Product User Guide and Specification

Soil Moisture

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History of modifications

Version	Date	Description of modification	Editor
0.0	15/10/2017	1st draft	DC
0.1	30/10/2017	Revision of 1st Draft	TS
0.2	31/10/2017	2nd draft	DC
0.3	03/11/2017	Reviewed	CPa
0.4	04/11/2017	Reviewed, Updated Doc Name, Doc footer, Removed Duplicate References and Reference Section, Revised Related Documents, formatting	RK
0.5	04/11/2017	Reviewed all in-line comments, formatted section numbers. Revision of scope and target requirements. Revision of Acronyms	RK
0.6	06/11/2017	Review of section 1.4	WD
V1.0	06/11/2017	To ECMWF for review and approval	RK
V1.1	21/12/2017	Revised section 1.5.1 to provide brief overview, and full reference to ATBD, for known retrieval issues for passive products. Revised section 1.5.2 to provide brief overview, and full reference to ATBD, for known retrieval issues for active products.	RK
	02/01/2018	V1.1 approved ECMWF. Created PDF	RK
V2.0	15/01/2018	Update to v201801 of the dataset. Inclusion of past versions table and “nobs” variable table (Table 17).	TS
V2.1	29/01/2018	Revision of document to support release of product version v201801. Update of all references to underlying	TS/RK

		CCI product version, L2 retrieval versions (LPRM/WARP) Inc Table 23. Removal of references to soil porosity map (since this is not currently delivered as ancillary data). Revision of Figure 1 to reflect input products, and inclusion of section 1.6 detailing product version change log. Reviewed	
2.2	23/02/2018	Created as PDF and delivered to ECMWF	RK
2.3	23/02/2018	Recreated without tracked changes, delivered to ECMWF	RK

Related documents

Reference ID	Document
D1	R. van der Schalie, R. De Jeu, C. Paulik, W. Dorigo, C. Reimer, R. Kidd, 2017. C3S D312a Lot 7.Algorithm Theoretical Basis Document (ATBD): Soil Moisture
D2	CECR, Comprehensive Error Characterisation Report, Version 1.0, 23 June 2016, ESA Climate Change Initiative Phase 2 Soil Moisture Project.
D3	W. Dorigo, T. Scanlon, D. Chung, R. Kidd, 2017. C3S D312a Lot 7.3.1.1 Product Quality Assurance Document (PQAD): Soil Moisture.
D4	W. Dorigo, T. Scanlon, D. Chung, R. Kidd, 2017. C3S D312a Lot 7.3.1.2 Product Quality Assessment Report (PQAR): Soil Moisture.
D5	NetCDF Climate and Forecast (CF) Metadata Conventions: Version 1.6, 5 December, 2011, Brian Eaton, Jonathan Gregory, Bob Drach, Karl Taylor, and Steve Hankin

Acronyms

Acronym	Definition
AMI-WS	Active Microwave Instrument - Windscat (ERS-1 & 2)
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System
AMSR2	Advanced Microwave Scanning Radiometer 2
ASCAT	Advanced Scatterometer (Metop)
ATBD	Algorithm Theoretical Basis Document
C3S	Climate Change Service
CDR	Climate Data Record
CDS	Climate Data Store
CCI	Climate Change Initiative
CDF	Cumulative Distribution Function
CF	Climate Forecast
DGG	Discrete Global Grid
DMSP	Defense Meteorological Satellite Program
DPM	Data Processing Model
EASE	Equal-Area Scalable Earth
ECV	Essential Climate Variable
ECMWF	European Centre for Medium Range Weather Forecasting
ERA-40	ECMWF ReAnalysis 40 data set
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
FAO	Food and Agriculture Organization of the United Nations
FTP	File Transfer Protocol
GCMD	Global Change Master Directory (NASA)
GCOS	Global Climate Observing System
GLDAS	Global Land Data Assimilation System
GLWD	Global Lakes and Wetlands Database
GRIB	Gridded Binary Format
GSFC	Goddard Space Flight Center (NASA)
ICDR	Intermediate Climate Data Record
IIASA	International Institute for Applied Systems Analysis
ISRIC	International Soil Reference and Information Centre (World Soil Information)
ISSCAS	Chinese Academy of Sciences
IODD	Input Output Data Description

JAXA	Dokuritsu-gyosei-hojin Uchu Koku Kenkyu Kaihatsu Kiko, (Japan Aerospace Exploration Agency)
JRC	Joint Research Centre of the European Commission
JULES	Joint UK Land Environment Simulator
LDAS	Land Data Assimilation System
LPRM	Land Parameter Retrieval model
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
NOBS	Number of Observations
NWP	Numerical Weather Prediction
PDF	Probability Distribution Function
PUGS	Product User Guide and Specification
SAR	Synthetic Aperture Radar
SM	Soil Moisture
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal to noise ratio
SSM	Surface Soil Moisture
SSMV	Surface Soil Moisture Volumetric
SSM/I	Special Sensor Microwave Imager
SURFEX	SURFace EXternalized module
TBD	to be determined
TC	Triple Collocation
TCDR	Thematic Climate Data Record
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey
UTC	Coordinated Universal Time
UUID	Universal Unique Identifier
VOD	Vegetation Optical Depth
WARP	soil Water Retrieval Package
WindSat	WindSat Spaceborne Polarimetric Microwave Radiometer

Table of Contents

List of Tables

List of Figures

Scope of the document

This Product User Guide and Specification PUGS relates to the C3S 312a Lot7 Soil Moisture Thematic Climate Data Record (TCDR) v201801 and Intermediate Climate Data Record (ICDR) products. It describes the Climate Data Records (CDRs) in a manner that is understood by the product user with focus on the:

- Geophysical data product content
- Known limitations of the product
- Practical Usage Considerations
- Product grid and geographic projection
- Ancillary data used
- Structure and format of the product
- Data file variables and attributes

Executive summary

The TCDR and the ICDR are soil moisture Climate Data Records (CDRs) based on the ESA CCI Soil Moisture data product version 03.3. The C3S Lot7 Soil Moisture products are available at the ECMWF C3S CDS. Both, the TCDR and the ICDR comprises three data products: The ACTIVE and the PASSIVE products are created by fusing scatterometer and radiometer soil moisture data, respectively; the COMBINED product is a blended product based on the former two products.

All products provide datasets featuring Daily, Dekadal (10-day) mean, and Monthly mean as NetCDF4 images at global scale. The data sets span a time period from November 1978 onwards. While the update policy of TCDR is subject to certain criteria, the ICDR represents a consistent extension of the TCDR. The generation of the ICDR uses the same algorithms and parameters, which are used to create the TCDR. The incremental update of the ICDR takes place every 10 days. The TCDR has a six monthly update cycle and either undergoes an evolution update in response to new merging algorithms, parameters, or new input data sets, or a maintenance update in response to processor maintenance.

The theoretical and algorithmic base of the CDRs is described in [D1], and the products and the applied algorithms are extensively discussed in Dorigo et al. (2017), and in Gruber et al. (2017).

1. Climate Data Records: TCDR and ICDR

The ECMWF C3S 312a Lot7 Soil Moisture provides two CDRs: the TCDR, and the ICDR. Each CDR consists of three surface soil moisture data sets: The ACTIVE and the PASSIVE product are created by using scatterometer, and radiometer soil moisture products, respectively; the COMBINED product is a blended product based on the former two data sets. For each data set the Daily, the Dekadal (10-days) mean, and the Monthly mean are available as NetCDF-4 classic format [D5] and comprise global merged surface soil moisture images at a 0.25 degree spatial resolution.
The theoretical and algorithmic basis of the product are described in [D1]. The Signal to Noise Ratio (SNR) merging algorithm is described in Gruber et al. (in prep.), and Gruber et al. (2017). An overview of all known errors of the soil moisture datasets is provided in [D2] and in (Dorigo et al. in 2017). Since this suite of products provided by this C3S service are based upon the scientific products developed in ESA's Climate Change Initiative Soil Moisture ECV project further background and reference documentation can be found on the CCI Soil Moisture project web site (http://www.esa-soilmoisture-cci.org). Noting that those documents relate to the ESA CCI SM v03.3 products.

1.1 TCDR

A detailed description of the algorithm for the product generation is provided in [D1].The underlying algorithm is based on that used in the generation of the ESA CCI SM v03.3 product. In addition, detailed provenance traceability information can be found in the metadata of the product (Section 3.3).

A new version of the TCDR will be produced in the following cases:

1. Merging algorithm updates
2. Processing parameter updates
3. Addition of new sensors using an existing algorithm
4. Change in input products that make a reprocessing necessary
5. Detected product errors requiring processor maintenance or upgrade.

1.2 ICDR

The Intermediate Climate Data Record is a consistent extension of the TCDR. The ICDR products are generated every dekad (approx. 10 days) and extend the TCDR of the same version as the ICDR. The same algorithm and software processor are used for generating the ICDR products, also input parameter are reused. New near real time observation data from the ASCAT-A/B and AMSR2 and SMOS sensors (Table 23) are processed to extend the ICDR products.

1.3 Product description

Both, the TCDR and the ICDR comprise the ACTIVE, PASSIVE, and the COMBINED surface soil moisture data products. For each of these data sets, the Daily, the Dekadal mean, and the Monthly mean are available as global images stored in NetCDF4-classic files following the CF1.6 convention [D5]. The Dekadal files feature a 10-day mean of a month, starting from the 1st to the 10th, from 11th to the 20th, and from 21st to the last day of a month. While the Monthly mean represents the soil moisture mean of each month, the Daily files are created directly through the merging of microwave soil moisture data from multiple satellite instruments (see Table 1). The Dekadal and Monthly means are calculated from these Daily files.
The soil moisture attributes of the Daily files are: day/night flag, satellite orbit mode, instrument operating frequency, sensor, original observation timestamp, soil moisture observation status flag, and soil moisture uncertainty. For the Dekadal and the Monthly mean the frequency band, the used sensor, and the number of observation are attributed to the soil moisture entity (see NetCDF data file variables and attributes).
The detailed the specifications including the geophysical parameters used in the TCDR products are described in Appendix A.

Table 1 TCDR / ICDR products and data sets: The mean data sets are calculated from the Daily files, which represent the daily observation derived by merging soil moisture data from multiple microwave sensors.

