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Product User Guide (PUG)

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Prepared by

Earth Observation Data Centre for Water Resources Monitoring (EODC) GmbH

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Definitions, acronyms and abbreviations

Acronym	Full Name
AMI-WS	Active Microwave Instrument - Windscat (ERS-1 & 2)
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System
ASCAT	Advanced Scatterometer (Metop)
ATBD	Algorithm Theoretical Basis Document
CCI	Climate Change Initiative
CECR	Comprehensive Error Characterization Report
DARD	Data Access Requirement Document
DMSP	Defense Meteorological Satellite Program
DPM	Data Processing Model
EASE	Equal-Area Scalable Earth
ECV	Essential Climate Variable
ERA-Interim	ECMWF Reanalysis Interim
ERA-Land	ECMWF Reanalysis land water resources dataset
ERS	European Remote Sensing Satellite (ESA)
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FTP	File Transfer Protocol
GCOS	Global Climate Observing System
GLDAS	Global Land Data Assimilation System
IODD	Input Output Data Description
ISEA	Icosahedron Snyder Equal Area
ISEA4H	Icosahedron Snyder Equal Area (ISEA) Aperture 4 Hexagonal Dokuritsu-gyosei-hojin Uchu Koku Kenkyu Kaihatsu Kiko, (Japan Aerospace Exploration Agency)
JAXA	
JULES	Joint UK Land Environment Simulator
LDAS	Land Data Assimilation System
MERRA	Modern-Era Retrospective Analysis for Research and Applications
METOP	Meteorological Operational Satellite (EUMETSAT)
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis
NaN	Not A Number
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form



NWP	Numerical Weather Prediction
PDF	Probability Distribution Function
PSD	Product Specification Document
PUG	Product User Guide
RFI	Radio Frequency Interference
SAR	Synthetic Aperture Radar
SM	Soil Moisture
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SRD	System Requirements Document
SSD	System Specification Document
SSM	Surface Soil Moisture
SSM/I	Special Sensor Microwave Imager
SURFEX	SURFace EXternalized module
SWI	Soil Water Index
TBD	to be determined
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
UTC	Coordinated Universal Time



Executive Summary

This Product User Guide provides the specifications of the ESA CCI Soil Moisture (SM) v09.1 product. The targeted audience of this document is mainly the product users. The ESA CCI SM v09.1 product consists of three surface soil moisture data sets: The “ACTIVE Product” and the “PASSIVE Product” were created by fusing scatterometer and radiometer soil moisture products, respectively; The “COMBINED Product” is a blended product based on the former two data sets. Data files are provided as NetCDF-4 classic format and comprise global merged surface soil moisture datasets at daily temporal resolution. The data set spans over 40 years covering the period from November 1978 to December 31st 2023.

The theoretical and algorithmic basis of the product is described in the Algorithm Theoretical Basis Document (ATBD) for ESA CCI SM v09.1 (Stradiotti et al. ,2024), and reported by Gruber et al. (2019). The SNR (signal-to-noise-ratio) merging algorithm introduced for the first time in version 3.2 is described in Gruber et al. (2017), and later updated in Gruber et al. (2019), and include an overview of the errors of the soil moisture datasets for those version numbers. Further documentation relating to the product can be found on the CCI Soil Moisture project web site (<http://www.esa-soilmoisture-cci.org>).

The location and full access details to the product are provided to users after completion and verification of a user registration form. Users can either register to access the product from the User Registration form on the CCI Soil Moisture Website, or can directly access the product, without requirement for registration from ESA’s CCI Open Data Portal¹.

The product is provided in a format that currently complies with the minimum standard format requirements as detailed by the CCI data standards working group (DSWG) (Bennet and James, 2013). For this reason ESA CCI SM v09.1 is provided in NetCDF-4 classic format and is also compliant with the NetCDF Climate and Forecasting group best practice² (Eaton et al., 2017).

The ACTIVE product of ESA CCI SM (consisting of soil moisture from the ERS and ASCAT sensors) uses the latest available version of the H SAF ASCAT SSM product (HSAF 2018). Improvement of the ACTIVE product of ESA CCI SM is therefore largely dependent from developments carried out by H SAF. Descriptions of ASCAT Soil Moisture in this document are just to highlight the differences between Scatterometer/Radiometer derived soil moisture products and should help the users of ESA CCI SM understand which product fits best for their purpose.

¹ <http://cci.esa.int/data>

² <http://cf-pcmdi.llnl.gov/documents/cf-conventions/latest-cf-conventions-document-1>



1 Introduction

The purpose of the Product User Guide (PUG), intended for users of the ESA CCI soil moisture product, is to describe the Essential Climate Variable (ECV) data product with a focus on:

- the geophysical data product content
- the product flags and metadata
- the data format
- the product grid and geographic projection
- the tools available

Since the users of the soil moisture product come from a wide and varied audience, with differing levels of knowledge in the field of retrieval of soil moisture information from satellite observations, this document provides some relevant background aiming to enable a common understanding (further information is available in the ATBD for v09.1, Stradiotti et al., 2024). Section 2 provides an overview of the pivotal role that soil moisture plays within the environment and section 3 provides an overview of its retrieval from earth observation satellites.

Section 4 provides details of the product characteristics including the geophysical parameters that are available in the products, their respective data volumes, and the physical structure and format of the product and associated quality flags and indicators.

In Section 5 the opportunity is taken to provide an overview of key points relating to data access, team contact, and restates the acknowledgement to be cited in the use of the ECV SM products.

For reference, Section 6 provides definitions of some common terminology used within the earth observation domain and the bibliography is provided in Section 7.



2 Soil Moisture within the environment

The central role of soil moisture for the environment is well known. Its contribution e.g. to hydrological and agricultural processes, linked to e.g. runoff generation, drought development, and irrigation, respectively, is evident. Moreover, it significantly impacts the climate system through feedbacks to the atmosphere. As a source of water for evapotranspiration over the continents, soil moisture is involved not only in the water but also in the energy cycle. Approximately 60% of precipitation over land is returned to the atmosphere as evapotranspiration (Oki and Kanae 2006), and this flux also uses up more than 50% of all net radiation over land (Dirmeyer et al. 2006). The investigations of possible effects of soil moisture on the climate date back to the 70s and 80s (Shukla and Mintz 1982). In the recent years soil moisture-climate interactions received an increasing attention (Seneviratne et al. 2010). Moreover, in 2004 soil moisture was recognised as an essential climate variable (ECV) and finally added in 2010 to the list of terrestrial ECV by the Global Climate Observation System (GCOS).

A number of numerical experiments have established the sensitivity of atmospheric fields to soil moisture dynamics (Diffenbaugh et al. 2007; Fischer et al. 2007a; Jaeger and Seneviratne 2011; Koster et al. 2004a; Seneviratne et al. 2006b). On short time scales, which are relevant for numerical weather prediction, soil moisture variations seem to have a more significant influence on the surface energy budget and on the planetary boundary layer structure than changes in other terrestrial variables such as roughness or albedo (Mahfouf 1991). The importance of soil moisture for sub-seasonal and seasonal forecasting is also well established (Koster et al. 2004a; Koster et al. 2010), and is additionally impacted by the memory associated with soil moisture (Entin et al. 2000; Seneviratne et al. 2006b; Vinnikov et al. 1996; Wu and Dickinson 2004).

Most of the impacts of soil moisture on the climate system are induced by its coupling to evapotranspiration, and resulting impacts on temperature and precipitation (Seneviratne et al. 2010). Strongest feedbacks between land and atmosphere are expected in regions with soil moisture-limited evapotranspiration regimes, given by the control of soil moisture on evapotranspiration (Hirschi et al. 2011). Mostly affected are transitional zones located between wet and dry climates (Koster et al. 2004a; Seneviratne et al. 2006b), where soil moisture is limiting for evapotranspiration and can strongly vary on both intra-annual and inter-annual time scales. This coupling has been shown to be of strong relevance for climate variability in mid-latitude regions, in particular for the occurrence of heat waves (Fischer et al. 2007c). Impacts on precipitation are less consistent across studies, but are found to include a number of direct and indirect feedbacks (Findell and Eltahir 2003). In the context of climate change, regions with transitional climate regimes are expected to be shifted poleward, with a possible increase in climate variability induced by soil moisture feedbacks in regions with currently wet climate regimes. Supporting numerical studies, recent observational studies



have shown evidence for soil moisture impacts on hot extremes (Hirschi et al. 2011) as well as global evapotranspiration (Jung et al. 2010).

Furthermore, it is possible that soil moisture anomalies may also affect large-scale circulation patterns. For the United States, the study of Pal and Eltahir (2003) has suggested that soil moisture anomalies over relatively small regions may induce floods and droughts not only locally, but also over distant areas. A relationship between the depletion of early summer soil moisture and the development of heat lows over the Mediterranean region in late summer has also been noticed in Haarmsa et al. (2009).

A factor influencing soil moisture-climate interaction is the vegetation. Transpiration is the evaporation through the plant stomata, which is regulated by several factors including soil moisture. Therefore, land cover and its variation in time are expected to play a crucial role for soil moisture-climate interactions. A possible impact of vegetation cover during the European heat wave 2003 was shown in Zaitchik et al. (2006) by comparing temperature anomalies over pastures and forests, showing higher heat anomalies over the pastures during the August peak of the 2003 European summer drought and heat wave. The study by Teuling et al. (2010), based on measurements from the Fluxnet network, also identified differences in the energy fluxes over grassland and forest sites during heat wave days, although the results were in partial contrast to those of Zaitchick et al. (2006). For typical heat wave days, it was found that the forest led to a higher warming of the atmosphere than grassland, because the former used less energy for evapotranspiration than the latter. However, the implications are that in the long term the soil moisture depletion over grassland is faster than over forest, and consequently grassland would lead to higher warming after long dry and hot periods. This study highlighted the time-scale dependence of feedbacks between land surface processes and the climate, and its strong relation to soil moisture dynamics.

All of the mentioned feedbacks and interactions are particularly relevant for drought development, and especially agricultural (or soil moisture) drought. This is another area where the increasing availability of soil moisture observations can help investigate and diagnose the underlying driving processes, e.g. the respective role of large-scale circulation patterns versus land-atmosphere feedbacks for drought development (Rowell and Jones 2006; Schubert et al. 2004).



3 Soil Moisture Data from Earth Observation Satellites

This section provides a general overview of the different types of data and the methods, technologies and processes employed to generate the Soil Moisture Data Products from the measurement to their application/analysis.

