapotranspiration (Brocca et al., 2008). The best performance was obtained when the Green-Ampt relation for infiltration, a gravity driven non-linear relationship for percolation and a linear relation between the actual and the potential evapotranspiration (computed through the Blaney and Criddle formula) were used.

In the following, the best model structure obtained for the soil water balance model is described. The surface soil layer is assumed as a spatially lumped system for which the following water content balance equation holds:

$$\begin{cases} dW(t)/dt = f(t) - e(t) - g(t) & W(t) \le W_{max} \\ W(t) = W_{max} & \text{otherwise} \end{cases} \tag{3}$$

where t is time, W(t) is the amount of water in the investigated soil layer, f(t) is the fraction of the precipitation infiltrating into the soil, e(t) is the evapotranspiration rate, g(t) is the drainage rate due to the interflow and/or the deep percolation, and $W_{max}$ is the maximum water capacity of the soil layer (see ***Figure 11***). The ratio $W(t)/W_{max}$ represents the saturation degree.

The infiltration rate, f(t), is estimated by using the Green-Ampt equation:

$$\begin{cases} f(t) = K_s[1 - \psi(W_{max} - W_i)/F(t)L] & f(t) \le r(t) \\ f(t) = r(t) & \text{otherwise} \end{cases} \tag{4}$$

where $K_s$ is the saturated hydraulic conductivity, $\psi$ is the wetting front soil suction head, $W_i$ is the amount of water at the beginning of the rainfall event,

L is the thickness of the soil layer, F(t) is the cumulated infiltration depth from the onset of the rainfall, and r(t) is the rainfall rate.

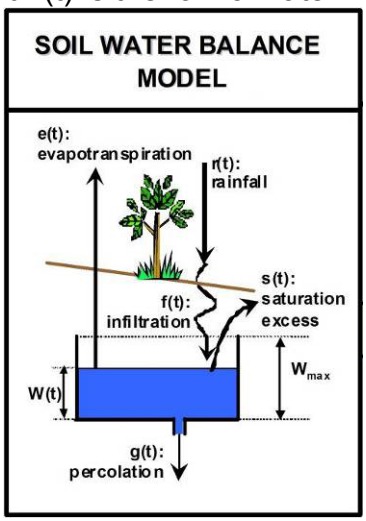


**Figure 11** Scheme of the soil water balance model used for this study.

For the drainage component, the following relation is adopted (Famiglietti and Wood, 1994):

$$g(t) = K_s\left[W(t)/W_{max}\right]^{3+2/\lambda} \tag{5}$$

where $\lambda$ is a pore size distribution index linked to the structure of the soil layer.

Evapotranspiration, which mainly controls the soil moisture temporal pattern in the periods without rainfall, is represented by a linear relation depending on the potential evapotranspiration, $ET_p(t)$, and the soil saturation:

$$e(t) = ET_p(t)W(t)/W_{max} \tag{6}$$

The potential evapotranspiration is computed through the empirical relation of Blaney and Criddle as modified by Doorenbos and Pruitt (1977):

$$ET_p(t) = -2 + b\left[\xi\left(0.46T_a(t) + 8.13\right)\right] \tag{7}$$

where $T_a(t)$ is the air temperature in °C, $\xi$ is the percentage of total daytime hours for the period used (daily or monthly) out of total daytime hours of the year (365 $\times$ 12) and b is a parameter to be calibrated.

The model requires as input data the meteorological variables routinely measured (rainfall and air temperature) and incorporates only five parameters ($W_{max}$, $K_s$, $\psi/L$, $\lambda$, b). Moreover, because the parameters are physically based and their value range is limited, the model was found consistent even when it was calibrated only with a limited number of observations (Brocca et al., 2008). These two characteristics allow to confidently use the model over large areas and for periods different from those employed for parameters calibration.

The soil water balance model showed a high degree of reliability both in simulating the saturation degree temporal pattern in the study area (Brocca et al., 2008) but also as a component of a continuous rainfall-runoff model for flood simulation (Brocca et al., 2010c). For instance, as it is shown in ***Figure 12***, the model provided a high degree of reliability for all the three investigated sites with RMSE less than 0.055 (0.017 $m^3/m^3$), Nash-Sutcliffe efficiency, NS,

higher than 0.84 and correlation coefficient, R, higher than 0.92. Therefore, the model can be assumed representative of the saturation degree behaviour of each site.

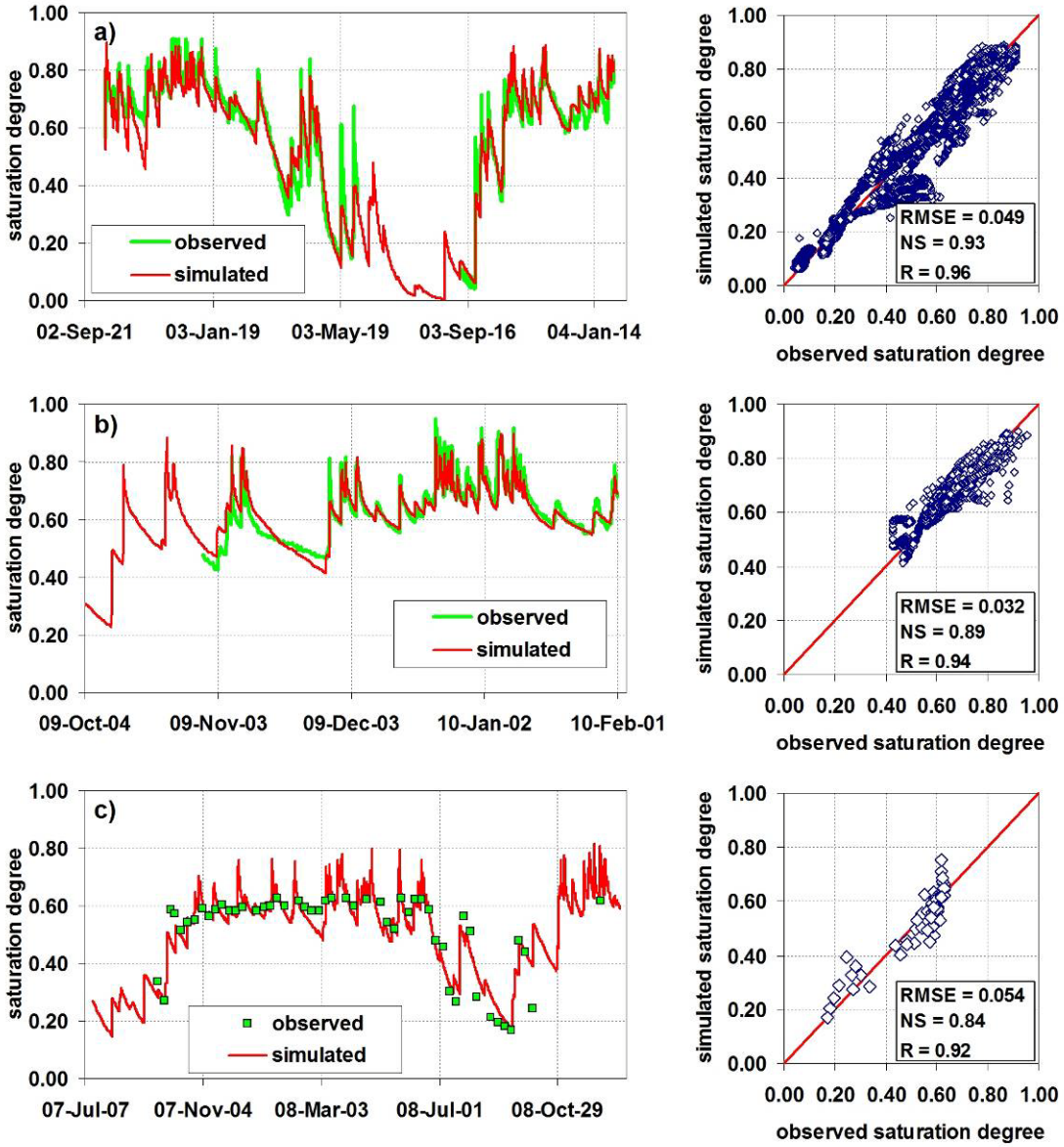


**Figure 12** Temporal pattern (left) and scatter plot (right) of 'observed' versus simulated saturation degree obtained through the soil water balance model for the three Umbria region test sites: a) Vallaccia, b) Cerbara, and c) Spoleto. (RMSE: root mean square error, NS: Nash-Sutcliffe efficiency, R: correlation coefficient).

# 4 Results

The results are reported subdivided by product (SM-OBS-1, SM-OBS-2 and SM-ASS-1) and by test site (located in Italy, Luxembourg, Spain and France). For each comparison the following statistical scores are used to evaluate the soil moisture product reliability:

$$\mathrm{RMSD} = \sqrt{\overline{\left(\mathrm{SM}_{\mathrm{SAT}} - \mathrm{SM}_{\mathrm{INSITU}}\right)^2}} \tag{8}$$

$$\mathrm{MD} = \overline{\left(\mathrm{SM}_{\mathrm{INSITU}} - \mathrm{SM}_{\mathrm{SAT}}\right)} \tag{9}$$

$$\mathrm{R} = \sqrt{1 - \frac{\left(\mathrm{SM}_{\mathrm{SAT}} - \mathrm{SM}_{\mathrm{INSITU}}\right)^2}{\left(\mathrm{SM}_{\mathrm{INSITU}} - \overline{\mathrm{SM}_{\mathrm{INSITU}}}\right)}} \tag{10}$$

where RMSD is the root mean square difference between in situ, $\mathrm{SM}_{\mathrm{INSITU}}$, and the different "satellite" soil moisture products, $\mathrm{SM}_{\mathrm{SAT}}$, $\overline{\phantom{x}}$ is the mean operator, MD is the mean difference and R is the correlation coefficient. It has to be noted that instead of RMSE (where E stands for 'error') we used RMSD to underline that also ground measurements contain errors (instrumental and representativeness) and, hence, they cannot be assumed as the "true" soil moisture at the ground. This point will be better clarified afterwards.

At the end of the Results section, a brief description of the experience gained in managing the files storing the different soil moisture products from the hydrologist (user) point of view is given.

## 4.1 SM-OBS-1

In the following, the SM-OBS-1 product reliability is assessed through the comparison with in situ and modeled saturation degree data. As mentioned above, together with the 'original' SM-OBS-1 product (surface saturation degree), also the SWI (profile saturation degree) and SWI* (linear rescaling of SWI) indices derived from it are considered. By analyzing separately the three products the effect of each change of the original data is clearly assessed.

The reliability of these three quantities (SM-OBS-1, SWI and SWI*) is analyzed through a comparison with:

1) in situ observed saturation degree data for a total of 14 locations;
2) simulated saturation degree data obtained applying the soil water balance model for a total of 20 locations.

Therefore, since three comparisons were made for each location, a total of 102 comparisons are carried out (42 for in situ observations and 60 for modeled data). In the following, a description of the corresponding results (divided by site) is reported pointing out the more significant aspects that require further investigations to improve the reliability of SM-OBS-1 product (and the indices derived from it). ***Table 3*** and ***Table 4*** summarize the results of the comparisons for in situ and modeled data, respectively, and they are discussed below.

**Table 3** Statistical scores for SM-OBS-1, SWI and SWI* versus in situ observed soil moisture data, results are shown in terms of saturation degree. (Z: depth in cm; N: sample size; MD: mean difference; RMSD: root mean square difference; R: correlation coefficient, T: characteristic time length). For VSC and VCE locations the results refer to the closest pixel not affected by mountains.

| Site | | Z | Period | | N | SM-OBS-1 | | | SWI | | | SWI* | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | \|MD\| | RMSD | R | \|MD\| | RMSD | R | RMSD | |
| c.IT | VAL | 10 | 04-07 | 05-08 | 340 | 0.15 | 0.26 | 0.67 | 0.14 | 0.22 | 0.91 | 0.12 | 19.8 |
| | VAL | 20 | 04-07 | 05-08 | 340 | 0.16 | 0.28 | 0.64 | 0.15 | 0.23 | 0.92 | 0.12 | 22.6 |
| | VAL | 40 | 04-07 | 05-08 | 340 | 0.16 | 0.29 | 0.60 | 0.16 | 0.23 | 0.94 | 0.11 | 28.8 |
| s.IT | BAG | 30 | 01-07 | 12-08 | 509 | 0.14 | 0.21 | 0.75 | 0.14 | 0.19 | 0.79 | 0.11 | 2.8 |
| | MEL | 30 | 01-07 | 12-08 | 579 | 0.29 | 0.39 | 0.62 | 0.30 | 0.37 | 0.88 | 0.16 | 40.0 |
| | TOR | 30 | 01-07 | 12-08 | 550 | 0.08 | 0.19 | 0.71 | 0.09 | 0.16 | 0.85 | 0.12 | 10.8 |
| | CHI | 30 | 01-07 | 12-08 | 538 | 0.13 | 0.18 | 0.65 | 0.14 | 0.17 | 0.83 | 0.09 | 15.4 |
| LUX | BIB | 5 | 01-07 | 12-08 | 773 | 0.09 | 0.24 | 0.63 | 0.09 | 0.16 | 0.90 | 0.11 | 11.6 |
| SP | K10 | 5 | 01-07 | 12-08 | 667 | 0.09 | 0.22 | 0.74 | 0.08 | 0.17 | 0.82 | 0.09 | 2.4 |
| | F11 | 5 | 01-07 | 12-08 | 633 | 0.01 | 0.22 | 0.67 | 0.02 | 0.15 | 0.77 | 0.13 | 5.0 |
| | I06 | 5 | 01-07 | 12-08 | 653 | 0.13 | 0.24 | 0.72 | -0.12 | 0.22 | 0.75 | 0.09 | 1.0 |
| | VCE | 10 | 01-07 | 12-08 | 651 | 0.19 | 0.33 | 0.44 | 0.19 | 0.29 | 0.55 | 0.21 | 4.8 |
| FR | VSC | 30 | 01-07 | 12-08 | 685 | 0.08 | 0.21 | 0.59 | 0.08 | 0.14 | 0.68 | 0.10 | 11.0 |
| | VSC | 50 | 01-07 | 12-08 | 685 | 0.04 | 0.20 | 0.60 | 0.04 | 0.14 | 0.69 | 0.10 | 12.0 |
| **MEAN** | | | | | **567** | **0.12** | **0.25** | **0.65** | **0.11** | **0.20** | **0.81** | **0.12** | **13.4** |