TCDR / ICDR Products	Data sets: Daily / Dekadal mean / Monthly mean	
ACTIVE	Data sets	Number of NetCDF4 files
	Daily	1 per day
	Dekadal mean	3 per month: 1–10, 11–20, 21–last day of month
	Monthly mean	1 per month
PASSIVE	Data sets	Number of NetCDF4 files
	Daily	1 per day
	Dekadal mean	3 per month: 1–10, 11–20, 21–last day of month
	Monthly mean	1 per month
COMBINED	Data sets	Number of NetCDF4 files
	Daily	1 per day
	Dekadal mean	3 per month: 1–10, 11–20, 21–last day of month
	Monthly mean	1 per month

1.3.1 ACTIVE Product

The ACTIVE product is the output of merging scatterometer-based soil moisture data, which are derived from AMI-WS and ASCAT (Metop-A and Metop-B). Please refer to Table 23 for detailed information of the active microwave instruments. The ACTIVE TCDR product spans the time period from 1991-08-05 to 2017-12-31, and the ACTIVE ICDR product is available from 2018-01-01 onwards. Table 2 shows the used sensors in the corresponding periods.

Table 2 SNR blending period for the ACTIVE TCDR and ICDR products

Sensors	Time Period	CDR
AMI-WS	1991-08-05 to 2006-12-31	TCDR
ASCAT-A	2007-01-01 to 2015-07-20	TCDR
ASCAT-A & ASCAT-B	2015-07-21 to 2017-06-30	TCDR
ASCAT-A & ASCAT-B	2017-07-01 onwards	ICDR

1.3.2 PASSIVE Product

The PASSIVE product merges data from SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2, and SMOS. The PASSIVE TCDR includes soil moisture data from 1978-11-01 to 2017-12-31, whereas the PASSIVE ICDR represents its extension from 2018-01-01 onwards. The blending periods and the used sensors are listed in Table 3.

Table 3 SNR blending period for the PASSIVE TCDR and ICDR products.

Sensors	Time Period	CDR
SMMR	1978-11-01 to 1987-07-08	TCDR
SSM/I	1987-07-09 to 1997-12-31	TCDR
[SSM/I, TMI, SSM/I]*	1998-01-01 to 2002-06-18	TCDR
AMSR-E	2002-06-19 to 2007-09-30	TCDR
AMSR-E & WindSat	2007-10-01 to 2010-01-14	TCDR
AMSR-E & WindSat & SMOS	2010-01-15 to 2011-10-04	TCDR
WindSat & SMOS	2011-10-05 to 2012-06-30	TCDR
SMOS & AMSR2	2012-07-01 to 2016-12-31	TCDR
AMSR2	2017-01-01 to 2017-12-31	TCDR
AMSR2	2018-01-01 onwards	ICDR

*The [SSM/I, TMI, SSM/I] period is latitudinally divided into [90S, 37S] and [90N, 37N] for SSM/I, and the region in between for TMI.

1.3.3 COMBINED Product

The COMBINED product is generated by merging the ACTIVE and the PASSIVE products, therefore the time span for this product ranges from 1978-11-01 to 2017-12-31. Table 4 shows, that the COMBINED TCDR spans the time period from 1978-11-01 to 2017-12-31, and the COMBINED ICDR extends the CDR from 2018-01-01 onwards.

Table 4 SNR blending period for the COMBINED TCDR and ICDR products.

Sensors (Active / Passive)	Time Period	CDR
SMMR	1978-11-01 to 1987-07-08	TCDR
SSM/I	1987-07-09 to 1991-08-04	TCDR
AMI-WS & SSMI	1991-08-05 to 1997-12-31	TCDR
AMI-WS & [SSM/I, TMI, SSM/I]*	1998-01-01 to 2002-06-18	TCDR
AMI-WS & AMSRE	2002-06-19 to 2006-12-31	TCDR
ASCAT-A & AMSRE	2007-01-01 to 2007-09-30	TCDR
ASCAT-A & AMSRE & WindSat	2007-10-01 to 2010-01-14	TCDR
ASCAT-A & AMSRE & WindSat & SMOS	2010-01-15 to 2011-10-04	TCDR
ASCAT-A & WindSat & SMOS	2011-10-05 to 2012-06-30	TCDR
ASCAT-A & SMOS & AMSR2	2012-07-01 to 2015-07-20	TCDR
ASCAT-A & ASCAT-B & SMOS & AMSR2	2015-07-21 to 2016-12-31	TCDR
ASCAT-A & ASCAT-B & AMSR2	2017-01-01 to 2017-12-31	TCDR
ASCAT-A & ASCAT-B & AMSR2	2018-01-01 onwards	ICDR

*The [SSM/I, TMI, SSM/I] period is latitudinally divided into [90S, 37S] and [90N, 37N] for SSM/I, and the region in between for TMI.

1.4 Product Target requirements

Table 5 assembles the C3S ECV Soil Moisture product target requirements adopted from the GCOS 2011 target requirements and shows to what extent these requirements are currently met by the latest C3S 312a Lot7 SM products. As one can see, the TCDR and ICDR products currently provided by the system are compliant with C3S target requirements and in many cases even go beyond. Further details on product accuracy and stability are provided in PQAD [D3] (methodology to assess) and PQAR [D4] (assessment).

Table 5 Summary of C3S ECV Soil Moisture requirements, the specification of the current ESA CCI SM products, and the target proposed by the consortium, Green shading indicates target requirement is obtained, Yellow shading indicates target requirement is being approached, Red shading indicates that target requirement is not achieved. Items highlighted in **bold** show where the target requirement has been exceeded

Requirement	C3S and GCOS target requirements	C3S 312a Lot 7 Products
Product Specification		
Parameter of interest	Surface Soil Moisture	Volumetric Surface Soil Moisture
Unit	Volumetric (m^3/m^3)	Volumetric (m^3/m^3 (passive merged product, combined active +passive merged product); (% of saturation (active merged product)
Product aggregation	L2 single sensor and L3 merged products	Gridded L2 single sensor products (passive microwave products only); L3 merged active, merged passive, and combined active + passive products
Spatial resolution	50 km	**25 km**

Record length	>10 years	**>38 years (1978/11 - running present)**
Revisit time	Daily	Daily
Product accuracy	0.04 m^3/m^3	Variable (0.04-0.10 m^3/m^3), depending on land cover and climate (current assessment for various climates, land covers and texture classes based on in-situ data shows accuracy to be < 0.1 m^3/m^3)
Product stability	0.01 $m^3/m^3/y$	0.01 $m^3/m^3/y$ (Assessment indicates stability to be within: to be formally assessed)
Quality flags	Not specified	Frozen soil, snow coverage, dense vegetation, retrieval failure, sensor used for each observation, overpass mode, overpass time, RFI
Uncertainty	Daily estimate, per pixel	Daily estimate, per pixel
Format Specification		
Product spatial coverage	Global	Global
Product update frequency	Monthly to annual	**10-daily ("extension"), and 6 months ("reprocessing")**
Product format	Daily images, Monthly mean images	Daily images, dekadal (10-day) mean, monthly mean images
Grid definition	0.25°	0.25°
Projection or reference system	Projection: Geographic lat/lon Reference system: WGS84	Projection: Geographic lat/lon Reference system: WGS84
Data format	NetCDF, GRIB	NetCDF 4
Data distribution system	FTP, WMS, WCF, WFS, OpenDAP	FTP/THREDDS
Metadata standards	CF, obs4mips	NetCDF Climate and Forecast (CF 1.7) Metadata Conventions; ISO 19115, obs4mips (distributed separately through ESGF)
Quality standards	QA4ECV	EQC to be implemented

1.5 Data usage information

The known issues and limitations for the passive and active product generation which underlie TCDR and ICDR products are provided as brief points in the following section. All issues and limitations are fully addressed in the product ATBD [D1] and references are provided to the specific ATBD section. Following this a summary of practical usage constraints (resulting from direct user feedback over the course of 6 ESA's CCI SM project) are presented.

1.5.1 Known Limitations for Passive product

The known limitations in deriving soil moisture from passive microwave observations are provided in detail in section 3.1.3 of the ATBD [D1]. It should be noted that these issues do not only apply to the current TCDR/ICDR data set release but also to soil moisture retrieval from passive microwave observations in general.

1.5.1.1 Vegetation
Vegetation affects the microwave emission, and under a sufficiently dense canopy the emitted soil radiation will become completely masked by the overlaying vegetation.
Please see section 3.1.3.1 of [D1]

1.5.1.2 Frozen surfaces and snow
Under frozen surface conditions the dielectric properties of the water changes dramatically
Please see section 3.1.3.2 of [D1]

1.5.1.3 Water bodies
Water bodies within the satellite footprint can strongly affect the observed brightness temperature due to the high dielectric properties of water.
Please see section 3.1.3.3 of [D1].

1.5.1.4 Rainfall
Rainstorms during the satellite overpass affect the brightness temperature observation
Please see section 3.1.3.4 of [D1]

1.5.1.5 Radio Frequency interference
Natural emission in several low frequency bands are affected by artificial sources, so called Radio Frequency Interference (RFI).
Please see section 3.1.3.5 of [D1]

1.5.1.6 Using night-time observations only
For the current version of the merged passive product only descending overpasses, corresponding to night-time / early morning observations, were considered. This is because near surface land surface temperature gradients are regarded to be reduced at night leading to more robust retrievals (Owe et al. 2008). However, (Brocca et al. 2011) suggest that for specific land cover types day-time observations may provide more robust retrievals than night-time observations, although the exact causes are still unknown. If day-time observations could be introduced to the blended product, this would significantly increase the observation density.

1.5.1.7 Intercalibration of AMSR-E and AMSR2
As AMSR-E fails to deliver data since 04 October 2011 the continuity of the passive radiometer data is prolonged by using the WindSat and AMSR2 data sets. The Passive product is extended by using WindSat to bridge the time gap between AMSR-E and AMSR2. A intercalibration technique was developed to adjust WindSat soil moisture to AMSR-E and AMSR2 to the adjusted Windsat data (Parinussa et al. 2015). However, the overlapping period use to compute the calibration constants was very short and need to be updated using a larger time window. Alternatively, JAXA announced to make an improved intercalibrated AMSR2 product available, which, if outperforming the empirical intercalibration used so far, will be used to generate level 2 AMSR2 LPRM soil moisture estimates.

1.5.2 Known Limitations for Active product
The known limitations in deriving soil moisture from active microwave observations are provided in detail in section 3.2.3 of the ATBD [D1]. It should be noted that these issues do not only apply to the

current TCDR/ICDR data set release but also to soil moisture retrieval from active microwave observations in general.