3.1 Microwave Instruments onboard Earth Observation Satellites

There are two principal types of remote sensing, corresponding to the following types of microwave instruments: (a) scatterometers and radars which measure the radar backscattering coefficient σ^0 in physical units [dB] or [m^2/m^2], and (b) radiometers which measure the brightness temperature T_B in physical unit [K]. Instruments in group (a) are called *active* because they use their own source of electromagnetic energy for the measurement, while the ones in group (b) are referred to as *passive* instruments because they measure energy that is reflected or emitted from the earth surface.

Figure 1 identifies the active (at the bottom) and the passive (at the top) microwave instruments that are used for the production of the Soil Moisture ECV Data Products, their hosting satellites, and their times of operation.

- AMI-WS and ASCAT are (active) C-band scatterometer instruments onboard the ERS and METOP satellites, respectively. Note that AMI-WS is still labelled “SCAT” in the picture, though the former name is nowadays preferred.
- SMMR, SSM/I, TMI, AMSR-E, AMSR-2, MIRAS, SMAP L-band Radiometer, GMI, MWRI and WindSat are (passive) multi-frequency radiometer instruments onboard the Nimbus-7, DMSP, TRMM, Aqua, GCOM-W1, SMOS, SMAP, GPM, FY and Coriolis satellites, respectively.

These instruments are characterized by their high suitability for Soil Moisture retrieval and their technological maturity.

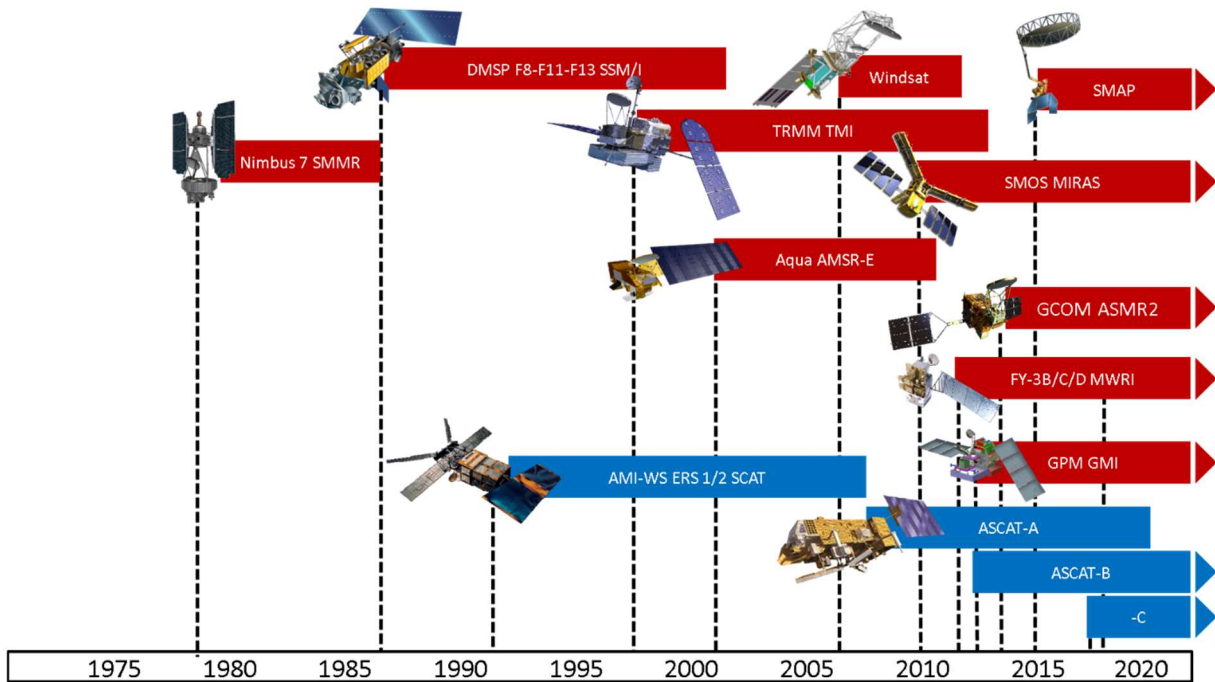


Figure 1: Microwave Instruments used for the generation of Soil Moisture ECV Data Products (version v09.1)

The ESA CCI SM processing system is designed to allow the integration of new instruments during its operational use phase. Since the initial product, many different satellite products have been added including SMAP, GPM and FY-3B.

In a single overpass (one orbit around the Earth) the satellite’s instrument observes a wide swath of the land surface of a width somewhere between 500 to 1400 km. Satellite swath data is made of individual nodes (syn. pixels), each node being a measurement of either backscattering coefficient σ^0 (active) or brightness temperature T_B (passive) from an area (footprint) of 10-50 km diameter on the Earth surface.

Figure 2 shows the geometry of the wide swath imaging measurements made by AMI-WS (SCAT) and ASCAT instruments onboard the ERS and METOP satellites. The AMI-WS scatterometer (left part of Figure 2) consists of three antennae producing three beams looking 45° forward, sideways (90°), and 45° backward with respect to the satellite's motion direction along the orbit. The measurements from each beam consist of 19 nodes spaced 25 km apart. As the satellite beams sweep along the Earth surface yielding an approximately

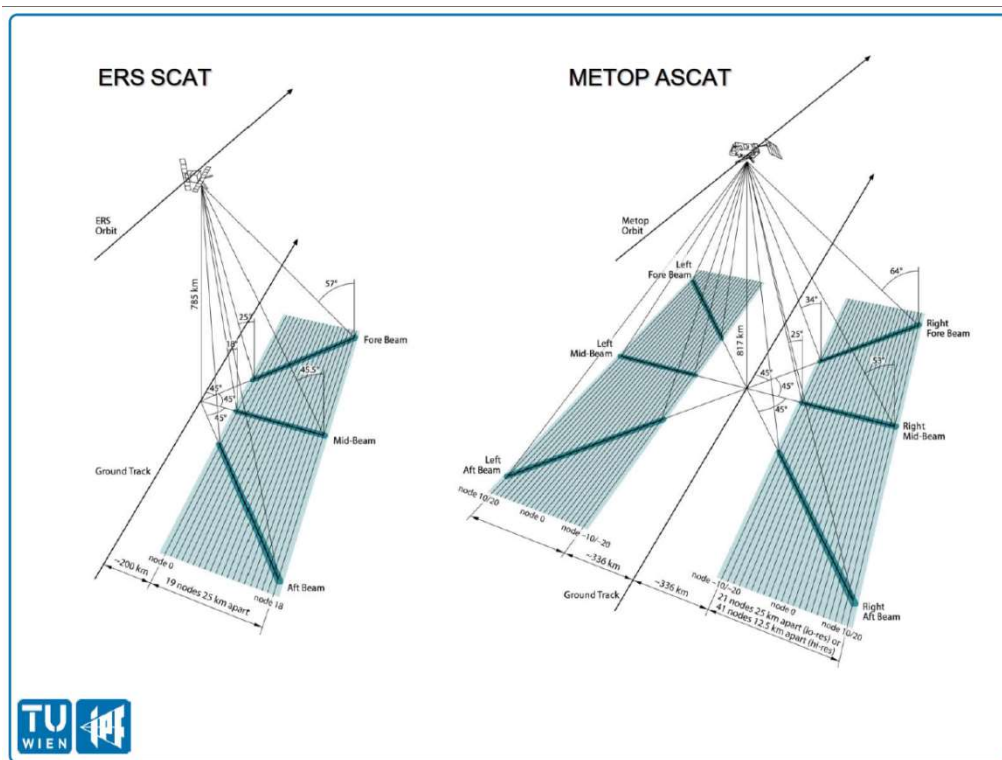


Figure 2: Beams and Wide Swaths of AMI-WS and ASCAT Instruments

500 km wide swath, each node produces its own σ^0 backscatter measurement, integrated over an area around 50 km in diameter. The three measurements originating from the three beams during the single satellite overpass are called triplets.

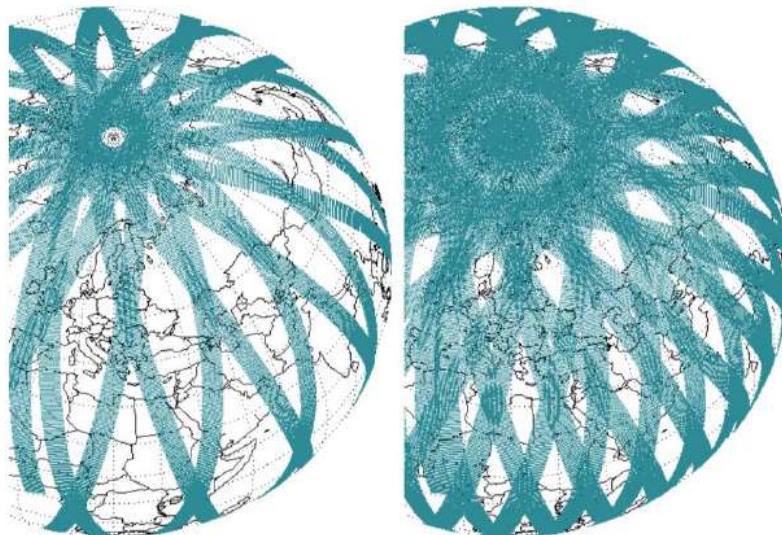


Figure 3: Wide Swaths and Daily Global Coverage of AMI-WS (left) and ASCAT (right)

The ASCAT scatterometer (right part of Figure 2) is similar but consists of three antennae on either side, producing six beams. The measurements from each beam consists of 21 nodes



spaced 25 km apart (lo-res) or 41 notes spaced 12.5 km apart (hi-res). While the satellite beams sweep along the earth surface a wide swath is observed on either side.

Figure 3 shows the orbits made by a single ERS satellite (left) and a single METOP satellite (right) and the wide swaths captured by AMI-WS and ASCAT instruments, respectively, during one day of observation time. The wide swaths of ASCAT have near-global revisiting times of 2–3 days.

Development of soil moisture retrieval algorithms from active MRS sensors is not part of the ESA CCI SM project. The latest available H SAF ASCAT SSM CDRs are used as input in ESA CCI SM. For a detailed description and the latest available products visit <http://hsaf.meteoam.it/>.

3.2 Data Processing Chain

The payload data received from a satellite passes through a chain of processing which has the following principal steps:

- Level 0: Reconstructing the raw instrument data from a satellite's payload data transmissions received at satellite ground stations, and archiving them at a data centre.
- Level 1: Converting the raw instrument data of a single overpass swath to calibrated measurements (observations) of radar backscattering coefficient σ^0 in [dB] or [m^2/m^2] (in case of active instrument), or brightness temperature T_B in [K] (in case of passive instrument).
- Level 2: Retrieving the Surface Soil Moisture (SSM) geophysical parameter – in physical units [%] or [m^3/m^3] – from the calibrated measurements of a single overpass swath.
- Level 3: Generating the consistent and global Soil Moisture ECV Data Products by merging the SSM time series acquired from many satellites over many years – this is the objective of the system specified herein.
- Level 4: Analysing the lower level data to determine the state or change of state (events, processes) of regional or global climate systems.