**Table 4** As in Table 3 but for modeled soil moisture data.

| Site | | Z | Period | | N | SM-OBS-1 | | | SWI | | | SWI* | T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | \|MD\| | RMSD | R | \|MD\| | RMSD | R | RMSD | |
| c.IT | VAL | 5 | 01-07 | 12-08 | 663 | 0.00 | 0.14 | 0.84 | 0.00 | 0.12 | 0.87 | 0.13 | 1.4 |
| | VAL | 15 | 01-07 | 12-08 | 663 | 0.24 | 0.32 | 0.70 | 0.25 | 0.30 | 0.87 | 0.14 | 19.2 |
| | SPO | 5 | 01-07 | 12-08 | 658 | 0.06 | 0.18 | 0.75 | 0.07 | 0.15 | 0.80 | 0.12 | 2.4 |
| | SPO | 15 | 01-07 | 12-08 | 658 | 0.19 | 0.27 | 0.70 | 0.20 | 0.22 | 0.83 | 0.09 | 14.4 |
| | CER | 5 | 01-07 | 12-08 | 666 | 0.04 | 0.16 | 0.82 | 0.04 | 0.15 | 0.84 | 0.12 | 0.8 |
| | CER | 15 | 01-07 | 12-08 | 666 | 0.11 | 0.21 | 0.78 | 0.11 | 0.18 | 0.83 | 0.11 | 2.2 |
| s.IT | BAG | 5 | 01-07 | 12-08 | 572 | -0.05 | 0.14 | 0.84 | -0.05 | 0.14 | 0.84 | 0.11 | 0.8 |
| | BAG | 30 | 01-07 | 12-08 | 572 | 0.11 | 0.19 | 0.78 | 0.11 | 0.18 | 0.80 | 0.13 | 1.8 |
| | MEL | 5 | 01-07 | 12-08 | 579 | -0.04 | 0.16 | 0.82 | -0.04 | 0.15 | 0.84 | 0.12 | 0.8 |
| | MEL | 30 | 01-07 | 12-08 | 579 | 0.26 | 0.32 | 0.76 | 0.27 | 0.31 | 0.90 | 0.13 | 16.6 |
| | TOR | 5 | 01-07 | 12-08 | 534 | -0.08 | 0.14 | 0.86 | -0.08 | 0.12 | 0.88 | 0.12 | 1.2 |
| | TOR | 30 | 01-07 | 12-08 | 534 | 0.03 | 0.14 | 0.80 | 0.03 | 0.10 | 0.91 | 0.09 | 7.4 |
| | CHI | 5 | 01-07 | 12-08 | 547 | -0.07 | 0.14 | 0.81 | -0.07 | 0.13 | 0.83 | 0.07 | 1.0 |
| | CHI | 30 | 01-07 | 12-08 | 547 | 0.00 | 0.12 | 0.78 | 0.01 | 0.08 | 0.86 | 0.07 | 4.0 |
| LUX | BIB | 5 | 01-07 | 12-08 | 814 | 0.10 | 0.24 | 0.63 | 0.10 | 0.14 | 0.91 | 0.09 | 12.2 |
| SP | K10 | 5 | 01-07 | 12-08 | 667 | -0.08 | 0.23 | 0.74 | -0.08 | 0.18 | 0.79 | 0.08 | 2.0 |
| | F11 | 5 | 01-07 | 12-08 | 633 | 0.02 | 0.20 | 0.75 | 0.02 | 0.13 | 0.84 | 0.10 | 3.4 |
| | I06 | 5 | 01-07 | 12-08 | 653 | -0.12 | 0.25 | 0.76 | -0.12 | 0.24 | 0.77 | 0.06 | 0.8 |
| FR | VSC | 5 | 01-08 | 12-08 | 353 | -0.03 | 0.20 | 0.68 | 0.03 | 0.18 | 0.70 | 0.10 | 0.8 |
| | VSC | 30 | 01-08 | 12-08 | 353 | 0.07 | 0.22 | 0.67 | 0.07 | 0.18 | 0.73 | 0.08 | 1.6 |
| **MEAN** | | | | | **596** | **0.04** | **0.20** | **0.76** | **0.04** | **0.17** | **0.83** | **0.10** | **4.7** |

### *4.1.1 Central Italy*

For VAL site and for each layer depth (10, 20 and 40 cm) the average water content of the soil layer is computed by weighing the volumetric soil moisture observations in the layer. Then, the saturation degree of each depth is computed from the average water content data by scaling them with the

maximum and minimum observed values thus obtaining the in situ 'observed' saturation degree data. Then, the values corresponding to SM-OBS-1 acquisition dates are extracted for each depth considering the ASCAT pixel whose centroid is located nearest to VAL site (see ***Figure 2a***). The same procedure is adopted also for the other test sites and for the other soil moisture products (SM-OBS-2 and SM-ASS-1). ***Figures 13-15*** show the comparison between SM-OBS-1, SWI and SWI* with in situ observations at 10, 20 and 40 cm depth for the VAL site. On the top of the figures the statistical score used for performance assessment are shown as well as the optimal value of the T parameter for the computation of the SWI index.

Firstly, for the comparison between SM-OBS-1 and in situ data, fairly low R values ranging between 0.60 (40 cm) and 0.67 (10 cm) are obtained. As expected, the best results come from the less deep observations, at 10 cm depth. However, these low values suggest that a method (as the exponential filter used in this study) relating surface to profile saturation degree data is required for a coherent validation of satellite data that are representative of a very thin soil layer.

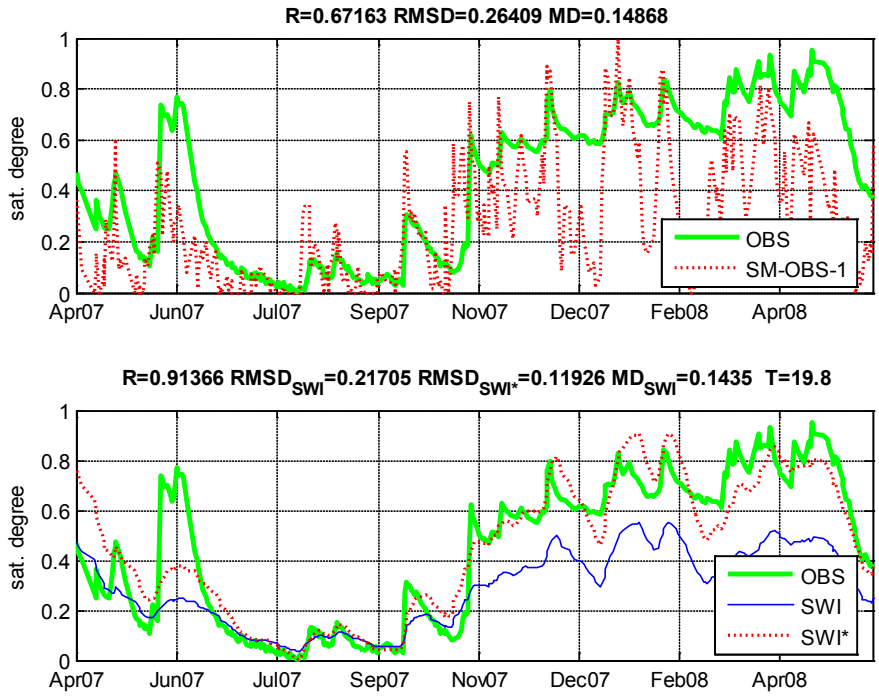


**Figure 13** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 10 cm depth for VAL site (Italy).

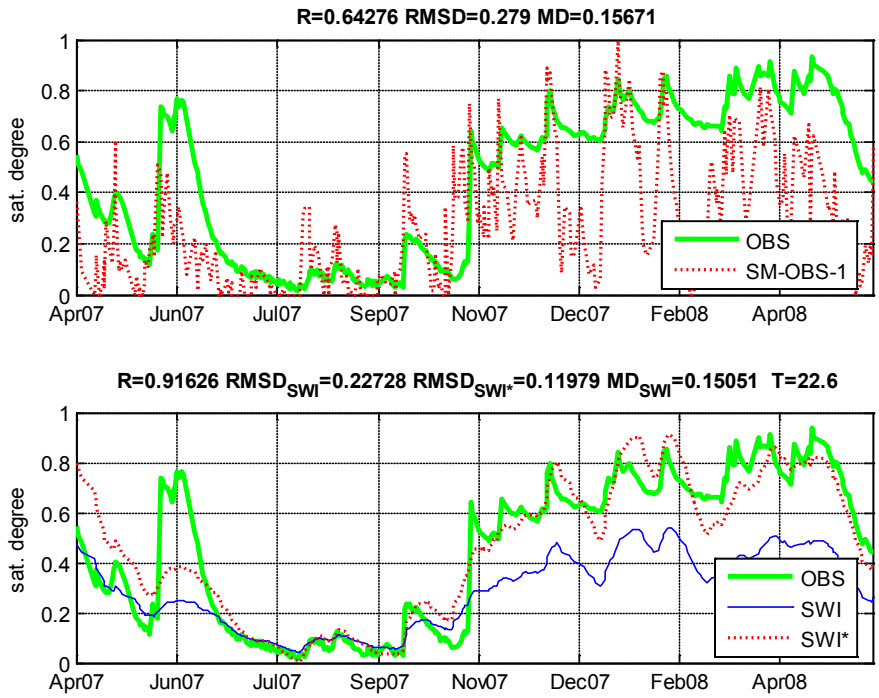


**Figure 14** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 20 cm depth for VAL site (Italy).

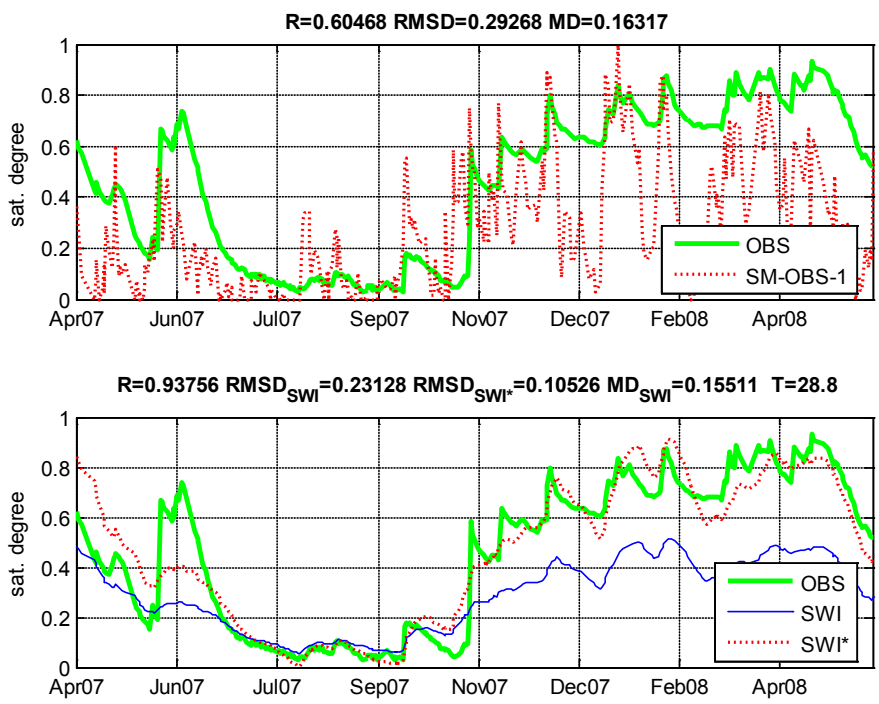


**Figure 15** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 40 cm depth for VAL site (Italy).

In order to compute the SWI, the T parameter has to be estimated optimizing the R between in situ and satellite data. In a physical consistent way, the optimal T value increases with layer depth and is equal to 19.8, 22.6

and 28.8 days for 10, 20 and 40 cm depth, respectively. These values are higher than that obtained by Albergel et al. (2009) who found an optimal T value equal to 14 days for a layer depth of 30 cm. However, Albergel et al. (2009) analyzed a shorter time period (9 versus 15 months) and only the optimal average T value for 11 locations is derived. On the other hand, Brocca et al. (2010b) obtained higher T values ranging between 30 and 90 days for modeled data of an approximate layer depth of 1-1.5 m. By using the optimal T values, R ranges between 0.92 (10 cm) and 0.94 (40 cm), slightly increasing with soil layer depth. It has to be noted that, if a T value equal to 15 days is used, R is equal to ~ 0.91 with only a trivial reduction in the performance. These values are much higher than those reported in Albergel et al. (2009) who obtained R values ranging between -0.257 and 0.918 (average R=0.558). The better results obtained in this study are most likely due to the difference in soil moisture retrievals: here they are based on model parameters derived from two years (2007-2008) of ASCAT measurements, whereas in Albergel et al. (2009) the parameters are derived from historical ERS scatterometer measurements (1992-2000). Considering the RMSD, it ranges between 0.217 and 0.231 which corresponds, in volumetric terms, to the range 0.065-0.069 $m^3/m^3$ (these values are easily obtained by multiplying for porosity - ***Table 1*** - the corresponding values expressed in terms of saturation degree).

These values are slightly high because of the SWI underestimation of in situ observations (see bottom of ***Figures 13-15***). This is related to the effect of the exponential filter that flattens the original time series mainly reducing the higher values. However, in some applications, it is more important that the general trend of soil moisture values (i.e. the relative soil moisture variations between different dates) is well reproduced rather than their actual values. This means that the best indicator to assess the data reliability should be the linear (or non linear, Spearman) correlation coefficient instead of the RMSD. In fact, for instance, if "observed" remote sensing saturation degree data has to be assimilated (with a data assimilation technique as, e.g., a Kalman filter) in a rainfall-runoff (or meteorological) model applied to a given area, both the modeled and the "observed" data would have the same range of variability and, hence, a linear (or non linear) transformation would be required before of the application of the data assimilation technique. It has to be noticed that both the modeled and the "observed" saturation degree data do not represent the actual soil moisture value of the area but only an indicator of the wetness condition that is used as an index in the model.

On this basis, a simple linear rescaling is applied to SWI data, ***equation (2)***, to match the range of variability of in situ observations thus obtaining the SWI* index that is more appropriate if the comparison are made in terms of RMSD. ***Figures 13-15*** show a good agreement between the SWI* and the in situ time series except in the starting period with an overestimation in April and a clear underestimation from the end of May to the middle of June. This last result, as shown later in the comparison with modeled data, can be also related to local effects non-representative of the whole ASCAT pixel. In fact, higher rainfall in the area surrounding the probes is observed in that period. When SWI* data are considered, the RMSD ranges between 0.11 (40 cm) and 0.12 (10 cm) corresponding, in volumetric terms, to the range 0.032-0.035 $m^3/m^3$ (see also ***Table 2***). Obviously, in terms of R, the results of SWI and

SWI* are identical. These results confirm the reliability of ASCAT sensor for wetness conditions estimation in the investigated area.

It has to be noted that the obtained performance improves the results found with the ASCAT predecessor, i.e. the ERS scatterometer, that achieved a RMSD around 0.040 $m^3/m^3$ (see e.g. Wagner et al., 1999; Ceballos et al., 2005; Brocca et al., 2009; Gruhier et al., 2010). In our opinion, this is likely due to the finer temporal resolution of the ASCAT sensor, mainly over Europe (Brocca et al., 2010d).

A further test of the three ASCAT products is carried out considering their reliability in reproducing modeled saturation degree data. For this purpose, the soil water balance model is applied in the three sites described in section 2.1. Consistently to the approach previously used, the in situ 'observed' saturation degree for the Spoleto and Cerbara sites is computed by scaling the in situ observed volumetric soil moisture data through their minimum and maximum values. Then, for each site, the model parameters are calibrated to reproduce, at best, the in situ observations. The model performance are found quite good (Brocca et al., 2010d) and, hence, it can be assumed representative of the saturation degree behaviour of each site.