1.5.2.1 Computation of Slope/Curvature Parameters
Please see section 3.2.3.1 of [D1]

1.5.2.2 Dry and Wet Crossover Angles
Crossover angles may vary across the globe depending upon the evolution of biomass of a specific vegetation type. Please see section 3.2.3.2 of [D1]

1.5.2.3 Backscatter in Arid Regions
In arid regions or more specifically in desert environments it appears that the dry reference shows seasonal variations, which are assumed to reflect vegetation phenology.
Please see section 3.2.3.1 of [D1]

1.5.2.4 Intercalibration of ERS and ASCAT
The generation of the ERS and ASCAT products is still based on their individual time series. The merged ERS + ASCAT could significantly profit from an appropriate Level 1 intercalibration. Besides improving the quality of the individual measurements this would improve the robustness of the calculation of the dry and wet references.

1.5.2.5 Data gaps
Similar as for the passive products, merging ERS and ASCAT into a merged dataset is based on a strict separation in time. Gaps in ASCAT time series can be potentially filled with ERS observations, although the spatial and temporal overlap between both sensors is limited.

1.5.3 Practical Usage Considerations
Some Practical Usage Considerations are provided in the following section. These considerations result from direct user feedback on the use of the ESA CCI SM product during the period 2011 to 2017 and form the core of the ESA CCI SM product FAQ.

1.5.3.1 Climate trends in general and relative dynamics
Before merging the ACTIVE and PASSIVE products into a COMBINED product we first scale both data sets into the dynamic range of the GLDAS-Noah surface soil moisture fields. We perform this processing step to obtain a final product in absolute volumetric units [m3/m3]. Even though the original dynamics of the remote sensing observations are preserved, this step imposes the absolute values and dynamic range (min-max) of the GLDAS-Noah product on the combined product. As a consequence, the COMBINED product **cannot** be considered an independent dataset representing absolute true soil moisture. Hence, the statistical comparison metrics like root-mean-square-difference and bias based on our combined dataset are scientifically not meaningful. However, the product can be used as a reference for computing correlation statistics or the unbiased root-mean-square-difference.

1.5.3.2 Temporal availability

In the time period 1978 – 1987 product is only based on the SMMR radiometer. SMMR had a 24 hr on-off cycle to save power, but this was sometimes changed. For example in 1986 there is a period with daily observations (they switched the 24 hr on-off cycle off). So, the observation density changes over time. In addition, SMMR observes the Earth surface at 12:00 and 24:00 local solar time, which sometimes leads to a shift of one day for the night-time observations.

1.5.3.3 Spatial availability

- For areas with dense vegetation (tropical, boreal forests), strong topography (mountains), ice cover (Greenland, Antarctica, Himalayas), a large fractional coverage of water, or extreme desert areas we are not able to make meaningful soil moisture retrievals. Hence, we mask them (see Table 14).

- Especially images of the first years from 1978 onwards show clearly these data stripes. This is a typical characteristic in the observation through satellite microwave instruments. Microwave images from the earth's surface are taken while the satellite is orbitting the earth in fixed paths. These paths represent the data stripes on the images. If we move forward in time, the spatial data availability is getting higher and higher, and the data stripes are getting closer and closer. This is due to the fact that not only the number of available input data sources (satellites) is growing, but also the technology of satellites instruments is getting better and better.

- Some image files do not provide any soil moisture data at all. All values are NaN. We call these images "blank" or "empty" days. Because of many reasons, e.g. technical failures, there is no data available for that day. Especially the SMMR and the AMI-WS (ERS1/2) instruments are known for their data outages causing these blank days. Other instruments also have short time periods with no data availability. In most cases these empty periods are replaced or filled with data from the remaining microwave sensor(s). So blank days are most likely experienced on days where only one sensor is used as input source, which then fails to deliver data for that time.

- When the soil is frozen or covered with soil, we are not able to make a meaningful soil moisture retrieval. Such observations are masked and indicated with flag number 1 in the NetCDF file.

- Based on the sensitivity to vegetation density, we decided for each pixel whether to use either the scatterometer or the radiometer retrievals, or to use a weighted average of the available observations from different sensors. This merging scheme may lead to data gaps in the following situations:
    - No observation is available (sensors fail). This is for example the case between 2001 and 2006 in Western Europe, parts of Siberia, parts of North and South America, due to failure of the onboard storage capacity of ERS-2.
    - Changes in observation wavelength (frequency) may lead to increased sensitivity to vegetation . Hence, larger areas need to be masked. This is for example visible for the

period after 1987 where based on the SSM/I Ku-band observations, the extent of masked areas increases with respect to the preceding SMMR period (C-Band).

1.5.3.4 Data inconsistencies

For AMI-WS and ASCAT soil moisture values may show jumps where ascending and descending swaths overlap with each other, e.g. in the higher northern latitudes. This is a natural phenomenon related to the differences in overpass time (up to 24h). Potentially different soil moisture values may result from precipitation or evaporation taking place between the two observation time steps. We therefore recommend to use the original observation time (t0) and not the nominal overpass time if you want to make a direct comparison e.g. with in-situ observations.

1.5.3.5 Data characteristics

The sensors used for each period are best described by the graphic in

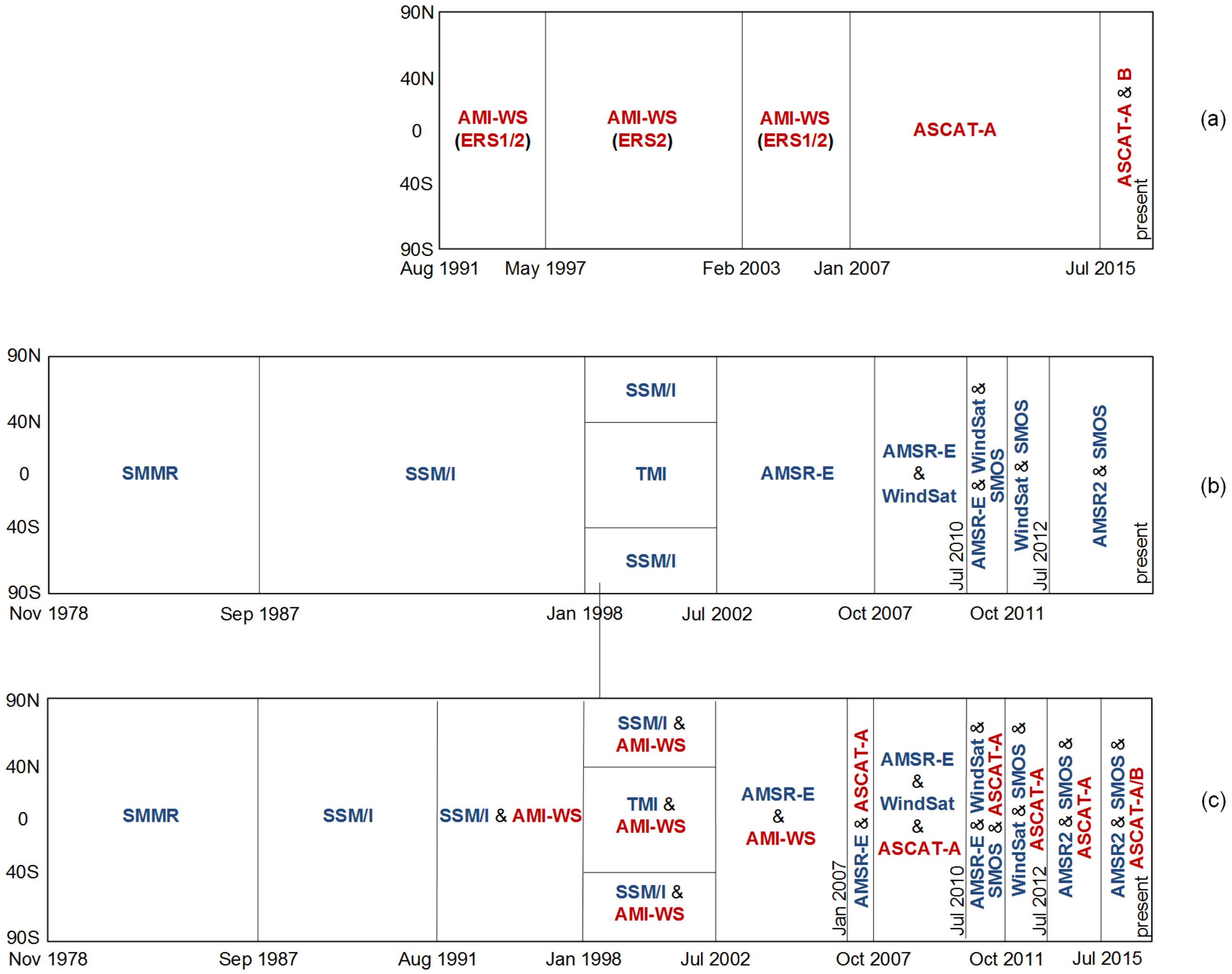

Figure 1.