The following section provides a brief survey of the different processing levels tailored to Soil Moisture. There is also a fine-grained organization within the levels, in terms of sublevels or product categories, but these are suppressed in the first survey. A full specification of data processing levels is available in IODD (Kidd et al., 2013).

Levels 0-1:

The steps up to Level 1, from the instrument to the calibrated measurement result, follow the principles of measurement as outlined in (JCGM 2008), and (JCGM 2012). Note that a measurement (syn. observation) is not necessarily made with a single antenna, instrument, or



even a single satellite. Crucial is that the individual measurement devices contributing to the measurement result are synchronized (with sufficient accuracy in space and time) to the spatial-temporal coherency characteristics of the observed source. Therefore, the calibrated measurement may be summed from many antennas (e.g. in case of the SMOS MIRAS instrument, which uses aperture synthesis) or even summed from satellites in formation flying. In any case, because the observations made at different orbits do not satisfy the coherency criteria, Level 1 data are observations from a single overpass.

Levels 2-3:

The situation changes for the Levels 2 and 3, which are about the art of estimating values of quantities that cannot be directly measured with remote sensing instruments. The mathematical-physical basis for this process is that there is a functional relation between object parameters X and instrument observables Y . Symbolically, the relation may be written as $Y = f(X)$ (forward model) or $X = g(Y)$ (inversion). It is known that at any time object parameters X and observables Y have definite values. Once sufficient information is obtained from measurements of Y , estimates of X can be determined under certain conditions, if there is sufficient knowledge of a suitable model or inversion. To indicate this radical difference, this process is no longer called measurement but “retrieval”.

In the case of the ECV Production System the observed object is an area of the top soil surface layer (of approx. 25x25 km size and < 2 cm thickness), and the retrieved geophysical parameter is Soil Moisture, expressed in the physical unit [%] or [m³/m³].

Depending if the measurement was made with an active or a passive microwave instrument, respectively, either a change detection approach or a forward modelling method is utilized. Both methods, like geophysical parameter retrieval in general, require use of additional ancillary data, which can be long-term reference data (historical data, climate data) or model parameters.

Levels 2 and 3 have in common that the retrieved parameters are local state variables: they characterize the state of a local and compact object in space (i.e. a local physical system), at a moment or period in time. They are thus distributions in space (over the land surface in case of Soil Moisture) and time. The difference between Level 2 and 3 is that the parameter retrieved by a process of Level 2 adheres to the locality condition of a single Level 1 measurement, while this condition is relaxed at Level 3. In practice, Level 3 is about merging Level 2 data from different observation times, orbits or instruments.

For full descriptions of the retrieval and merging methods cf. ATBD for v09.1 (Stradiotti et al., 2024) and (Gruber et al., 2019).

Level 4:



At Level 4 analyses of data from Levels 3, 2 or 1 are performed in order to determine the state or the change of state of specific geo-physical systems of interest, in particular regional and global climate systems. Detection of change of state typically involves statistical analysis methods (e.g. trend analysis) and process model calculations (simulations) using lower level data as input.

Present at all Levels of the data processing chain (but omitted in the discussion so far) are processes to determine measures for the degree of uncertainty associated with the resulting data. At Levels 0 and 1 an adequate measure is the measurement uncertainty as described e.g. in (JCGM 2008), and at Levels 2 and 3 the error characterization as described in the E3UB (Scanlon et al. 2020). We do not know what measures are used at Level 4 but we note that results of analyses and simulations may be in the range of evidentiary to indicative.

3.3 Grid Types

The data acquired by a satellite instrument constitute individual measurements per swath node (actually one measurement result per beam, overpass and swath node) and are spatially arranged in the geometry of a *swath grid*, as illustrated in Figure 2. Swath grids are dynamical (with respect to the Earth surface) because they are a projection made by the moving satellite. The Level 0 data are necessarily raster data from a swath grid. Typically, Level 1 and 2 data provided by ESA, EUMETSAT, NASA and JAXA are still in the geometry of swath grids, and annotated with time- and geo-referencing information to allow inference of time and geo-location of each swath node. Data in swath grid geometry are usually distributed as one raster per half-orbit i.e. one raster for the ascending orbit direction and a second raster for the descending orbit direction. The format of geo-referencing information varies; it may be given per raster as a whole or even as (latitude, longitude) coordinates per grid node.

Technically, it can be of advantage to map the swath grid nodes, onto a (spatial) *global grid*³ which is uniformly and statically covering the Earth surface. Cases where mapping to a global grid is already performed at Level 1 are Nimbus-7 SSMR, DMSP SSM/I and SMOS MIRAS, and at Level 2 METOP ASCAT. Note that a global grid maps the space dimensions only, while time-referencing annotation is still maintained for the individual measurements.

Figure 4 shows the equally spaced, equal area WARP 5 global grid used for the ASCAT Level 2 SSM. The principle of construction (indicated in the upper part of Figure 4) is as follows: a) create equally spaced latitude small circles at distances a , and b) on each latitude circle create grid points at discrete longitudes, again with a fixed spacing of a . Due to the construction the global grid has areas with irregularities. The lower part of Figure 4 shows: a) the regularity at origin, b) the divergence at the North Pole, and c) the dislocation at the 180° meridian.

³ The technical term is Discrete Global Grid (DGG), however, as we do not know how a non-discrete (i.e. continuous) grid would look like, we do not use this term herein.

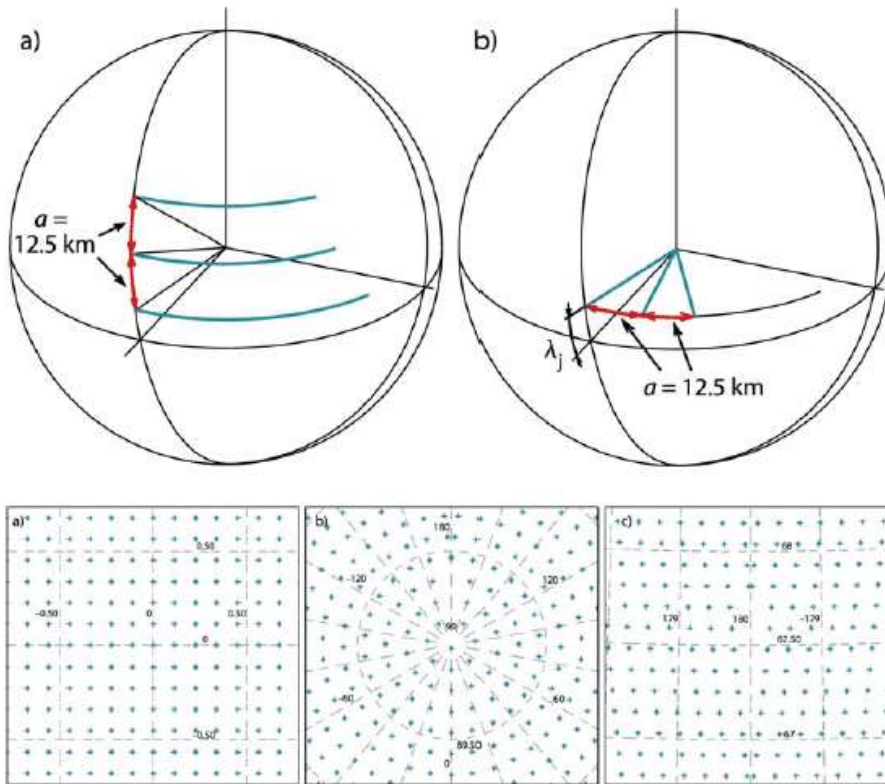


Figure 4: Construction of the WARP 5 Global Grid used for ASCAT L2 Data

Figure 5 a) shows the geodesic grid used for the SMOS Level 1 and Level 2 data, known as Icosahedron Snyder Equal Area (ISEA) Aperture 4 Hexagonal (ISEA4H) global grid. This grid is constructed by a subdivision method. Creating the grid involves subdividing the 20 equilateral triangles forming the faces of the regular icosahedron into more triangles, yielding 20 hexagons and 12 pentagons on the surface of the sphere (the so-called resolution 1 grid). Higher resolution grids are formed iteratively by tessellating the obtained shapes.

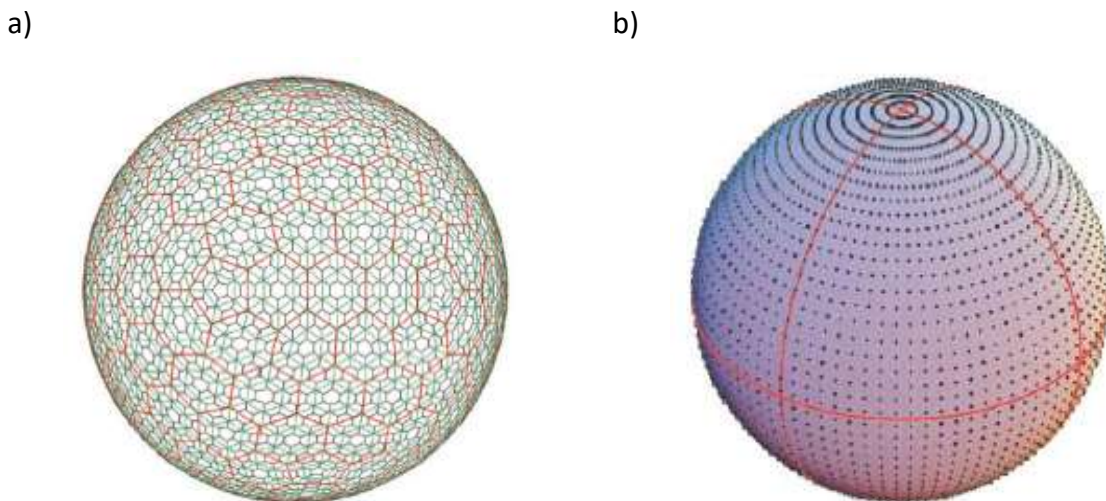


Figure 5: a) Geodesic ISEA4H grid of SMOS; b) regular latitude-longitude grid used for SM ECV

Figure 5 b) shows a regular latitude-longitude grid. Grid points are equally spaced in the latitude-longitude coordinate system, however, as can be readily seen in Figure 5, they are not equally spaced / equal area on the earth surface. This grid type is utilized for the Soil Moisture ECV Data Products.