The simulated saturation degree of each site is computed by running the model from 1st January 2007 to 31st December 2008 and by using, as input data, the rainfall and temperature data averaged at the scale of the satellite pixel (625 $km^2$). Specifically, the model is run considering a layer depth of both 5 and 15 cm; the six simulated time series (2 depth, 3 sites) are used for the comparison with the different soil moisture products. As before, simulated saturation degree values corresponding to ASCAT acquisition dates are extracted for each site and depths considering the ASCAT pixel whose centroid is located nearest to each site (see ***Figure 2a***). ***Figures 16-18*** show the comparison between SM-OBS-1, SWI and SWI* with modeled data at 5 cm depth for the three central Italy site; the statistical scores used for performance assessment are also shown.

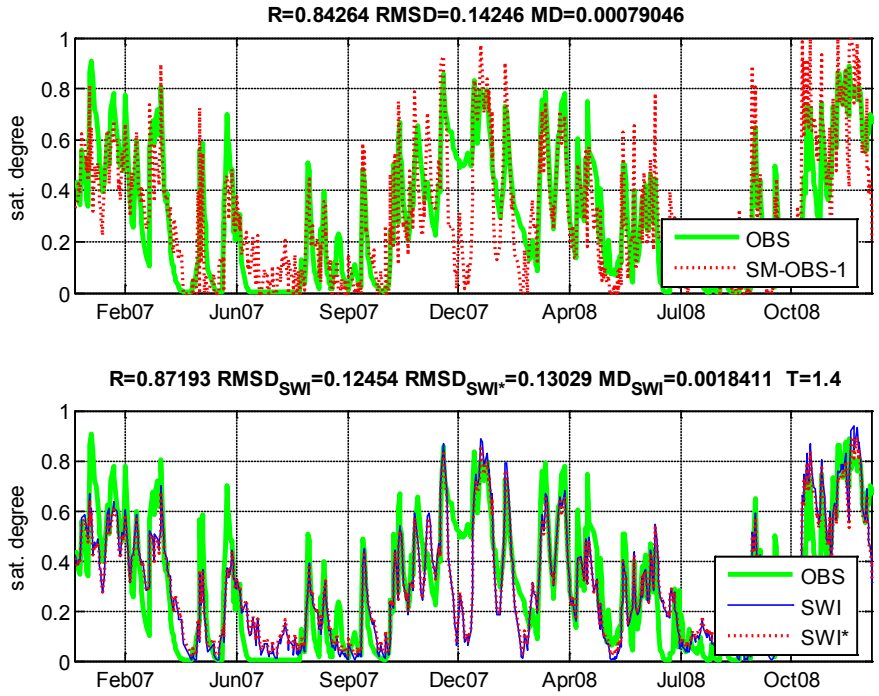


**Figure 16** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for VAL site (Italy).

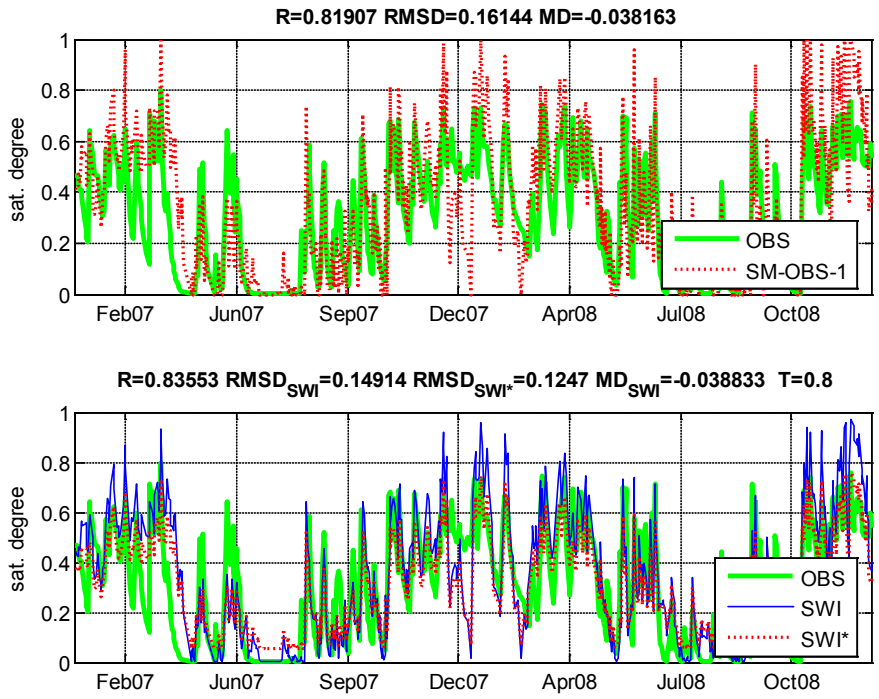


**Figure 17** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for CER site (Italy).

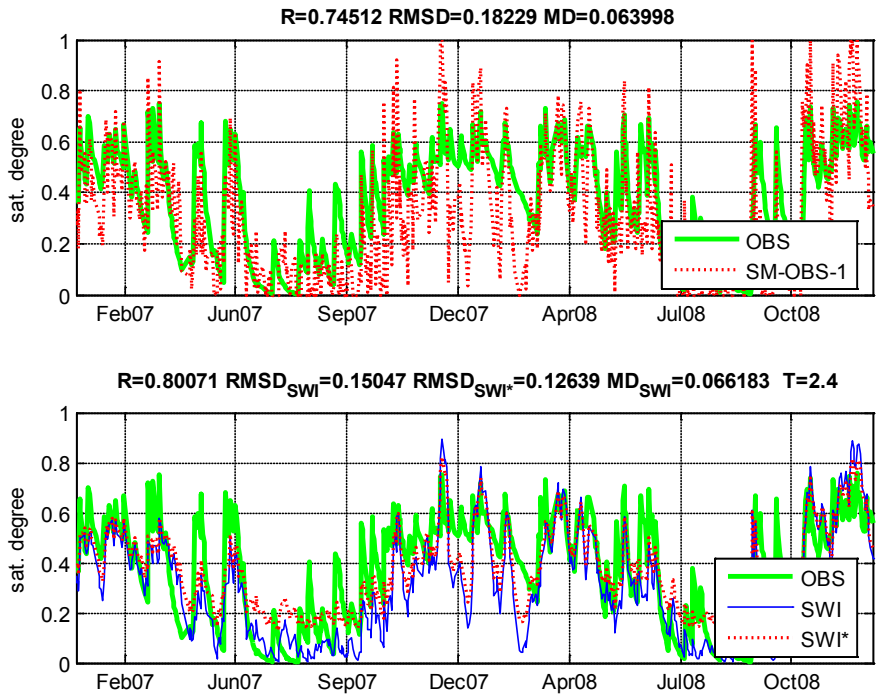


**Figure 18** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for SPO site (Italy).

The comparison between SM-OBS-1 and simulated data are quite good: R values range between 0.75 (SPO) and 0.84 (VAL) and RMSD between 0.14 (VAL) and 0.18 (SPO) (less than 0.055 $m^3/m^3$ in volumetric terms). If compared with previous results reported in the scientific literature (e.g. Prigent et al., 2005; Pellarin et al., 2006; Parajka et al., 2009; Rudiger et al., 2009; Gruhier et al., 2010), the SM-OBS-1 appears reliable and outperforming the ERS scatterometer index. In fact, it is able to accurately reproduce the temporal pattern of the simulated saturation degree in terms of both timing and entity of its variations also at fine temporal scale. Considering the VAL site (***Figure 16***), it can be seen that in the period from the end of May 2007 to the first days of June 2007 the underestimation previously found for in situ observations is no more present, likely due to the reduced spatial mismatch of the simulated data. This result corroborates the validity of using both in situ observations and modeled data for satellite data validation to have a more comprehensive view of the soil moisture behaviour in the investigated area. However, it can be seen that during the period December 2007-January 2008 SM-OBS-1 tends to underestimate simulated data likely due to soil freezing that strongly affects ASCAT reliability.

When the SWI, or SWI* index, are considered, a slight improvement is obtained but of less importance than those reported in the comparison with in situ data. This is clearly related to the shallower depth analyzed here that is more close to that investigated by the ASCAT sensor. However, it has to be noted that for SWI* RMSD ranges between 0.12 and 0.13 which is less than 0.040 $m^3/m^3$ in volumetric terms. The T values are found ranging between 1.0 and 2.5 for CER and SPO site, respectively. These values are related to soil hydraulic characteristics of the sites and, in particular, to hydraulic conductivity which increases from SPO to CER site (consequently, T decreases).

However, as for in situ data, if a constant T value equal to 1 is adopted, results are quite similar with RMSD less than 0.14.

As far as the simulated saturation degree at 15 cm depth is concerned, the results are only briefly described (see ***Table 3***) because they are in good accordance with those previously obtained for the in situ comparison, with R values ranging between 0.83 and 0.87 (for *SWI*) and RMSD between 0.09 and 0.14 (for *SWI**). Considering that in the comparison with simulated data a 2-year period and three different sites are considered (more than 650 pairs), the reliability and robustness of SM-OBS-1 product is confirmed once more.

### *4.1.2 South Italy*

For the other test sites, findings are similar to those obtained for the central Italy test sites and, hence, a shorter description is carried out. The purpose is to highlight the drawbacks of the SM-OBS-1 product that can be enhanced in further developments of the algorithm.

For south Italy test sites located in Campania and Calabria regions, results are as good as central Italy. By way of example, ***Figures 19-22*** show the comparison between SM-OBS-1, SWI and SWI* with observed (30 cm) and modeled data (5 cm) for the BAG (Campania) and TOR (Calabria) test sites; the statistical scores used for performance assessment are also shown.

In particular, as far as in-situ observations are concerned, results are better when the SWI index is considered (R ranges between 0.79 and 0.88) due to the thick layer depth at which the sensors are installed (30 cm). In fact, if modeled data at 5 cm depth are investigated, correlation values are good (ranging between 0.81 and 0.86) also when the original SM-OBS-1 product is used, i.e. without applying the exponential filter.