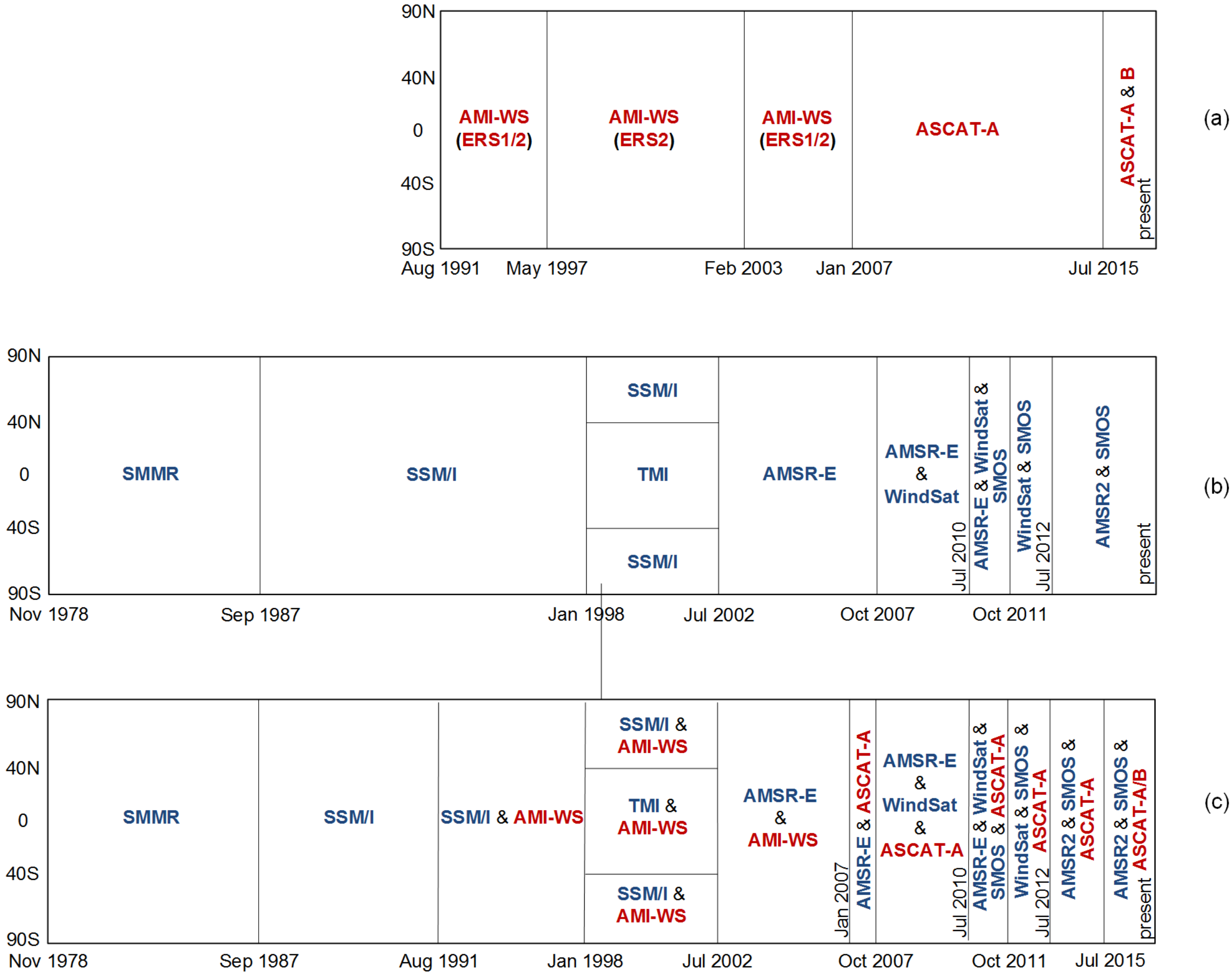

Figure 1 Spatial-temporal coverage of input products used to construct the TCDR/ICDR (a) ACTIVE, (b) PASSIVE, (c) COMBINED. Blue colours indicate passive, red colours active microwave sensors. The periods of unique sensor combinations are referred to as ‘blending period’. Modified from Dorigo et al. (2017).

1.5.3.6 Data usage in models

In theory, the COMBINED product combines the best of the active and passive products, so we consider it as most suitable for model verification.

Only for the mountain ranges in southern Turkey the merged dataset is known to be inferior to the PASSIVE product, see also: http://www.geosci-model-dev.net/7/931/2014/gmd-7-931-2014.html

1.5.3.7 Converting volumetric soil moisture in soil wetness content

The equation to convert volumetric soil moisture (SM_{vol} in m^3m^{-3}) into degree of saturation (SM_{sat} in %) is the following:

SM (%) = SM_vol (m^3m^{-3}) / porosity_vol (m^3m^{-3}).

$$SM_{sat} = \frac{SM_{vol}}{\phi_{vol}}$$

Where φvol is the soil porosity which can be obtained from soil porosity maps.

1.6 Product Change Log

Table 6 provides an overview of the differences between different versions of the product up-to, and including, the current version.

Table 6 Changes in the product between versions.

Version	Product Changes
v201801	Updated TCDR includes SMOS data from the end of 2016 onwards. SMOS is also included in the ICDRs produced from January 2018 onwards. TCDR produced until 2017-12-31; ICDR produced from 2018-01-01.
v201706	First release of the dataset. TCDR produced until 2017-06-30; ICDR produced from 2017-07-01.

2. Data access information

2.1 Climate Data Store

The Copernicus Climate Change Service provides data storage infrastructure and make ECV data products available through the CDS. The store provides not only consistent estimates of ECVs, but also climate indicators, and other relevant information about the past, present, and future evolution of the coupled climate system, on global, continental, and regional scales. It supports users with data dissemination and visualisation tools.[1]

2.2 C3S Soil Moisture data

All C3S 312a soil moisture TCDRs and ICDRs are expected to be available via the CDS starting in Q1 2018.

2.3 User Support

A dedicated service desk has been set up, the Copernicus User Support (CUS) team, which provides support to users of the CAMS and C3S services at ECMWF. All enquiries about the soil moisture dataset must be submitted through the service desk where appropriate agents will deal with it.

There is a portal (http://copernicus-support.ecmwf.int) where customers can submit enquiries using a form (split into "Data Request", "Documentation and Scientific Questions", "Events, Media and Legal" and "Report an Incident"). The information provided in this form is received by the CUS. Once submitted, the user may add comments or further information to the issue, including responding to questions / requests for additional information from the support team.

[1]Source: https://climate.copernicus.eu/climate-data-store. Web page retrieved 2017-10-15.

The C3S 312a Lot7 service provides dedicated level 2 user support to the CUS Jira Ticketing Service

In addition to submitting enquires through the portal a knowledge base is available to users which can be searched for information.

3. Specifications for TCDR and ICDR

3.1 Geophysical parameters

The ACTIVE product is the output of merging scatterometer-based soil moisture data, which were derived from AMI-WS and ASCAT (Metop-A and Metop-B). The PASSIVE product merges data from SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2, and SMOS. The COMBINED product merges the ACTIVE and the PASSIVE products. The merging algorithm of the described here (version v03.2) is an evolution of the algorithm described in (Dorigo et al. in review; Liu et al. 2012; Liu et al. 2011; Wagner 2012), which was used in all previous product versions. The introduced algorithm is described in detail (Gruber et al. in prep.). The homogenised and merged products present surface soil moisture with a global coverage and a spatial resolution of 0.25°. The Daily data set has a temporal resolution of 1 day, the Dekadal mean represents a 10-day average of the Daily data, and the Monthly mean performs the averaging of the Daily files for each month. The reference time is set at 0:00 UTC for all products. 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 percentage of saturation [%].

3.1.1 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 incremental from West (-180°) to East (180°), and the second dimension, Y (latitude) is incremental from South (-90°) to North (90°). Grid edges are at multiple of quarter-degree values (e.g. 90.00, 89.75, 89.50, 89.25, …), and the grid centers are exactly between the two grid edges:

First point center = (–89.875°S, –179.875°W) = Grid Point Index = 0
Second point center = (–89.875°S, –179.625°W) = Grid Point Index = 1
…
1441st point center = (–89.625°S, –179.875°W) = Grid Point Index = 1440
…
Last point center = (89.875°N, 179.875°E) = Grid Point Index = 1036799

In total, there are 1440 x 720 = 1036800 grid points, where 244243 points are land points. The land mask has been derived from the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG v2.2.2) (Wessel and Smith 1996). Lakes and rivers with areas less than 600 km^2 were not considered in the calculation of the land points. Figure 1 shows the land points which are used for each product described in this document.

The Tropical forest mask – derived from the mean AMSR-E VOD (Figure 3) for 2002 to 2011 –has been applied to the soil moisture product images. The soil moisture and the soil moisture uncertainty values are set to NaN in these rainforest regions.

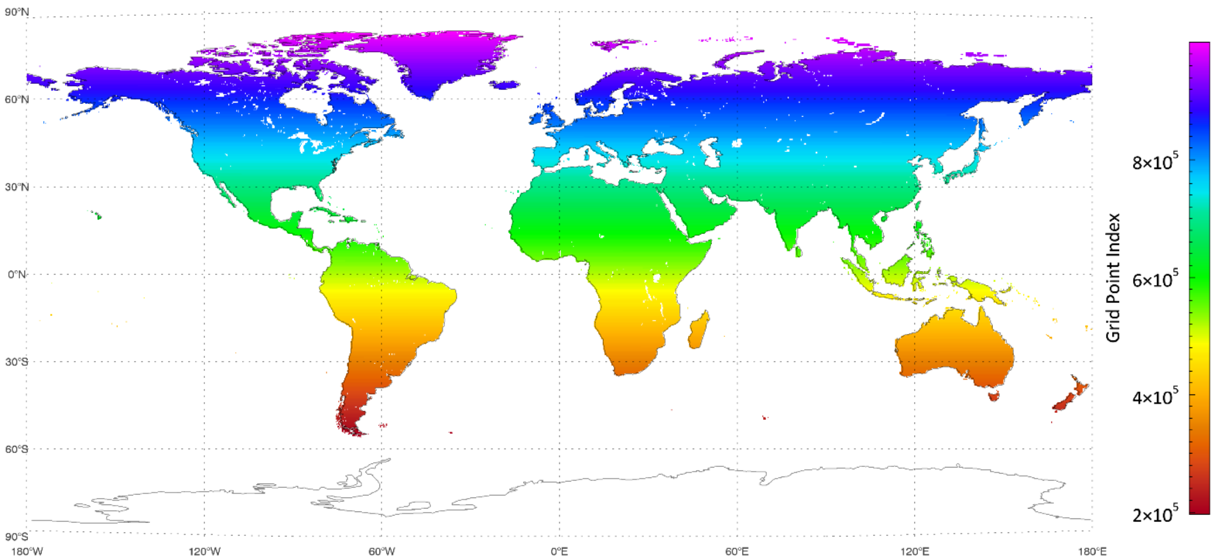

Figure 2 Land mask used for the merged product. The 0.25° grid starts indexing from “lower left” to the “upper right”. Note that not every grid points are available for all sensors, e.g. ASCAT retrievals are available between Latitude degrees 80° and –60°.