Still for technical reason, it can be of advantage to proceed further and to map the value distributions onto a *global space-time grid*. This happens usually at Level 3 because it facilitates combining data from many orbits and satellites. Satellite data mapped to a space-time grid can be viewed in two ways: For a given time index we have a raster image that can be projected to and visualized on a geographic map; for a given spatial grid point we have a time series that can be visualized as a graph.

Table 1: Grid Systems used for Calibrated Measurement Data and SSM Geophysical Parameter Data

		Active		Passive						
		ERS AMI-WS	METOP ASCAT	Nimb.7 SMMR	DMSP SSM/I	TRMM TMI	Aqua AMSR-E	Coriolis WindSat	SMOS MIRAS	GCOM-W1 AMSR-2
σ^0/T_B	L1	swath	swath	EASE	EASE	swath	swath	swath	ISEA4H	swath
SSM	L2	WARP5	WARP5	lat-lon	lat-lon	swath	swath	swath	EASE2	swath

Table 1 lists the grid types used for the Level 1 calibrated measurements of radar backscattering coefficient σ^0 and brightness temperature T_B , and the SSM geophysical parameter data.

In the process of generating the Level 3 Soil Moisture ECV Data Products, the SSM geophysical parameter data available in the different grid types are converted into a common space-time grid: a latitude-longitude grid (spatial resampling) and a reference time of 0:00 UTC (temporal resampling). This is the first step to produce a merged and harmonized ECV Data Product on a global and uniform space-time grid with a spatial resolution of 0.25 degree and a temporal resolution of one day.

A web-based tool to visualize and search for grid point information (e.g. geo-location, grid index, surface type) is available here: <https://dgg.geo.tuwien.ac.at/>

For more information about global grid systems cf. (Kidd 2005) and (Bartalis 2009).

3.4 Soil Moisture Data Products

As an example of a Soil Moisture product, Figure 6 shows the average Soil Moisture deviations from the 1991-2020 baseline for the year 2023, as derived from the ESA CCI SM v09.1 COMBINED4 product. Given that the input radiometric and scatterometric data brought into



the data space of the reference land surface model in COMBINED, the values are provided in m^3m^{-3} .

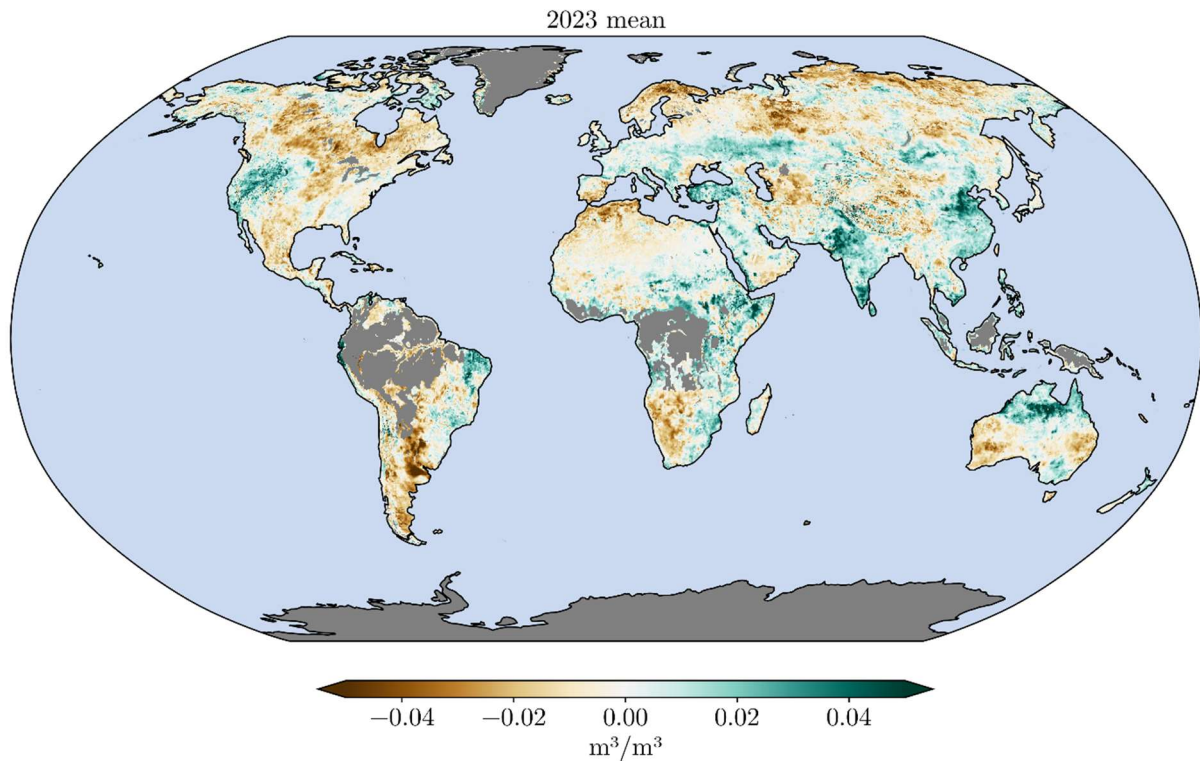


Figure 6: Mean Soil Moisture anomaly for 2023, with respect to the 1991-2020 baseline for the ESA CCI SM v09.1 COMBINED product.

Surface Soil Moisture (SSM) parameter data from ERS AMI-WS and METOP ASCAT are an example of a Level 2 data product. It is retrieved from calibrated measurements of an active microwave instrument using the change detection method of TUW (ERS) and the further developed implementation by H SAF. The method relies upon the multi-incidence observation capabilities of the ERS and METOP scatterometers to model the effects of vegetation phenology. The SSM values of Active soil moisture retrievals are scaled between 0 and 1, representing zero Soil Moisture and saturation respectively. Parameter retrieval is not possible over tropical forest which affects about 6.5% of the land surface area.

Soil Water Index (SWI) parameter data are an example of a Level 3 data product. SWI is a measure of the profile Soil Moisture content obtained by filtering the SSM time series with e.g. an exponential function. Other typical examples of Level 3 products are the estimates of the Soil Moisture content for different soil layers and different temporal and spatial sampling characteristics, tailored to the needs of specific user groups.



3.5 ESA CCI SM Algorithm

The overall setup of systems follows a modular design to make best use of existing European and international services, and to ensure that new satellites and instruments can be integrated. All products integrated into the ESA CCI SM product are Level 2 SM products, further details of which can be found in the ATBD for v09.1 (Stradiotti et al., 2024).

In summary, the major processing steps to produce the ESA CCI SM product are (also shown in Figure 7):

1. Spatial resampling and temporal resampling (including flagging and cross-flagging of observations)
2. Rescaling passive and active level 2 observations into radiometer and scatterometer climatologies (for the ACTIVE and PASSIVE product), and separately rescaling all level 2 observations into a common model-based climatology (for the COMBINED product); in parallel, rescaling all level 2 observations using a L-band satellite reference, in place of the model-based climatology, for the “Model-independent” experimental product
3. Triple collocation analysis (TCA)-based error characterisation of all rescaled level 2 products
4. Polynomial regression between VOD and error estimates to fill spatial gaps where errors could not be reliably retrieved i.e., where TCA is deemed unreliable
5. Merging rescaled passive and active time series into the PASSIVE, ACTIVE, and COMBINED products, respectively.
6. Break-adjusting all products using the method of Preimesberger et al. (2021).
7. The two experimental “Root-Zone” and “Gap-filled” products are generated from COMBINED, the experimental “Model-independent” product is generated in parallel to COMBINED. For more information see the ATBD (Stradiotti et al., 2024)

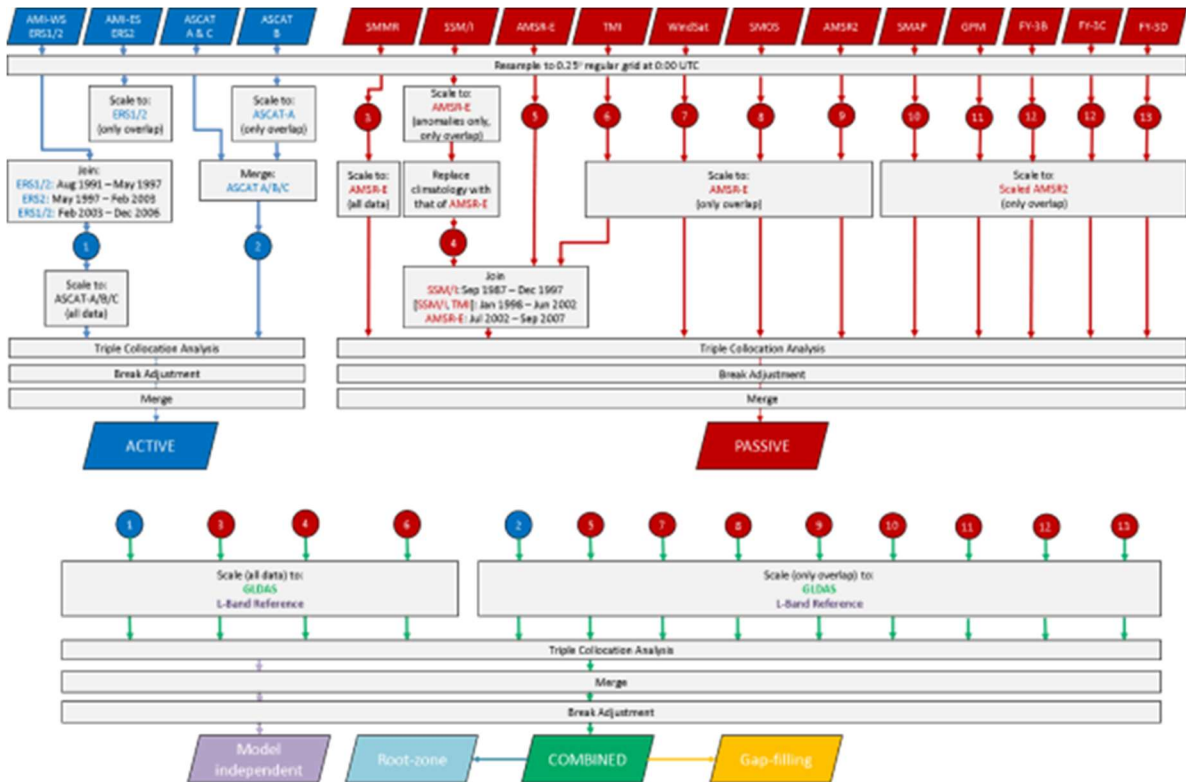


Figure 7: Principal Data Flow for the generation of Soil Moisture ECV Data Products, an overview of the processing steps in the ESA CCI SM product generation (v09.1). A model-independent (purple), a root-zone (blue) and a gap-filled (yellow) product are distributed as experimental products. For more information see the ATBD.