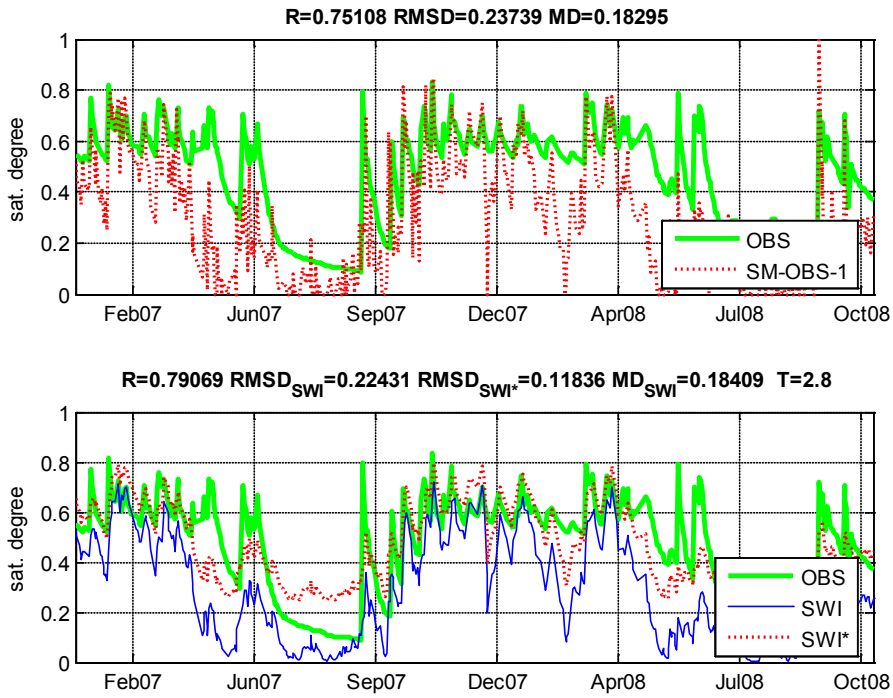


**Figure 19** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 30 cm depth for BAG site (Italy).

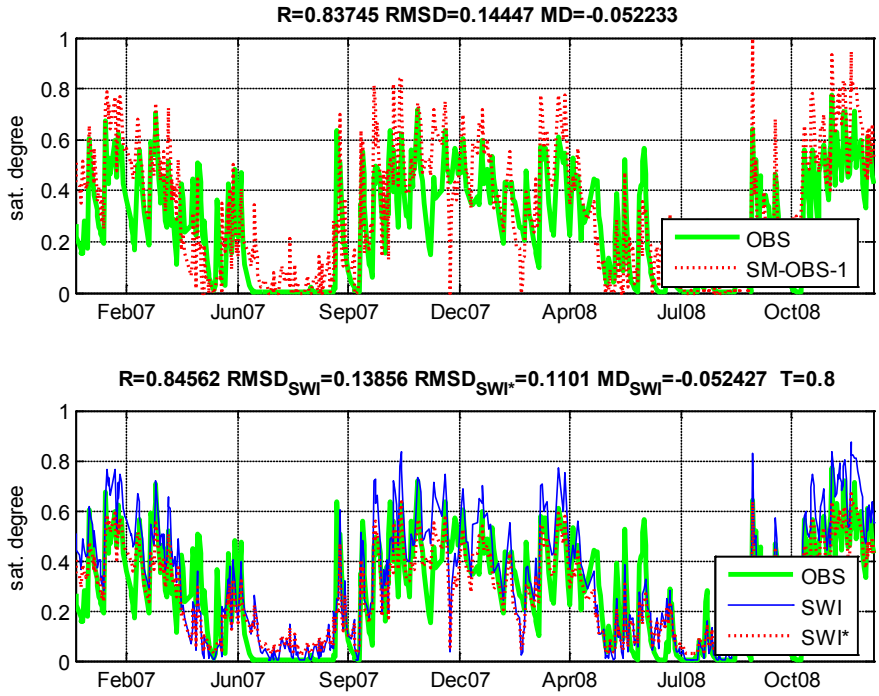


**Figure 20** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for BAG site (Italy).

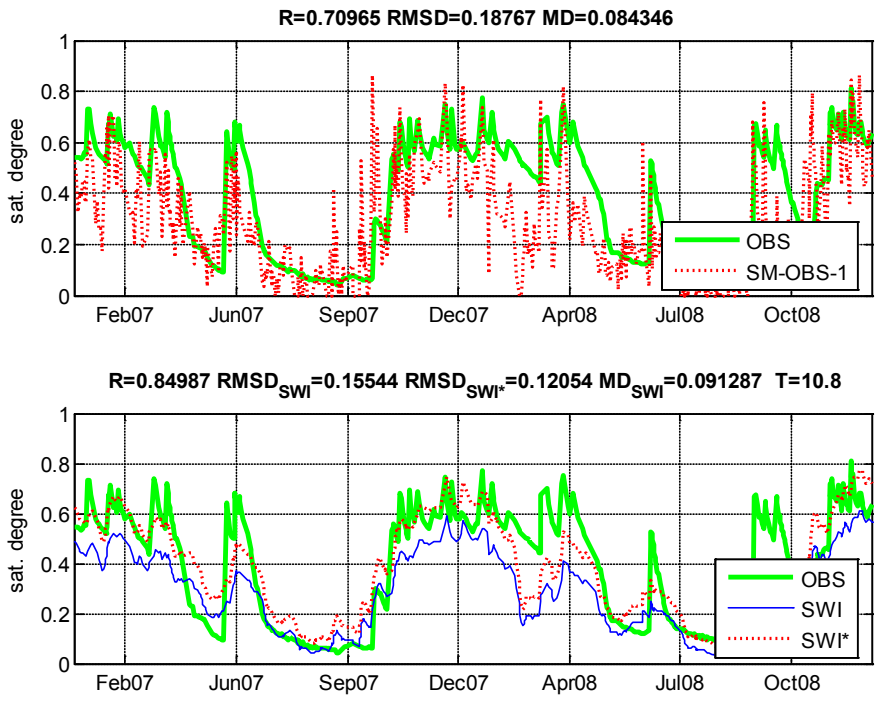


**Figure 21** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 30 cm depth for TOR site (Italy).

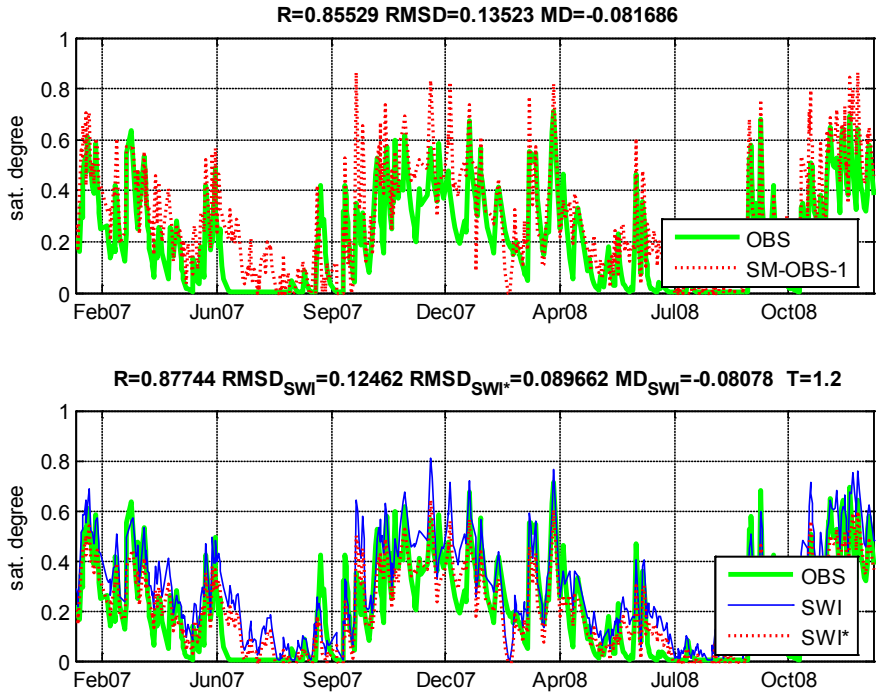


**Figure 22** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for TOR site (Italy).

### *4.1.3 Luxembourg*

The same analysis conducted before, it is also done for in situ and modeled data on BIB site in Luxembourg. ***Figures 23-24*** show the comparison between SM-OBS-1, SWI and SWI* with in situ and modeled data at 5 cm depth for BIB site. As it can be seen, very similar results to those previously described are obtained. In particular, R is equal to ~0.63 when SM-OBS-1 is considered and becomes higher than 0.90 for the SWI index. The RMSD for the SWI* index is equal to 0.11 and 0.09 for in situ and modeled data, respectively. In volumetric terms, it is less than 0.035 $m^3/m^3$. However, for this site two interesting points can be detected by inspecting in depth ***Figures 23-24***.

Firstly, looking at ***Figure 23***, on December 2007 a sudden decrease in saturation degree can be observed for both in situ and SWI* data. This decrease is related to soil freezing that affects both the ASCAT sensor but also the TDR technology used for in situ measurement of soil moisture. If modeled data are considered (***Figure 24***), this fast decrease is no more observed since the adopted soil water balance model does not account of soil freezing in the formulation. Therefore, it can be inferred that the model is more reliable if one is interested to the total water content of the soil layer whereas in situ and ASCAT observations are able to detect only the liquid water.

Secondly, as for the modeled data of VAL site, if the period between May and June 2008 is analyzed it can be seen that SM-OBS-1 underestimates in situ observations but the same does not occur for modeled data. Again, it can be related to the non-representativeness of in situ observations at the ASCAT

pixel scale and, hence, highlights that considering both modeled and in situ data a better insight on the soil moisture product performance can be obtained.

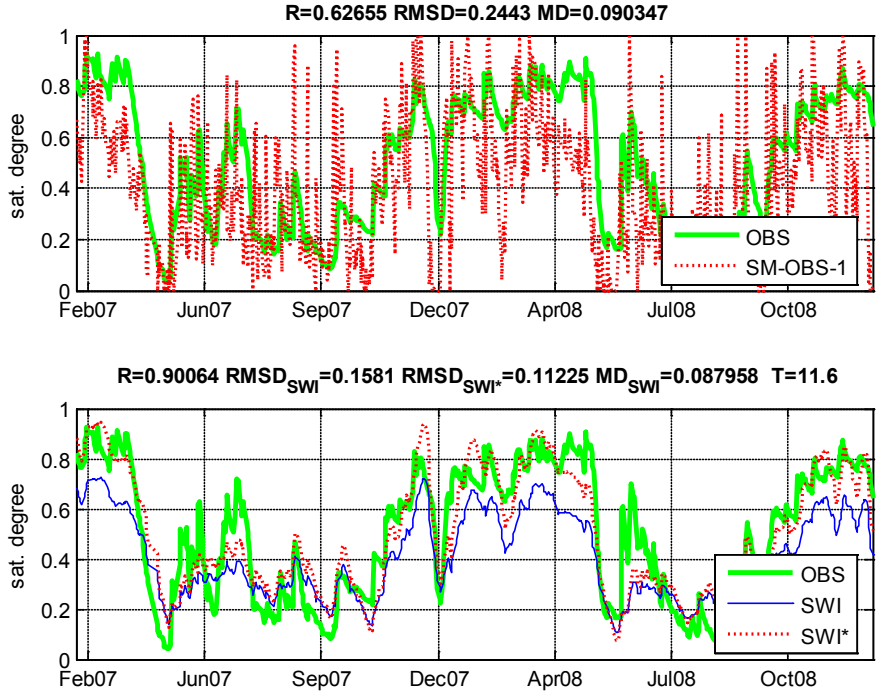


**Figure 23** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 5 cm depth for BIB site (Italy).

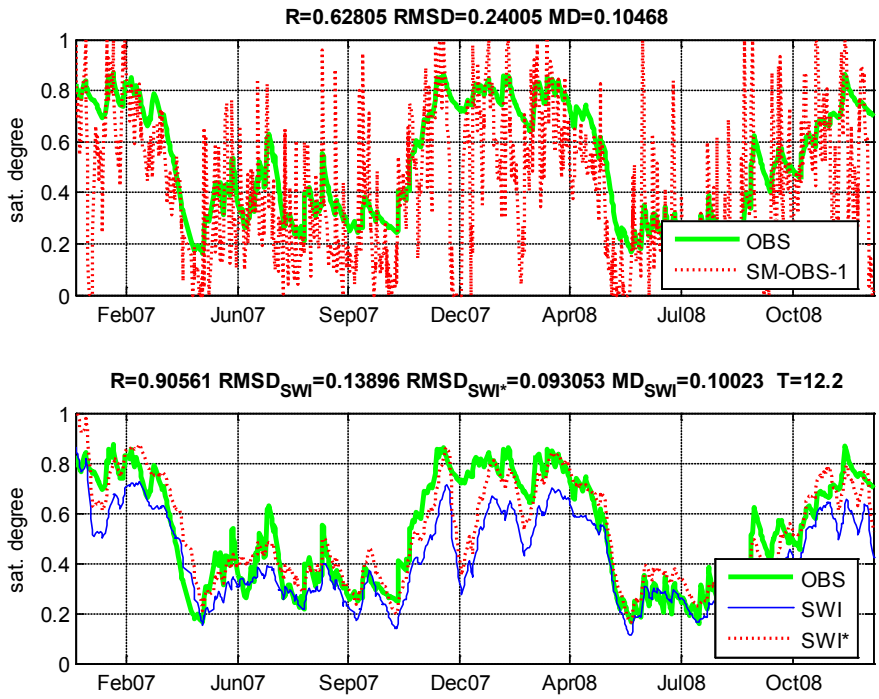


**Figure 24** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for BIB site (Italy).

### *4.1.4 Spain - REMEDHUS*

***Figures 25*** shows the comparison between SM-OBS-1, SWI and SWI* with in situ observed data at 5 cm depth for the F11 site of the REMEDHUS network.

As far as in situ observed saturation degree data are concerned, for the three sites the results are quite similar with R ranging between 0.67 and 0.74 for SM-OBS-1 and between 0.75 and 0.82 for SWI index. In terms of RMSD it ranges between 0.22 and 0.24 for SM-OBS-1 and 0.09 and 0.13 for SWI*. It has to be noted that, due to the limited interval of variability of in situ observations (see ***Table 1***), the RMSD for SWI* is less than 0.024 $m^3/m^3$ for the three Spain sites. Therefore, in terms of correlation results for these sites are slightly worse than those obtained in Italy and Luxembourg whereas in terms of RMSD the opposite is found. As mentioned above, in our opinion the best indicator for assessing the performance of the different soil moisture products should be the correlation coefficient and, hence, the ASCAT sensor seems to be less reliable over these Spain sites. Probably, for these sites the reliability of in situ observations is not as good as in Italy and Luxembourg. In fact, as it is shown in ***Figure 26***, where the comparison with modeled data was carried out, results clearly improve. By way of example, for modeled data, R ranges between 0.74 and 0.76 for SM-OBS-1 and between 0.77 and 0.84 for SWI index. As mentioned above, the combined use of observed and modeled data provides a better assessment of ASCAT products reliability.

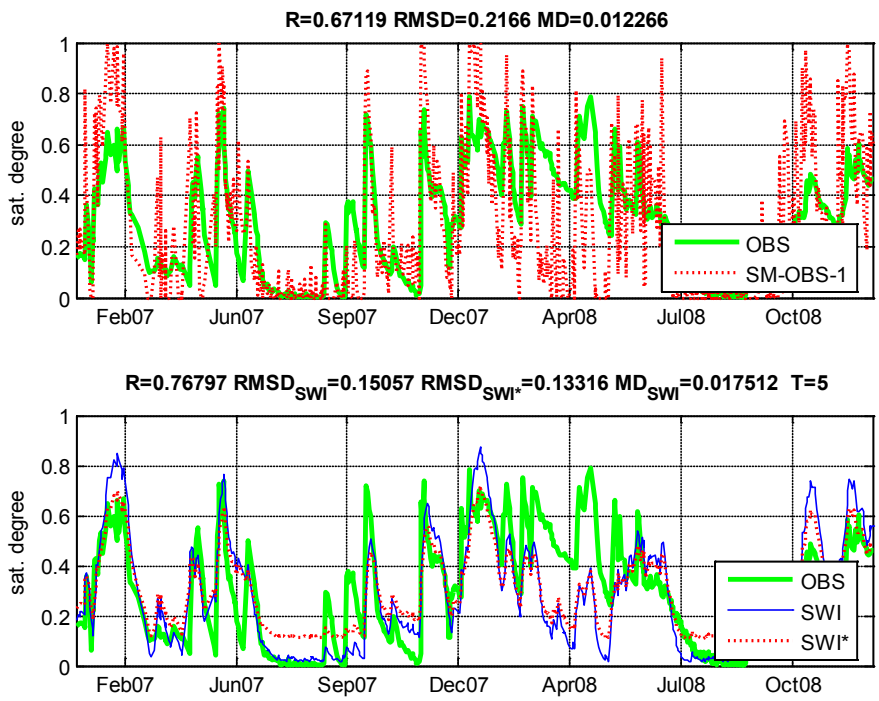


**Figure 25** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor K10 (Spain).

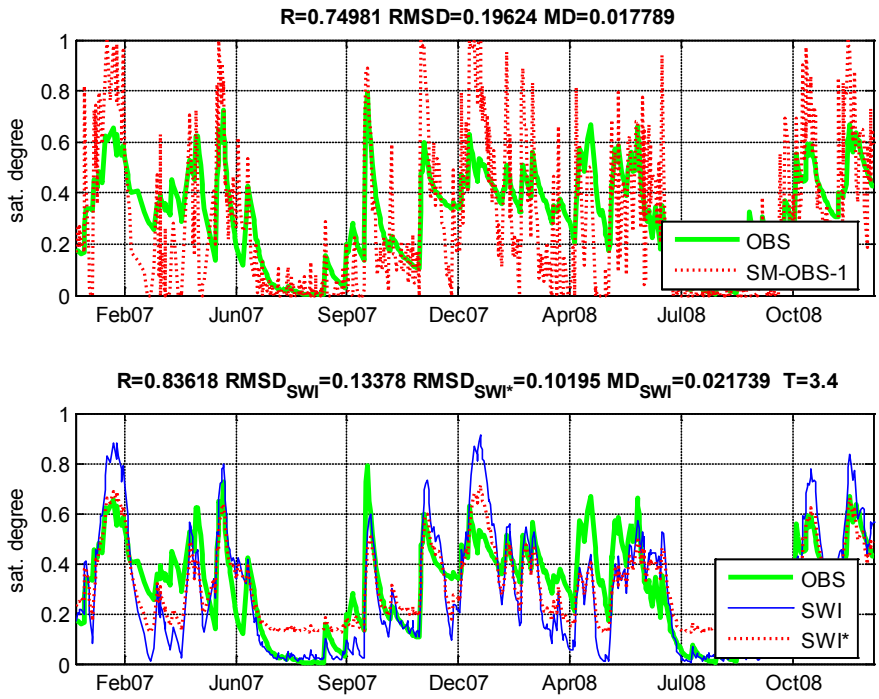


**Figure 26** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor F11 (Spain).

### *4.1.5 Spain - Vallcebre*

As reported in Section 2, the Vallcebre catchment is located on the southern margin of the Pyrenees with a mean elevation of ~1300 m a.s.l. Therefore, the ASCAT soil moisture product is expected to be characterized by high retrieval noise due to the orographic effect and also to the role played by snow. To investigate this aspect, ***Figure 27*** shows the correlation map between in situ observed saturation degree data for VCE site and the ASCAT pixels surrounding the in situ location along with the elevation map of the area. As it can be seen, correlation values strongly decrease in correspondence of the mountains. This results can be also due to the different behaviour of soil moisture in mountainous areas (it rains e.g. much more often than in the surrounding land).

For this study, we masked ASCAT pixels whose mean elevation is higher than 500 m a.s.l. and, hence, the pixel (not masked) closest to the VCE site is selected. ***Figure 28*** shows the comparison between SM-OBS-1, SWI and SWI* with in situ observed data at 20 cm depth for the VCE site. The correlation (with SWI) is equal to 0.55 and the RMSD (with SWI*) to 0.21; as expected, these values are much worse than those previously obtained. Generally, it is not easy to understand what comes from the retrieval and what from natural effects and, deeper investigations are needed to clearly understand the ASCAT soil moisture reliability over mountain regions.

