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Article

Quality Assessment of the CCI ECV Soil Moisture Product Using ENVISAT ASAR Wide Swath Data over Spain, Ireland and Finland

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Abstract: During the last decade, great progress has been made by the scientific community in generating satellite-derived global surface soil moisture products, as a valuable source of information to be used in a variety of applications, such as hydrology, meteorology and climatic modeling. Through the European Space Agency Climate Change Initiative (ESA CCI), the most complete and consistent global soil moisture (SM) data record based on active and passive microwaves sensors is being developed. However, the coarse spatial resolution characterizing such data may be not sufficient to accurately represent the moisture conditions. The objective of this work is to assess the quality of the CCI Essential Climate Variable (ECV) SM product by using finer spatial resolution Advanced Synthetic Aperture Radar (ASAR) Wide Swath and *in situ* soil moisture data taken over three regions in Europe. Ireland, Spain, and Finland have been selected with the aim of assessing the spatial and temporal representativeness of the ECV SM product over areas that differ in climate, topography, land cover and soil type. This approach facilitated an understanding of the extent to which geophysical factors, such as soil texture, terrain composition and altitude, affect the retrieved ECV SM product values. A good temporal and spatial agreement has been observed between the three soil moisture datasets for the Irish and Spanish sites, while poorer results have been found at the Finnish sites. Overall, the two different satellite derived products capture the soil moisture temporal variations well and are in good agreement with each other.

Keywords: ESA Climate Change Initiative; essential climate variable; soil moisture; ENVISAT ASAR WS; temporal variability; spatial variability

1. Introduction

The amount of water stored in the soil is a key parameter for the energy and mass fluxes at the land surface-atmosphere boundary and is of fundamental importance to many agricultural, meteorological, biological and biogeochemical processes [1–3]. For these reasons, soil moisture (SM) has been identified as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) secretariat [4]. Monitoring such a complex phenomenon over wide areas is not trivial. In fact, it has been observed that particular meteorological conditions, geological characteristics, topography and land cover can affect the soil moisture variation in a small area as much as in a large region [5–7]. Moreover, the amount of water stored in the top layer of the soil can change significantly within a few hours [8] due to the influences of the atmosphere.

Spaceborne remote sensing has shown itself to be a suitable tool to monitor soil moisture over large regions at regular time intervals. Great progress has been made by the scientific community in the last three decades aiming at developing soil moisture retrieval techniques by using optical, thermal infrared (TIR) and microwave (MW) sensors [9,10]. Since the late 1970s, coarse resolution (25–50 km) soil moisture products derived from past and present microwave radiometers (Advanced Microwave Scanning Radiometer (AMSR-E) [11] and WindSat [12]) and scatterometers (European Remote Sensing satellites (ERS) scatterometer (SCAT) [13] and Meteorological Operational satellite (MetOp) Advanced Scatterometer (ASCAT) [14,15]) have been available on an operational basis. A first global soil moisture product meeting the requirements set by GCOS was created within the framework of the European Space Agency (ESA) Water Cycle Multi-mission Observation Strategy (WACMOS) project [16], by merging soil moisture products derived from multi-frequency radiometer and C-band scatterometer observations into a single dataset covering the period from 1979 to 2010 [17–19]. The WACMOS soil moisture product is currently being extended and enhanced in the framework of the ESA-funded Climate Change Initiative (CCI) program [20]. Despite the advantageous high temporal frequency (up to daily data available) of such a product, its relatively coarse spatial resolution (0.25 × 0.25 deg) may not be suitable to represent the soil moisture variation within a quite large area. Increasing confidence in the use of the CCI ECV SM product (we will refer to it as "ECV SM" in this paper) can be achieved by assessing its quality through inter-comparisons with independent soil moisture datasets. Commonly, ground measurements, models or other satellite acquisitions are used to provide validation soil moisture datasets ([21,22]).

In situ data-based validation has generally been achieved over small temporal and spatial scales but has been significantly advanced since the establishment of the Global Soil Moisture Data Bank [23] and the International Soil Moisture Network [24]. Such an approach was used in [25], where three global soil moisture products, including the WACMOS time series, have been validated using a combination of 196 *in situ* stations taken from five soil moisture networks across the world. Similarly, in [26] and [27], over 600 *in situ* stations have been used for validating ASCAT and ECV SM products, respectively, finding general good agreement between the satellite-derived and *in situ* observations. However, soil moisture records provided by the *in situ* networks represent only single point locations and usually cover limited observation periods. The necessity of a comprehensive characterization of *in situ* representativeness errors when considering satellite-derived and *in situ* soil moisture inter-comparison has been highlighted in [28], where the quality of over 1400 *in situ* stations of the ISMN for representing soil moisture at satellite footprint scales (~25 km) has been investigated on a global basis by adopting a triple collocation approach.

The higher spatial resolution and the regular coverage provided by spaceborne Synthetic Aperture Radars (SARs) make them a promising additional data source for measuring seasonal and long-term variations in surface soil moisture content and for a better understanding of coarse scale soil moisture products ([29,30]). For instance, the advanced synthetic aperture radar (ASAR) instrument onboard the ENVISAT satellite was capable of providing global measurements at 1 km and 150 m spatial resolution every four to seven days, depending on the acquisition plan. However, the comparison of time series of soil moisture datasets acquired by different sources and representing different spatial scales is challenging due to the scale differences between products and/or observations [31]. However, given the temporal stability of soil moisture patterns, their inter-comparisons are useful where soil moisture values at smaller scales are representative of the mean soil moisture content over larger areas [32].

This study is focused on investigating the capability of the coarse scale ECV SM product in capturing the temporal and spatial variations in surface soil moisture, as recorded by *in situ* instruments and retrieved from ASAR Wide Swath (WS) acquisitions. It is an extension of the work presented in [33], where the first released version of the global ECV SM product was validated over three sites in South Ireland. This former study proved that despite the adopted validation method do not make use of dense *in situ* station networks, nor hydrological models, it has the potential to be an efficient and cost-effective approach, whose reliability was proved by the consistency of the achieved results with those reported in other papers using different sensors and classical methods. Although a quite good quality of the first version of the ECV SM product in South Ireland has been observed in [33], the study highlighted also its poor capability in capturing the driest and wettest soil conditions, as well as a decrease in its reliability in the presence of particular types of soil and at higher altitudes. Because this former work was carried out over a limited and quite homogeneous region, the influence of other factors (e.g., land cover, complex topography, climate zone) on soil moisture behavior and on the accuracy of the global ECV SM dataset could not be investigated. However, the actual advantage for climate change studies, which can be derived from the availability of such a long, temporally frequent and global SM product, has to be further tested. Aiming at a more comprehensive understanding of the ECV SM product, which would lead to an increase in the confidence in its use, the study presented in [33] needs to be extended to other areas worldwide, especially focusing on those which could be representative of specific climate zone and characterized by a variety of land cover, soil type, and different topography.

Recently, the ECV SM dataset has been temporally extended and enhanced, and a new version has been made available in July 2014. Continuing and extending the validation activity of this global SM product, a more comprehensive analysis is presented in this study, which shows the results of the quality assessment of the latest released ECV SM product carried out over three different countries characterized by contrasting climate conditions: Spain, Ireland and Finland.

2. Test Sites Description

The quality assessment of the ECV SM product has been focused on three different areas located in the Duero basin in Spain, in southern Ireland, and in Finland (see Figure 1). The choice has been driven by the interest in investigating the capability of the ECV SM data in describing the soil moisture dynamics in different scenarios especially in terms of climate and land cover.

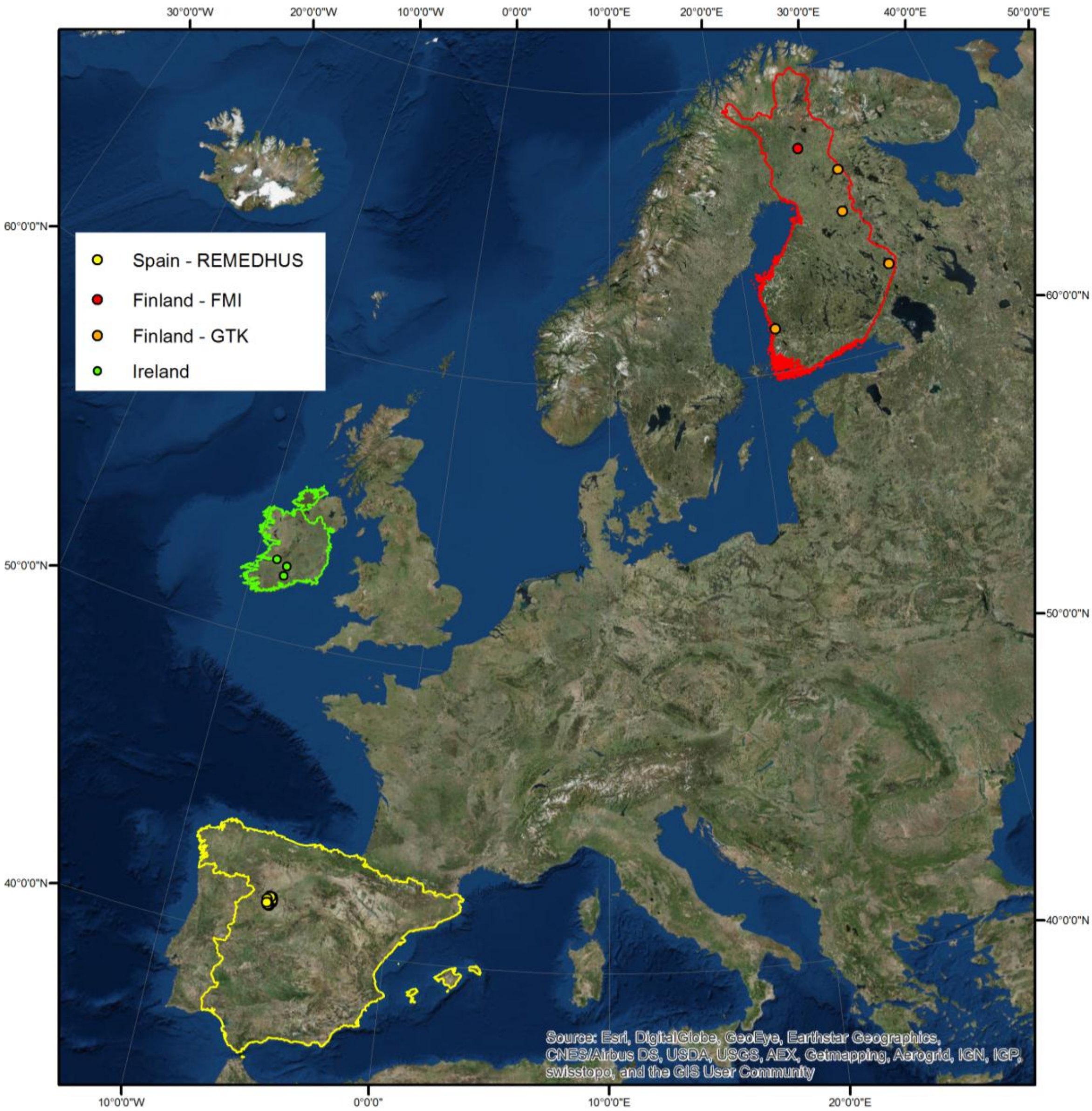

Figure 1. Areas and sites under investigation in Spain (REMEDHUS soil moisture network), Ireland (soil moisture network from AEON project) and Finland (FMI and GTK soil moisture network).

The Duero basin is characterized by a semi-arid continental Mediterranean climate, with an average annual precipitation of 385 mm and a mean temperature of 12 °C [34]. This quite flat region (slope: <10%; altitude: 700–900 msl) is mainly covered by cereal fields and vineyards, but patchy areas of forest and pasture can also occur. The soil texture is mainly sandy, with a mean sand content of about 71%.

The Irish region under investigation is characterized by a humid mild temperate climate, with a mean annual precipitation of ~1200 mm·yr^{-1} and a mean temperature of 10 °C. The *in situ* stations are installed in grassland areas, which represent almost 80% of the agricultural area of Ireland (4.4 million hectares) [35]. The region is typically low lying, with altitudes ranging between 15 m and 104 m above sea level, and relatively flat (slope lower than 6°). On the basis of the United States Department of Agriculture (USDA) classification, the soil texture is classified as sandy loam in Kilworth and as loam in Pallaskenry and Solohead.

The Finnish sites are mainly distributed along the eastern edge of the country, with the exception of Pori, on the south-west, and Sodankylä, which is located in Northern Finland, north of Arctic Circle [36]. All the sites are in low-lying regions (altitude: <400 msl), typically covered by boreal forests, open and forested bogs and tundra highlands. Due to the boreal climate characterizing this area, winters are very cold and snow precipitations are very common. Along its eastern border with Russia, and in the northern areas the snow coverage is often deep, with some remaining on the ground into early May, and much later to the north of the Arctic Circle. The annual amount of rain precipitation varies between 500 mm in Northern Finland and 650 mm in south-east of the country. The annual mean temperature varies from more than 5 °C in Southwestern Finland, to a couple of degrees below zero in Northern Finland.