4 Specification of the products

4.1 Soil Moisture

The ACTIVE product is the output of merging scatterometer-based soil moisture data, which were derived from AMI-WS and ASCAT. The PASSIVE product merges data from SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2, SMOS, SMAP, GPM and FY. The COMBINED is directly generated from the Level 2 products used in both the ACTIVE and PASSIVE products. The data sets have been produced following the method as described by (Gruber et al. 2019; Liu et al. 2011; Wagner 2012). Further information can be found in the ATBD for v09.1 (Stradiotti et al., 2024).

The homogenised and merged products provide surface soil moisture with a global coverage and a spatial resolution of 0.25°, and a temporal resolution of 1 day with a reference time at 0:00 UTC. The soil moisture data for the PASSIVE and the COMBINED product are provided in volumetric units [m^3m^{-3}], while the ACTIVE soil moisture data are expressed in percent of saturation [%].

4.2 Product Data Volume

The ESA CCI SM product version v09.1 is provided as global daily images, in NetCDF-4 classic file format and covers the period (yyyy-mm-dd) 1978-11-01 to 2023-12-31 for the PASSIVE and COMBINED products. The ACTIVE product covers the period from 1991-08-05 to 2023-12-31.

Table 2 Temporal coverage and volume size of the products.

Product	Coverage dates	Number of files (days)	Volume size
ACTIVE	19910805 – 20231231	11838	8.8 GB
PASSIVE	19781101 – 20231231	16498	21.3 GB
COMBINED	19781101 – 20231231	16498	23.3 GB
Total	N/A	44834	53.4 GB

4.3 Structure and format of the product

4.3.1 Data file format and file naming

The file format used for storing the data is NetCDF-4 classic. All (NetCDF) files follow the NetCDF Climate and Forecast (CF) Metadata Conventions version 1.7. The NetCDF soil



moisture data files are stored in folders for each year with one file per day. The following file naming convention, based on available CCI ECV standards, is applied:

```
ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc
```

<CCI Project>

Following the file naming convention of CCI data standards working group (DSWG) the name of this project is SOILMOISTURE.

<Processing Level>

The processing level for the ESA CCI SM products is “**L3S**” (super-collated), where observations from multiple instruments are combined into a space-time grid.

<Data Type>

The data type for the ACTIVE product is “**SSMS**” (surface soil moisture degree of saturation absolute), and for the PASSIVE and COMBINED product it is “**SSMV**” (surface soil moisture volumetric absolute).

<Product String>

The product string for the ACTIVE product is defined as “**ACTIVE**”, for the PASSIVE product it is “**PASSIVE**”, and “**COMBINED**” for the COMBINED product.

<Additional Segregator>

Additional segregator not used and not defined.

<Indicative date and time>

This field indicates the date and time for soil moisture data that are stored in the NetCDF file. The format is YYYYMMDDHHmmSS, where YYYY is the four digit year, MM is the two digit month from 01 to 12, DD is the two digit day of the month from 01 to 31, HH the two digit hour from 00 to 23, mm the two digit minute from 00 to 59, and SS the two digit second from 00 to 59. All times relate to UTC.

fv<file version>

The file version number in form xy.z provides information relating the version of the file format that has been used to provide the product. In the global NetCDF header of each data file the product version number specifies the version of the current product. Since product version 02.1 the file version and the product version number are the same.

4.3.2 NetCDF file structure

4.3.2.1 Global NetCDF Attributes

The Global NetCDF attributes are described in Table 3; where differences exist between the ACTIVE, PASSIVE and COMBINED products, these are noted in the table. Global attributes are provided in the data files for two reasons. The attributes “**title**” and “**product version**” provide the minimum usage information about the data, whilst the remaining attributes starting with the “**summary**” attribute provide product discovery metadata for harvesting into catalogues and data federations.

In general, the Global Attributes will be static and not vary between files for the same product version. Explicitly the following attributes vary for every file within a product: “**tracking id**” and “**filename**”.

*Table 3 Global NetCDF Attributes for the ESA CCI SM products. Differences between the ACTIVE, PASSIVE and COMBINED products are noted. * denotes used in the ACTIVE and COMBINED products; † denotes used in the PASSIVE and COMBINED products.*

Global Attribute Name	Content
Title	ESA CCI Surface Soil Moisture COMBINED / ACTIVE / PASSIVE Product
institution	TU Wien (AUT); VanderSat B.V. (NL); Planet Labs (NL); CESBIO (FR), EODC Gmbh (AUT)
contact	cci_sm_contact@eodc.eu
source	* WARP 5.5R1.1/AMI-WS/ERS12 Level 2 Soil Moisture; WARP 5.4R1.0/AMI-WS/ERS2 Level 2 Soil Moisture; H115: Metop ASCAT Surface Soil Moisture Climate Data Record v5 12.5 km sampling, DOI: 10.15770/EUM_SAF_H_0006; *H116: Metop ASCAT Surface Soil Moisture Climate Data Record v5 Extension 12.5 km sampling; H115: Metop ASCAT Surface Soil Moisture Climate Data Record v5 12.5 km sampling, DOI: 10.15770/EUM_SAF_H_0006; H116: Metop ASCAT Surface Soil Moisture Climate Data Record v5 Extension 12.5 km sampling; † LPRMv7/SMMR/Nimbus 7 L3 Surface Soil Moisture, Ancillary Params, and quality flags; † LPRMv7/SSMI/F08, F11, F13 DMSP L3 Surface Soil Moisture, Ancillary Params, and quality flags; †LPRMv7/TMI/TRMM L2 Surface Soil Moisture, Ancillary Params, and QC; † LPRMv7/AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Params, and QC;



Global Attribute Name	Content
	<p>† LPRMv7/WINDSAT/CORIOLIS L2 Surface Soil Moisture, Ancillary Params, and QC;</p> <p>† LPRMv7/AMSR2/GCOM-W1 L3 Surface Soil Moisture, Ancillary Params;</p> <p>† LPRMv7/SMOS/MIRAS L3 Surface Soil Moisture, CATDS Level 3 Brightness Temperatures (L3TB) version 300 RE03 & RE04;</p> <p>† LPRMv7/SMAP_radiometer/SMAP L2 Surface Soil Moisture, Ancillary Params, and QC</p>
platform	†Nimbus 7, †DMSP, †TRMM, †AQUA, †Coriolis, † GCOM-W1, †MIRAS, †SMAP; *ERS-1, *ERS-2, *METOP-A, *METOP-B
processing_level	Quality-controlled, super-collocated (L3S) Satellite Soil Moisture (SM) data from multiple sensors
sensor	†SMMR, †SSM/I, †TMI, †AMSR-E, †WindSat, †AMSR2, †SMOS, †SMAP_radiometer; *AMI-WS, *ASCAT-A, *ASCAT-B
references	<p>http://www.esa-soilmoisture-cci.org;</p> <p>Dorigo, W.A., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., Chung, D., Ertl, M., Forkel, M., Gruber, A., Haas, E., Hamer, D. P. Hirschi, M., Ikonen, J., De Jeu, R. Kidd, R. Lahoz, W., Liu, Y.Y., Miralles, D., Lecomte, P. (2017) ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. In Remote Sensing of Environment, 2017, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2017.07.001.</p> <p>Gruber, A., Scanlon, T., van der Schalie, R., Wagner, W., Dorigo, W. (2019) Evolution of the ESA CCI Soil Moisture Climate Data Records and their underlying merging methodology. Earth System Science Data 11, 717-739, https://doi.org/10.5194/essd-11-717-2019.</p> <p>Gruber, A., Dorigo, W. A., Crow, W., Wagner W. (2017). Triple Collocation-Based Merging of Satellite Soil Moisture Retrievals. IEEE Transactions on Geoscience and Remote Sensing. PP. 1-13. https://doi.org/10.1109/TGRS.2017.2734070</p>
product_version	09.1
id	<filename>
tracking_id	<xxxxxxxx-yyyy-zzzz-nnnn-mmmmmmmmmmm> a UUID (Universal Unique Identifier) value
conventions	CF-1.9
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention



Global Attribute Name	Content
summary	This dataset was produced with funding of the ESA CCI+ Soil Moisture project; ESRIN Contract No: 4000126684/19/I-NB
keywords	Soil Moisture/Water Content
naming_authority	TU Wien
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Grid
comment	This dataset was produced with funding of the ESA CCI+ Soil Moisture project; ESRIN Contract No: 4000126684/19/I-NB
history	< file creation date > - product produced
date_created	<file creation date>
creator_name	Department of Geodesy and Geoinformation, Vienna University of Technology
creator_url	http://climbers.geo.tuwien.ac.at
creator_email	cci_sm_developer@eodc.eu
project	Climate Change Initiative – European Space Agency
license	data use is free and open for all registered users
key_variables	sm
time_coverage_start	19781101T000000Z (PASSIVE and COMBINED); 19911101T000000Z (ACTIVE)
time_coverage_end	20231231T235959Z
time_coverage_duration	P45Y
time_coverage_resolution	P1D
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
geospatial_lat_min	-90.0
geospatial_lat_max	90.0
geospatial_lon_min	-180.0
geospatial_lon_max	180.0
geospatial_vertical_min	0.0
geospatial_vertical_max	0.0



Global Attribute Name	Content
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
geospatial_lat_resolution	0.25 degree
geospatial_lon_resolution	0.25 degree
spatial_resolution	25km



4.3.2.2 NetCDF Data File Variables and Attributes

lon

Table 4 Attribute Table for Variable lon

NetCDF Attribute	Description
standard_name	longitude
units	degrees_east
valid_range	[-180.0, 180.0]
_CoordinateAxisType	Lon

lat

Table 5 Attribute Table for Variable Lat

NetCDF Attribute	Description
standard_name	latitude
units	degrees_north
valid_range	[-90.0, 90.0]
_CoordinateAxisType	Lat

time

Table 6 Attribute Table for Variable time (reference time). The type of this variable is double.