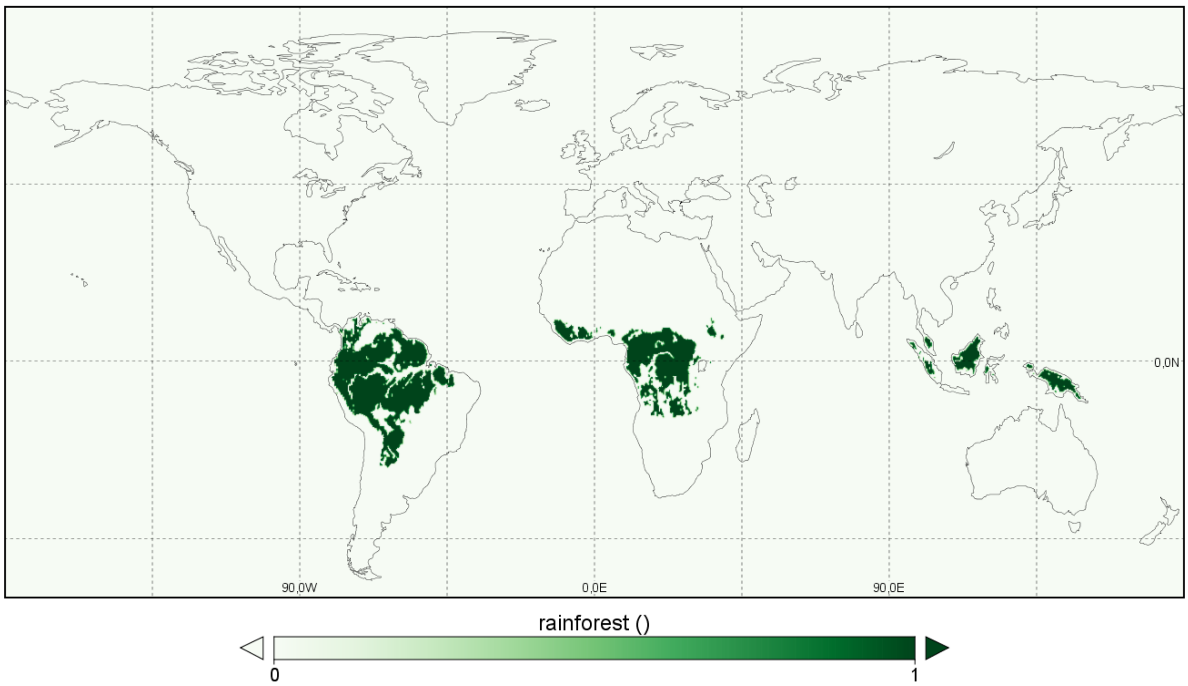

Figure 3 Tropical forest Mask used applied to the product images. 1 (green) represents rainforest regions.

3.2 Ancillary data

The process of generating the C3S 312a soil moisture products requires the usage of various ancillary data sets. These ancillary datasets are described in the following subsections.

3.2.1 Global Land Data Assimilation System (GLDAS)

The PASSIVE and ACTIVE products represent volumetric soil moisture (m^3m^{-3}) and degree of saturation (%), respectively. To combine these data, both products need to be adjusted to a common reference which can be achieved using a reference dataset. The reference dataset requires global coverage with a spatial resolution and temporal interval that are comparable to both of the microwave products (i.e., approximately 25 km resolution and daily interval), a long time record, and reasonable surface soil moisture estimates for all land cover types (i.e., representative soil layer is not deeper than 10 cm).

The GLDAS-1-Noah Land Surface Model L4 3 Hourly 0.25 x 0.25 degree soil moisture model data satisfies these requirements and is employed as the reference dataset. Both (the PASSIVE and ACTIVE) products were rescaled against the GLDAS-1-Noah data using the CDF matching technique. The methodology behind the use of this data set is provided in [D1].

3.2.2 ASCAT Advisory Flag

The following two ASCAT advisory flags (Scipal 2005) are used to mask out regions of frozen soils, or snow covered soils:

- **Probability of snow covered land**
  Derived from historic analysis of SSM/I (Special Sensor Microwave/Imager) snow cover data (averaged over the 9 years 1996-2004) and gives the probability for the occurrence of snow for any day of the year.
- **Probability of frozen land**
  Derived from historic analysis of modelled climate data (7 years 1995-2001 of ECMWF ERA-40 soil temperature) and gives the probability for the frozen soil/canopy conditions for each day of the year.

3.2.3 Average Vegetation Optical Depth from AMSR-E

Vegetation optical depth (VOD) estimated from AMSR-E with the VUA-NASA LPRM method are provided to give an indication of vegetation density. The provided global values represent the averaged VOD from 2002 to 2011.

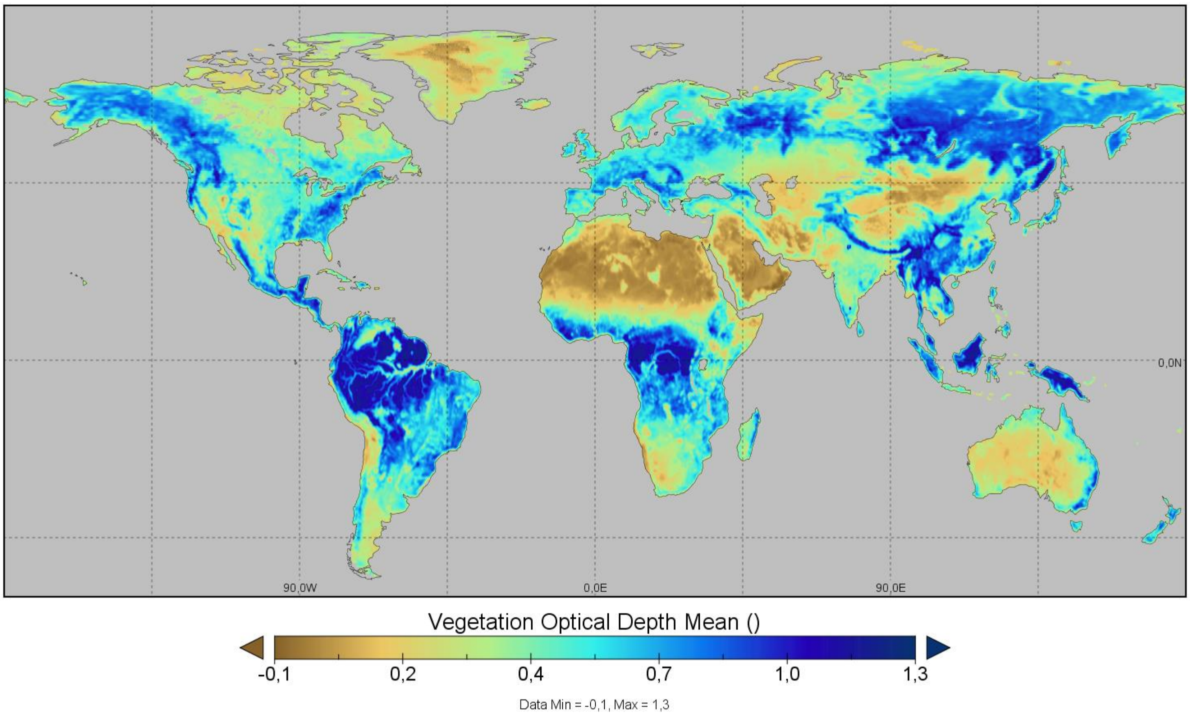

Figure 4: AMSR-E average vegetation optical

3.2.4 Topographic Complexity

The topographic complexity(Normalized standard deviation of topography) is derived from the USGS 30-second Global Elevation Data (GTOPO30) (USGS 1996). This can be used to help understand the potential distortion of backscatter in mountainous regions (i.e. calibration errors due to the deviation of the surface from the assumed ellipsoid and the rough terrain, the influence of permanent snow and ice cover, a reduced sensitivity due to forest and rock cover and highly variable surface conditions). The topographic complexity flag is derived from GTOPO 30 data. For each cell of the DGG, the standard deviation of elevation is calculated and the result is normalized to values between 0 and 100 % .

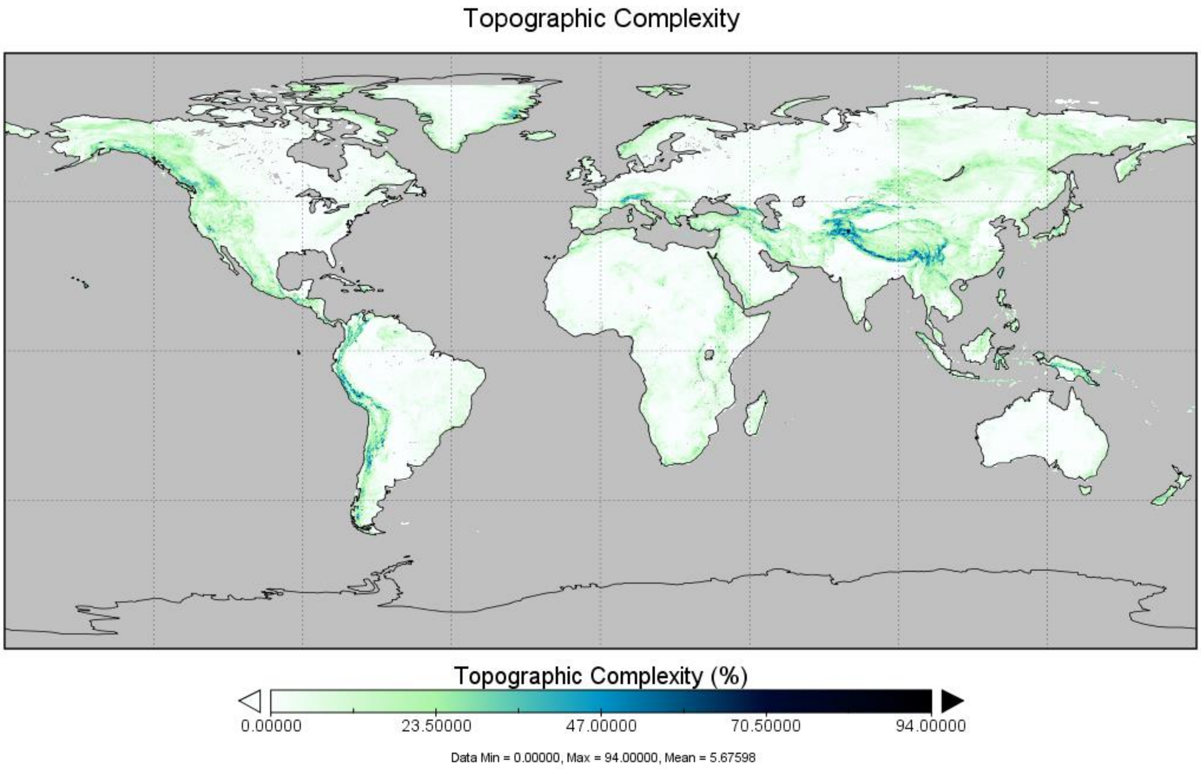

Figure 5: Topographic complexity from the USGS 30-second Global Elevation Data (GTOPO30).