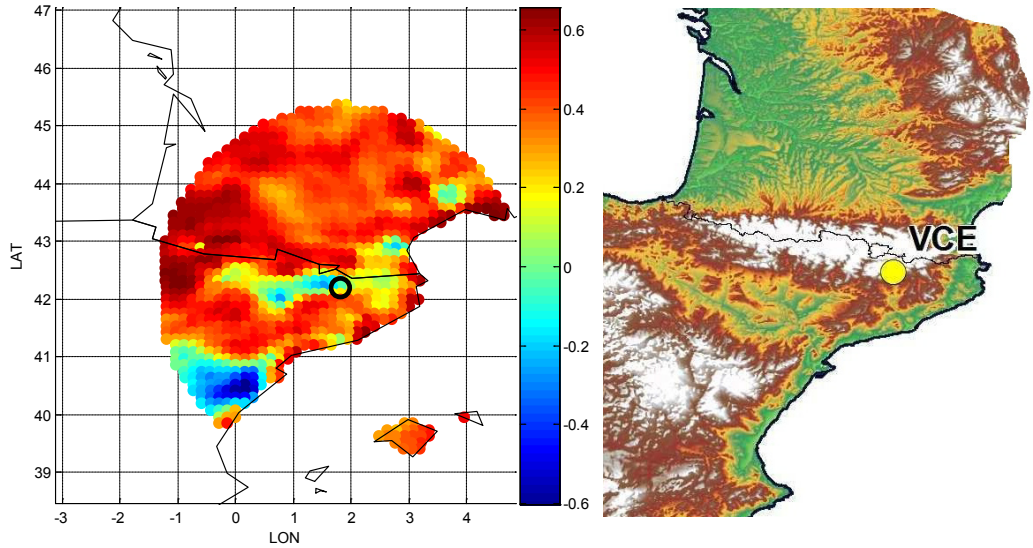


**Figure 27** Correlation map (left) between in situ observed saturation degree data at 20 cm depth for VCE site (Spain) and the ASCAT pixels surrounding the in situ location (black circle). Digital elevation map of the area (right).

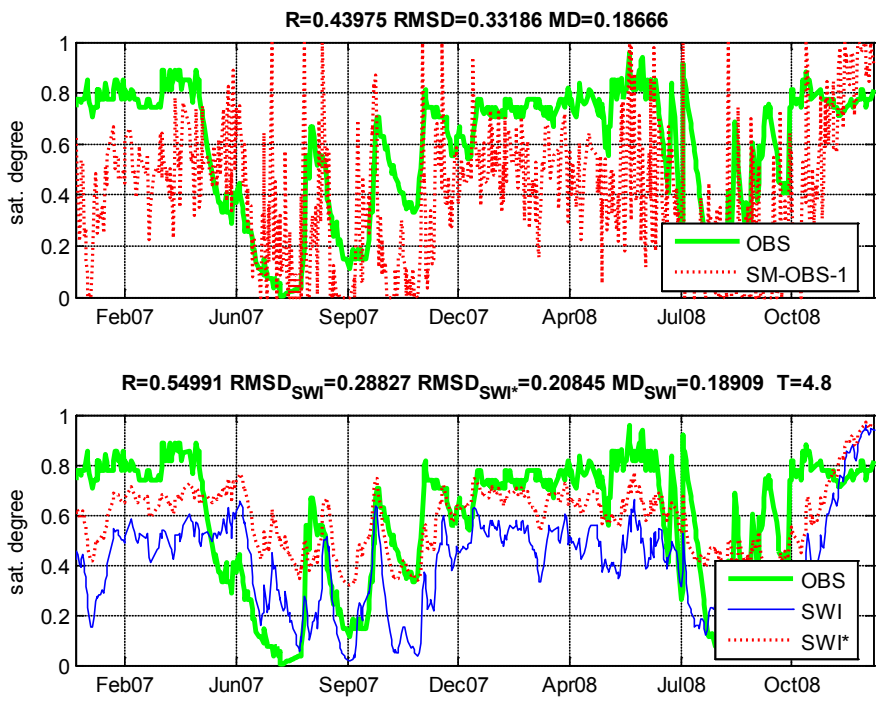


**Figure 28** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 20 cm depth for VCE site (Spain).

### *4.1.6 France*

Also the Valescure catchment is located on the southern boundary of the Cevennes mountain area even though with a mean catchment elevation (~500 m a.s.l.) much lower than the Vallcebre catchment. ***Figures 29-30***

show the comparison between SM-OBS-1, SWI and SWI* with in situ observed data at 30 cm depth and modeled data at 5 cm depth for the VSC site. The correlation values (with SWI) range between 0.68 and 0.73 while the RMSD (with SWI*) between 0.08 and 0.10.

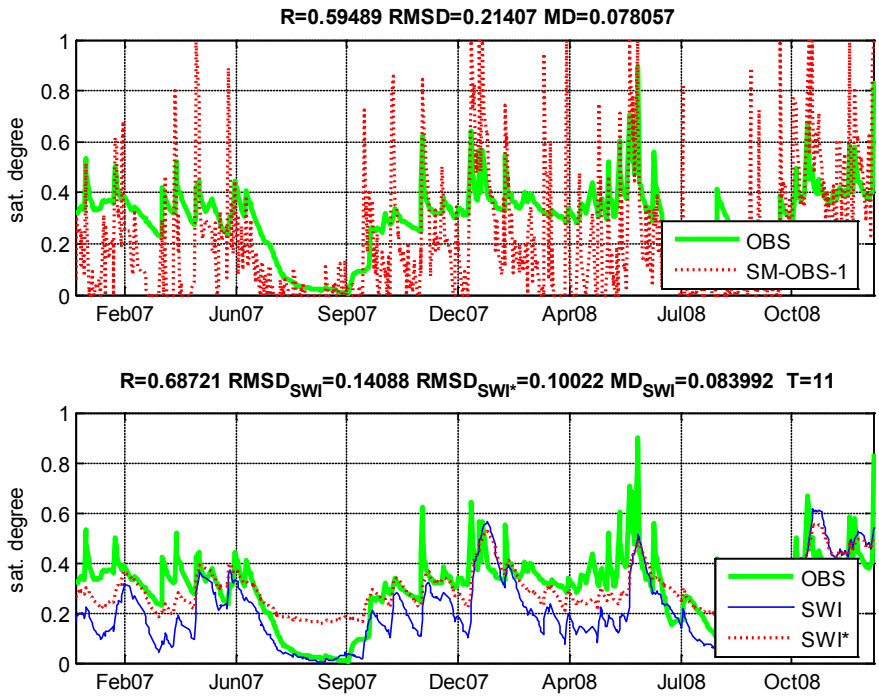


**Figure 29** SM-OBS-1, SWI and SWI* versus in situ observed saturation degree data, OBS, at 30 cm depth for VSC site (France).

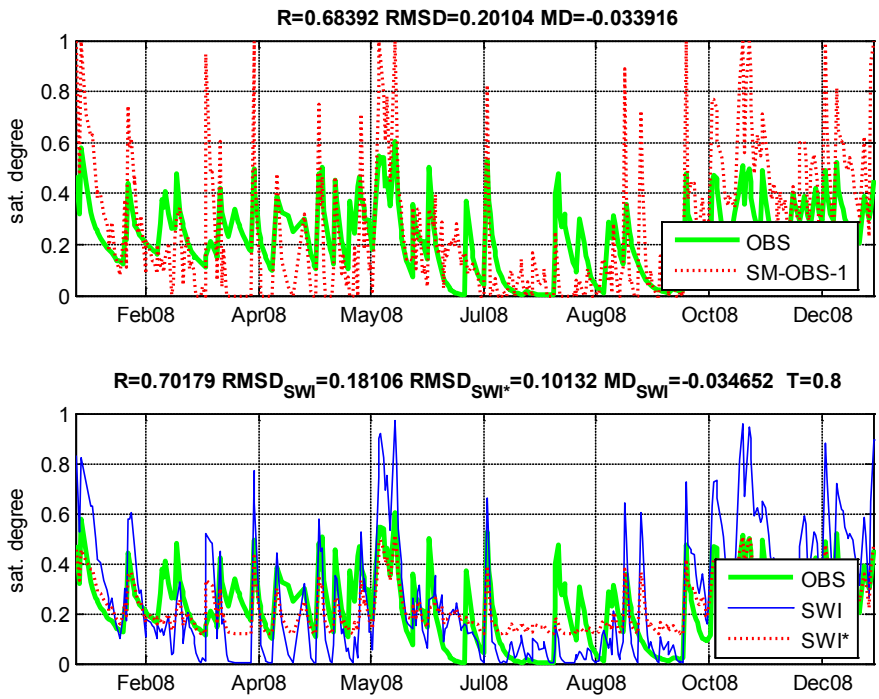


**Figure 30** SM-OBS-1, SWI and SWI* versus modeled saturation degree data, OBS, at 5 cm depth for VSC site (France).

## 4.2 SM-OBS-2

As described in the section 2.5, the SM-OBS-2 data set is derived from SM-OBS-1 through a linear downscaling approach based on background information on soil moisture spatial variability retrieved from Envisat ASAR images. Since the downscaling is linear, it is expected that the results of SM-OBS-2 versus ground data are essentially the same of those obtained for SM-OBS-1, at least in terms of correlation coefficient.

However, the actual version of SM-OBS-2 is derived from the downscaling of the "old" SM-OBS-1 v1 product (see ***Table 2***) that is characterized by much more noise than the actual SM-OBS-1 v2 product due to the different calibration based on ERS Scatterometer data. By way of example, ***Figure 31*** shows the comparison between SM-OBS-1 v2 and the SWI and SWI* indices derived from it with modeled data at 5 cm depth for the VAL site in Italy. As it can be seen, mainly for the surface product in dry conditions, high noise is present that affects the ASCAT performance. On the other hand, during wet conditions the noise seems to reduce likely due to the more consistent calibration between ASCAT and ERS parameter. In terms of correlation, for SM-OBS-1 v1 product it is equal to 0.73 against the value of 0.84 that we obtained with SM-OBS-1 v2 product (see ***Figure 16***). Thanks to the capability of the exponential filter to reduce noise, the results for the two products are more similar when SWI (or SWI*) indices are considered.

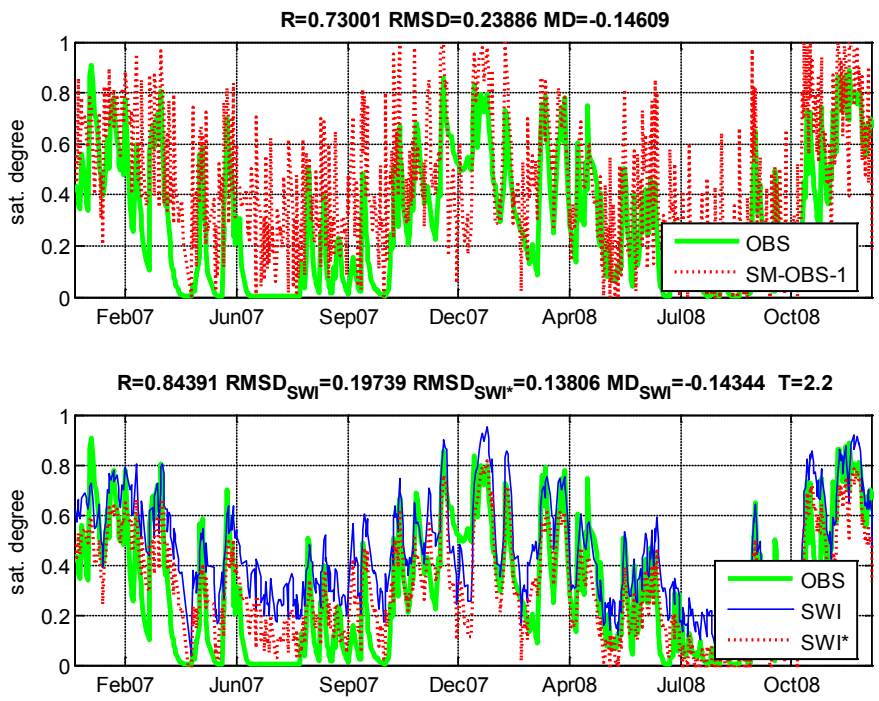


**Figure 31** SM-OBS-1 v1, SWI and SWI* products versus modeled saturation degree data, OBS, at 5 cm depth for VAL site (Italy).

Based on the above results, it can be expected that the actual version of SM-OBS-2 product suffers of the same drawbacks of SM-OBS-1 v1 product. ***Figure 32*** shows the same comparison of ***Figure 31*** when SM-OBS-2 product

is used. Results are basically the same as of SM-OBS-1 v1 product and, hence, for a reliable evaluation of the SM-OBS-2 product, further data processing is required starting from the actual (less noisy) version of SM-OBS-1 (v2).

In ***Figures 33-35***, by way of example, the comparison between SM-OBS-2 and the SWI and SWI* indices derived from it with observed and modeled data for further three representative sites in Italy, Luxembourg and Spain is reported. As it can be seen, also for these sites the results for SM-OBS-2 product are less reliable than SM-OBS-1 v2 but, if the SWI index is used, only a slightly decrease in the performance is observed.

Overall, these results already show that the reliability of SM-OBS-2 product should be nearly the same of SM-OBS-1. The improved spatial resolution of SM-OBS-2 will be surely an added value for the use of remotely sensed soil moisture estimates on many operational application (flood prediction and forecasting, numerical weather prediction, ...). However, further analyses are required in order to reasonably validate this data set both in space and time.

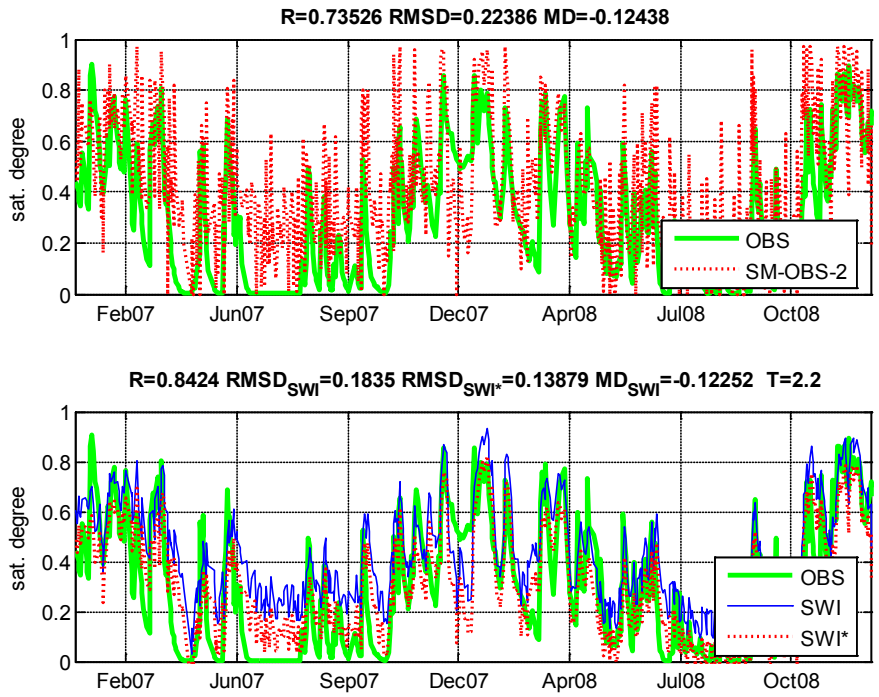


**Figure 32** SM-OBS-2, SWI and SWI* products versus modeled saturation degree data, OBS, at 5 cm depth for VAL site (Italy).