NetCDF Attribute	Description
standard_name	Time
units	days since 1970-01-01 00:00:00 UTC
calendar	Standard
_CoordinateAxisType	Time

sm (ACTIVE product)

Table 7 Attribute Table for Variable sm for the ACTIVE product

NetCDF Attribute	Description
long_name	Percent of Saturation Soil Moisture
units	percent
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)

sm (PASSIVE and COMBINED product)

Table 8 Attribute Table for Variable sm for the PASSIVE and COMBINED products

NetCDF Attribute	Description
long_name	Volumetric Soil Moisture
units	m ³ m ⁻³
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)

sm_uncertainty (ACTIVE product)

Table 9 Attribute Table for Variable sm_noise

NetCDF Attribute	Description
long_name	Percent of Saturation Soil Moisture Uncertainty
Units	percent
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)



sm_uncertainty (PASSIVE and COMBINED product)

Table 10 Attribute Table for Variable sm_uncertainty for the PASSIVE and COMBINED products

NetCDF Attribute	Description
long_name	Volumetric Soil Moisture Uncertainty
Units	m3 m-3
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)

dnflag

Table 11 Attribute Table for Variable dnflag

NetCDF Attribute	Description
long_name	Day / Night Flag
flag_values	[0, 1, 2, 3]
flag_meanings	0 = NaN 1 = day 2 = night 3 = combination of day and night
_CoordinateAxes	lat lon time
_FillValue	0 (NaN); type: signed byte



flag

Table 12 Attribute Table for Variable flag

NetCDF Attribute	Description
long_name	Flag
flag_values	<list of flag values present in the file>
flag_meanings	<list of meanings for the flags present in the file >
bits	[0UB, 1UB, 2UB, 3UB, 4UB, 5UB, 6UB, 7UB, 8UB]
bit_meanings	-9999 = NaN, 0 = no_data_inconsistency_detected, 1 = snow_coverage_or_temperature_below_zero 2 = dense_vegetation 3 = others_no_convergence_in_the_model_thus_no_valid_sm_estimates 4 = soil_moisture_value_exceeds_physical_boundary 5 = weight_of_measurement_below_threshold 6 = all_datasets_deemed_unreliable 7 = barren_ground_advisory_flag 8 = Not used
_CoordinateAxes	lat lon time
_FillValue	-9999 (NaN); type: signed byte



freqbandID

Table 13 Attribute Table for Variable freqbandID

NetCDF Attribute	Description																																																																																																																																												
long_name	Frequency Band Identification																																																																																																																																												
flag_values	[0, 1, 2, 3, 4, 8, 9, 10, 11, 16, 17, 18, 19, 24, 25, 26, 27, 32, 33, 34, 35, 64, 65, 66, 67, 72, 73, 74, 75, 80, 81, 82, 83, 128, 130]																																																																																																																																												
flag_meanings	<p>Flag values and their meaning</p> <table border="1"> <thead> <tr> <th>Value</th> <th>Meaning</th> <th>Value</th> <th>Meaning</th> <th>Value</th> <th>Meaning</th> </tr> </thead> <tbody> <tr><td>0</td><td>NaN</td><td>19</td><td>L14+C53+C69</td><td>67</td><td>L14+C53+X107</td></tr> <tr><td>1</td><td>L14</td><td>24</td><td>C68+C69</td><td>72</td><td>C68+X107</td></tr> <tr><td>2</td><td>C53</td><td>25</td><td>L14+C68+C69</td><td>73</td><td>L14+C68+X107</td></tr> <tr><td>3</td><td>L14+C53</td><td>26</td><td>C53+C68+C69</td><td>74</td><td>C53+C68+X107</td></tr> <tr><td>4</td><td>C66</td><td>27</td><td>L14+C53+C68+C69</td><td>75</td><td>L14+C53+C68+X107</td></tr> <tr><td>8</td><td>C68</td><td>32</td><td>C73</td><td>80</td><td>C69+X107</td></tr> <tr><td>9</td><td>L14+C68</td><td>33</td><td>L14+C73</td><td>81</td><td>L14+C69+X107</td></tr> <tr><td>10</td><td>C53+C68</td><td>34</td><td>C53+C73</td><td>82</td><td>C53+C69+X107</td></tr> <tr><td>11</td><td>L14+C53+C68</td><td>35</td><td>L14+C53+C73</td><td>83</td><td>L14+C53+C69+X107</td></tr> <tr><td>16</td><td>C69</td><td>64</td><td>X107</td><td>128</td><td>K194</td></tr> <tr><td>17</td><td>L14+C69</td><td>65</td><td>L14+X107</td><td>130</td><td>C53+K194</td></tr> <tr><td>18</td><td>C53+C69</td><td>66</td><td>C53+X107</td><td></td><td></td></tr> </tbody> </table> <p>List of major codes and the corresponding frequency bands</p> <table border="1"> <thead> <tr> <th>Binary</th> <th>Decimal</th> <th>Frequency [GHz]</th> <th>BandID</th> </tr> </thead> <tbody> <tr><td>00000000</td><td>0</td><td>NaN</td><td>N/A</td></tr> <tr><td>00000001</td><td>1</td><td>1.4</td><td>L14</td></tr> <tr><td>00000010</td><td>2</td><td>5.3 / 5.255</td><td>C53</td></tr> <tr><td>00000100</td><td>4</td><td>6.6</td><td>C66</td></tr> <tr><td>00001000</td><td>8</td><td>6.8</td><td>C68</td></tr> <tr><td>00010000</td><td>16</td><td>6.9 / 6.93</td><td>C69</td></tr> <tr><td>00100000</td><td>32</td><td>7.3</td><td>C73</td></tr> <tr><td>01000000</td><td>64</td><td>10.65 / 10.7</td><td>X107</td></tr> <tr><td>10000000</td><td>128</td><td>19.35 / 19.4</td><td>K194</td></tr> </tbody> </table> <p>Sensors and their operating frequencies:</p> <table border="1"> <thead> <tr> <th>Sensor</th> <th>Operating Frequency [GHz]</th> </tr> </thead> <tbody> <tr><td>SMMR</td><td>6.6 / 10.7</td></tr> <tr><td>SSM/I</td><td>19.35</td></tr> <tr><td>TMI</td><td>10.65</td></tr> <tr><td>AMSR-E</td><td>6.93 / 10.65</td></tr> <tr><td>AMSR2</td><td>6.93 / 7.3 / 10.65</td></tr> <tr><td>WindSat</td><td>6.8 / 10.7</td></tr> <tr><td>SMOS</td><td>1.4</td></tr> <tr><td>SMAP</td><td>1.4</td></tr> <tr><td>AMI-WS</td><td>5.3</td></tr> <tr><td>ASCAT-A/B</td><td>5.255</td></tr> </tbody> </table>	Value	Meaning	Value	Meaning	Value	Meaning	0	NaN	19	L14+C53+C69	67	L14+C53+X107	1	L14	24	C68+C69	72	C68+X107	2	C53	25	L14+C68+C69	73	L14+C68+X107	3	L14+C53	26	C53+C68+C69	74	C53+C68+X107	4	C66	27	L14+C53+C68+C69	75	L14+C53+C68+X107	8	C68	32	C73	80	C69+X107	9	L14+C68	33	L14+C73	81	L14+C69+X107	10	C53+C68	34	C53+C73	82	C53+C69+X107	11	L14+C53+C68	35	L14+C53+C73	83	L14+C53+C69+X107	16	C69	64	X107	128	K194	17	L14+C69	65	L14+X107	130	C53+K194	18	C53+C69	66	C53+X107			Binary	Decimal	Frequency [GHz]	BandID	00000000	0	NaN	N/A	00000001	1	1.4	L14	00000010	2	5.3 / 5.255	C53	00000100	4	6.6	C66	00001000	8	6.8	C68	00010000	16	6.9 / 6.93	C69	00100000	32	7.3	C73	01000000	64	10.65 / 10.7	X107	10000000	128	19.35 / 19.4	K194	Sensor	Operating Frequency [GHz]	SMMR	6.6 / 10.7	SSM/I	19.35	TMI	10.65	AMSR-E	6.93 / 10.65	AMSR2	6.93 / 7.3 / 10.65	WindSat	6.8 / 10.7	SMOS	1.4	SMAP	1.4	AMI-WS	5.3	ASCAT-A/B	5.255
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mode

Table 14 Attribute Table for Variable mode

NetCDF Attribute	Description
long_name	Satellite Mode
flag_values	[0, 1, 2, 3]
flag_meanings	0 = NaN 1 = ascending 2 = descending 3 = combination of ascending and descending
_CoordinateAxes	lat lon time
_FillValue	0 (NaN); type: signed byte

sensor

Table 15 Attribute Table for Variable sensor

NetCDF Attribute	Description																																
long_name	Sensor																																
flag_values	[0, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 4096, 8192]*																																
flag_meanings	<table border="1"> <thead> <tr> <th>Value</th> <th>Sensor Combination</th> <th>Value</th> <th>Sensor Combination</th> </tr> </thead> <tbody> <tr> <td>0</td> <td>NaN</td> <td>64</td> <td>SMOS</td> </tr> <tr> <td>1</td> <td>SMMR</td> <td>128</td> <td>AMIWS</td> </tr> <tr> <td>2</td> <td>SSM/I</td> <td>256</td> <td>ASCATA</td> </tr> <tr> <td>4</td> <td>TMI</td> <td>512</td> <td>ASCATB</td> </tr> <tr> <td>8</td> <td>AMSRE</td> <td>1024</td> <td>SMAP</td> </tr> <tr> <td>16</td> <td>WindSat</td> <td>4096</td> <td>GPM</td> </tr> <tr> <td>32</td> <td>AMS2</td> <td>8192</td> <td>FY-3B</td> </tr> </tbody> </table> <p>* Note: All value combinations are provided in the netCDF files.</p>	Value	Sensor Combination	Value	Sensor Combination	0	NaN	64	SMOS	1	SMMR	128	AMIWS	2	SSM/I	256	ASCATA	4	TMI	512	ASCATB	8	AMSRE	1024	SMAP	16	WindSat	4096	GPM	32	AMS2	8192	FY-3B
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32	AMS2	8192	FY-3B																														
_CoordinateAxes	lat lon time																																
_FillValue	0 (NaN); type: signed integer																																

Table 16 Attribute Table for Variable t0

NetCDF Attribute	Description
long_name	Observation Time Stamp
units	days since 1970-01-01 00:00:00 UTC
valid_range	<individual decimal numbers depending on observation timestamp>

 soil moisture cci	Product User Guide (PUG)	Product Version v09.1 Date 30/09/2024
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_CoordinateAxes	lat lon time
_FillValue	-9999.0; type: double

4.4 Annotation datasets

The surface soil moisture data (sm) are generated by blending passive and active microwave soil moisture retrievals. The data provided are in percentage of saturation [%] units for the ACTIVE product, and volumetric [m^3m^{-3}] units for the PASSIVE and COMBINED products. Quality Flags and Indicators.