3. Material and Methods

3.1. In Situ SM Data

In situ soil moisture data have been used in this study as reference for the validation of the soil moisture products retrieved from the satellite acquisitions. The ground-based measurements in Spain and Finland have been obtained through the International Soil Moisture Network (ISMN) ([24,37]) freely available at http://ismn.geo.tuwien.ac.at/. Sixteen stations belonging to the REMEDHUS (Red de MEDición de la HUmedad del Suelo) network have been considered for the validation activity in Spain. *In situ* soil moisture time series have been collected at three Irish sites, belonging to a network of seven stations installed in 2007 under the framework of the Aeon project (http://aeon.ucc.ie/). *In situ* soil moisture data from the FMI (Finnish Metereological Institute) and GTK (Geological Survey of Finland) networks have been used for the analysis in the Finnish area, where a total of five sites have been studied.

3.1.1. REMEDHUS Network

The REMEDHUS soil moisture network [34] includes twenty-four *in situ* stations located in the Duero Basin. Since ground-based measurements have been used to assess the quality of both ASAR WS and ECV SM products, the selection of the sites has been carried out by considering the availability of SAR acquisitions over the study area. Therefore, soil moisture data from sixteen *in situ* stations have been finally collected (see Table 1). The Corine Land Cover (CLC2006) map and the Digital Elevation

Model (DEM) corresponding to the four ECV cells analyzed, each including one or more labeled *in situ* stations are provided as supplementary material provided with this paper (Figure S2).

Table 1 provides geographic coordinates and land cover information for each site. Since March 2005 soil moisture values expressed in volumetric units (m^3 m^{-3}) are measured by Stevens Hydra Probe instruments horizontally installed at a 5-cm depth of a mainly sandy soil. The quality and the amount of data makes such long time series suitable for several applications, particularly for the validation of either soil moisture models or retrieval algorithms applied to remote sensing data ([25,38–41]).

Table 1. REMEDHUS *in situ* stations, grouped according to the ECV size pixel to which they belong. The land cover information is provided by the Corine Land Cover 2006. The porosity values are provided by the Harmonized World Soil Database 2012.

ECV Cell	Site	SMS	Lat.	Lon.	Land Cover
ECV-A Porosity: 0.51 m^3 m^{-3}	Carretoro	K10	41°16′N	−5°22′E	Non irrigated arable land
	Casa Periles	M05	41°24′N	−5°19′E	Agriculture/natural vegetation areas
	El Coto	I06	41°22′N	−5°25′E	Non irrigated arable land
	Granja G	K09	41°18′N	−5°21′E	Non irrigated arable land
	Granja Toresana	I03	41°28′N	−5°27′E	Non irrigated arable land
	Guarrati	H09	41°17′N	−5°25′E	Non irrigated arable land
	Las Brozas	L03	41°27′N	−5°21′E	Agriculture/natural vegetation areas
	La Cruz de Elias	M09	41°17′N	−5°18′E	Non irrigated arable land
	Las Victorias	K04	41°25′N	−5°22′E	Non irrigated arable land
	Llanos de la Boveda	L07	41°21′N	−5°19′E	Agriculture/natural vegetation areas
	Paredinas	J03	41°27′N	−5°24′E	Vineyards
ECV-B Porosity: 0.31 m^3 m^{-3}	Las Arenas	F06	41°22′N	−5°33′E	Non irrigated arable land
ECV-C Porosity: 0.47 m^3 m^{-3}	Casa Gorrizo	H11	41°14′N	−5°28′E	Non irrigated arable land
	La Atalaya	J14	41°9′N	−5°24′E	Non irrigated arable land
	Las Bodega	H13	41°10′N	−5°28′E	Coniferous forest
ECV-D Porosity: 0.37 m^3 m^{-3}	Zamarron	F11	41°14′N	−5°32′E	Non irrigated arable land

3.1.2. Irish Network

Three out of seven *in situ* stations available in Ireland have been selected for the ECV SM product validation activity. These are located in Kilworth, Pallaskenry and Solohead, whose characteristics in terms of soil porosity, location and land cover are reported in Table 2. The CLC2006 and DEM maps of the studied areas are shown in the Supplementary Material provided with this paper (Figure S3).

Campbell Scientific CS616 time domain reflectometers (TDR), installed horizontally at each of the three study sites, recorded soil moisture measurements at 30-min intervals, together with precipitation and soil temperature, since 2007. The *in situ* instruments provide soil moisture values to a depth of 5 cm from the surface, and are expressed as the soil water-filled pore space ($SM_{\%}$). Since the SM ground measurements taken at the Spanish and Finnish sites are expressed as m^3 m^{-3}, we converted the soil moisture observations taken at the Irish sites to the same volumetric units. To achieve this, the following equation has been applied:

$$\theta_v = SM_{\%} \frac{f}{100} \quad (1)$$

where *f* is the soil porosity. The network, which also measured precipitation and soil temperature, has been used predominantly for modeling N_2O fluxes from agricultural grasslands, but has been recently used also for the validation of soil moisture products [33].

Table 2. Irish Soil Moisture *in situ* stations. The land cover information is provided by the Corine Land Cover 2006. The porosity values are provided by the Harmonized World Soil Database 2012.

Site	Porosity (m^3 m^{-3})	Lat.	Lon.	Land Cover
Kilworth	0.59	52°10′N	−8°14′E	Pastures
Pallaskenry	0.61	52°39′N	−8°51′E	Pastures
Solohead	0.63	52°30′N	−8°12′E	Pastures

3.1.3. FMI Network

The Sodankylä *in situ* station (Figure S4 in the Supplementary Material, Table 3) belonging to the Finnish Meteorological Institute (FMI) network has been considered for this study [36]. Soil moisture and temperature are provided each hour since January 2007. Volumetric soil moisture at 2 and 10 cm depth is estimated from the measurement of the apparent dielectric constant taken by five TE Theta Probe ML2X instruments, installed in a sandy soil in a forest free area. Only the observations taken at 2 cm depth have been used in this study.

Table 3. FMI and GTK *in situ* stations. The land cover information is provided by the Corine Land Cover 2006. The porosity values are provided by the Harmonized World Soil Database 2012.

SM Network	Site	Lat.	Lon.	Land Cover
FMI Porosity: 0.55 m^3 m^{-3}	Sodankylä	67°21′N	26°37′E	Shrub
GTK Porosity: 0.47 m^3 m^{-3}	Ilomantsi	62°46′N	30°58′E	Agricultural area
	Kuusamo	66°19′N	29°24′E	Shrub
	Suomussalmi	64°55′N	28°45′E	Mixed forest
	Pori	61°30′N	21°48′E	Non irrigated arable soil

3.1.4. GTK Network

Four out of seven stations belonging to the Geological Survey of Finland (GTK) network have been selected for the quality assessment of the ECV SM product (Figure S5 in the supplementary material, Table 3). Soil moisture and temperature time series from May 2001 to May 2012 were collected. Water content reflectometers (CS616, CS615) were used to estimate volumetric soil moisture at various depths, deeper than 10 cm. For this work, only top soil measurements, taken at 10 cm depth, have been used for the validation activity.

3.2. Remotely Sensed Data

3.2.1. ECV SM Product

Building on the WACMOS project [16], the ECV SM global time series has been extended and enhanced, by improving the retrieval and merging algorithms, in the context of the ESA-funded Climate Change Initiative (CCI) programme. The latest version of the global soil moisture product has been released by the Vienna University of Technology (TUW) in July 2014, and it is freely available at http://www.esa-cci.org/. By extending the time series, which currently covers 35 years, from 1978 to 2013, new microwave sensors have been exploited to create the most consistent global soil moisture data archive. Specifically, WindSat and AMSR-2 have been added to the list of exploited multi-frequency radiometers, which already includes SMMR, SSM/I, TMI, AMSR-E. Data acquired by these passive systems have been processed by using the VUA-NASA (Vrije Universiteit Amsterdam and NASA) Land Parameter Retrieval Model (LPRM) software package in order to retrieve the soil moisture data. Aiming at removing calibration differences and other structural biases between data acquired by different sensors, the passive soil moisture time series have been rescaled into common reference climatology. Since AMSR-E provides the most reliable climatology for the passive soil moisture product, it has been chosen as the reference for data rescaling. Afterwards, a homogenized product (*i.e.*, "Passive Product") has been created by merging the rescaled passive datasets [42].

Concerning the generation of the soil moisture time series from data acquired by the C-band ERS-1/2 and ASCAT scatterometers, the Water Retrieval Package (WARP) developed at TUW has been used for the retrieval processing. Successively, the ensemble of active data has been rescaled to the ASCAT climatology. Finally, a unique soil moisture product (*i.e.*, "Active Product") has been generated by merging the previously processed active datasets [43].

The "Active Product" and the "Passive Product" have further undergone a rescaling phase, by using as reference a globally-consistent climatology, that is the GLDAS-Noah (Global Land Data Assimilation System) data assimilation system [44]. This has been performed using the cumulative distribution function (CDF) matching approach ([17,45–47]). Finally, the "Active Product" and the "Passive Product" have been blended together, and a "Combined Product" has been generated ([17–19,48]). To combine the merged active and merged passive datasets, data availability (at a daily time step) and data sensitivity to vegetation have been taken into account. The average vegetation optical depth (VOD) over transitional regions (*i.e.*, regions between sparsely and moderately vegetated areas) has been calculated and used as the threshold for separating sparsely from moderately vegetated regions outside of the transition zones. Active soil moisture data have been used for regions with moderate vegetation density (a VOD value higher than the threshold), whereas the passive product has been used for (semi-) arid regions (a VOD value lower than the threshold) [49]. When, at a given location in transition zones, the correlation coefficient (R) between the merged active and passive soil moisture products was greater than 0.65, both products have been used [50]. This has been done by simply averaging merged passive and merged active products for time steps where both products were available; if only one product type was available, that one was used [49].

The SM time series maps are provided on an almost daily basis, with a spatial resolution of approximately 0.25 degrees. Data are provided in volumetric units (m^3 m^{-3}), together with quality flags indicating the possible presence of dense vegetation, snow or a temperature below 0 °C.

Three separate long-term soil moisture datasets are available at http://www.esa-cci.org/: (1) "Active Product"; (2) "Passive Product"; and (3) "Combined Product". In this study only the "Combined Product" has been used.

3.2.2. ENVISAT ASAR WS SM Data

The quality assessment of the ECV SM dataset has been carried out by using the finer spatial resolution satellite soil moisture product retrieved from the ENVISAT ASAR acquisitions. Funded by the European Space Agency (ESA), the ENVISAT mission operated for ten years, from 2002 to 2012, during which the C-band (5.3 GHz) ASAR sensor acquired images in multiple modes, polarizations and at various incidence angles [51]. In this work, data acquired in the ScanSAR mode have been used in order to cover wide areas (405 km swath widths). Although ASAR Global Monitoring (GM) images have been preferred in a number of soil moisture studies ([52–54]), the finer spatial resolution (150 m) of the Wide Swath (WS) mode and its better radiometric accuracy (less than 0.6 dB), led us to focus on this product. Both ascending and descending orbits (*i.e.*, daytime and night-time observations) have been considered in order to collect a larger dataset to be used for the quality assessment of the almost daily ECV SM product. In fact, the theoretical capability of ASAR WS of acquiring images of the same region up to 3–5-times a month improved by combining ascending and descending orbits, allowing image acquisitions up to 10-times a month. As active sensors are only marginally affected by the sun-induced radiation at these electromagnetic frequencies, the accuracies of soil moisture products retrieved from ascending and descending observations are likely to be very similar. As regards the ASAR WS polarization, on the basis of the archive data availability, VV images were considered for the Spanish and Irish test sites, whereas both VV and HH acquisitions were used for the study in the Finnish regions.

Several algorithms have been developed to retrieve soil moisture from remotely-sensed data [29]. In particular, the use of multi-temporal SAR acquisitions allows, with few assumptions, to effectively estimate soil moisture by analysing changes in the backscattering over time [55]. Therefore, a change detection approach has been adopted in this work, by applying the algorithm developed by TUW originally for ERS scatterometer images [56], and successively adapted for ENVISAT ASAR GM data (1-km spatial resolution) [52]. Bearing in mind that the radar backscattering depends on both sensor parameters (*i.e.*, incidence angle, polarization) and land characteristics (*i.e.*, surface roughness, vegetation cover and soil moisture), such technique adopts assumptions and approaches whose complete explanation can be found in [52]. For instance, the influence of the incidence angle on the SAR backscattering is addressed by carrying out a pixel-wise multi-temporal incidence angle normalization by using a linear model and a reference angle of 30°. In fact, in [52], it has been observed that within the incidence angle range covered by ASAR (20°–40°), changes in backscattering due to vegetation growth are, in general, much smaller than changes due to soil moisture. The sensitivity of the backscatter coefficient to soil moisture variations is estimated as the difference between the highest and lowest historical values, which represent the historical wettest and driest observations, respectively. The relative soil moisture index ϑ is then expressed as:

$$\vartheta = \frac{\sigma^{\circ}(30^{\circ}) - \sigma^{\circ}_{dry}(30^{\circ})}{\sigma^{\circ}_{wet}(30^{\circ}) - \sigma^{\circ}_{dry}(30^{\circ})} \quad (2)$$

where $\sigma°(30°)$ is the normalized backscatter coefficient, $\sigma_{dry}°(30°)$ and $\sigma_{wet}°(30°)$ are the driest and wettest backscattering values extracted from the $\sigma°(30°)$ time series per pixel.