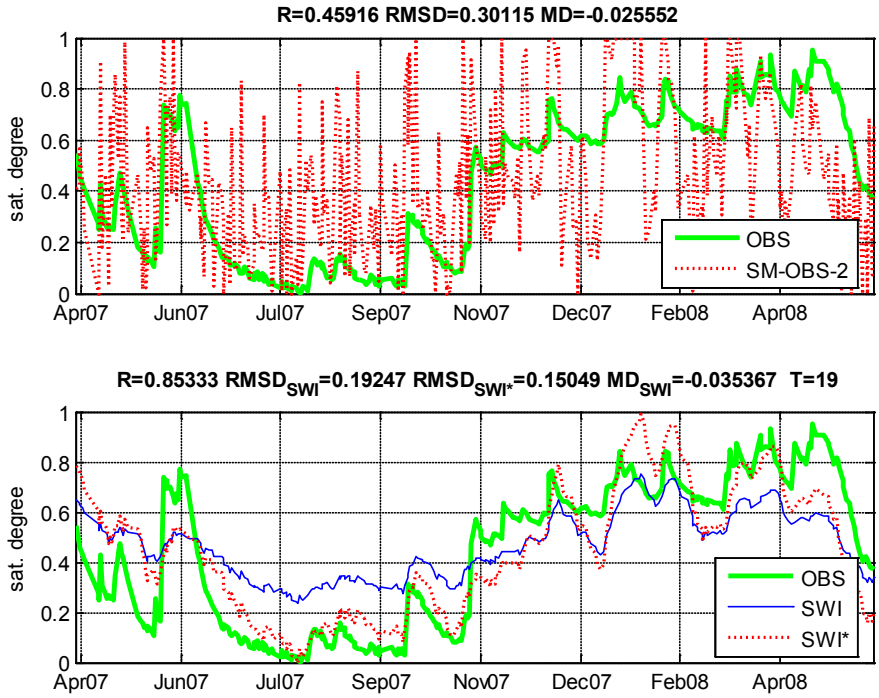


**Figure 33** SM-OBS-2, SWI and SWI* products versus modeled saturation degree data, OBS, at 5 cm depth for VAL site (Italy).

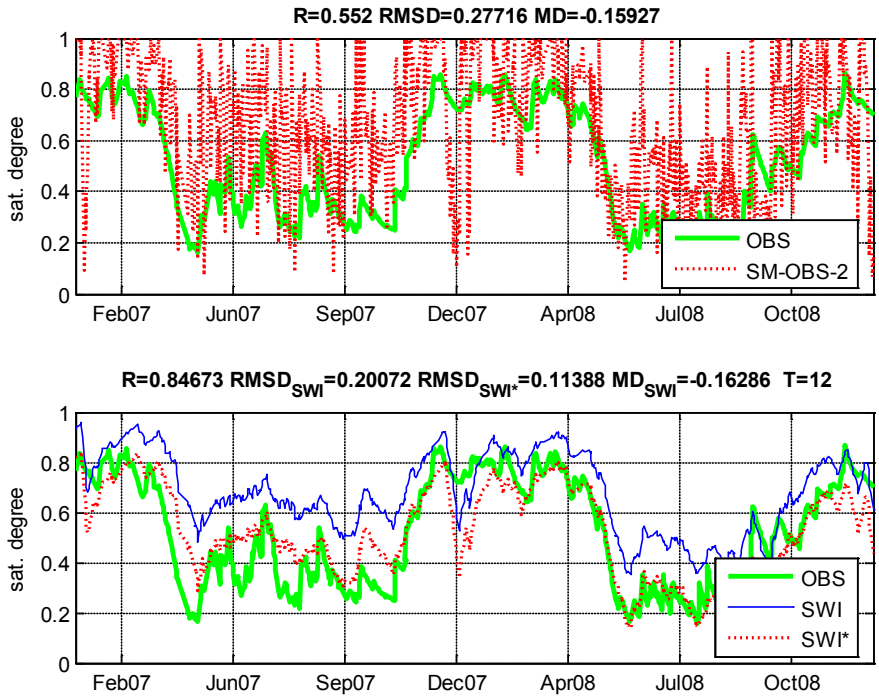


**Figure 34** SM-OBS-2, SWI and SWI* products versus modeled saturation degree data, OBS, at 5 cm depth for BIB site (Luxembourg).

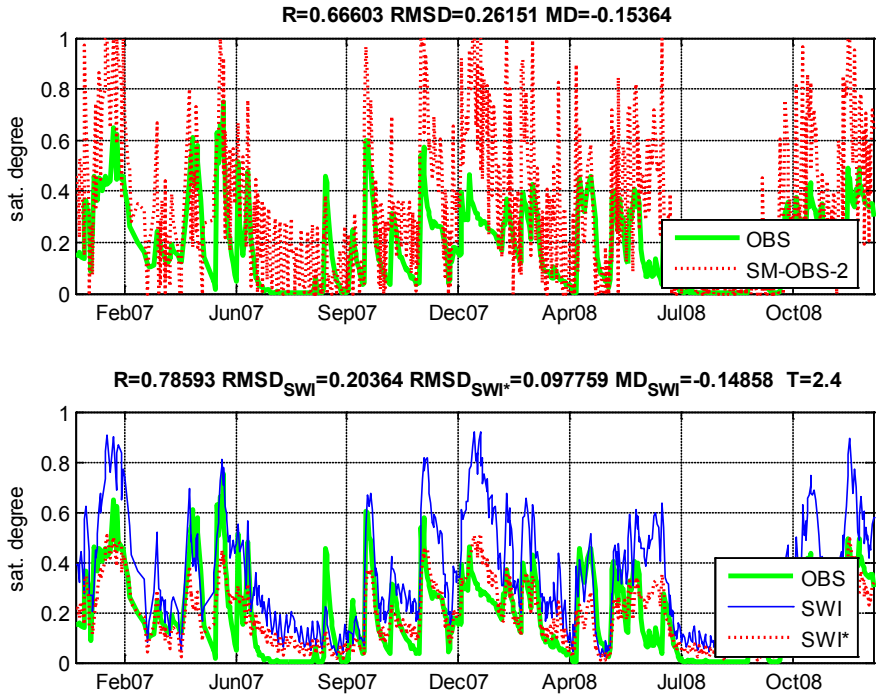


**Figure 35** SM-OBS-2, SWI and SWI* products versus in situ observed saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor K10 (Spain).

## 4.3 SM-ASS-1

In the following, the SM-ASS-1 product reliability is assessed through the comparison with in situ and modeled saturation degree data. It has to be noted that the SM-ASS-1 product is provided in volumetric terms ($m^3/m^3$) and, hence, to be consistent with the ASCAT products, the data are normalized , based on the times series residual and saturation soil moisture values to obtain the data in terms of saturation degree. Moreover, the same linear rescaling employed for the computation of SWI* index is used also for SM-ASS-1 product in order to match the range of variability of ground and ECMWF data sets.

The purpose of this comparison is to assess the reliability of SM-ASS-1 product against ground observations. Please note that this simple re-scaling of SM-ASS-1 is based on the volumetric soil moisture time series for each validation point. It is not based on the soil texture properties as will be done for the H-SAF CDOP for SM-ASS-2 which will be directly produced as an index according to texture and soil properties.

The reliability of these two quantities (SM-ASS-1 and SM-ASS-1*) is analyzed through a comparison with:

1) in situ observed saturation degree data for a total of 11 locations;
2) simulated saturation degree data obtained applying the soil water balance model for a total of 20 locations.

Therefore, since three comparisons were made for each location, a total of 62 comparisons are carried out (22 for in situ observations and 40 for

modeled data). In the following, a description of the corresponding results (divided by site) is reported trying to underline the more significant aspects that require further investigations in order to improve the reliability of SM-ASS-1 product.

***Table 5*** and ***Table 6*** summarize the results of all the comparisons for in situ and modeled data, respectively, and they are discussed below.

**Table 5** Statistical scores for SM-ASS-1 and SM-ASS-1* products versus in situ observed soil moisture data, results are shown in terms of saturation degree. (Z: depth in cm; N: sample size; MD: mean difference; RMSD: root mean square difference; R: correlation coefficient).

| Site | | Z | Period | | N | SM-ASS-1 | | | SM-ASS-1* |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | \|MD\| | RMSD | R | RMSD |
| s.IT | BAG | 30 | 07-08 | 12-09 | 417 | 0.21 | 0.25 | 0.82 | 0.12 |
| | MEL | 30 | 07-08 | 12-09 | 548 | 0.16 | 0.20 | 0.88 | 0.16 |
| | TOR | 30 | 07-08 | 04-10 | 668 | 0.11 | 0.13 | 0.94 | 0.08 |
| | CHI | 30 | 07-08 | 04-10 | 668 | 0.27 | 0.32 | 0.78 | 0.12 |
| LUX | BIB | 5 | 07-08 | 04-10 | 668 | 0.11 | 0.14 | 0.92 | 0.11 |
| SP | K10 | 5 | 07-08 | 12-09 | 548 | 0.17 | 0.22 | 0.86 | 0.08 |
| | F11 | 5 | 07-08 | 12-09 | 548 | 0.11 | 0.14 | 0.86 | 0.10 |
| | I06 | 5 | 07-08 | 12-09 | 548 | 0.20 | 0.27 | 0.69 | 0.10 |
| | VCE | 10 | 07-08 | 01-10 | 579 | 0.13 | 0.17 | 0.71 | 0.17 |
| FR | VSC | 30 | 07-08 | 12-09 | 548 | 0.16 | 0.18 | 0.87 | 0.09 |
| | VSC | 50 | 07-08 | 12-09 | 548 | 0.17 | 0.20 | 0.87 | 0.09 |
| **MEAN** | | | | | **572** | **0.16** | **0.20** | **0.84** | **0.11** |

**Table 6** As in Table 5 but for modeled soil moisture data.

| Site | | Z | Period | | N | SM-ASS-1 | | | SM-ASS-1* |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | \|MD\| | RMSD | R | RMSD |
| c.IT | VAL | 5 | 07-08 | 12-09 | 548 | 0.17 | 0.22 | 0.87 | 0.14 |
| | VAL | 15 | 07-08 | 12-09 | 548 | 0.08 | 0.12 | 0.91 | 0.11 |
| | SPO | 5 | 07-08 | 12-09 | 548 | 0.14 | 0.18 | 0.84 | 0.14 |
| | SPO | 15 | 07-08 | 12-09 | 548 | 0.13 | 0.18 | 0.86 | 0.08 |
| | CER | 5 | 07-08 | 01-10 | 579 | 0.26 | 0.30 | 0.80 | 0.15 |
| | CER | 15 | 07-08 | 01-10 | 579 | 0.15 | 0.18 | 0.86 | 0.10 |
| s.IT | BAG | 5 | 07-08 | 12-09 | 548 | 0.29 | 0.33 | 0.84 | 0.12 |
| | BAG | 30 | 07-08 | 12-09 | 548 | 0.17 | 0.18 | 0.91 | 0.08 |
| | MEL | 5 | 07-08 | 12-09 | 548 | 0.13 | 0.20 | 0.85 | 0.17 |
| | MEL | 30 | 07-08 | 12-09 | 548 | 0.13 | 0.17 | 0.84 | 0.15 |
| | TOR | 5 | 07-08 | 04-10 | 668 | 0.27 | 0.31 | 0.87 | 0.11 |
| | TOR | 30 | 07-08 | 04-10 | 668 | 0.15 | 0.17 | 0.96 | 0.07 |
| | CHI | 5 | 07-08 | 04-10 | 668 | 0.34 | 0.40 | 0.82 | 0.08 |
| | CHI | 30 | 07-08 | 04-10 | 668 | 0.27 | 0.31 | 0.90 | 0.07 |
| LUX | BIB | 5 | 07-08 | 12-08 | 183 | 0.07 | 0.09 | 0.92 | 0.08 |
| SP | K10 | 5 | 07-08 | 12-09 | 548 | 0.15 | 0.20 | 0.88 | 0.07 |
| | F11 | 5 | 07-08 | 12-09 | 548 | 0.08 | 0.11 | 0.93 | 0.07 |
| | I06 | 5 | 07-08 | 12-09 | 548 | 0.12 | 0.16 | 0.90 | 0.08 |
| FR | VSC | 5 | 07-08 | 12-09 | 548 | 0.27 | 0.32 | 0.78 | 0.09 |
| | VSC | 30 | 07-08 | 12-09 | 548 | 0.22 | 0.25 | 0.86 | 0.06 |
| **MEAN** | | | | | **557** | **0.18** | **0.22** | **0.87** | **0.10** |

### *4.3.1 Central Italy*

For central Italy test sites, only the comparison with modeled saturation degree data is carried out. It has to be noted that for the comparison with modeled data at 5 cm depth the first layer (0-7 cm) is used whereas the second layer (7-28 cm) when modeled data at 5 cm depth are analyzed. By way of example, ***Figures 36-37*** show the comparison between SM-ASS-1 and SM-ASS-1* with modeled data for VAL site at 5 and 15 cm depth. On the top of the figures the statistical score used for performance assessment are shown. In general, SM-ASS-1 displays a very good behaviour correlation coefficients ranging between 0.78 and 0.94 and RMSD between 0.13 and 0.32. However, when the simple linear rescaling is applied (SM-ASS-1*), ***equation (2)***, RMSD strongly reduces with values lower than 0.16 for all the comparison made in the central Italy test sites.

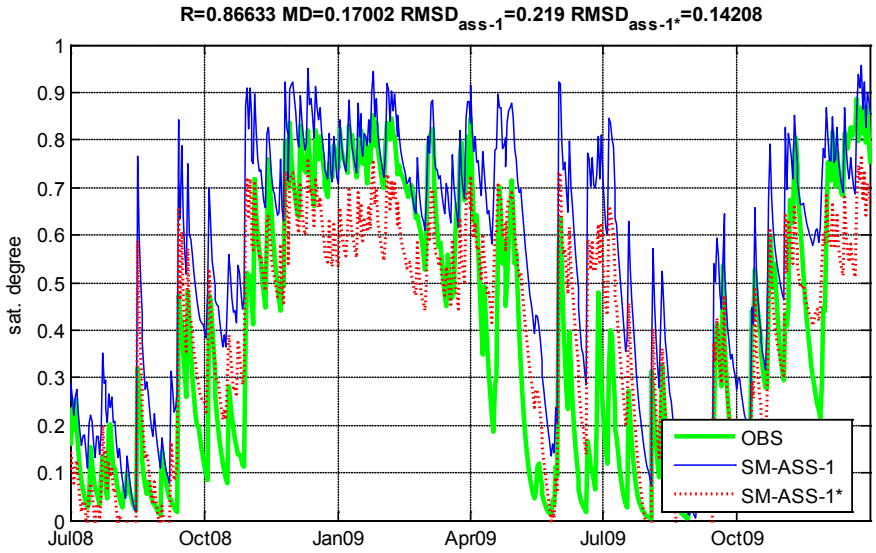


**Figure 36** SM-ASS-1 and SM-ASS-1* products versus modeled saturation degree data, OBS, at 5 cm depth for VAL site (Italy).