4.4.1 *sm_uncertainty*

The merging of soil moisture data from different sensors requires a harmonisation of the data. The data need to be brought into a common climatology by running them through several scaling procedures performing the mean-standard deviation matching technique. The provided “sm_uncertainty” parameter represents the error variance of the data sets (in the respective climatology of the dataset), estimated through triple collocation (TC) analysis and gap-filled using a Signal-to-Noise Ratio/Vegetation Optical Depth regression approach (Gruber et al., 2019). In the 1978-1981 SMMR period where TCA cannot be computed, sm_uncertainty is set to NaN. The unit of sm_uncertainty for the ACTIVE product is percentage of saturation [%]. For the PASSIVE and the COMBINED product the unit is volumetric [m^3m^{-3}]. For the ACTIVE and the PASSIVE products, the error variance is directly estimated using TC analysis. For the COMBINED product, these estimates are propagated through the SNR blending model using a standard error propagation scheme.

Table 17 *sm_uncertainty data provided in the ESA CCI SM Products*

Product	Time Period
ACTIVE	1991-08-05 to 2023-12-31
PASSIVE	1987-07-09 to 2023-12-31
COMBINED	1987-07-09 to 2023-12-31

4.4.2 *dnflag*

The Day or Night Flag gives information, whether the observation(s) occurred at local day (1) or night (2) time. A value of 3 indicates that the data is a result of merging satellite microwave data observed during day as well as during night time. In cases where the information cannot be determined the value is set to 0 (zero).

4.4.3 *flag*

Flag values are stored as signed bytes, and the default value (NaN, not a number) is -9999. By reading the flag for the surface soil moisture data, the user gets information for that grid point. The following table summarises the various flag bit values and their meaning:

Table 18: *Flag bit values and meanings*

Bit value	Name	Meaning
0b0	no_data_inconsistency_detected	The sm value is reliable
0b1	snow_coverage_or_temperature_below_zero	The ground was frozen or covered by snow
0b10	dense_vegetation	Dense vegetation affects the retrieval
0b100	others_no_convergence_in_the_model_thus_no_valid_sm_estimates	LPRM is not converging for the observation
0b1000	soil_moisture_value_exceeds_physical_boundary	The sm value is outside of the allowed (0-1 m ³ /m ³ or 0-100%) range
0b10000	weight_of_measurement_below_threshold	The observation is too noisy
0b100000	all_datasets_deemed_unreliable	All observations are flagged by the producers

**0b1000000	barren_ground_advisory_flag	The conditions of the ground are barren, affecting the retrieval
0b10000000	not_used	Reserved bit

**The barren ground flag is provided as advisory, i.e. sm is not masked when this bit is raised

Flag value interpretation

The flag value can be either referring to a single bit meaning (e.g., 2 = dense_vegetation, 4 = soil_moisture_value_exceeds_physical_boundary) or to a combination of multiple bits (e.g., 10 = combination_of_flag_values_2_and_4).

The flag value 0 indicates that there are no active bits, or in other words the retrieved soil moisture value is not flagged (bit_meaning = 'no_data_inconsistency_detected'). For all other values, to convert the flag value to the individual meanings, the following steps should be taken (illustrated in Figure 8):

1. The flag integer value should be converted to the corresponding binary string
2. The binary string should be converted to a list of bit values corresponding to the positions of the '1' in the array
3. The bit values list corresponds to the 'bit_meanings' attribute field

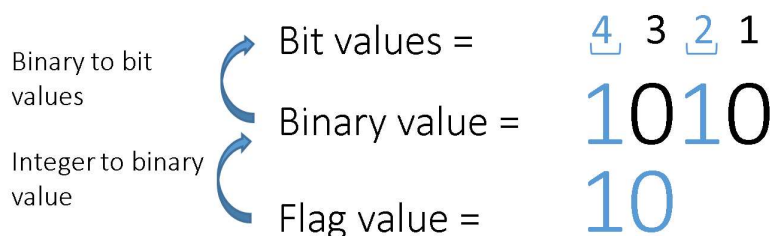


Figure 8: Flag value interpretation. The flag value 10 is converted to the respective binary 1010. The positions 2 and 4 are occupied by '1'. Hence, the bit value meanings 'dense_vegetation' and 'soil_moisture_value_exceeds_physical_boundary' correspond to the flag value 10.

Flags usage

In the ESA CCI SM products, the fields 'sm' and 'sm_uncertainty' do not provide values when the flag field value is different from 0, meaning that no soil moisture information is given when any of the flags (or combinations thereof) are raised. The only exception to this is the bit value 8 = 'barren_ground_advisory_flag' (new in ESA CCI SM v07.1). This is included as an advisory flag, meaning that the soil moisture values are not automatically masked in the product where (only) this flag value is raised. For more information see the ATBD.



4.4.4 *freqbandID*

The surface soil moisture data has its sources from multiple and different satellite sensors, which operate in various frequencies. The *freqbandID* values are representing the operating frequencies and comprise the combination of different frequency bands. Table 13 lists these combinations.

4.4.5 *mode*

The NetCDF variable *mode* stores the information of the sensor's orbit direction. Ascending direction are denoted as 1, and descending orbit as 2. In cases where the orbit direction cannot be determined, the NaN value 0 (zero) is used. A value of 3 means that the merged data comprises both ascending and descending satellite modes.

4.4.6 *sensor*

The values for *sensor* are stored as signed integer, with NaN as 0 (zero). These values indicate the satellite sensors that have been used for a specific grid point. Valid values range from 1 to 864. Table 15 list all available sensor combinations.

4.4.7 *t0*

The original observation timestamp is stored within the NetCDF variable *t0* (t-naught). Time values coming from two different sensors are averaged. Values of -9999.0 are used as NaN values. *t0* data values are stored as number of "days since 1970-01-01 00:00:00 UTC" (see Table 16).

4.4.8 *time*

The reference timestamp of the day is saved in the "time" variable. The data values for the reference time are stored as number of "days since 1970-01-01 00:00:00 UTC"

4.5 Product Grid and Projection

The grid is a 0.25° x 0.25° longitude-latitude global array of points, based on the World Geodetic System 1984 (WGS 84) reference system. Its dimension is 1440 x 720, where the first dimension, X (longitude) is incrementing most rapidly West (-180°) to East (180°), and the second dimension, Y (latitude) is incrementing South (-90°) to North (90°). Grid edges are at multiple of quarter-degree values (e.g. 90, 89.75, 89.5, 89.25, ...), and the grid centers are exactly between two grid edges:



First point centre = $(-89.875^{\circ}\text{S}, -179.875^{\circ}\text{W})$ = Grid Point Index = 0

Second point centre = $(-89.875^{\circ}\text{S}, -179.625^{\circ}\text{W})$ = Grid Point Index = 1

1441st point centre = $(-89.625^{\circ}\text{S}, -179.875^{\circ}\text{W})$ = Grid Point Index = 1440

Last point centre = $(89.875^{\circ}\text{N}, 179.875^{\circ}\text{E})$ = Grid Point Index = 1036799

In total, there are $1440 \times 720 = 1036800$ grid points, where 244243 points are land points. Figure 9 shows the land points that are used for the merged product.

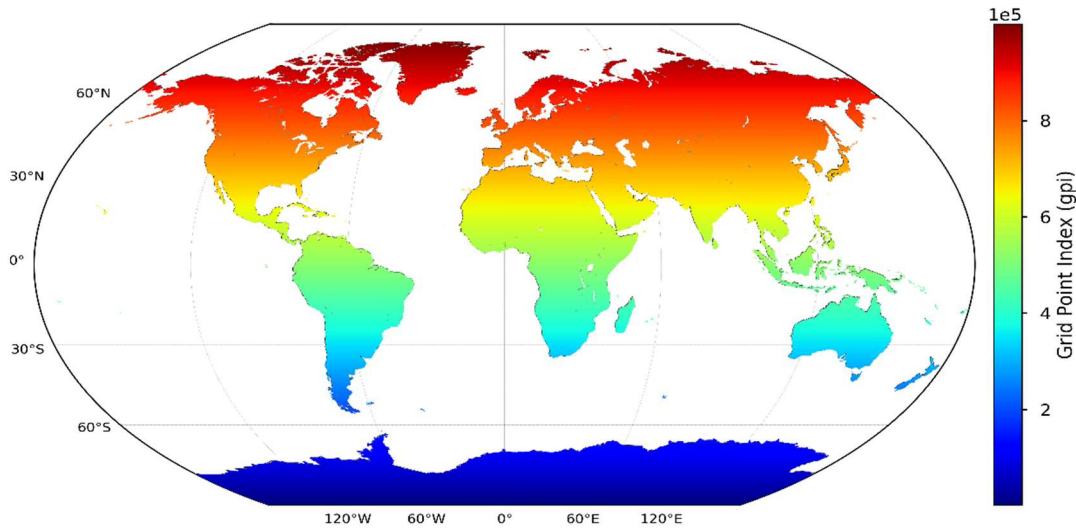


Figure 9: Land mask used for the merged product. The 0.25° grid starts indexing from “lower left” to the “upper right”. Note that not every grid points are available for all sensors, e.g. ASCAT retrievals are available between Latitude degrees 80° and -60° .



5 Data Access and Acknowledgements

5.1 Data Access

The ACTIVE, PASSIVE and COMBINED products are freely available for download after the completion of a simple user registration and the approval by the CCI SM team. User registration is available at:

<https://climate.esa.int/en/projects/soil-moisture/data/>

Registration is required to deter automated systems having direct access to the product. Data downloaded by the registered user can be used by the user and the associated organisation, no onward distribution is permitted.

The current product version is ECV SM v09.1. If you are interested in previous product versions, please search the CEDA archive:

<https://catalogue.ceda.ac.uk/>

5.2 Data Reader

The `esa_cci_sm` Python package available on the TU Wien GEO GitHub repository (https://github.com/TUW-GEO/esa_cci_sm) provides readers for the ESA CCI soil moisture datasets (images and time series within the “interface” module). It also allows conversion of daily images to gridded time series via the “reshuffle” module. The README.rst file contains information about installation of the package. Please contact the CCI SM team for advice on using the reader.

5.3 Contact

The CCI SM team can be contact directly via cci_sm_contact@eodc.eu.

E-mails sent to this address reaches both data managers and key project scientists.

5.4 Scientific use only

The ESA CCI SM product is intended for scientific purposes only.

5.5 No onward distribution

Re-export or transfer of the original data (as received from the ECV SM SFTP) by the data users to a third party is prohibited. This is in the best interest of both the individual data providers



and the potential users as unrestricted copying of the original data by multiple, independent users may lead to errors in the data.

5.6 Intellectual Property Rights

User acknowledges the respective data owner's full title and ownership of the data and nothing in these terms and conditions shall be construed as granting or implying any rights to, or interest in copyrights or intellectual property rights of the respective data owners.

5.7 Acknowledgement and citation

Whenever the product, made available by the CCI SM project, is used for publication, the data's origin (i.e. the CCI SM project) must be acknowledged and referenced.