The adopted change detection algorithm is based on the assumption of the time-invariance of surface roughness and vegetation cover, which allows differences in the backscatter to be directly related to the soil moisture variations. Unfortunately, despite the better radiometric accuracy of the ASAR WS product compared to the ASAR GM product, the noise level affecting such high-resolution imagery still does not allow estimating a seasonal vegetation correction as it is the case of coarse-resolution data (e.g., ASCAT). Therefore, the hypothesis of the time-invariance of vegetation cover is a necessary assumption for the retrieval of soil moisture from ASAR observations. However, it has been observed that this assumption is reasonable over a large variety of land cover types, in particular over areas with sparse or low vegetation cover, such as those characterising the Spanish cropland and natural areas, or the Irish grassland, as there is little influence on the C-band backscattering signal and can generally be neglected [57]. This change detection algorithm has been used in several studies, providing promising results when applied to ASAR GM data ([58,59]). On the basis of such outcomes, and given the similarity of the ASAR GM and WS products, the same technique has been adopted to handle also the finer spatial resolution SAR data (150-m spatial resolution) [33]. Each ASAR WS scene has undergone a pre-processing phase, which includes geocoding, calibration and resampling to a regular grid characterized by a sampling interval of 15 arcsec. Although this last step of the pre-processing chain causes a degradation of the ASAR WS spatial resolution (1 km after resampling), it significantly improves the signal to noise ratio of the images. On the other hand, assuming a regular grid for the resampling of data acquired at sub-polar latitudes, such as at the Finnish sites, generates a loss of accuracy in the estimation of the backscattering, and hence it introduces a further error in the retrieval of soil moisture.

Aiming at the selection of the most reliable soil moisture time series, two masking processes have been carried out. The first one made use of the Corine Land Cover 2006 Map, which allowed the identification of those classes where the soil moisture values are not reliable (*i.e.*, urban, evergreen broadleaf forest, water bodies, barren or sparsely vegetated areas, snow or ice). Pixels belonging to these land covers have been masked out from each soil moisture map, and excluded from the subsequent analysis.

The second masking process had the objective of selecting only the pixels where the adaptation of the algorithm to the ASAR data works better. The temporal stability of soil moisture fields gives rise to an associated temporal stability in the backscatter signal [41]. A strong correlation between local and regional backscatter is usually a good indicator of the capability of local SM datasets in representing the soil moisture dynamics at the regional scale. At locations with a weak correlation, either the backscatter response to soil moisture dynamics is dominated by noise and speckle or the backscatter characteristics are adversely influenced by factors, such as dense vegetation, complex topography or soil structure/texture characteristics, which inhibit the retrieval of reliable soil moisture estimates. Therefore, for each 1 km × 1 km ASAR pixel, the correlation between the time series of the local σ^0 and the average of the backscattering over the 25 km × 25 km area covering the ASAR one has been evaluated. Pixels exhibiting a coefficient of determination R^2 lower than 0.3 have been masked out.

The change detection algorithm applied to the ASAR WS images provides soil moisture values expressed as degree of saturation, whereas the datasets available through the ECV SM product represent the volumetric moisture content of the soil. In order to compare time series characterized by the same measurement units, the soil moisture values retrieved from ASAR acquisitions have been transformed using Equation (1).

3.3. Regional Scale Analysis of SM Temporal Variability

In this study we investigated how well the ECV SM product represents local soil moisture dynamics, despite covering quite large areas, whose size is the same as of an ECV pixel (*i.e.*, 0.25 × 0.25 deg). The actual extension of such regions depends on their geographical location. Therefore, in the Boreal Hemisphere, ECV cells located at lower latitudes are larger than those located close to the North Pole. Specifically, the dimension of the Spanish ECV pixels is approximately equal to 21 km × 28 km, while smaller cells (*i.e.*, 17 km × 28 km) occur at the Irish latitudes, and the narrowest ones (*i.e.*, 13 km × 28 km) include the Finnish sites. Each ECV cell has been identified by plotting the geographical position of the *in situ* stations on a georeferenced grid. Then, the surrounding areas, which exactly coincide with the ECV pixels, have been considered. It has to be observed that, after the masking process, the number of accessible ASAR pixels in each grid cell is smaller than the maximum obtainable (*i.e.*, 61 × 61 pixels). In Table 4, the percentage of available 1 km × 1 km (after resampling) pixels in each area under study is reported. Moreover, the amount of ASAR soil moisture data in the same cell could differ due to the variability of the satellite coverage. In order to make the analysis statistically consistent, only the ASAR acquisitions that cover the ECV pixels for more than 50% of the available pixels (after masking) were considered in the study. It can be observed that at the higher latitude of the Finnish sites, the shorter revisit time of the ASAR sensor allowed the collection of a larger number of images.

While the ECV SM time series is provided on an almost daily basis, ground measurements are taken every hour or half an hour, and ASAR WS acquisitions are much less frequent. Given the different temporal frequency of each dataset, only the ECV SM and *in situ* SM data corresponding to the ASAR WS acquisition dates have been considered.

Soil moisture temporal variability has been studied on a regional scale in each area of interest, by comparing the ECV SM product with the finer spatial resolution ASAR WS SM data and *in situ* measurements. The mean value of soil moisture retrieved from each SAR image has been evaluated within the corresponding ECV cell, and the time series of averaged ASAR SM data has been used for the datasets comparison. Moreover, the daily averages of ground measurements have been used for the analysis. Despite daily variability in the moisture content, it has been observed that the standard deviation of SM evaluated within the twenty-four hours of observation is generally negligible in all the sites. Specifically, the daily soil moisture standard deviation is on average equal to 0.007 $m^3\ m^{-3}$ in Spain, 0.006 $m^3\ m^{-3}$ in Ireland, and 0.003 $m^3\ m^{-3}$ in Finland. Therefore, using the average daily *in situ* soil moisture values does not affect the results of the study.

Table 4. Number of ASAR WS acquisitions temporally compatible with the ECV and *in situ* soil moisture data at each site. For each ECV cell, it is also shown the percentage of corresponding ASAR pixels (1 km × 1 km after resampling) still available after the land cover and correlation based masking process.

Region	Site		Temporal Interval	% Available ASAR Pixels	N. Data
Spain	ECV-A	K10	16/03/2005–29/03/2010	99.6%	52
		M05	01/04/2005–29/03/2010		52
		I06	01/04/2005–29/03/2010		47
		K09	19/03/2005–29/03/2010		49
		I03	06/05/2005–05/04/2006		14
		H09	16/03/2005–29/03/2010		55
		L03	01/04/2005–29/03/2010		52
		M09	16/03/2005–29/03/2010		55
		K04	06/05/2005–29/03/2010		51
		L07	16/03/2005–29/03/2010		55
		J03	01/04/2005–29/03/2010		53
	ECV-B	F06	01/04/2005–29/03/2010	99.4%	59
	ECV-C	H11	16/03/2005–05/04/2006	92.5%	18
		J14	16/03/2005–30/12/2009		43
		H13	16/03/2005–29/03/2010		53
	ECV-D	F11	19/03/2005–10/03/2010	75.4%	50
Ireland	Kilworth		27/06/007–15/09/2009	92.1%	77
	Pallaskenry		26/08/2007–15/09/2009	80.5%	63
	Solohead		23/05/2007–15/09/2009	94.7%	70
Finland	Sodankyl ä		09/05/2007–17/11/2009	100.0%	120
	Kuusamo		09/05/2007–21/10/2009	100.0%	67
	Suomussalmi		18/10/2005–21/10/2009	90.3%	101
	Ilomantsi		16/06/2007–23/11/2009	86.7%	49
	Pori		13/04/2007–13/04/2010	83.7%	111

Since the three time series are provided in different dynamic ranges, the data have been firstly scaled into a common climatology. A typical method based on the Cumulative Distribution Function (CDF) matching has been applied ([17,45,60]). Through this technique, the satellite data are rescaled so that both ASAR CDF and ECV CDF match the CDF of the *in situ* SM dataset.

Furthermore, a seasonal based analysis has been carried out to investigate the capability of the satellite soil moisture products in capturing the annual cycle and short-term variability of surface SM. Because of the frozen soil conditions occurring during the winter season in Finland, we limited the seasonal based study to SM time series collected in spring, summer and autumn.

The temporal agreement between each pair of soil moisture time series has been characterized through the Pearson correlation coefficient (R). The actual reliability of the evaluated statistics has been examined through the Student's *t*-test, by estimating the probability (*p*-*value*) of the achieved correlation to be a coincidence, *i.e.*, not significant. The threshold for accepting such a hypothesis (null hypothesis) has been set to 0.05.

Note that even though many studies evaluate soil moisture products in terms of both the correlation coefficient (R) and the root mean square difference (RMSD) [61,62], we omit the investigation of the RMSD in this study as it, due to the prior application of the CDF-matching, does not provide additional information. In fact, the (unbiased) RMSD is solely determined by R, scaled with the variance of the reference dataset [63], which hampers a meaningful interpretation of spatial patterns [64,65].

3.4. Analysis of SM Spatial Variability

Soil moisture is known to be a very complex phenomenon, not only concerning its temporal dynamics, but also its spatial distribution. Variations in the terrain composition, land cover and topography affect the moisture content of the soil, which can be highly variable even over short distances [66]. Such behavior is mitigated in the ECV SM product, due to the coarse spatial resolution. However, it is important to understand the local scale variability within the ECV SM pixel areas as well as to investigate which local geophysical characteristics (e.g., terrain composition, altitude and slope, land cover) mainly lead to this variability. These issues have been addressed here by studying the SM spatial variability at the resampled ASAR scale (1-km spatial resolution). A first analysis has been carried out by comparing the average of the retrieved ASAR SM within each ECV-size cell with the coefficient of variation (CV):

$$CV_j = \frac{\sigma_j}{\bar{\vartheta}_j} = \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\vartheta_{ij}-\bar{\vartheta}_j\right)^2}}{\bar{\vartheta}_j} \quad j = 1, \ldots, \mathrm{M} \qquad (3)$$

where N is the number of ASAR pixels within the ECV cell, ϑ_{ij} is the soil moisture estimated at time j in the ASAR pixel i, σ_j is the SM standard deviation and $\bar{\vartheta}_j$ its mean.

In a second study, the ASAR SM datasets retrieved in each 1 km × 1 km pixel have been compared with the corresponding ECV SM time series, and with the ground measurements taken in each of the stations belonging to the same cell under investigation. When multiple *in situ* stations were located within a single ECV size pixel, the average values of the ground measurements were considered for the comparison. Such analyses have provided correlation maps, which are a quite suitable and effective tool to highlight the presence of correlation patterns, and for a better understanding of their possible relationship with geophysical features.

4. Results

4.1. Soil Moisture Temporal Variability

4.1.1. Spain

The temporal variability of soil moisture provided by ASAR WS acquisitions, ECV product and *in situ* continuous measurements in the Spanish sites under study can be observed in Figure 2. Where multiple stations were located within the same cell, *i.e.*, in the ECV-A and ECV-C, the average of the daily ground soil moisture values has been plotted. It can be observed that most of the temporally compatible data have been collected from August 2008 until March 2010 due to a lack of ASAR data availability from 2006 to 2008. Daily ground measurements highlight a typical periodical variation of soil moisture, with almost dry conditions in summer and wetter soil in winter. Such seasonal variability is less evident in the ECV-D, where despite the soil moisture, reaches the lowest values in summer;

quite dry conditions also persist in winter, when the highest *in situ* SM measurements do not exceed 0.12 $m^3 m^{-3}$. On the contrary, the north area corresponding to the ECV-A and ECV-C, is characterized by slightly wetter conditions in summer, but much higher soil moisture values in winter. In particular, the wettest winter occurred in 2005 in the ECV-B, where the *in situ* instrument at the Zamarron station recorded soil moisture values up to 0.4 $m^3 m^{-3}$. For a clearer understanding of the differences in the capability of each SM product in capturing such seasonal SM behavior, please refer to the provided supplementary material, where the temporal evolution of ASAR, ECV and *in situ* SM anomalies evaluated considering the whole period of observation are shown in Figure S9.

Correlation values between each pair of SM datasets are shown in Table 5 for each ECV pixel. In order to verify the reliability of the statistics, the *p-values* have been also evaluated and reported in Table 5. Because of the necessity of collecting ASAR WS images including each of the *in situ* stations, the size of the datasets varies even within the same ECV cell. Moreover, the parameters used to scale the satellite datasets depend on the CDF of the *in situ* SM time series. For these reasons, ASAR and ECV SM datasets are slightly different in each site, and therefore the inter-comparison results differ from site to site.