3.2.5 Wetland fraction

The open water fraction is defined as fraction coverage of areas with inundation potential. The inundation potential has been derived from the Global Lakes and Wetlands Database (GLWD) level 3 product, which includes several wetland and inundation types. The wetland fraction is calculated for the Discrete Global Grid (DGG)and the conversion from DGG to the 0.25 degree grid is based on the nearest-neighbour search algorithm.

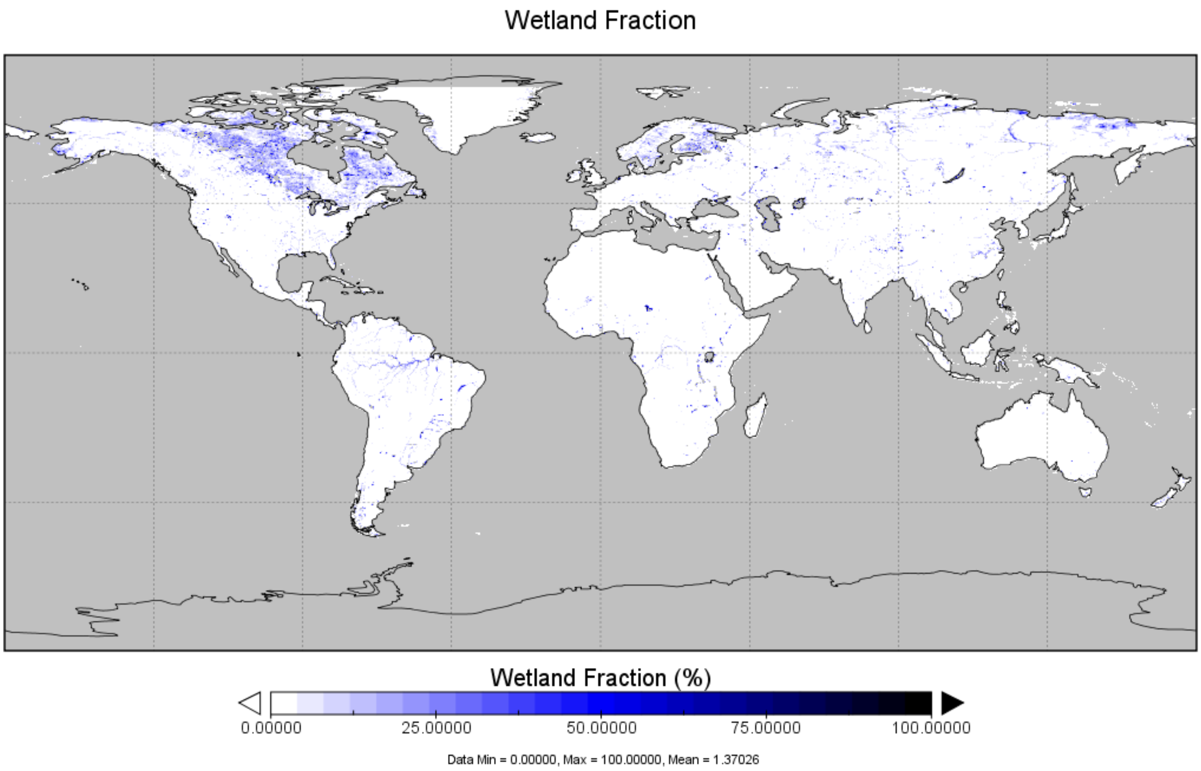

Figure 6: Wetland fraction derived from the Global Lakes and Wetlands Database (GLWD).

3.3 Structure and file format

3.3.1 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 1.6. The NetCDF soil moisture data files are stored in folders for each year with one file per day. The following file naming convention is applied:

```
C3S-SOILMOISTURE-L3S-<Variable>-<Dataset>-<Interval>-<Reference_date>-<CDR>-v<Version>.nc
```

<Variable>
Active product: SSMS (surface soil moisture degree of saturation absolute); Passive and Combined product: SSMV (surface soil moisture volumetric absolute).

<Dataset>
ACTIVE; PASSIVE; COMBINED

<Interval>
DAILY; DEKADAL; MONTHLY

<Reference_date>

YYYYMMDDhhmmss – Reference date and time of the file in UTC. Each daily file contains data from this reference time +- 12 hours. For monthly and dekadal files this reference time is the start of the period. E.g. for the dekadal data the dates can only be YYYYMM01000000, YYYYMM11000000, or YYYYMM21000000. The reference date for the monthly data is always YYYYMM01000000.

<CDR>
Type of Climate Data Record: TCDR; ICDR

v<Version>
Major.Minor.Run e.g. v201706.0.0
The Major number usually represents the year (YYYY) and month (MM) of date. The initial value for Minor is zero, and will increment when updating the file. If there is a need – e.g. because of technical issues – to replace a file which already has been made public, the Run number of the replacement file shifts to the next increment. The initial Run number is zero.

3.4 NetCDF global attributes for the ACTIVE products

Table 7 Global NetCDF Attributes for the ACTIVE Daily product

Global Attribute Name	Content
title	C3S Surface Soil Moisture merged ACTIVE Product
institution	EODC (AUT); TU Wien (AUT); Transmissivity B.V. / VanderSat B.V. Noordwijk (NL)
contact	C3S_SM_Science@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; ASCSMR02/ASCAT/MetOp-A SSM Swath Grid 12.5 km sampling; ASCSMR02/ASCAT/MetOp-B SSM Swath Grid 12.5 km sampling
history	<date and time auditing trail of modifications to the original data> - file produced
references	https://climate.copernicus.eu; Liu, Y.Y., Dorigo, W.A., Parinussa, R.M., de Jeu, R.A.M. , Wagner, W., McCabe, M.F., Evans, J.P., van Dijk, A.I.J.M. (2012). Trend-preserving blending of passive and active microwave soil moisture retrievals, Remote Sensing of Environment, 123, 280-297, doi: 10.1016/j.rse.2012.03.014; Liu, Y.Y., Parinussa, R.M., Dorigo, W.A., De Jeu, R.A.M., Wagner, W., van Dijk, A.I.J.M., McCabe, M.F., & Evans, J.P. (2011): Developing an improved soil moisture dataset by blending passive and active microwave satellite based retrievals. Hydrology and Earth System Sciences, 15, 425-436; Wagner, W., W. Dorigo, R. de Jeu, D. Fernandez, J. Benveniste, E. Haas, M. Ertl (2012): Fusion of active and passive microwave observations to create an Essential Climate Variable data record on soil moisture. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-7, 2012. XXII ISPRS Congress, 25 August - 01 September 2012, Melbourne, Australia; Dorigo, W.A., Gruber, A., De Jeu, R.A.M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R.M., Kidd, R. (2015). Evaluation of the ESA CCI soil moisture product using ground-based observations. Remote Sensing of Environment; 162, 380-395, doi: 10.1016/j.rse.2014.07.023.
tracking_id	<xxxxxxxx-yyyy-zzzz-nnnn-mmmmmmmmmmmm> a UUID value
conventions	CF-1.6
product_version	v201801

Global Attribute Name	Content
summary	The data set was produced with funding from the Copernicus Climate Change Service.
keywords	Soil Moisture/Water Content
id	<filename>
naming_authority	EODC
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Grid
comment	These data were produced as part of the Copernicus Climate Change Service. Service Contract No 2016/C3S_312a_LOT7_EODC/SC1
date_created	<file creation date>
creator_name	Earth Observation Data Center (EODC)
creator_url	http://eodc.eu
creator_email	C3S_SM_Science@eodc.eu
project	Copernicus Climate Change Service.
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
time_coverage_start	<date time start>
time_coverage_end	<date time end>
time_coverage_duration	<Daily> P1D; <Dekadal mean>: P10D|P8D|P9D|P10D|P11D; <Monthly mean> : P1M
time_coverage_resolution	P1D
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention
license	Copernicus Data License
platform	ERS-1, ERS-2, METOP-A, Metop-B
sensor	AMI-WS, ASCAT-A, ASCAT-B
spatial_resolution	25km
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
geospatial_lon_resolution	0.25 degree
geospatial_lat_resolution	0.25 degree

3.5 NetCDF global attributes for the PASSIVE products

Table 8 Global NetCDF Attributes for the PASSIVE Daily product

Global Attribute Name	Content
title	C3S Surface Soil Moisture merged PASSIVE Product
institution	EODC (AUT); TU Wien (AUT); Transmissivity B.V. / VanderSat B.V. Noordwijk (NL)
contact	C3S_SM_Science@eodc.eu
source	LPRMv05/SMMR/Nimbus 7 L3 Surface Soil Moisture, Ancillary Params, and quality flags; LPRMv05/SSMI/F08, F11, F13 DMSP L3 Surface Soil Moisture, Ancillary Params, and quality flags; LPRMv05/TMI/TRMM L2 Surface Soil Moisture, Ancillary Params, and QC; LPRMv05/AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Params, and QC; LPRMv05/WINDSAT/CORIOLIS L2 Surface Soil Moisture, Ancillary Params, and