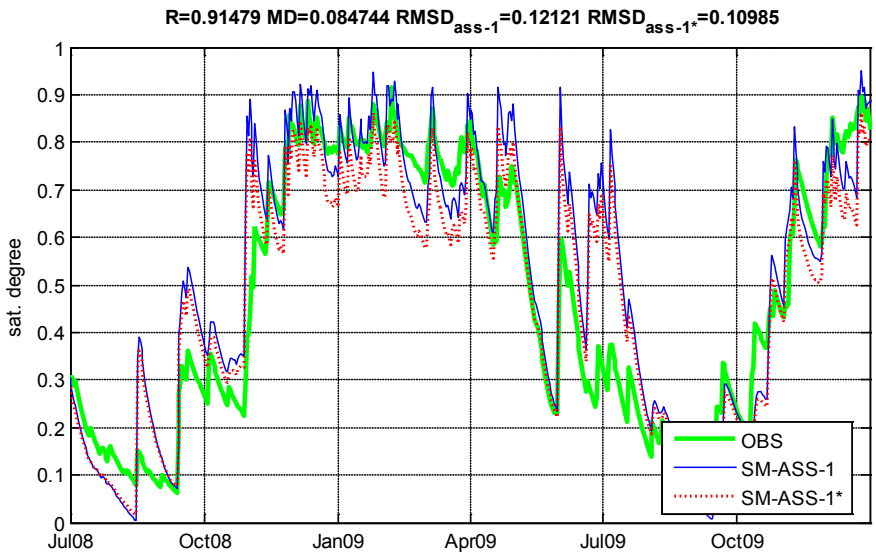


**Figure 37** SM-ASS-1 and SM-ASS-1* products versus modeled saturation degree data, OBS, at 15 cm depth for VAL site (Italy).

### *4.3.2 South Italy*

For south Italy test sites, both in situ observations and modeled data are available and, hence, a more comprehensive comparison can be conducted. In particular, for the two sites located in the Calabria region, data are available until the end of April; more than 650 pairs of data are analyzed. ***Figures 38-39*** show the comparison between SM-ASS-1 and SM-ASS-1* with observed and modeled data for TOR site at 30 cm depth (the second layer of the ECMWF product is used). As it can be seen, very high R values (R>0.93) and very low RMSD (<0.09) were obtained. In volumetric terms (i.e. multiplying for the porosity, see ***Table 1***), it means a RMSD less than 0.02 $m^3/m^3$ which is a quite impressive result. Also for the other sites results are quite good.

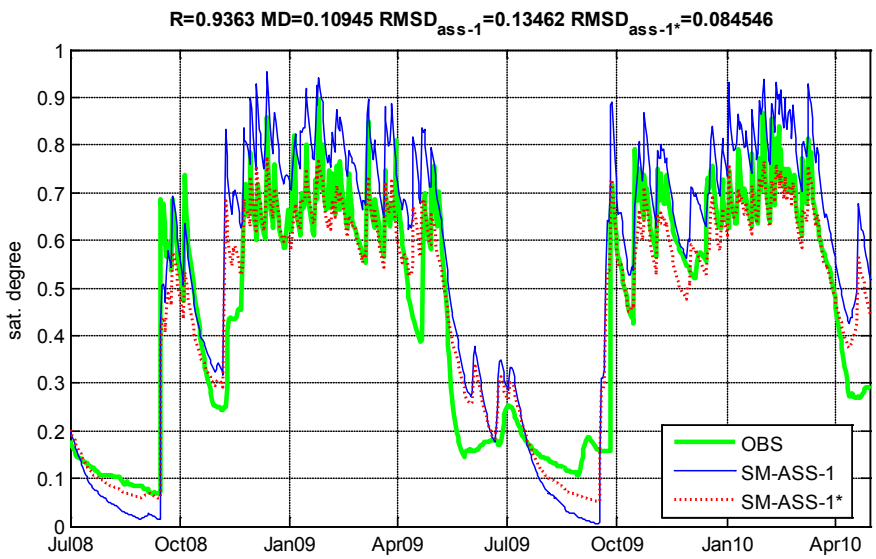


**Figure 38** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 30 cm depth for TOR site (Italy).

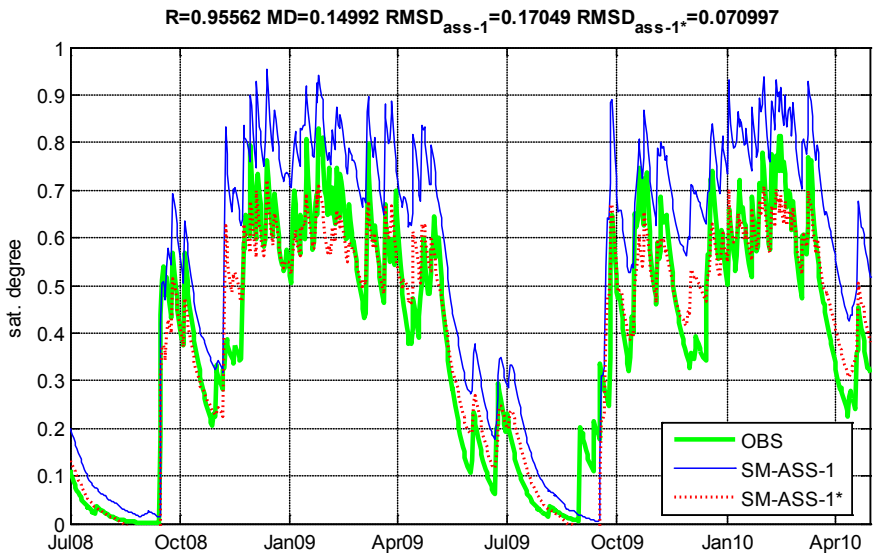


**Figure 39** SM-ASS-1 and SM-ASS-1* products versus modeled saturation degree data, OBS, at 30 cm depth for TOR site (Italy).

### *4.3.3 Luxembourg*

***Figure 40*** shows the comparison between the first layer of SM-ASS-1 and SM-ASS-1* with in situ observed data for BIB site at 5 cm depth. When the rescaled quantity is considered (SM-ASS-1*), results are quite similar to those previously obtained for central and south Italy test sites (R=0.92 and RMSD~0.11). When modeled data are analyzed, similar results are obtained (R=0. 0.92 and RMSD=0.08) but a shorter period is considered (183 versus 668 days) and, hence, findings are less robust.

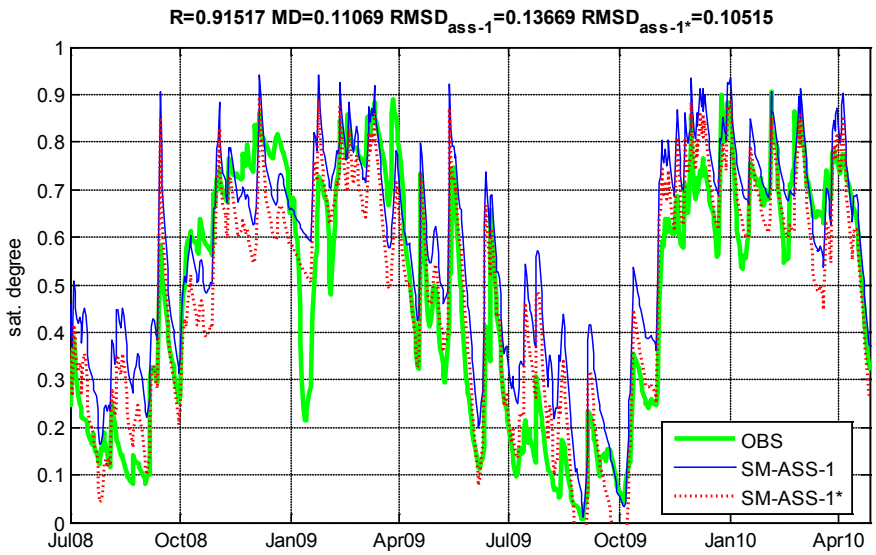


**Figure 40** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 5 cm depth for BIB site (Luxembourg).

### *4.3.4 Spain - REMEDHUS*

***Figures 41-43*** show the comparison between the first layer of SM-ASS-1 and SM-ASS-1* with in situ data for the three REMEDHUS site at 5 cm depth. For these sites, a bias is observed and the same happens for most of sandy sites (Albergel et al., 2010). This is likely due to the soil texture map used within the ECMWF IFS model which tends to have too much medium textured soil (with larger soil moisture values). However, when the linearly rescaled products are considered, very good results are obtained also for REMEDHUS sites except for in situ observed data of the site I06. However, by closely inspecting these data, the poor reliability of observations is revealed due to an unexpected temporal pattern in the period November 2008 - February 2009. In fact, when modeled data are used for the same site, results clearly improves (R from 0.69 to 0.90).

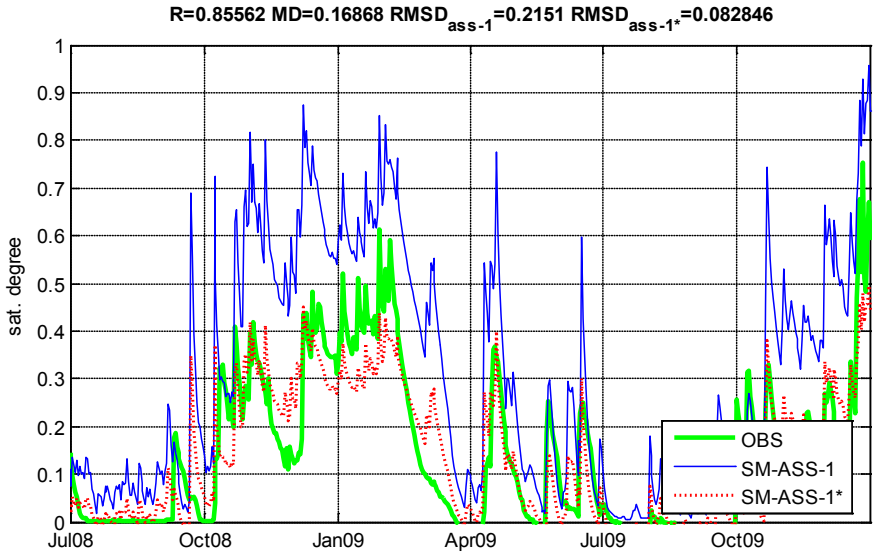


**Figure 41** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor K10 (Spain).

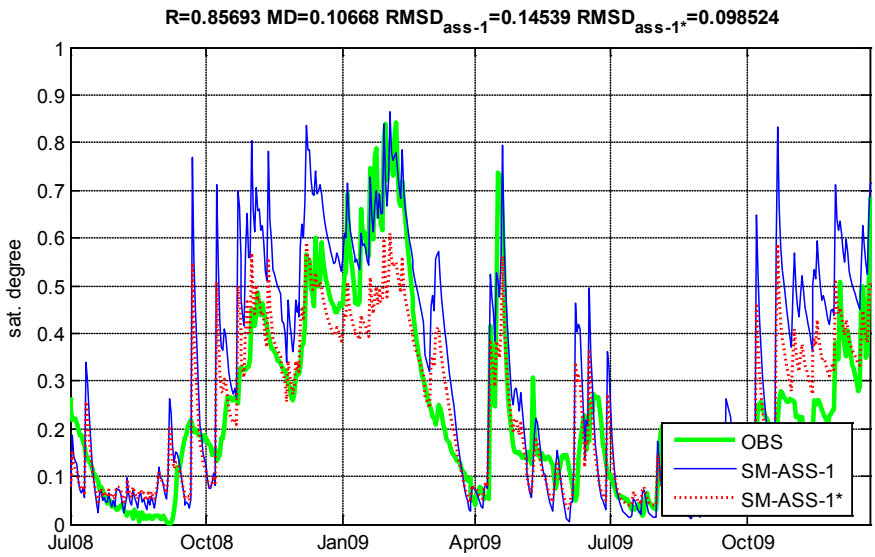


**Figure 42** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor F11 (Spain).

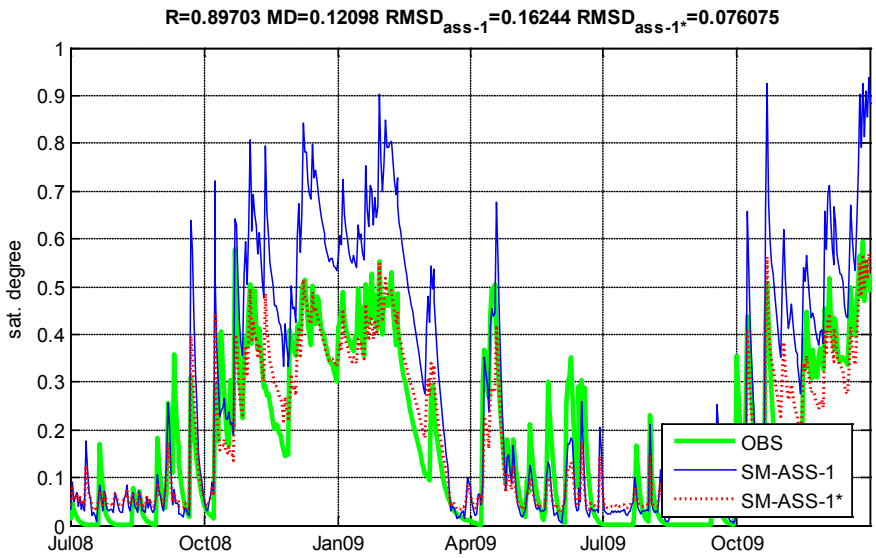


**Figure 43** SM-ASS-1 and SM-ASS-1* products versus modeled saturation degree data, OBS, at 5 cm depth for REMEDHUS network, sensor I06 (Spain).

### *4.3.5 Spain - Vallcebre*

***Figures 44*** shows the comparison between the second layer of SM-ASS-1 and SM-ASS-1* with in situ observed data for the VCE site at 20 cm depth. As it can be seen, also the reliability of the SM-ASS-1 product decreases over mountain regions; in fact R is equal to 0.71 and the RMSD to 0.17.

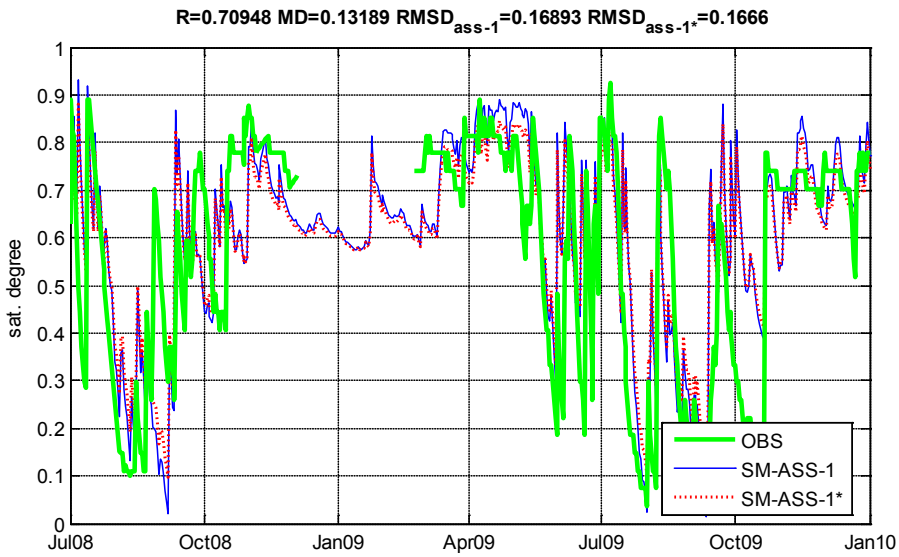


**Figure 44** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 20 cm depth for VCE site (Spain).

### *4.3.6 France*

***Figures 45*** shows the comparison between the second layer of SM-ASS-1 and SM-ASS-1* with in situ observed data for the VSC site at 30 cm depth. For this site, notwithstanding the presence of mountains, the reliability is nearly the same of that obtained for the other sites with R ranging between 0.78 and 0.87 and the RMSD between 0.06 and 0.09.