Table 5. Correlation values evaluated between each pair of soil moisture datasets. Correlation levels are statistically significant (p-values < 0.05). When more than one *in situ* station was included in a single ECV size pixel (*i.e.*, ECV-A and ECV-C cells), the average values of SM recorded by all the *in situ* stations within these cells have been also considered for the inter-dataset comparisons. Results referred to this type of analysis are reported in the table at rows named "mean".

Cell	**Site**	**ASAR *vs.* ECV**		**ASAR *vs. In situ***		**ECV *vs. In situ***	
		R	***p***	**R**	***p***	**R**	***p***
ECV-A	K10	0.73	<0.001	0.60	<0.001	0.82	<0.001
	M05	0.58	<0.001	0.67	<0.001	0.66	<0.001
	I06	0.66	<0.001	0.56	<0.001	0.49	<0.001
	K09	0.63	<0.001	0.52	<0.001	0.81	<0.001
	I03	0.69	0.003	0.80	<0.001	0.82	<0.001
	H09	0.78	<0.001	0.45	<0.001	0.71	<0.001
	L03	0.61	<0.001	0.45	<0.001	0.82	<0.001
	M09	0.65	<0.001	0.62	<0.001	0.90	<0.001
	K04	0.68	<0.001	0.52	<0.001	0.83	<0.001
	L07	0.58	<0.001	0.54	<0.001	0.89	<0.001
	J03	0.72	<0.001	0.53	<0.001	0.81	<0.001
	mean	0.69	<0.001	0.59	<0.001	0.87	<0.001
ECV-B	F06	0.80	<0.001	0.56	<0.001	0.64	<0.001
ECV-C	H11	0.59	0.005	0.70	<0.001	0.87	<0.001
	J14	0.79	<0.001	0.54	<0.001	0.71	<0.001
	H13	0.60	<0.001	0.52	<0.001	0.79	<0.001
	mean	0.73	<0.001	0.63	<0.001	0.87	<0.001
ECV-D	F11	0.77	<0.001	0.71	<0.001	0.86	<0.001

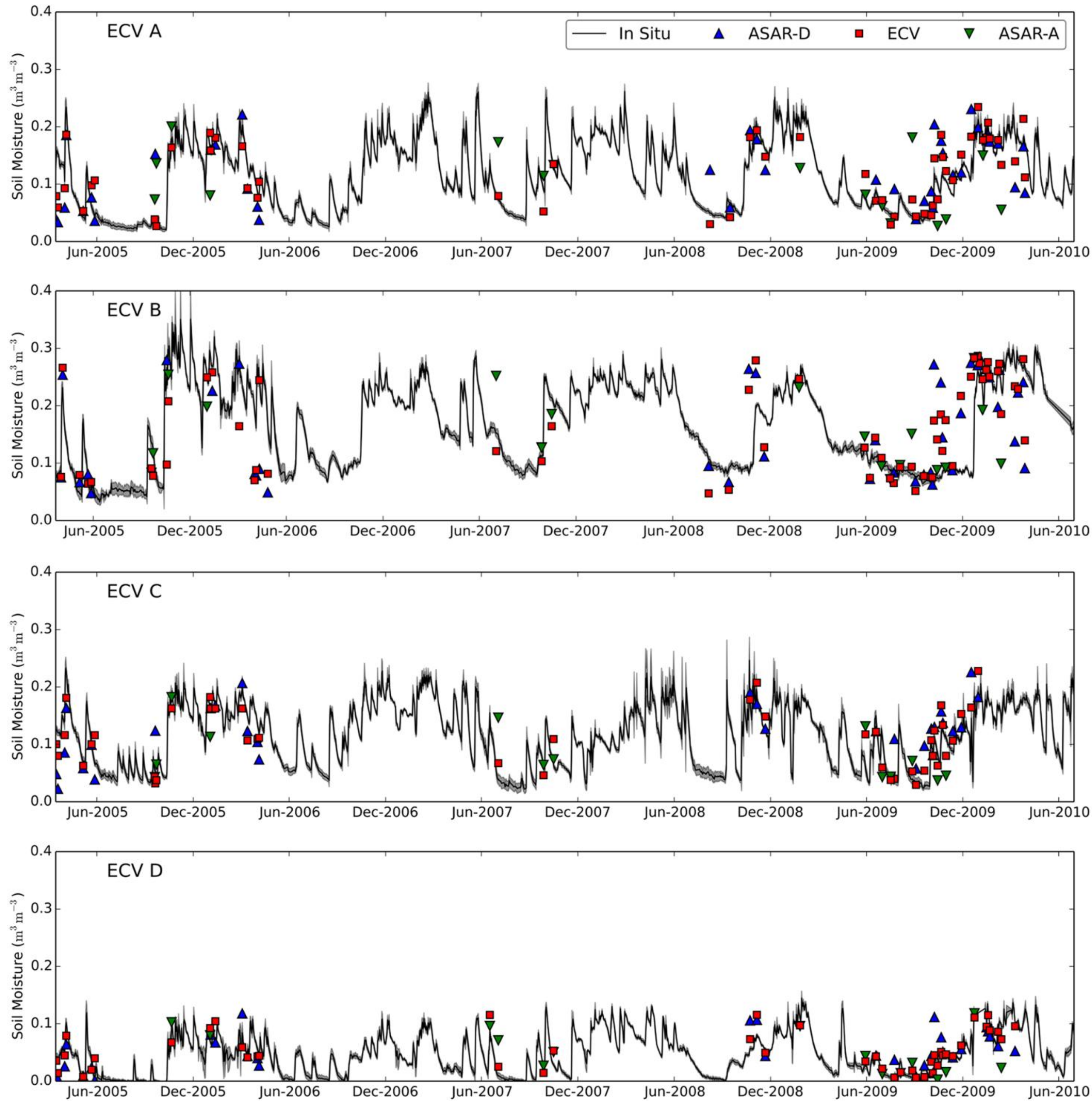

Figure 2. Time series of *in situ* (continuous black line), ASAR (descending (blue triangle) and ascending (green triangle) passes), and ECV (red square) soil moisture values for each Spanish ECV cell.

The evaluation of the correlation (R) between each pair of SM datasets provided quite high values in all the ECV size pixels and sites (Table 5). Specifically, a good agreement between ASAR WS SM and ECV SM has been found, with R values within the interval 0.58–0.80 (p-values < 0.05).

The validation of the retrieved SM from ASAR WS time series through the comparison with the *in situ* SM dataset provided slightly lower values of correlation. In fact, R generally varies between 0.45 and 0.67 (p-values < 0.001) in the ECV-A, with the only exception being the I03 station, whose ASAR-*in situ* SM comparison provided R = 0.80 (p-value < 0.001). Similarly, a reasonable correlation (R = 0.56, p-value < 0.001) was obtained between ASAR SM and ground SM measurements in the ECV-B pixel. Better results were achieved in the ECV-D (R = 0.71) and in the H11 (R = 0.70) station belonging to ECV-C (Table 5).

The ECV SM datasets have been compared with the *in situ* SM time series, highlighting very good agreement in all the sites under investigation (Table 5). Correlation values were mainly higher than 0.80 in the ECV-A, with the only exceptions represented by the M05 (R = 0.66, *p*-value < 0.001), I06 (R = 0.49, *p*-value < 0.001) and H09 (R = 0.71, *p*-value < 0.001). High correlation values were also evaluated for all the sites in ECV-C (R > 0.71, *p*-values < 0.001) and ECV-D (R = 0.86, *p*-value < 0.001). In contrast, a poorer agreement was found between ECV SM and ground SM datasets in the ECV-B, with an R equal to 0.64 (*p*-value < 0.001).

The same comparisons have been carried out in ECV-A and ECV-C by considering the average values of soil moisture recorded by all the *in situ* stations within these cells. Results are consistent with those obtained by using the actual ground measurements recorded by each instrument installed within the same areas. The highest agreements have been observed by comparing the ECV SM datasets with the averaged *in situ* SM time series (R = 0.87, *p*-value < 0.001 in both the ECV cells), whereas poorer results have been obtained by comparing the ASAR SM datasets with the averaged ground measurements (R = 0.59, *p*-value < 0.001 in ECV-A; R = 0.63, *p*-value < 0.001 in ECV-C). Relatively high correlation values have been evaluated by relating the two satellite SM products: R = 0.69, *p*-value < 0.001 in ECV-A and R = 0.73, *p*-value < 0.001 in ECV-C.

4.1.2. Ireland

Similar to the study of the Spanish sites, and to the regional based analysis reported in [33], the representativity of the ECV SM product has been explored by using ASAR SM time series and *in situ* SM datasets collected over Kilworth, Pallaskenry and Solohead in Ireland. Figure 3 shows the temporal behavior of three soil moisture datasets in each analyzed ECV cell during the period of observation, while we recommend referring to the supplementary material (Figure S10) for a more complete overview of similarities and differences in the seasonal SM variability described through the anomalies evaluated for each dataset. The latest and improved version of the ECV SM product has been used in this work, whereas in [33] the performance of the WACMOS soil moisture dataset [16] was investigated. In addition, a different approach has been used in the present study, where the CDF matching technique has been applied to scale both the satellite time series to the *in situ* SM dataset. Such a method leads to a significant reduction of the bias between the datasets, which exhibit the same periodic behavior, with wetter soil condition in winter, and drier states in summer. However, a few exceptions occur, which are particularly evident in winter 2008, when high soil moisture values recorded by the *in situ* instruments in all the sites are not always well represented by the ASAR acquisitions or the ECV SM products where some very low SM values have been retrieved. Similarly, in summer 2008, some quite high ASAR and ECV soil moisture values do not agree with the lower SM ground measurements. Despite these occurrences, we can state that an enhanced capability of the ECV SM dataset in representing extreme dry and wet conditions has been achieved by the new version of the CCI product [33].

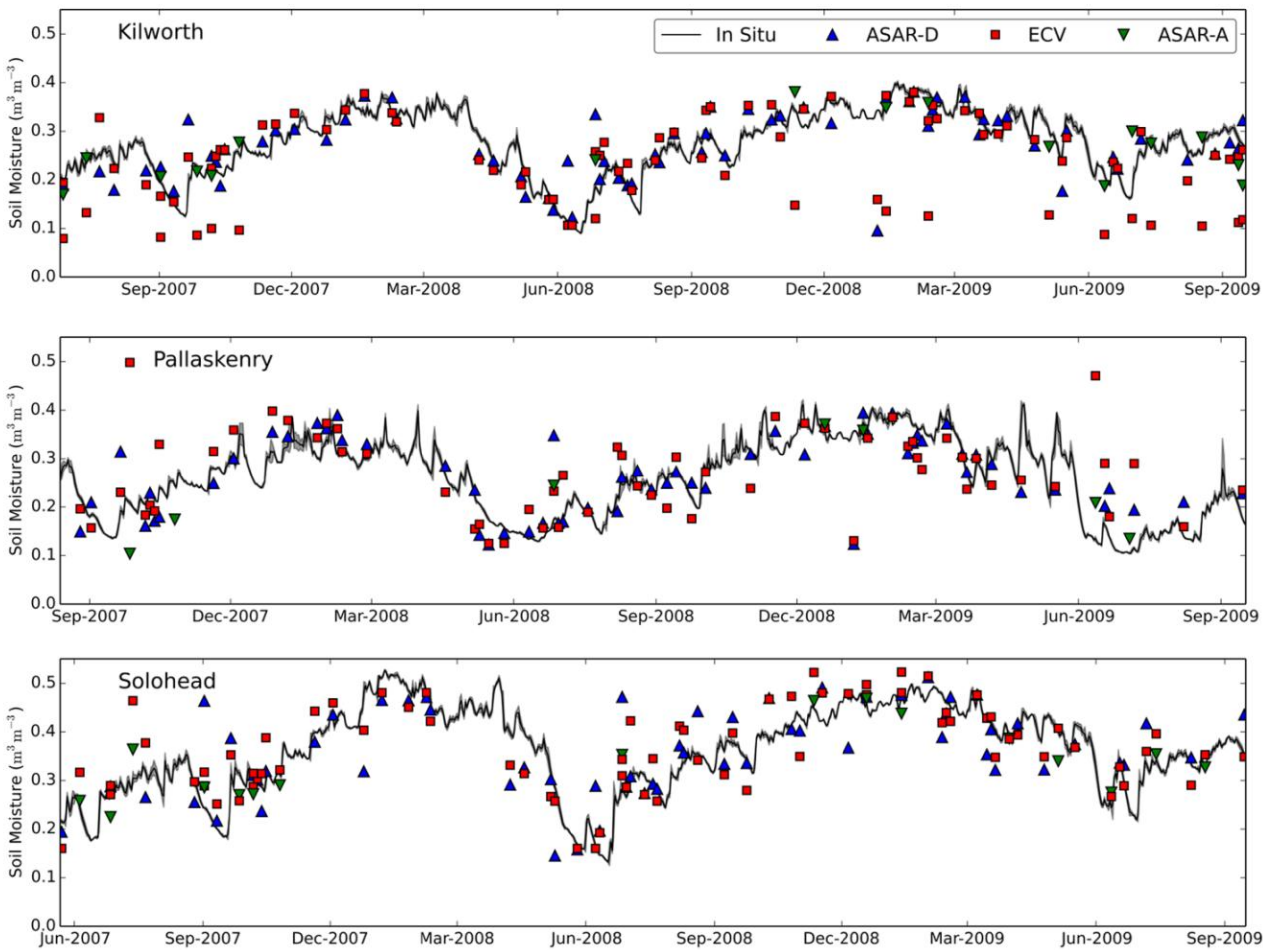

Figure 3. Time series of *in situ* (continuous black line), ASAR (descending (blue triangle) and ascending (green triangle) passes), and ECV (red square) soil moisture values for each Irish ECV cell.