Global Attribute Name	Content
	QC; LPRMv06/AMSR2/GCOM-W1 L3 Surface Soil Moisture, Ancillary Params; LPRMv05/SMOS/MIRAS L3 Surface Soil Moisture, CATDS Level 3 Brightness Temperatures (L3TB) version 300 RE03 & RE04
history	<date and time auditing trail of modifications to the original data> - file produced
references	https://climate.copernicus.eu; Liu, Y.Y., Dorigo, W.A., Parinussa, R.M., de Jeu, R.A.M. , Wagner, W., McCabe, M.F., Evans, J.P., van Dijk, A.I.J.M. (2012). Trend-preserving blending of passive and active microwave soil moisture retrievals, Remote Sensing of Environment, 123, 280-297, doi: 10.1016/j.rse.2012.03.014; Liu, Y.Y., Parinussa, R.M., Dorigo, W.A., De Jeu, R.A.M., Wagner, W., van Dijk, A.I.J.M., McCabe, M.F., & Evans, J.P. (2011): Developing an improved soil moisture dataset by blending passive and active microwave satellite based retrievals. Hydrology and Earth System Sciences, 15, 425-436; Wagner, W., W. Dorigo, R. de Jeu, D. Fernandez, J. Benveniste, E. Haas, M. Ertl (2012): Fusion of active and passive microwave observations to create an Essential Climate Variable data record on soil moisture. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-7, 2012. XXII ISPRS Congress, 25 August - 01 September 2012, Melbourne, Australia; Dorigo, W.A., Gruber, A., De Jeu, R.A.M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R.M., Kidd, R. (2015). Evaluation of the ESA CCI soil moisture product using ground-based observations. Remote Sensing of Environment; 162, 380-395, doi: 10.1016/j.rse.2014.07.023.
tracking_id	<xxxxxxxx-yyyy-zzzz-nnnn-mmmmmmmmmmmm> a UUID value
conventions	CF-1.6
product_version	v201801
summary	The data set was produced with funding from the Copernicus Climate Change Service.
keywords	Soil Moisture/Water Content
id	<filename>
naming_authority	EODC
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Grid
comment	These data were produced as part of the Copernicus Climate Change Service. Service Contract No 2016/C3S_312a_LOT7_EODC/SC1
date_created	<file creation date>
creator_name	Earth Observation Data Center (EODC)
creator_url	http://eodc.eu
creator_email	C3S_SM_Science@eodc.eu
project	Copernicus Climate Change Service.
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
time_coverage_start	<date time start>
time_coverage_end	<date time end>
time_coverage_duration	<Daily> P1D; <Dekadal mean>: P10D|P8D|P9D|P10D|P11D; <Monthly mean> : P1M
time_coverage_resolution	P1D
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention
license	Copernicus Data License
platform	Nimbus 7, DMSP, TRMM, AQUA, Coriolis, GCOM-W1, MIRAS
sensor	SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2, SMOS
spatial_resolution	25km

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

3.6 NetCDF global attributes for the COMBINED products

Table 9 Global NetCDF Attributes for the COMBINED Daily product

Global Attribute Name	Content
title	C3S Surface Soil Moisture COMBINED active+passive Product
institution	EODC (AUT); TU Wien (AUT); Transmissivity B.V. / VanderSat B.V. Noordwijk (NL)
contact	C3S_SM_Science@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; ASCSMR02/ASCAT/MetOp-A SSM Swath Grid 12.5 km sampling; ASCSMR02/ASCAT/MetOp-B SSM Swath Grid 12.5 km samplingLPRMv05/SMMR/Nimbus 7 L3 Surface Soil Moisture, Ancillary Params, and quality flags; LPRMv05/SSMI/F08, F11, F13 DMSP L3 Surface Soil Moisture, Ancillary Params, and quality flags; LPRMv05/TMI/TRMM L2 Surface Soil Moisture, Ancillary Params, and QC; LPRMv05/AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Params, and QC; LPRMv05/WINDSAT/CORIOLIS L2 Surface Soil Moisture, Ancillary Params, and QC; LPRMv06/AMSR2/GCOM-W1 L3 Surface Soil Moisture, Ancillary Params; LPRMv05/SMOS/MIRAS L3 Surface Soil Moisture, CATDS Level 3 Brightness Temperatures (L3TB) version 300 RE03 & RE04
history	<date and time auditing trail of modifications to the original data> - file produced
references	https://climate.copernicus.eu; Liu, Y.Y., Dorigo, W.A., Parinussa, R.M., de Jeu, R.A.M. , Wagner, W., McCabe, M.F., Evans, J.P., van Dijk, A.I.J.M. (2012). Trend-preserving blending of passive and active microwave soil moisture retrievals, Remote Sensing of Environment, 123, 280-297, doi: 10.1016/j.rse.2012.03.014; Liu, Y.Y., Parinussa, R.M., Dorigo, W.A., De Jeu, R.A.M., Wagner, W., van Dijk, A.I.J.M., McCabe, M.F., & Evans, J.P. (2011): Developing an improved soil moisture dataset by blending passive and active microwave satellite based retrievals. Hydrology and Earth System Sciences, 15, 425-436; Wagner, W., W. Dorigo, R. de Jeu, D. Fernandez, J. Benveniste, E. Haas, M. Ertl (2012): Fusion of active and passive microwave observations to create an Essential Climate Variable data record on soil moisture. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-7, 2012. XXII ISPRS Congress, 25 August - 01 September 2012, Melbourne, Australia; Dorigo, W.A., Gruber, A., De Jeu, R.A.M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R.M., Kidd, R. (2015). Evaluation of the ESA CCI soil moisture product using ground-based observations. Remote Sensing of Environment; 162, 380-395, doi: 10.1016/j.rse.2014.07.023.
tracking_id	<xxxxxxxx-yyyy-zzzz-nnnn-mmmmmmmmmmmm> a UUID value
conventions	CF-1.6

Global Attribute Name	Content
product_version	v201801
summary	The data set was produced with funding from the Copernicus Climate Change Service.
keywords	Soil Moisture/Water Content
id	<filename>
naming_authority	EODC
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Grid
comment	These data were produced as part of the Copernicus Climate Change Service. Service Contract No 2016/C3S_312a_LOT7_EODC/SC1
date_created	<file creation date>
creator_name	Earth Observation Data Center (EODC)
creator_url	http://eodc.eu
creator_email	C3S_SM_Science@eodc.eu
project	Copernicus Climate Change Service.
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
time_coverage_start	<date time start>
time_coverage_end	<date time end>
time_coverage_duration	<Daily> P1D; <Dekadal mean>: P10D|P8D|P9D|P10D|P11D; <Monthly mean> : P1M
time_coverage_resolution	P1D
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention
license	Copernicus Data License
platform	Nimbus 7, DMSP, TRMM, AQUA, Coriolis, GCOM-W1, MIRAS; ERS-1, ERS-2, METOP-A, METOP-B
sensor	SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2, SMOS; AMI-WS, ASCAT-A, ASCAT-B
spatial_resolution	25km
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
geospatial_lon_resolution	0.25 degree
geospatial_lat_resolution	0.25 degree

4. NetCDF data file variables and attributes

Lon (Daily, Dekadal, Monthly)

Table 10 Attribute Table for Variable lon

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

Lat (Daily, Dekadal, Monthly)

Table 11 Attribute Table for Variable lat

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

Time (Daily, Dekadal, Monthly)

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.”

Table 12 Attribute Table for Variable time (reference time)

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

dnflag (Daily)

The Day or Night Flag specifies, 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).

Table 13 Attribute Table for Variable dnflag, only available in the Daily files

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 (Daily)

Flag values are stored as signed bytes, and the default value (NaN) is 127. By reading the flag for the surface soil moisture data, the user gets information for that grid point. A "0" (zero) informs the user that the sm value for that grid point has been checked, but there was no inconsistency found. A flag value of "1" denotes, that the soil for that location is covered with snow or the temperature is below zero;"2" indicates that the observed location is covered by dense vegetation; "4" stands for undefined other cases, e.g. no convergence in the model, thus no valid soil moisture estimates; "8" denotes days that are masked because not all data sets have valid observations and those which do are deemed unreliable when used alone; and "16" denotes locations where all data sets are deemed unreliable. Please see Table 14 for the meaning of all other flag values.

Table 14 Attribute Table for Variable flag, only available in the Daily files

NetCDF Attribute	Description
long_name	Flag
flag_values	[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49. 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 127]
flag_meanings	**0 = no data inconsistency detected** **1 = snow coverage or temperature below zero** **2 = dense vegetation** 3 = combination of flag values 1 and 2 **4 = others - no convergence in the model thus no valid sm estimates** 5 = combination of flag values 1 and 4 6 = combination of flag value 2 and 4 7 = combination of flag values 1, 2, and 4 **8 = soil moisture value exceeds physical boundary** 9 = combination of flag values 1, and 8 10 = combination of flag values 2, and 8 11 = combination of flag values 1, 2, and 8 12 = combination of flag values 4, and 8 13 = combination of flag values 1, 4, and8 14 = combination of flag values 2, 4, 8 15 = combination of flag values 1, 2, 4, and 8 **16 = weight of measurement below threshold** 17 = combination of flag values 1 and 16 18 = combination of flag values 2 and 16 19 = combination of flag values 1 and 2 and 16 20 = combination of flag values 4 and 16 21 = combination of flag values 1 and 4 and 16 22 = combination of flag values 2 and 4 and 16 23 = combination of flag values 1 and 2 and 4 and 16 24 = combination of flag values 8 and 16 25 = combination of flag values 1 and 8 and 16 26 = combination of flag values 2 and 8 and 16 27 = combination of flag values 1 and 2 and 8 and 16 28 = combination of flag values 4 and 8 and 16 29 = combination of flag values 1 and 4 and 8 and 16 30 = combination of flag values 2 and 4 and 8 and 16 31 = combination of flag values 1 and 2 and 4 and 8 and 16 **32 = all datasets deemed unreliable** 33 = combination of flag values 1 and 32 34 = combination of flag values 2 and 32 35 = combination of flag values 1 and 2 and 32 36 = combination of flag values 4 and 32 37 = combination of flag values 1 and 4 and 32 38 = combination of flag values 2 and 4 and 32 39 = combination of flag values 1 and 2 and 4 and 32 40 = combination of flag values 8 and 32

	41 = combination of flag values 1 and 8 and 32 42 = combination of flag values 2 and 8 and 32 43 = combination of flag values 1 and 2 and 8 and 32 44 = combination of flag values 4 and 8 and 32 45 = combination of flag values 1 and 4 and 8 and 32 46 = combination of flag values 2 and 4 and 8 and 32 47 = combination of flag values 1 and 2 and 4 and 8 and 32 48 = combination of flag values 16 and 32 49 = combination of flag values 1 and 16 and 32 50 = combination of flag values 2 and 16 and 32 51 = combination of flag values 1 and 2 and 16 and 32 52 = combination of flag values 4 and 16 and 32 53 = combination of flag values 1 and 4 and 16 and 32 54 = combination of flag values 2 and 4 and 16 and 32 55 = combination of flag values 1 and 2 and 4 and 16 and 32 56 = combination of flag values 8 and 16 and 32 57 = combination of flag values 1 and 8 and 16 and 32 58 = combination of flag values 2 and 8 and 16 and 32 59 = combination of flag values 1 and 2 and 8 and 16 and 32 60 = combination of flag values 4 and 8 and 16 and 32 61 = combination of flag values 1 and 4 and 8 and 16 and 32 62 = combination of flag values 2 and 4 and 8 and 16 and 32 63 = combination of flag values 1 and 2 and 4 and 8 and 16 and 32
_CoordinateAxes	lat lon time
_FillValue	127 (NaN); type: signed byte

freqbandID (Daily, Dekadal, Monthly)

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 15 lists these combinations.