The data set should be cited using the complete references as follows:

- Gruber, A. Scanlon, T., van der Schalie, R., Wagner, W., Dorigo, W. (2019) Evolution of the ESA CCI Soil Moisture Climate Data Records and their underlying merging methodology. *Earth System Science Data* 11, 717-739, <https://doi.org/10.5194/essd-11-717-2019>
- Gruber, A., Dorigo, W. Crow, W., & Wagner, W. (2017). Triple collocation-based merging of satellite soil moisture retrievals. *IEEE Transactions on Geoscience and Remote Sensing*, 1-13. <https://doi.org/10.1109/TGRS.2017.2734070>.
- Dorigo, W.A., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., Chung, D., Ertl, M., Forkel, M., Gruber, A., Haas, E., Hamer, P. D., Hirschi, M., Ikonen, J., de Jeu, R., Kidd, R., Lahoz, W., Liu, Y. Y., Miralles, D., Mistelbauer, T., Nicolai-Shaw, N., Parinussa, R., Pratola, C., Reimer, C., van der Schalie, R., Seneviratne, S. I. Smolander, T., Lecomte, P. (2017). ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions, *Remote Sensing of Environment*. <https://doi.org/10.1016/j.rse.2017.07.001>.

5.8 User feedback

User feedback is warmly welcomed and encouraged. All questions and remarks concerning the product can be addressed to our contact e-mail address provided in Section 5.3.



6 Terminology of Remote Sensing and Earth Observation

Table 19 lists the prime business domain terms from the scientific and technological domains of remote sensing, satellite-based Earth Observation and Soil Moisture retrieval.

Table 19: Business Domain Terminology: Remote Sensing, Earth Observation, Soil Moisture

Term (Acronym)	Description	Synonyms
Remote sensing	Is the acquisition of information about an object or phenomenon without making physical contact with the object. There are two main types of remote sensing: passive remote sensing and active remote sensing, corresponding to active and passive instruments, respectively (see below).	
Sensed object	The object subject of a remote sensing activity.	Sensed target Sensed system
Instrument	In the given context: An imaging microwave instrument flying onboard of an earth observation satellite. The instrument is a payload of the satellite. In a wide sense: Any device that can be used to perform a measurement.	Sensor Measurement device
Active instrument	An instrument that uses its own source of electromagnetic energy for the measurement.	
Scatterometer	An active microwave instrument, measuring the radar backscattering coefficient σ^0 in physical units [dB] or [m ² /m ²].	Radar
Passive instrument	An instrument that measures energy that is reflected or emitted from the sensed object.	
Radiometer	A passive microwave instrument, measuring the brightness temperature T_B in physical unit [K].	
Beam	The direction sensed by single antennae; used to express the fact that a satellite instrument may have several antennas each with its own field of view (FOV).	
Satellite	In the given context always means Earth Observation (EO) satellite.	
Orbit	The path of a satellite on its way around the earth.	
Single overpass Single orbit	The term is used to stress the fact that a satellite instrument scans only once across the earth surface and makes a single or a tuple of measurements per swath node. Implies that individual beams contributing to a measurement result are synchronized to the sensed object.	Single scan



Term (Acronym)	Description	Synonyms
Revisiting orbit	The term is used to stress the fact that measurements of a satellite instrument were not made in a single overpass.	Overlapping orbits Multi-pass orbits
Swath	The area of the earth surface along the ground track of a satellite that is sensed by the instrument in a single overpass; has a definite width but indefinite begin and end; made of an explicit number of nodes in the width-dimension that repeat in regular intervals along the direction of the ground track; each node is the sensed object of a single or a tuple of measurements.	
L<n> Level Processing Level	Processing levels L0 to L4 are an organization of the chain of data processing performed on the payload data from EO satellites.	
Merging	Process of combining the measurements or retrievals from revisiting orbits of a satellite or from many satellites with the aim to reach an improved coverage of the observed domain in space or time. Terms 'merging', 'blending' and 'fusion' appear in the literature sometimes synonymously and sometimes with diversified meanings.	Blending Fusion
Grid	Narrow: A set of nodes, lines or areas in a two-dimensional space that are arranged in a repeated pattern; may result from a construction principle or an actual process that repeats in regular intervals. Wide: Extended to n-dimensional space, and to space-time.	
Node	One point (or area) out of a set of similar points (areas) that together form a grid.	
Grid type	Classification of grids by construction principle.	
Swath grid	The grid originating from a satellite instrument when it senses the individual areas of the earth surface in a repetitive pattern during a single overpass; each grid node represents a single or a tuple of measurements. A swath grid is the result of the projection made by the instrument's beams; images in swath grid are in the perspective of the instrument's point of view (POV). Nodes of revisiting orbits do not coincide, thus swath grids are dynamic and not statically linked to the earth surface.	Data in orbit geometry. Data in instrument projection. Image in the perspective of the instrument's point of view (POV).
Global grid	A spatial grid that is uniformly and statically covering the earth surface. Some global grids use a geoid model (e.g. WGS84 reference ellipsoid) to account for the earth's oblateness. Swath grids can be mapped onto global grids by means of a spatial resampling.	Discrete Global Grid (DGG) (Global) grid system



Term (Acronym)	Description	Synonyms
Global space-time grid	The Cartesian product of a global grid and a timeseries index.	
Geo-referencing	Linkage of grid nodes to points of the earth surface; expressed in latitude and longitude coordinates. Geo-referencing parameters (e.g. satellite ephemeris) allow linking measurement results with the remotely sensed objects on the land surface.	
Time referencing	Linkage of a timeseries index (e.g. swath nodes) to UTC time.	
Measurement	The process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.	Observation
Quantity	A property of a phenomenon, body, or substance, where the property can take on a value that can be expressed as a number and a reference.	Observable Variable
Quantity value	A pair of number and reference, together expressing the value of a quantity.	
Reference	A reference can be a measurement unit, a measurement procedure, a reference material, or a combination of such.	Scale
Measurand	A quantity that is intended to be measured.	
Calibration	An operation performed for an instrument that establishes a relation between measurement standards and the quantity values and uncertainties indicated by the instrument. In case of L1 data, radiometric and geometric calibration coefficients may be either attached (L1a) or applied (L1b).	
Distribution	A function that assigns values to the points of a space, time or space-time domain; the assignment may be continuous or discrete, e.g. to the points of a grid.	
Domain	The range in space, time or space-time that is designated for value assignment.	
Coverage	The fraction of the domain where values have been actually assigned.	
Raster	A two-dimensional array; every element is accessible by the pair of row and column index, is called a pixel, and contains a single or a tuple of values.	Image Raster image
Pixel	An element of a raster.	
Timeseries	A one-dimensional vector; every element is accessible by an index and contains a single or a tuple of values; the index represents points or periods in time that are sampled in equal (or near-equal) intervals.	
Physical system	A part of nature chosen for analysis. The part outside the system is its environment. Effects of the environment on the system are taken into account by an abstraction, and vice-versa. The cut between system and environment is a free choice, generally made to simplify analysis. An isolated system is one which has negligible interaction with its environment.	Geo-physical system



Term (Acronym)	Description	Synonyms
Parameter	A measurable quantity suited to express the state of a physical system. In the given context synonymous for “geophysical parameter”.	State variable Geophysical parameter Environmental Variable
Local parameter	Characterizes the state of a local and compact object in space (i.e. a local physical system). A Local parameter may be measurable with remote sensing instruments, while others may not be measurable with such instruments, but can still be inferred from direct measurements and additional knowledge about the sensed system (retrieval by an inversion or modelling approach).	Local state variable
Model	A relation between parameters of a physical system, expressed in a mathematical or computable manner. E.g. as an equation system, $Y = f(X)$, where X and Y being tuples of system parameters; or as a computer simulation.	Mathematical model Simulation
Retrieval	The process of obtaining parameter values of a physical system from remote sensing measurements, although the parameters cannot be directly measured (observed) with the used remote sensing instruments. A retrieval is made on a mathematical-physical basis as follows: (1) It is known that at any time quantities X and quantities Y have definite values; (2) it is known that there exists a functional relation between system parameters X and instrument observables Y ; (3) there is partial knowledge about the functional relation, e.g. in the form of a forward model $Y = f(X)$ or an inversion $X = g(Y)$; and (4) under certain conditions the knowledge of the functional relation is sufficient to determine X from the measurements of Y .	Parameter retrieval
Retrieval algorithm	The algorithm (or approach, or method) used to retrieve a parameter value from remote sensing measurements.	Retrieval approach or method
Surface Soil Moisture (SSM)	A local geophysical parameter expressing the content of water in the top soil surface layer (of < 2 cm thickness), in physical units [%] or [m^3/m^3]. Typical SSM data products from global satellite observations have a spatial resolution of 25x25 km. Regional products downscaled with use of SAR data are available in a resolution of 1x1 km.	
TUW change detection algorithm	The algorithm used to retrieve the SSM parameter from calibrated measurements of the radar backscattering coefficient σ^0 made by an (active) scatterometer microwave instrument. Uses climate data timeseries of seasonally varying dry and wet reference values. Developed at TUW; implemented by the WARP processing module.	



Term (Acronym)	Description	Synonyms
Land Parameter Retrieval Model (LPRM)	An iterative forward modelling approach used to retrieve the SSM parameter from calibrated measurements of the brightness temperature T_B made by a (passive) radiometer microwave instrument. Uses a global database of physical soil properties. Developed by NASA and VUA.	
Soil Water Index (SWI)	A measure of the profile Soil Moisture content of soil surface layers within 2-100 cm obtained by using an infiltration model (filtering the SSM timeseries with an exponential function).	
Climate	Climate is a measure of the average pattern of variation of meteorological variables (e.g. temperature, humidity, atmospheric pressure, wind, precipitation, atmospheric particle count, etc.) in a given region over long periods of time. A region's climate is generated by the climate system, which has five components: atmosphere, hydrosphere, cryosphere, land surface, and biosphere.	
Essential Climate Variable (ECV)	Essential Climate Variables are geophysical parameters that are required to support the work of the United Nations Framework Convention on Climate Change (UNFCCC), and that are technically and economically feasible for systematic observation. An ECV Data Product combines observations from multiple remote-sensing instruments into a space-time grid; is complete and consistent, with a global and continuing coverage; and is intended for use in climate modeling. Synonyms are Super-collated (L3S) Data and TCDR.	L3S Thematic Climate Data Record (TCDR)
Climatology	Average of a geophysical parameter for a given region; obtained from long-term (many year) observation.	
Seasonality	Seasonal variation of a parameter's climatology, e.g. variation over the months of a year.	



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