By comparing the three SM datasets, an actual improvement has been observed with respect to the results reported in [33]. In fact, results reported in Table 6 show that the correlation between the new ECV SM dataset and both ASAR SM and *in situ* time series increased in all the sites. Good agreements have been also found between the ASAR SM datasets and ground measurements in all the Irish sites (R = 0.70–0.73, *p*-values < 0.001).

Table 6. Correlation values evaluated between each pair of soil moisture dataset. Correlation levels are all statistically significant (*p*-values < 0.05).

Site	ASAR *vs.* ECV		ASAR *vs. in situ*		ECV *vs. In situ*	
	R	*p*	R	*p*	R	*p*
Kilworth	0.82	<0.001	0.70	<0.001	0.76	<0.001
Pallaskenry	0.79	<0.001	0.71	<0.001	0.67	<0.001
Solohead	0.79	<0.001	0.73	<0.001	0.83	<0.001

4.1.3. Finland

Frozen soil conditions, which typically occur during the Finnish winter, make the retrieval of soil moisture from satellite acquisitions unreliable. These cases are highlighted through a specific flag associated to the corresponding daily ECV SM value, and they are not used in this validation study. In Figure 4 the time series of soil moisture recorded by the FMI and GTK *in situ* instruments are plotted together with those retrieved from ASAR acquisitions and those provided by the ECV SM product. The temporal evolution of the SM anomalies evaluated by considering the whole period of observation is displayed in Figure S11 of the supplementary material.

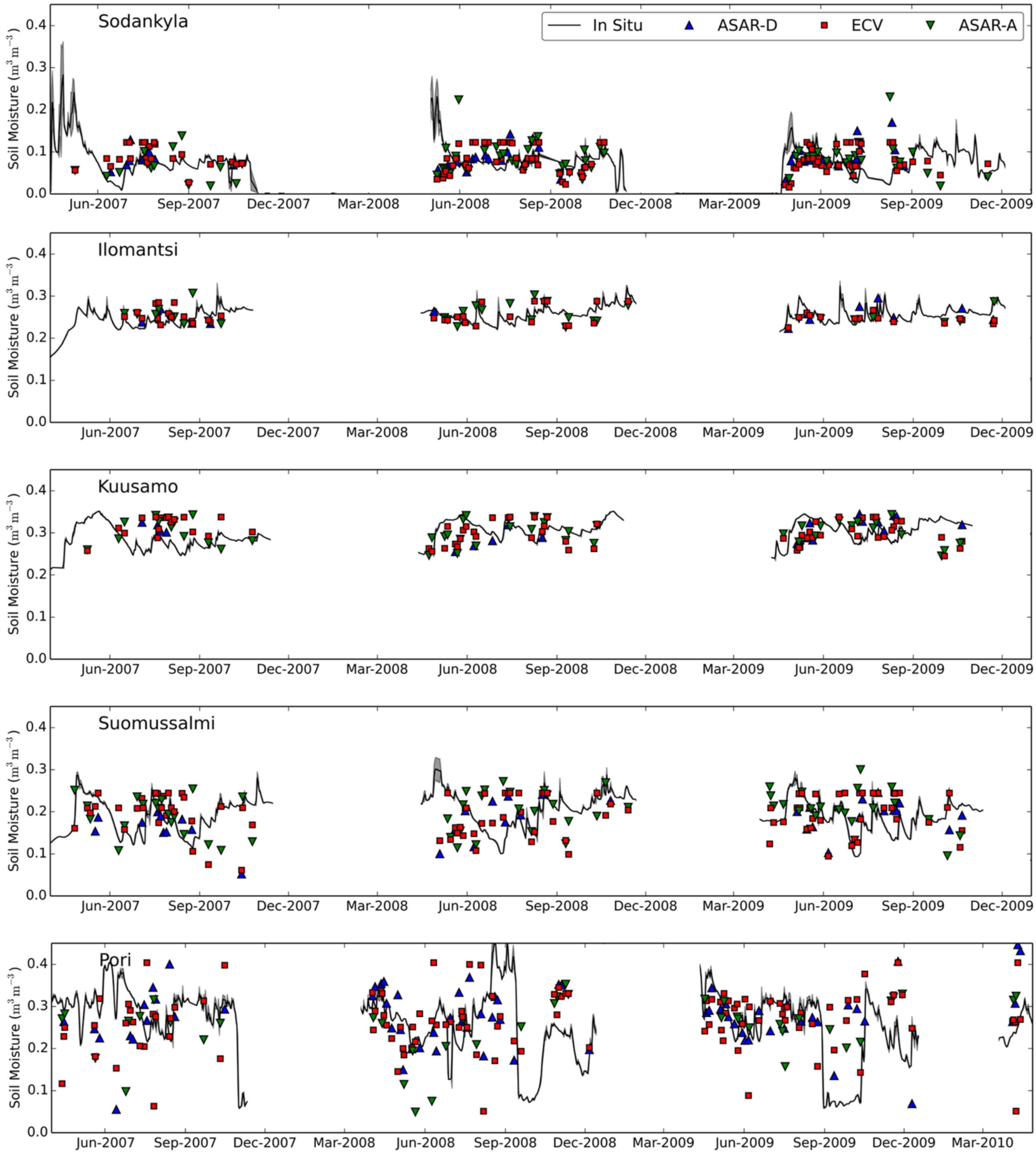

Figure 4. Time series of *in situ* (continuous black line), ASAR (descending (blue triangle) and ascending (green triangle) passes), and ECV (red square) soil moisture values for each Finnish ECV cell.

By comparing the ECV SM product with the FMI and GTK soil moisture ground measurements, it has been found that in a few cases (9 in Sodankylä, 2 in Ilomantsi, 5 in Kuusamo, 6 in Suomussalmi and 27 in Pori) local frozen soil conditions detected by the instruments installed in each *in situ* station have not been flagged in the ECV SM product. In order to understand if and to what extent local frozen soil conditions affect the quality of the ECV soil moisture product, two different approaches have been adopted. Firstly only the frozen conditions highlighted in the ECV SM product have been excluded from the datasets comparison. Results obtained by comparing ASAR, ECV and *in situ* SM time series are shown in Table 7. In a second study, *in situ* soil moisture values corresponding to soil temperature below 0 °C have also been rejected, reducing further the size of the datasets. Results showed that the correlations between each pair of SM datasets are rather low in all sites, irrespective of the method used for excluding frozen soil condition observations (please note that results achieved by adopting the second approach are reported in Table S1 of the Supplementary Material).

Table 7. Correlation values evaluated between each pair of soil moisture dataset.

ISMN	Site	n	ASAR *vs.* ECV		ASAR *vs. In situ*		ECV *vs. In situ*	
			R	*p*	R	*p*	R	*p*
FMI	Sodankylä	120	0.52	<0.001	−0.18	0.02	−0.24	0.004
GTK	Ilomantsi	49	0.43	0.001	0.05	0.37	0.06	0.34
	Kuusamo	67	0.50	<0.001	−0.27	0.03	−0.30	0.02
	Suomussalmi	101	0.41	<0.001	−0.09	0.18	0.14	0.08
	Pori	111	0.32	<0.001	0.05	0.30	−0.04	0.34

4.2. Soil Moisture Seasonal Based Analysis

A seasonal based comparison has been carried out between satellite retrieved SM datasets and ground measurements. Table 8 reports the resulting statistics in terms of correlation. Due to the winter frozen soil condition in the Finnish sites, no values have been included in the analysis in these months. It can be observed that generally the poorer agreement between datasets occurs in winter in all sites. However, a high winter correlation value, equal to 0.76, has been estimated between the ECV SM product and *in situ* time series in the ECV-C grid cell. Similarly to the long period datasets comparisons, also the seasonal comparisons provided the lowest correlation values at the Finnish sites where, aside from a few exceptions, R generally lies below 0. The best agreement between both ASAR and ECV SM and ground measurements in the FMI and GTK stations occur in autumn. Particularly high R value, equal to 0.8 has been evaluated between ECV SM and *in situ* SM time series in Ilomantsi. In Ireland, the best agreement between satellite time series and *in situ* SM measurements has been observed in spring. In this season, very high correlation values (R > 0.9) have been evaluated between ECV and *in situ* SM time series. In Spain, quite high correlations have been found between the ECV SM time series and the ground measurements in autumn (ECV-A and ECV-C) and spring (ECV-B and ECV-D). Differently, the comparison between the ASAR SM and the *in situ* datasets highlighted the best agreement in spring for the ECV-A, in summer for the ECV-B and the ECV-D, and in autumn for the ECV-C.

Table 8. Seasonal correlation values (R) between *in situ* SM measurements and both ASAR and ECV SM datasets, evaluated in each ECV cell under study.

ECV Cell	Winter		Spring		Summer		Autumn	
	ASAR	ECV	ASAR	ECV	ASAR	ECV	ASAR	ECV
ECV-A	0.02	0.46	0.67	0.68	0.04	0.01	0.57	0.85
ECV-B	−0.21	−0.01	0.71	0.83	0.78	0.23	0.47	0.13
ECV-C	−0.69	0.76	0.60	0.78	−0.08	0.75	0.78	0.87
ECV-D	0.49	0.34	0.78	0.92	0.83	0.91	0.73	0.78
Kilworth	0.25	0.26	0.91	0.94	0.43	0.59	0.77	0.75
Pallaskenry	−0.08	−0.15	0.78	0.90	0.32	0.48	0.58	0.66
Solohead	−0.03	0.14	0.83	0.93	0.60	0.73	0.75	0.76
Sodankylä	-	-	−0.41	−0.53	−0.01	0.26	0.29	0.45
Kuusamo	-	-	0.18	0.32	−0.29	−0.04	−0.22	−0.38
Ilomantsi	-	-	−0.17	−0.23	0.46	0.30	0.49	0.80
Suomussalmi	-	-	−0.50	0.18	0.12	0.42	0.48	0.65
Pori	-	-	0.24	0.17	−0.08	−0.09	0.25	0.23

4.3. Soil Moisture Spatial Variability

4.3.1. Spain

The spatial variability of soil moisture within each ECV size pixel has been analyzed through the evaluation of the coefficient of variation (CV) of the ASAR SM datasets. The plots in Figure 5 show the trend of the CV for increasing soil moisture values. Different colors have been used to distinguish data taken at each season.

In all the sites drier conditions lead to higher soil moisture spatial variability. In contrast, when the mean soil moisture over the region is higher, the area is more homogeneously wet. Such a behavior is well described through a decreasing power function, with a coefficient of determination generally higher than 0.8. A similar trend has been observed in the Irish areas, as reported in [33] and shown also in Figure S12 in the Supplementary Material for sake of comparison, where it has also highlighted that above values of 0.2 $m^3 \cdot m^{-3}$, the CV tends to vary linearly with the mean of the soil moisture [67,68]. Such an observation is clearly applicable also to the Spanish sites under investigation.

Correlation maps depicted in Figure 6a have been generated by comparing each ASAR SM local time series and the corresponding ECV SM dataset. It can be noted that correlation values larger than 0.5 occur across all the four ECV cells. By comparing these maps with the CLC2006 (Figure S2a in supplementary material), there is a quite good correspondence between patches of higher correlation and the "non-irrigated arable land" class. The best agreement between the two datasets has been found in the ECV-B, where R is generally higher than 0.7, reaching peaks of 0.9 in the south-east area. On the contrary, a very small number of ASAR pixels within all the ECV cells exhibit a poor correlation. However, in ECV-A five larger patterns of pixels characterized by R lower than 0.4 occur. Such areas are covered by vineyards and fruit trees cultivations. The C-band signal backscattered from these regions mainly interacts with the canopy of such plantations, without reaching the soil underneath. This is likely to be the reason of a less accurate retrieval of soil moisture from satellite acquisitions, and therefore of a lower performance of the soil moisture product.