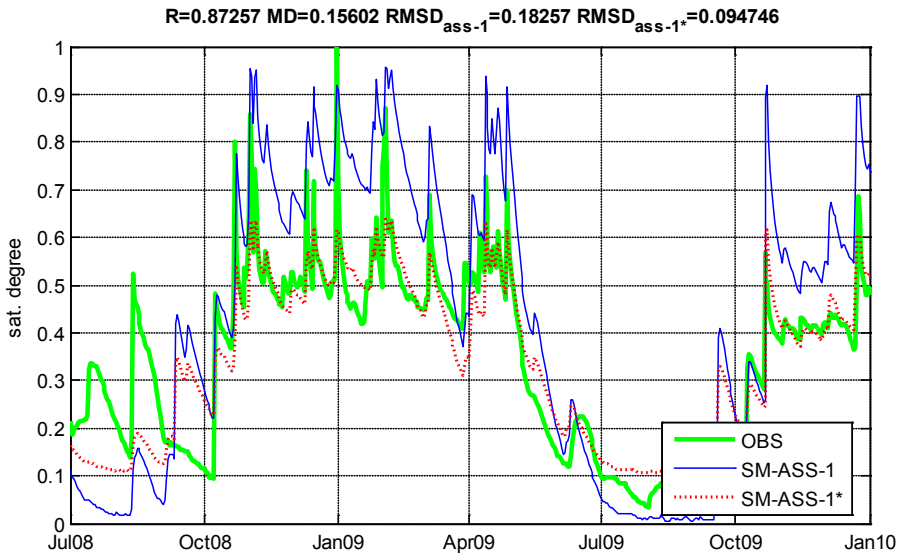


**Figure 45** SM-ASS-1 and SM-ASS-1* products versus in situ observed saturation degree data, OBS, at 30 cm depth for VSC site (France).

## 4.4 File handling and product usability

In this study the following file formats are used for the different soil moisture products:

1) ASCII time series files for SM-OBS-1
2) GEOTIFF image files for SM-OBS-2
3) GRIB files for SM-ASS-1

Emphasis was given on the datasets itself, rather than on the product format. Therefore, for SM-OBS-1 and SM-OBS-2 not the official file format has been used (BUFR) but time series in ASCII format and GeoTiff files that have been processed offline and delivered by TU-Wien. This is also the case because several versions of the products were investigated, and offline product delivery for the test-site regions only was quicker than working with the online generation chain products.

As far as GEOTIFF files are concerned, they can be easily read by using standard GIS software (e.g. ESRI Arcgis, GRASS etc.) but again the management of this large number of data is not easy, especially if one is interested to extract a time series of only few points within the image. For this purpose, a Matlab® routine is implemented that allows to read and extract the data in a few minutes.

Finally, a tool to read SM-ASS-1 GRIB files with Matlab® has been also developed. Specifically, library to read general GRIB files can be downloaded from ftp://polar.ncep.noaa.gov/pub/ofs/reference/ whereas an example to read and visualize the SM-ASS-1 product is freely available at: http://www.ecmwf.int/research/EUMETSAT_projects/SAF/HSAF/ecmwf-hsaf/how_read_smass1.html

# 5 Summary of results and Conclusions

This final section gives information on general statistics recorded in the previous sections and considerations are reported on the behaviour of the products in the specific area of competence. The purpose is to synthesize the common findings that might characterize the different soil moisture products at the end of the Development Phase. The analysis exploits the two main statistical scores used in this study, i.e. the root mean square difference (RMSD) and the correlation coefficient (R).

***Figure 46*** shows an overall view of the obtained results for the SM-OBS-1 and SWI* products divided by test site (central and south Italy, Luxembourg, Spain REMHEDUS and Vallcebre, France) and type of ground data (in situ and modeled). It can be seen that, on average, SM-OBS-1 provides a fairly good agreement with in situ data with R equal to ~0.67 and a RMSD equal to ~0.23. As expected, if the SWI* index is concerned, results greatly improve (R ~ 0.80 and RMSD ~ 0.11) but at the expense of an additional parameter, T (characteristic time length). However, T is found not so much variable in the different areas and, hence, can be set as a constant (only function of the soil layer depth) as previously reported in scientific literature (see e.g. Wagner et al., 1999; Parajka et al., 2006; Albergel et al., 2009; Brocca et al., 2010b; 2010d).

Comparing the obtained results on the different test sites, worst results are clearly found for the Vallcebre catchment in Spain and for the Valescure catchment in France. If these two sites are removed R is equal to ~ 0.86 and the RMSD to ~0.10 when SWI* index is used. As mentioned above, the decrease in ASCAT product reliability over these areas is related to the presence of mountains that introduce noise both in the satellite retrievals and also on the representativeness of in situ measurements.

During short time periods, for SM-OBS-1 and SWI* products, poor performance are obtained if soil freezing occurs (see e.g. ***Figures 23-24***).

Both these conditions can be masked, to improve the ASCAT products reliability. For instance, an air temperature threshold can be used to avoid the problem of soil freezing and a threshold on the mean elevation of the pixel to reduce the orographic effects (as it was done in the present study).

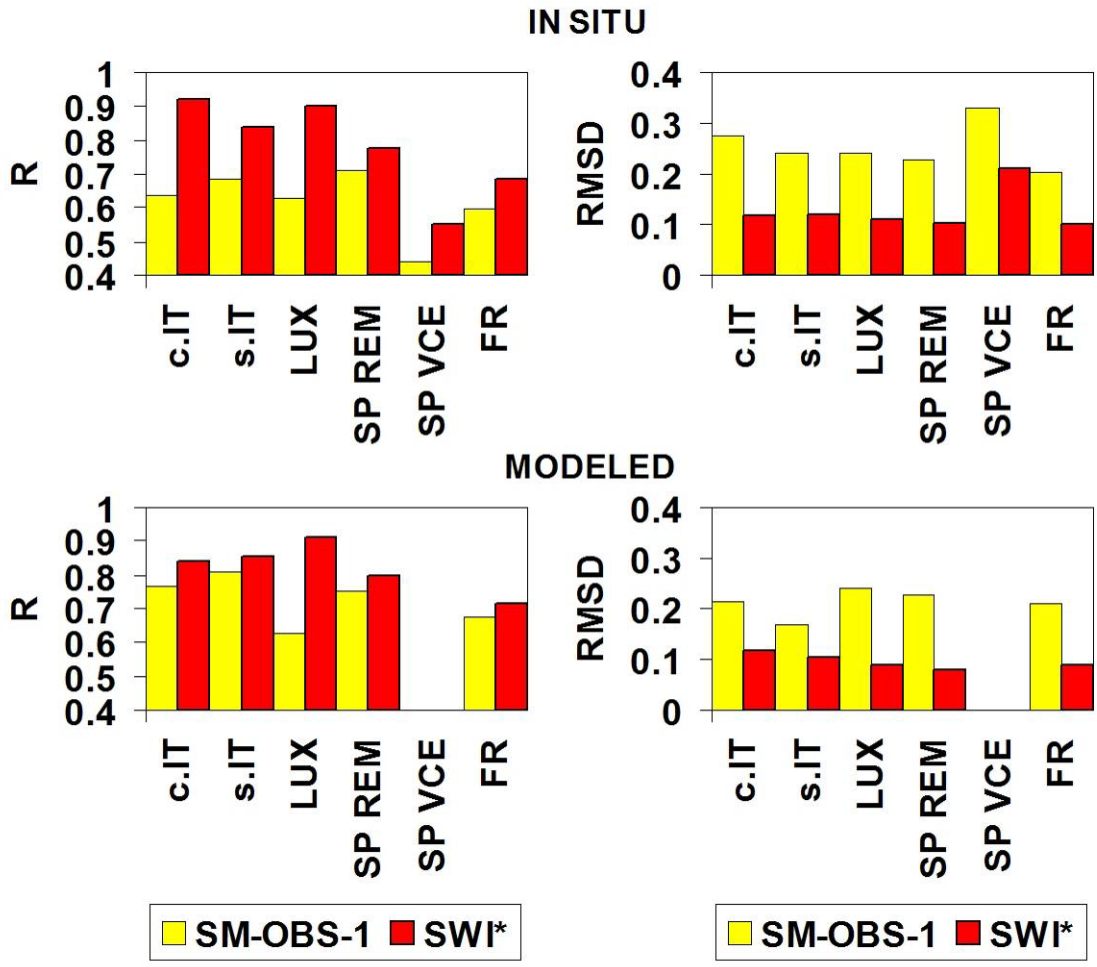


**Figure 46** Summary results for the three different test sites in terms of correlation coefficient, R, and root mean square difference, RMSD, for SM-OBS-1 and SWI* products. For Italy and Spain sites the average value are reported.

Concerning the SM-OBS-2 product (derived from SM-OBS-1 v1 product), it is characterized by high noise mainly during dry conditions but this is an effect of the old calibration employed for SM-OBS-1 v1. The use of the actual version of SM-OBS-1 (v2) is desirable to effectively assess the reliability of SM-OBS-2 product over the different test sites.

***Figure 47*** shows a summary of the obtained results for the SM-ASS-1* product divided by test site and type of ground data. As previously, also the two ECMWF products provide a good agreement with ground data with R~0.85 and a RMSD of 0.10. These results are comparable to those obtained with the SWI* index and they are quite similar for all the test sites analyzed in this study.

For ECMWF soil moisture products several issues should be resolved before to achieve more general conclusions. In fact, the effect of the assimilation method versus the ASCAT assimilation should be separated and analyzed comparing the results in terms of soil moisture retrieval with and without assimilation. Moreover, also the results in terms of air temperature and humidity forecast should be assessed. Moreover, also for the derivation of

SM-ASS-1 the "old" version of SM-OBS-1 product is used (v1) and, hence, with the new version further improvements can be expected.

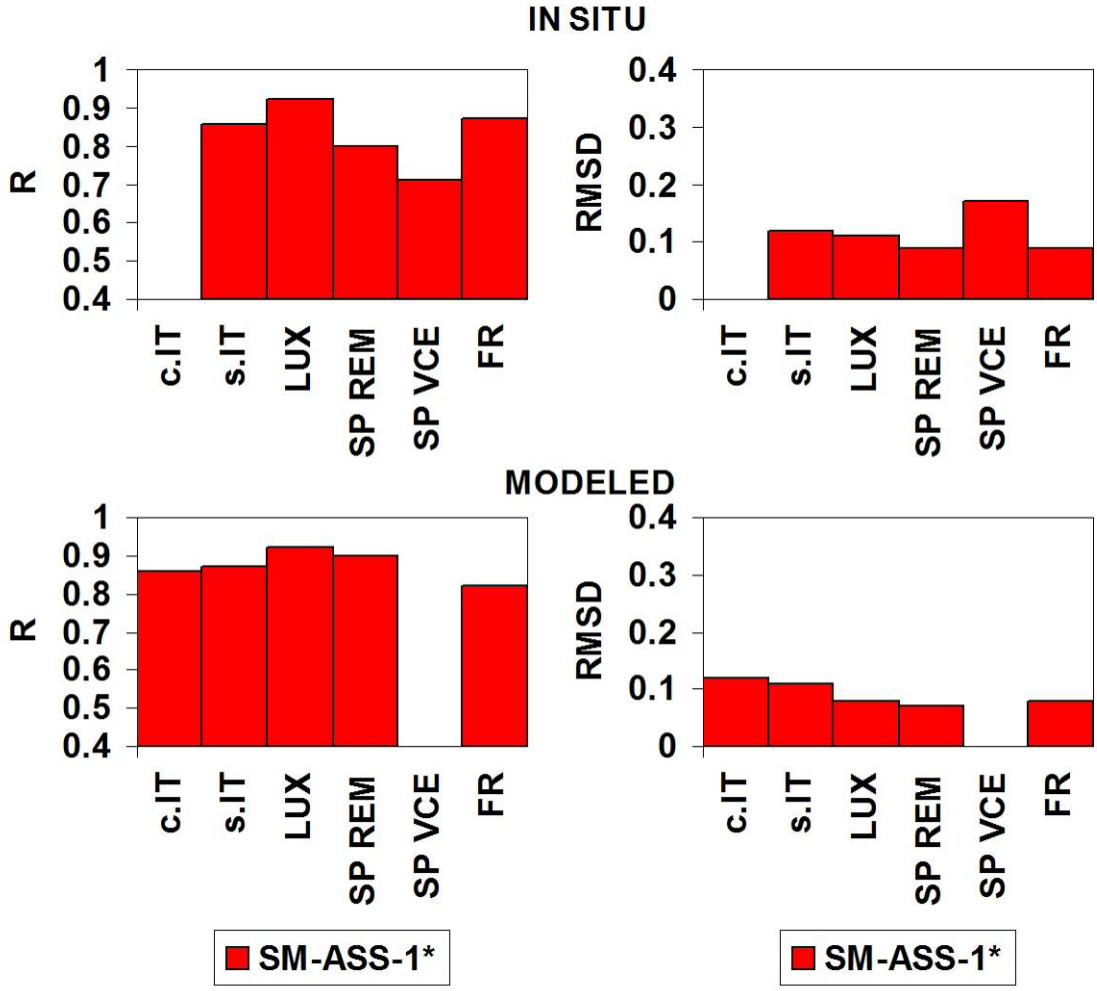


**Figure 47** As In Figure 27 but for SM-ASS-1* product.

Overall, the validation activity conducted allowed to determine the reliability of ASCAT and ECMWF soil moisture products through a robust and standardized comparison with ground observation for 13 sites 13 sites across four different countries (Italy, France, Spain and Luxembourg) in Europe. The obtained results are encouraging for the efficient use of these products to support operational hydrology and water management activities. In fact, notwithstanding the spatial mismatch between ground data and ASCAT or ECMWF products (point measurements against 25x25 km pixel average), the correlation between the data sets is quite good over all investigated sites (R>0.80).

Moreover, it is shown that when these products are compared with ground data sets particular attention should be paid to assess the reliability of the latter. In fact, in situ data suffer of problems related to measurement errors but also to their representativeness at the "satellite" pixel scale (ASCAT or ECMWF pixel). On the other hand, ground modeled data reliability is related to the uncertainties of forcing data (rainfall and temperature in this study), model structure and parameters. Therefore, we showed that only using

different ground data set (both in situ measurements and model), a comprehensive and efficient evaluation of ASCAT and ECMWF products reliability could be performed.

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