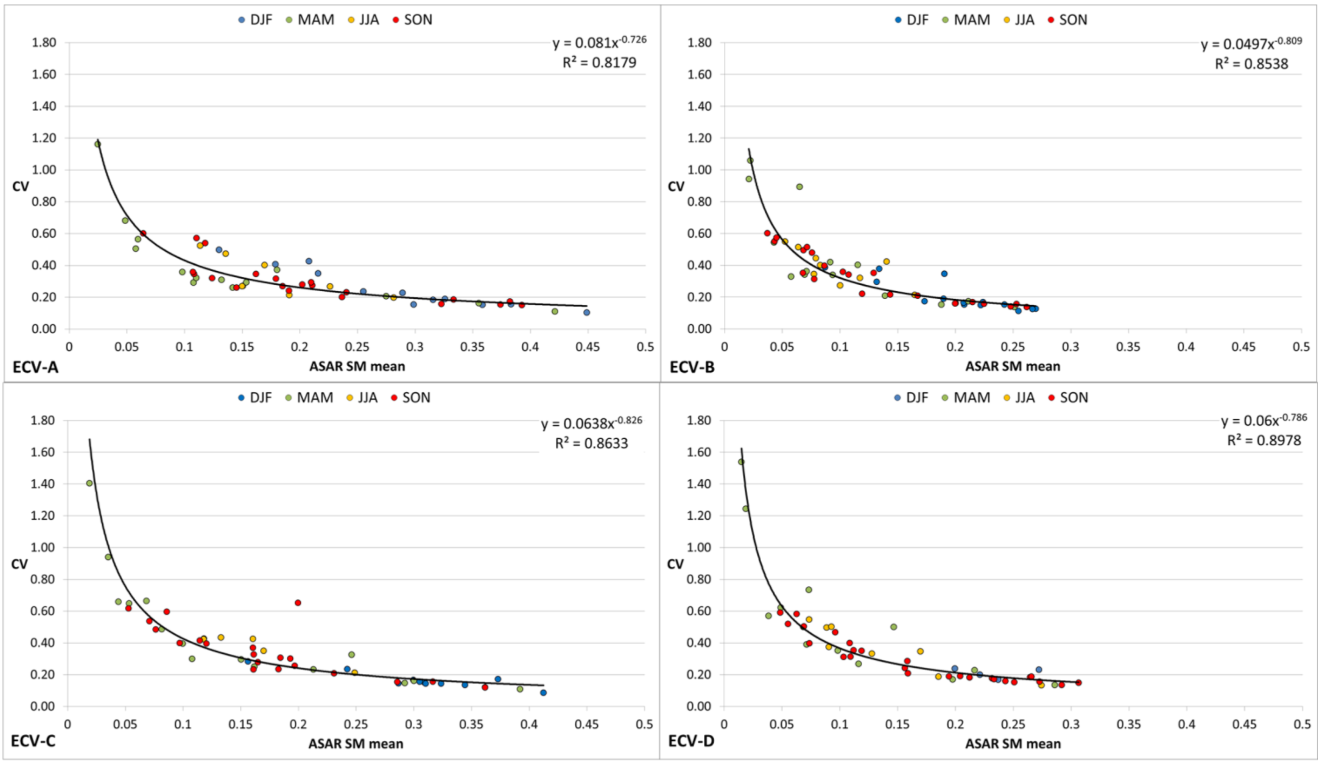

Figure 5. Coefficient of variation (CV) of the ASAR SM mean, evaluated for each ASAR acquisition over the Spanish ECV-sized pixels, during the observation period 2005–2010. Seasonal-based values are highlighted by different colors. (Winter: DJF; Spring: MAM; Summer: JJA; Autumn: SON).

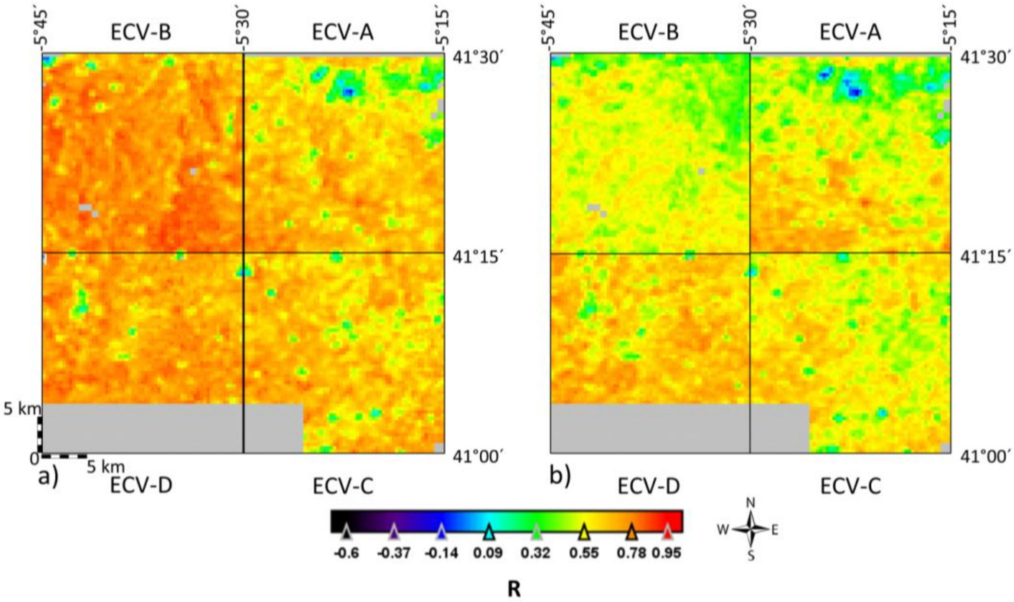

Figure 6. (**a**) ASAR SM *vs.* ECV SM and (**b**) ASAR SM *vs. in Situ* SM correlation maps evaluated for each ASAR WS pixel (1 km × 1 km after resampling). The soil moisture ground measurements in ECV-B and ECV-D are provided by a single instrument installed in each of the ECV cell areas. For the analysis in ECV-A and ECV-C, where multiple soil moisture stations are located, the daily mean values of soil moisture recorded by each instrument within a single ECV cell has been considered.

A further analysis has been carried out by comparing the local ASAR SM datasets and the *in situ* time series collected within the same ECV cell. Where multiple stations are included within the same ECV pixel size, the average of soil moisture records has been considered. Results shown in Figure 6b are consistent with those in Figure 6a. In fact, despite general lower correlation, there is a quite good correspondence between patterns of pixels having similar R values. Therefore, groups of ASAR pixels showing higher correlation values are the same in both the maps displayed in Figure 6.

4.3.2. Ireland

In [33], the study of the spatial variability of SM retrieved from ASAR WS acquisitions over the Irish sites has been already presented. Since the same ASAR WS dataset has been used in the present work, here we do not replicate such analysis. However, for sake of comparison with the results achieved over the other regions under study, we show the CV trend plots published in [33] in the supplementary material provided with this manuscript (Figure S12). On the contrary, we repeated the study presented in [33], assessing the performance of the latest released version of the ECV SM product throughout the comparison of ASAR SM local time series and the corresponding ECV SM datasets. Furthermore, in this study, soil moisture values retrieved in each ASAR pixel have been correlated with the ground measurements recorded at the *in situ* station located within the associated ECV cell. The outcomes of this analysis are represented in Figure 7a as correlation maps. With respect to the results observed in [33], the correlation maps depicted in Figure 7a exhibit the same patterns of quite homogeneous correlation values. While very similar correlation maps have been obtained in the Solohead cell, a significant improvement has been observed in the other sites and particularly in the Pallaskenry ECV pixel size, where R reaches values higher than 0.7 in most of the ASAR pixels.

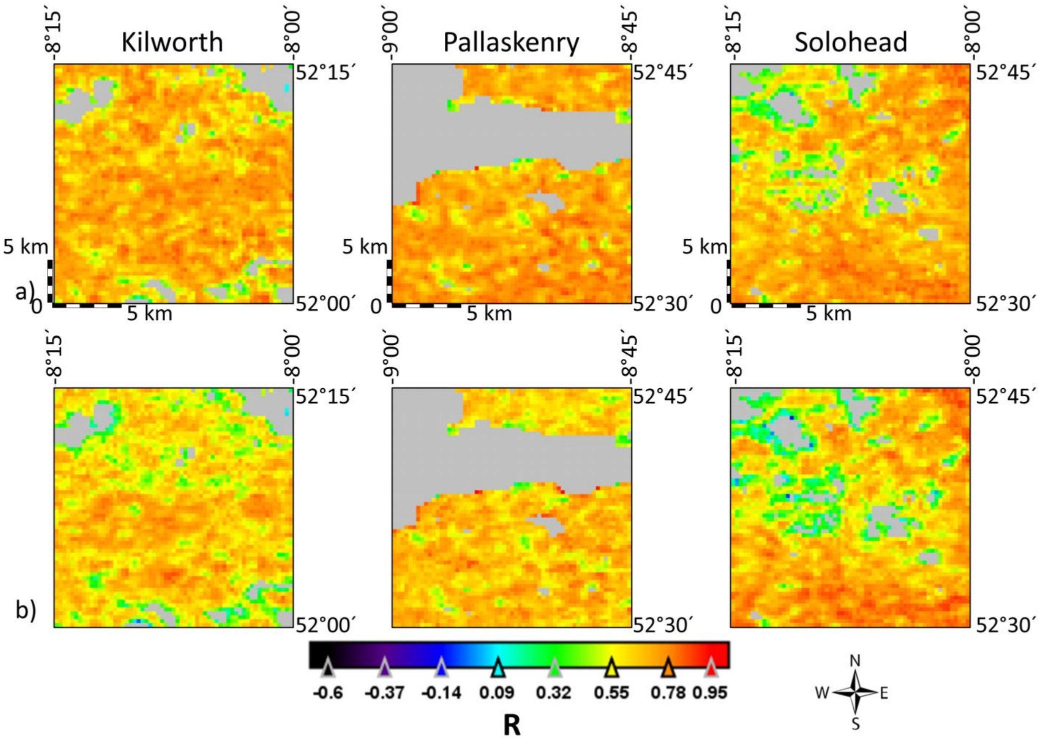

Figure 7. (**a**) ASAR SM *vs.* ECV and (**b**) ASAR SM *vs.* *in situ* SM correlation maps evaluated for each ASAR WS pixel (1 km × 1 km after resampling).

Given the consistency of such outcomes with those found in [33], it is possible to confirm what has been observed in this previous work: the combination of altitude and soil type affects the soil moisture variations and hence the representativity of the ECV SM product. It has been noted that the soil moisture behavior over those areas characterized by lower altitudes is better described by the ECV SM dataset (high correlation values), and that these regions mainly correspond to zones where the soil type is classified as deep well-drained mineral and mineral alluvium [33].

Correlation maps generated by comparing ASAR and *in situ* SM dataset exhibit lower R values on average (Figure 7b). However, highest and lowest correlation patterns are consistent with those observed by comparing ASAR and ECV SM datasets. This is particularly evident in Solohead, where the results achieved from both analyses are rather similar.

4.3.3. Finland

The spatial variability of soil moisture within the Finnish ECV cells is presented in Figure 8. The CV values have been plotted as a function of the average of the soil moisture retrieved from ASAR acquisitions over the areas of interest, where either the FMI or the GTK *in situ* stations are located. As it has already been observed for the Spanish and Irish sites [33], drier soil conditions in Finland mean higher SM spatial variability, which is described by larger CV values. Also in these case studies, such behavior can be represented quite well by a decreasing power function. The dependency of the spatial variability of SM on the spatial average of soil moisture in Ilomantsi is however less meaningful, as the behavior is described by a decreasing power function with a coefficient of determination equal to 0.4.

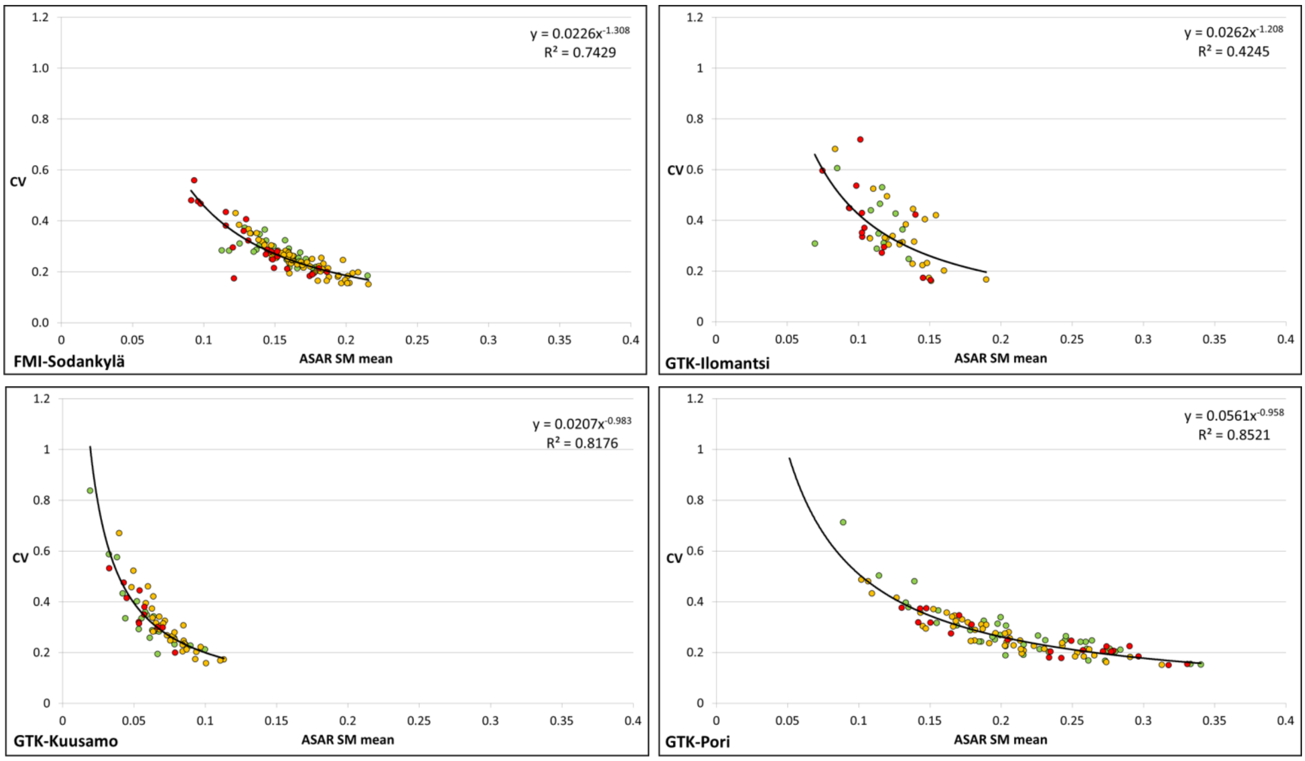

Figure 8. *Cont.*

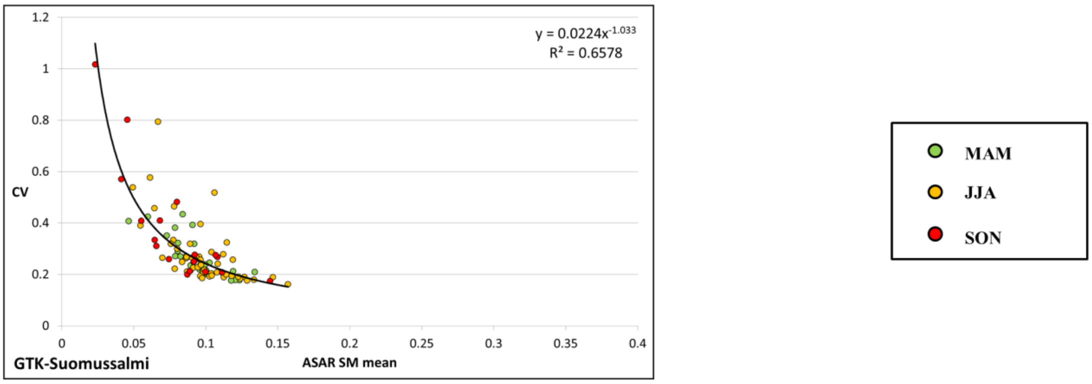

Figure 8. Coefficient of variation (CV) of the ASAR SM mean, evaluated for each ASAR acquisition over the FMI and GTK ECV sized pixels, during the observation period 2007–2009 for Sodankylä, Ilomantsi and Kuusamo, 2007–2010 for Pori, and 2005–2009 for Suomussalmi. Seasonal based values are highlighted by different colors. (Spring: MAM; Summer: JJA; Autumn: SON).

By comparing the ASAR retrieved SM time series in each 1 km × 1 km pixel and the ECV SM dataset corresponding to the Sodankylä cell, as well as the ground measurements collected in this station, the correlation maps in Figure 9 have been created. It can be observed that locally, at the ASAR pixel scale, the correlation between the satellite datasets reaches values larger than 0.4 almost all over the area under study. The lowest correlation (0.1 < R < 0.3) can be associated to the closeness to the water course, which crosses the region (Figure S4b in the supplementary material). With respect to the Spanish and Irish sites, the Sodankylä cell exhibits poorer spatial agreement between the satellite SM time series. A possible reason may be the forest coverage characterizing this area, as well as the unsuitability of the SM retrieval algorithm in handling data acquired at near-boreal latitudes.

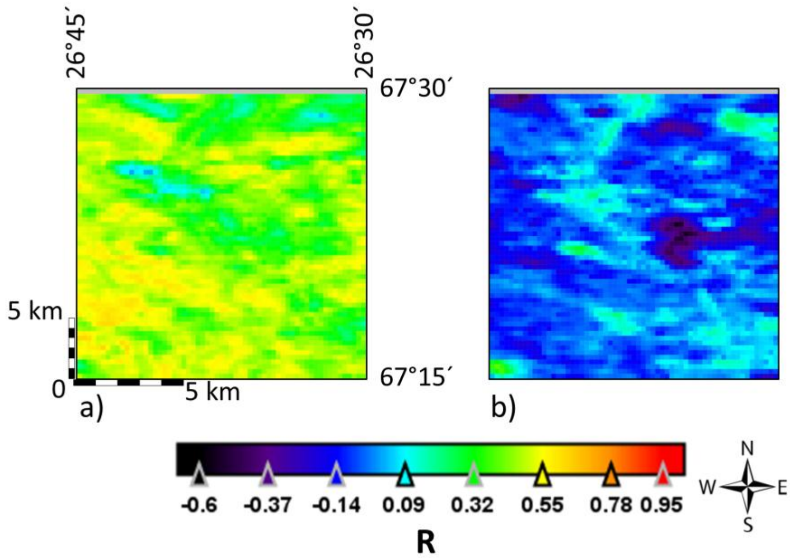

Figure 9. (**a**) ASAR SM *vs.* ECV SM and (**b**) ASAR SM *vs. in situ* SM correlation maps evaluated for each ASAR WS pixel (1 km × 1 km after resampling) within the Sodankylä (FMI) ECV size cell.

By comparing the correlation maps displayed in Figure 9, the same patterns of pixels characterized by similar correlation values can be observed. Nevertheless, the highest correlation patterns obtained by relating the ASAR SM time series with the *in situ* SM measurements (Figure 9b) are those where the poorest agreement is achieved between ASAR and ECV SM. On the contrary, the large higher correlation zones in Figure 9a correspond to those where the representativity of the ground SM measurements is worst (Figure 9b). Very low and negative correlation values ($R < -0.4$) can be noted in the central area of the ECV cell (Figure 9b) where peat bogs occur (Figure S4b).

Figure 10 shows the correlation maps resulting from the study carried out over the ECV cells including the GTK *in situ* stations. The capability of the ECV SM product in representing the soil moisture conditions at the ASAR pixel scale is quite variable. The soil moisture trend is better represented by the ECV SM datasets in Ilomantsi and Kuusamo, where a large percentage of the ASAR size pixels exhibits R values larger than 0.7 (Figure 10a). Nevertheless, the Ilomantsi cell exhibits also patterns characterized by low correlation (R = 0.3), that could be possibly related to the peat bog coverage (Figure S5b in the supplementary material) or to the proximity to water bodies. The correlation between ASAR and ECV SM time series is rather homogenous and poor over the Pori and Suomussalmi cells, equal to 0.3 on average. An even lower correlation area can be observed in Pori ($-0.14 < R < 0.09$), which is classified as peat bog in the CLC2006 map (Figure S5b in the supplementary material).

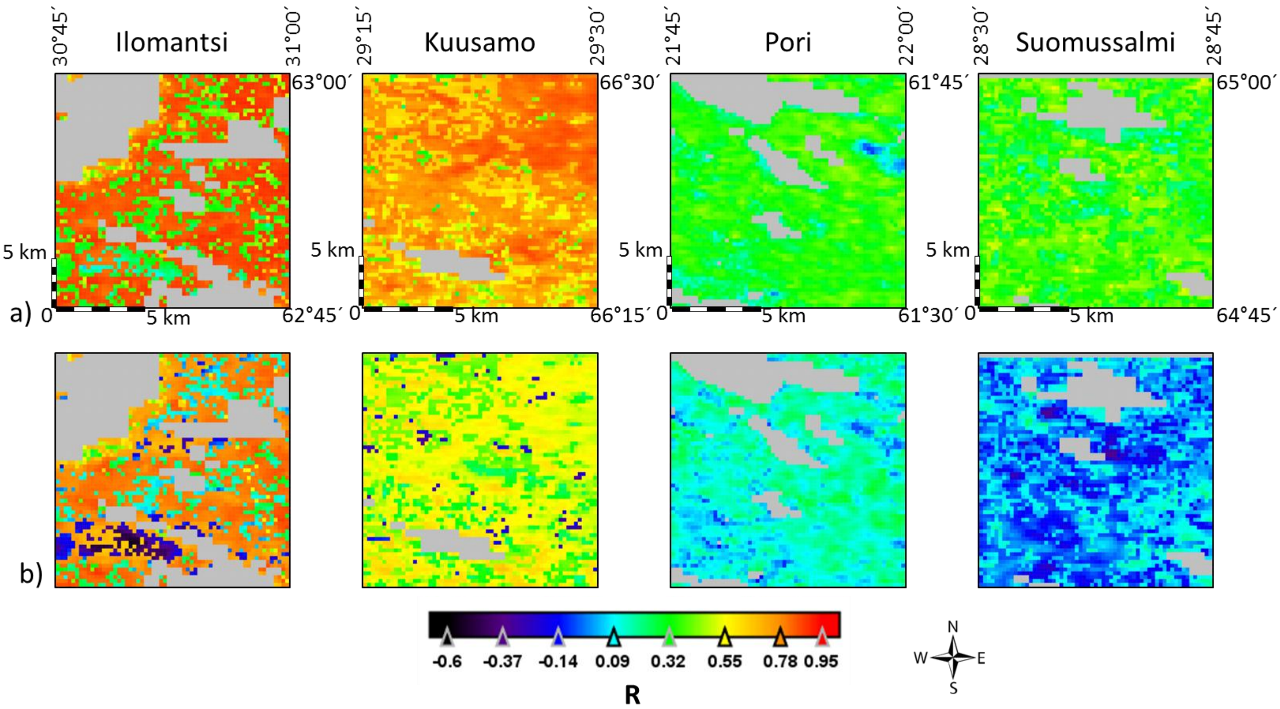

Figure 10. (**a**) ASAR SM *vs.* ECV SM and (**b**) ASAR SM *vs. in situ* SM correlation maps evaluated for each ASAR WS pixel (1 km × 1 km after resampling) within the GTK ECV size cells.

The spatial analysis of soil moisture through the comparison between the ASAR SM time series and the ground measurements provided consistent results (Figure 10b): the highest correlation values belong to the ASAR pixels within the Ilomantsi cell, while the poorest agreement between the datasets occurs in Suomussalmi, where negative R values characterize most of the pixels. Some small negative correlation patterns occur also in the south-west corner of the Ilomantsi ECV cell (Figure 10b), possibly due to the presence of peat bogs, or to the proximity to water bodies.

5. Discussion

This work has focused on the quality assessment of the latest released version of the global soil moisture product provided through the ESA CCI program. The long SM time series (up to five years of observations) collected over three regions in Spain, Ireland and Finland have been temporally and spatially compared to the finer spatial resolution SM product retrieved from ASAR WS acquisitions, and to *in situ* soil moisture datasets.

The suitability of using ASAR WS data for the purpose of this study has been proved by comparing the retrieved SM time series with the ground measurements. In fact, high correlation values have been observed both in Spain and Ireland. In contrast, poor agreement has been found by comparing the ASAR SM datasets and *in situ* measurements recorded at the Finnish sites. Such outcomes can be possibly due to the unsuitability of the soil moisture retrieval algorithm in accurately processing satellite acquisitions taken at latitudes higher than 60° north. In fact, data are resampled on a regular grid, regardless of the geolocation of the observed areas. Such an approach leads to a less precise backscattering estimation at the Northern latitudes, and therefore it introduces a further error in the retrieval of soil moisture. Indeed, all the dataset inter-comparisons carried out in this study provided the weakest correlations at the Finnish sites. Beside the algorithm related issues, several other possible reasons could be associated to this poor performance. Firstly, the area contained within these ECV cells is dominated by forests. Dense vegetation cover attenuates the backscattered signal and decreases the sensitivity of the radar backscatter to soil moisture [69]. Secondly, the GTK *in situ* soil moisture sensors are buried at a depth of 0.1 m which is beyond the depth at which the satellite is sensitive to surface soil moisture. Nevertheless, no significantly improved correlation values have been found for the FMI Sodankylä ECV cell, where the *in situ* sensor is buried at a depth of 0.02 m. Similar low correlations have been observed in [26] using ASCAT data and in [21] for the northern latitudes. Conversely, in [70] relatively high correlations have been evaluated in Norway between both ASCAT ($0.68 < R < 0.72$) and AMSR-E ($0.52 < R < 0.64$) SM retrieved data and *in situ* measurements taken by sensors buried at a depth of 0.1 m. However, the analysis carried out in the present work displayed reasonable agreement between the ASAR and ECV SM datasets, with R values varying between 0.41 and 0.51 in all the Finnish study areas. In [26], the authors hypothesize that the poor correlation found between SM measurements taken at the FMI *in situ* station and ASCAT retrieved soil moisture values may be partly explained by improper freeze/thaw flagging. They achieved increased correlation by excluding from the dataset comparisons of those measurements recorded in early spring, when soil moisture is still artificially low due to frozen soil. In order to verify whether an inaccurate flagging of the ECV SM product occurred, we exploited the soil temperature information provided together with the soil moisture data *in situ*, and we excluded from the validation exercise those observations taken over frozen soil (temperature below 0 °C). However, such an approach did not lead to any significant improvement or variation in terms of correlation. A possible reason could be the small number of observations taken over frozen soil that did not lead to any major change of the SM datasets.

Quite high correlation values between the ECV SM and ASAR SM time series in the Spanish and Irish regions demonstrated the capability of the ECV SM product in describing the soil moisture temporal dynamics, despite its coarser spatial resolution. Even better agreement has been observed between the ECV SM datasets and the ground measurements recorded at the Irish Solohead station and at many of the Spanish sites. Such results are consistent with the outcomes provided in previous works dealing with the validation of satellite SM products by using ground measurements taken at the REMHEDUS stations. For instance, in [25,27], the authors compared the earlier version of the ECV SM dataset and *in situ* SM measurements recorded at a number of REMHEDUS stations. In [25], the average correlation was evaluated equal to 0.63 (±0.036). In [27] results are provided in terms of Spearman correlation, which varies within the interval 0.6–0.7. It is worth noting the fact that the quality assessment of the latest released version of the merged ECV SM product exhibited higher correlations in all the Spanish ECV size pixels. In fact, we found correlation values generally higher than 0.7. Similar results have been observed in previous works where the SM time series recorded at the REMHEDUS stations have been compared to only ASCAT [26], or both ASCAT and AMSR-E SM products [71].

The actual improvement of the ECV SM product has been observed also by carrying out the analysis at the Irish sites, where the SM datasets inter-comparisons provided enhanced results in terms of correlation, with respect to the findings published in [33]. In [60,72], correlation values calculated between ASCAT SM and *in situ* values taken in humid regions are similar to those calculated at the Irish sites between ECV SM data (in our work, generated by using only ASCAT acquisitions) and *in situ* measurements. Our results are also consistent with those presented in [52], where the soil moisture retrieved from ASAR GM acquisitions has been compared with that derived from ERS scatterometer data and *in situ* measurements.

The typical seasonal variation of soil moisture has been quite well captured by the *in situ* SM time series. By carrying out the comparison between the three SM datasets on a seasonal basis, in [33] it was observed that the ECV SM product failed in capturing the wettest and driest conditions in Ireland, as the poorest agreement between satellite derived SM time series and ground measurements was found in winter (wettest season) and summer (driest season). Despite the present study has shown an actual improvement of the ECV SM dataset in this regard, the seasonal based analysis confirmed what was previously observed. This is possibly due to the limited number of available satellite images for the retrieval of the soil moisture by applying the change detection algorithm, which is likely to lead to the underestimation of the sensitivity of the microwave signal to soil moisture (the difference between the driest and wettest signal) [73,74]. This can explain the low correlation between ASAR and *in situ* SM data in winter and summer observed in most of the sites analyzed in this study. On the other hand, the highest correlation values between the satellite SM time series and the *in situ* datasets have been achieved in spring and/or autumn, both in Ireland and in Spain. In spite of being located in different climate zones, Southern Ireland and Northern Spain are both characterized by wet winters and dry summer. As discussed in [33], when heavy and/or continuous precipitation occur over a poorly-drained soil, a water layer could persist on the surface, reducing the satellite microwave backscattering sensitivity to soil moisture and, hence, providing incorrect estimates of the moisture content. Typical poor drained soils are those with a high clay percentage content, such as Solohead in Ireland [33] (22%) or the REMHEDUS stations M09 (26%) and L07 (33%) within the ECV-A [38,41]. In contrast, summer is the driest season, during which the vegetation reaches the maximum growth in Ireland. This may affect the quality of the retrieved soil moisture from SAR and scatterometer images. The seasonal correlation values evaluated for each Finnish site under study are generally very low or even negative. However, there is some consistency with the results achieved in the other areas, as the best agreements have been observed in spring at Kuusamo station, and in autumn in the other sites. Aiming at the understanding of the extent to which geophysical factors, such as soil texture, terrain composition and altitude, affect the retrieved ECV SM product values, the spatial distribution of soil moisture has been investigated at the ASAR scale (1 km) within the ECV size pixels. The approach here adopted makes use of actual observations covering the whole area, differently from classical methods which analyze the soil moisture spatial variability through geostatistical analysis by using hydrological models and *in situ* networks over wide regions.

In [75], it was observed that heavier rains and higher mean moisture contents are often associated with lower spatial variability (CV). In principle, the spatial distribution of surface soil moisture content is controlled by environmental attributes, such as land use and topography. In this work we firstly analyzed the possible relationship between the average of soil moisture retrieved from ASAR WS acquisitions over the ECV cells and the CV. In [66], the authors observed that the SM spatial variability increases over sandy soil as the soil dries, reaching the maximum CV near the residual moisture content. Such behavior is well described by a decreasing power function. However, above SM values of 0.2 $m^3\ m^{-3}$, a decreasing linear function is an effective approximation of the relationship between soil moisture and CV values. A linear relationship was found also in [67,68], where the authors focused their study about the spatial variability of soil moisture over humid grassland. The more recent work presented in [33] confirmed what has been previously observed: by focusing on the spatial variability of soil moisture over the Irish grasslands, a decreasing power function was found to be a very good approximation of the relationship between SM and CV ($R^2 > 0.87$). Results achieved by replicating the study over the sandy soil of the semi-arid Duero Basin region are consistent with those described above, with a coefficient of determination higher than 0.8 in all the ECV cells. By comparing the soil moisture variability in wet and dry catchments in New Zealand and Australia, respectively, the study published in [76] highlighted that the decreasing variability associated to the increasing moisture content, and the increasing variability exhibited at the drier locations, are due to differences in the seasonal patterns of controlling processes associated with seasonal changes in spatial mean soil moisture. While, in [33], the ability of ASAR WS retrieved SM data to track this full spectrum of varying moisture content and seasonal behavior was proved, in the Spanish sites no evidence of a specific seasonal spatial variability could be observed. Indeed, the driest soil conditions associated to the highest spatial variability (CV = 1.0–1.4) occurred in spring. However, because such extreme low soil moisture occurrences occur only twice along the multi-year period of observation, we could hypothesize that these dry soil conditions were unusual. While winter soil moisture observations are mainly associated to wetter soil conditions and lower CV, summer and autumn ASAR SM values are quite variable as well as the associated SM spatial variability over the ECV size pixels ($0.19 < CV < 0.65$).

A decreasing power function has been found to estimate quite well the spatial variability of soil moisture associated to its amount over the Finnish sites as well. In Finland soil moisture values are generally lower than 0.2 and more homogenously distributed over the ECV cell ($0.19 < CV < 0.4$).

The spatial variability of soil moisture has also been investigated by comparing SM time series in each ASAR pixel to the corresponding ECV SM dataset. High correlation ($R > 0.5$) values have been evaluated all over the four Spanish regions, proving the capability of the coarser spatial resolution product in capturing the soil moisture behavior within quite large areas. Patterns of pixels exhibiting poorer agreement between the datasets (low R) are due to artificial surfaces which have not been accurately masked out in the pre-processing phase (north-west corner), or correspond to areas covered by forests (North and Middle East side), whose presence hinder the accurate retrieval of soil moisture from microwave satellite acquisitions. Similarly, vineyard and fruit trees lead to quite large patches of ASAR pixels characterized by low correlation ($R < 0.3$) in the ECV-A cell. Correlation maps generated by comparing ASAR SM and *in situ* SM datasets in each 1 km × 1 km pixel provided a picture of the representativity of the ground measurements over the ECV size pixels. Despite the larger spatial scale difference led to a slight worsening of the performance, correlation maps are consistent with those generated by using the ECV SM dataset. The correlation maps generated through the ASAR and ECV SM time series comparison at the SAR spatial scale over the Irish sites further demonstrated the enhancement of the CCI SM product with respect to the previous released version [33]. Although poorer agreement has been noted between ASAR and *in situ* SM datasets, the highest and lowest correlation patterns correspond well to those observed by comparing the satellite SM time series.

Issues related to the adopted SM retrieval algorithm, as well as the presence of forests all over the Finnish regions led to generally lower correlation values between the satellite SM products at the ASAR spatial scale. Nevertheless, a rather good agreement between the SM time series is achieved in the FMI cell, where few lower correlation patterns of ASAR pixels occurred in the proximity of the water course crossing the ECV cell and over peat bogs. The correlation map derived from the comparison between ASAR and *in situ* SM datasets taken at Sodankylä station resulted to be almost complementary to the one generated from the satellite SM time series comparison. The geographic coordinates of the FMI station pinpoint the site in proximity of the river and in the middle of the ECV cell. Therefore, the ground measurements are likely to better represent the soil moisture conditions in those ASAR pixels characterized by the same features as the station site.

The effect of specific land covers on the representativity of the ECV SM product has been highlighted also within the GTK cells, where the presence of peat bogs and the proximity to water bodies lead to lower correlation values associated to the corresponding ASAR pixels.

6. Conclusions

This paper presented an inter-comparison study of two satellite derived surface soil moisture products with *in situ* measurements in three European countries belonging to different climate zones. The main objective of this work was to assess the quality of the latest released CCI ECV SM product by investigating its ability to capture the same relative temporal behavior as the finer spatial resolution ASAR SM dataset. Regional (at ECV cell spatial scale) and pixel (at ASAR spatial scale) based analysis have been carried out. *In situ* soil moisture observations were also used as a reference to verify the accuracy of both the satellite SM products.

Without using any hydrological model or dense *in situ* networks, the validation activity presented in this work provided results consistent with those published in previous papers using different sensors and classical methods. Such an outcome demonstrated that our approaches are efficient and cost-effective validation techniques for low-resolution SM products.

The study proves that the coarse scale ECV product is representative of the temporal soil moisture variations observed through finer scale ASAR-derived and *in situ* soil moisture observations at the selected study sites. Strong correlations were observed over humid and semi-arid sites. Specifically, the satellite-derived SM products inter-comparison provided correlation values ranging between 0.70 and 0.73 in the Irish sites, and between 0.58 and 0.80 in all the analyzed Spanish ECV cells. Even better agreement has been observed between the ECV SM datasets and the ground measurements recorded at the Irish Solohead station (R = 0.83) and at many of the Spanish sites ($0.70 < R < 0.86$). Weaker correlations between ASAR and ECV SM time series were observed over the Finnish sites ($R < 0.5$), irrespective of the method used for excluding frozen soil condition observations. Poorer results, highlighted by even negative correlation values, have been observed when comparing satellite SM products with ground measurements.

The quality assessment of the ECV SM product through the ASAR pixel-based analysis exhibited R values larger than 0.55 all over the Spanish and Irish ECV cells, where also very high correlation patterns have been observed. Poorer agreement generally occurred over the FMI and GTK regions, where R lies below 0.5, with the exceptions of Ilomantsi and Kuusamo where quite large patterns of ASAR pixels characterized by very high correlation values ($0.7 < R < 0.95$) have been observed.

The effect of geophysical factors, such as soil type, topography and land cover, on the spatial variability of soil moisture and on the accuracy of satellite-derived soil moisture products, has been also investigated. In terms of soil type, it has been found that less accurate SM values are estimated over soil with higher clay content. Although the areas under study are characterized by quite low complex topography, it has been observed that the quality of the satellite-derived SM datasets decreases over the Irish regions located at higher altitudes [33]. Concerning the influence of specific land cover on the ECV SM quality, we found that the presence of forests (tall or dense vegetation), peat bogs or the proximity to water bodies, lead to a poorer representativity of the satellite-derived SM product.

On the basis of the overall outcomes of this work, we can state that the ECV SM product is a good representation of the soil moisture condition over the $0.25° \times 0.25°$ cell. Moreover, an improvement of the quality of the latest released version of the ECV SM dataset has been proved by comparing the results reported in the present manuscript with those published in [33]. However, although providing confidence in the use of the ECV SM product, results and observations presented in this work highlighted also the need of further investigating on the source of error related to SM retrieval algorithms, particularly over high latitude areas (*i.e.*, north of 60 deg), as well as on the sensitivity of the accuracy of satellite-derived SM datasets to the soil type and clay content, forest coverage and complex topography. Future studies addressing these issues may benefit from the results presented in this work to be used as a benchmark for a better understanding of soil moisture products.

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Author Contributions

Chiara Pratola carried out all of the analyses under the supervision of Edward Dwyer and Brian Barrett. Alexander Gruber performed the ASAR SM retrieval. All of the authors contributed to the preparation of the paper through their review, editing and comments. Brian Barrett provided some of the plots shown in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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