Table 15 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	Flag values and their meaning

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		

List of major codes and the corresponding frequency bands

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

Sensors and their operating frequencies:

Sensor	Operating Frequency [GHz]

<table>
<tr><td></td><td><table>
<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>AMI-WS</td><td>5.3</td></tr>
<tr><td>ASCAT-A/B</td><td>5.255</td></tr>
</table></td></tr>
<tr><td>_CoordinateAxes</td><td>lat lon time</td></tr>
<tr><td>_FillValue</td><td>0 (NaN); type: signed integer</td></tr>
</table>

mode (Daily)
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.

Table 16 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

nobs (Dekadal, Monthly)
The NetCDF variable nobs stores an integer which is the number of valid observations which have been used to compute the dekadal or monthly mean.

Table 17 Attribute Table for Variable nobs

NetCDF Attribute	Description
long_name	Number of valid observations
units	N/A
_CoordinateAxes	lat lon time
_FillValue	-1 (NaN); type: short integer

sensor (Daily, Dekadal, Monthly)
The values for sensor are stored as signed integer, with NaN as 0 (zero). These values indicate the satellite sensors which have been used for a specific grid point. Valid values range from 1 to 864. Table 18 lists all available sensor combinations.

Table 18 Attribute Table for Variable sensor

NetCDF Attribute	Description
long_name	Sensor

<table>
<tr><td>flag_values</td><td>[0, 1, 2, 4, 8, 16, 24, 32, 64, 72, 80, 88, 96, 128, 130, 132, 136, 256, 264, 272, 280, 288, 320, 328, 336, 344, 352, 512, 544, 576, 608, 768, 800, 832, 864]</td></tr>
<tr><td>flag_meanings</td><td>
<table>
<tr><th>Value</th><th>Sensor Combination</th><th>Value</th><th>Sensor Combination</th></tr>
<tr><td>0</td><td>NaN</td><td>264</td><td>AMSRE+ASCATA</td></tr>
<tr><td>1</td><td>SMMR</td><td>272</td><td>WindSat+ASCATA</td></tr>
<tr><td>2</td><td>SSMI</td><td>280</td><td>AMSRE+WindSat+ASCATA</td></tr>
<tr><td>4</td><td>TMI</td><td>288</td><td>AMSR2+ASCATA</td></tr>
<tr><td>8</td><td>AMSRE</td><td>320</td><td>SMOS+ASCATA</td></tr>
<tr><td>16</td><td>WindSat</td><td>328</td><td>AMSRE+SMOS+ASCATA</td></tr>
<tr><td>24</td><td>AMSRE+WindSat</td><td>336</td><td>WindSat+SMOS+ASCATA</td></tr>
<tr><td>32</td><td>AMSR2</td><td>344</td><td>AMSRE+WindSat+SMOS+ASCATA</td></tr>
<tr><td>64</td><td>SMOS</td><td>352</td><td>AMSR2+SMOS+ASCATA</td></tr>
<tr><td>72</td><td>AMSRE+SMOS</td><td>512</td><td>ASCATB</td></tr>
<tr><td>80</td><td>WindSat+SMOS</td><td>544</td><td>AMSR2+ASCATB</td></tr>
<tr><td>88</td><td>AMSRE+WindSat+SMOS</td><td>576</td><td>SMOS+ASCATB</td></tr>
<tr><td>96</td><td>AMSR2+SMOS</td><td>608</td><td>AMSR2+SMOS+ASCATB</td></tr>
<tr><td>128</td><td>AMIWS</td><td>768</td><td>ASCATA+ASCATB</td></tr>
<tr><td>130</td><td>SSMI+AMIWS</td><td>800</td><td>AMSR2+ASCATA+ASCATB</td></tr>
<tr><td>132</td><td>TMI+AMIWS</td><td>832</td><td>SMOS+ASCATA+ASCATB</td></tr>
<tr><td>136</td><td>ASMRE+AMIWS</td><td>864</td><td>AMSR2+SMOS+ASCATA+ASCATB</td></tr>
<tr><td>256</td><td>ASCATA</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>_CoordinateAxes</td><td>lat lon time</td></tr>
<tr><td>_FillValue</td><td>0 (NaN); type: signed integer</td></tr>
</table>

sm (Daily, Dekadal, Monthly)

The “sm” parameter holds the surface soil moisture estimates are generated by blending passive and active microwave soil moisture retrievals as a weighted average with the weights being proportional to the signal-to-noise ratio (SNR) of the data sets. SNRs are estimated using triple collocation (TC) analysis Gruber et al. (2017).. The data are provided in percentage of saturation [%] units for the ACTIVE product, and volumetric [m^3m^{-3}] units for the PASSIVE and COMBINED products. Figure 7 shows a plotted example of the sm variable.

Table 19 Attribute Table for Variable sm for the PASSIVE and COMBINED products

NetCDF Attribute	Description
long_name	ACTIVE: Percent of Saturation Soil Moisture PASSIVE and COMBINED: Volumetric Soil Moisture
units	ACTIVE: percent PASSIVE and COMBINED: m^3m^{-3}
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)

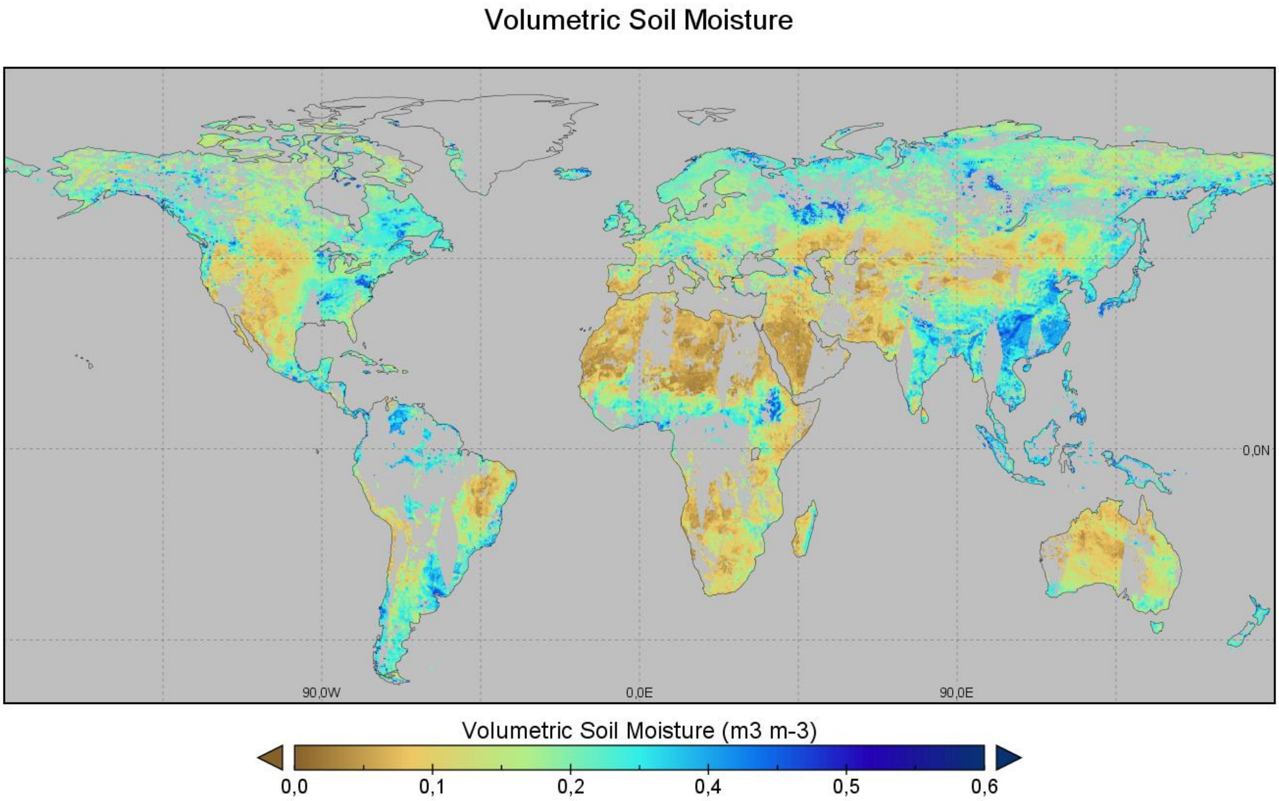

Figure 7 Visualisation of the NetCDF data variable “sm” for day 2017-07-07 from the COMBINED ICDR product using Panoply[2]

sm_uncertainty (Daily, Dekadal, Monthly)
The merging of soil moisture data from different sensors requires a harmonization of the data. The data need to be brought into a common climatology by running them through several scaling procedures performing the cumulative distribution function (CDF) matching technique. The provided “sm_uncertainty” parameter represents the error standard deviation of the data sets (in the respective climatology of the dataset), estimated through triple collocation (TC) analysis, which are used to calculate the relative weighting of the data sets. In periods where TC cannot be applied, or in cases where the TC-based error standard deviation estimates do not converge, 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 soil moisture [m^3m^{-3}]. On days where only measurements of one single data set are available, sm_uncertainty represents their error standard deviation as obtained from TC analysis. On days where two or more data sets are merged, sm_uncertainties represents the estimated error standard deviation of the merged soil moisture measurements, obtained by propagating the TC-based error standard deviation estimates of the contributing data sets through the merging algorithm using a standard error propagation scheme. sm_uncertainty values exceeding the maximum value of 100 (ACTIVE) or 1 (PASSIVE and COMBINED) are set to the maximum value respectively. Table 21 lists the availability of the soil

[2] Panoply source: https://www.giss.nasa.gov/tools/panoply

moisture uncertainty information for each product. Figure 8 plots the uncertainty for day 2017-06-30 of the TCDR COMBINED product.

Table 20 Attribute Table for Variable sm_uncertainty

NetCDF Attribute	Description
long_name	ACTIVE: Percent of Saturation Soil Moisture Uncertainty PASSIVE and COMBINED: Volumetric Soil Moisture Uncertainty
Units	ACTIVE: percent PASSIVE and COMBINED: m3 m-3
_CoordinateAxes	lat lon time
_FillValue	-9999.0 (NaN); type: float32 (4 bytes)

Table 21 sm_uncertainty data provided in the Daily data sets

Product	Time Period
ACTIVE	1991-08-05 onwards
PASSIVE	1987-07-09 onwards
COMBINED	1987-07-09 onwards

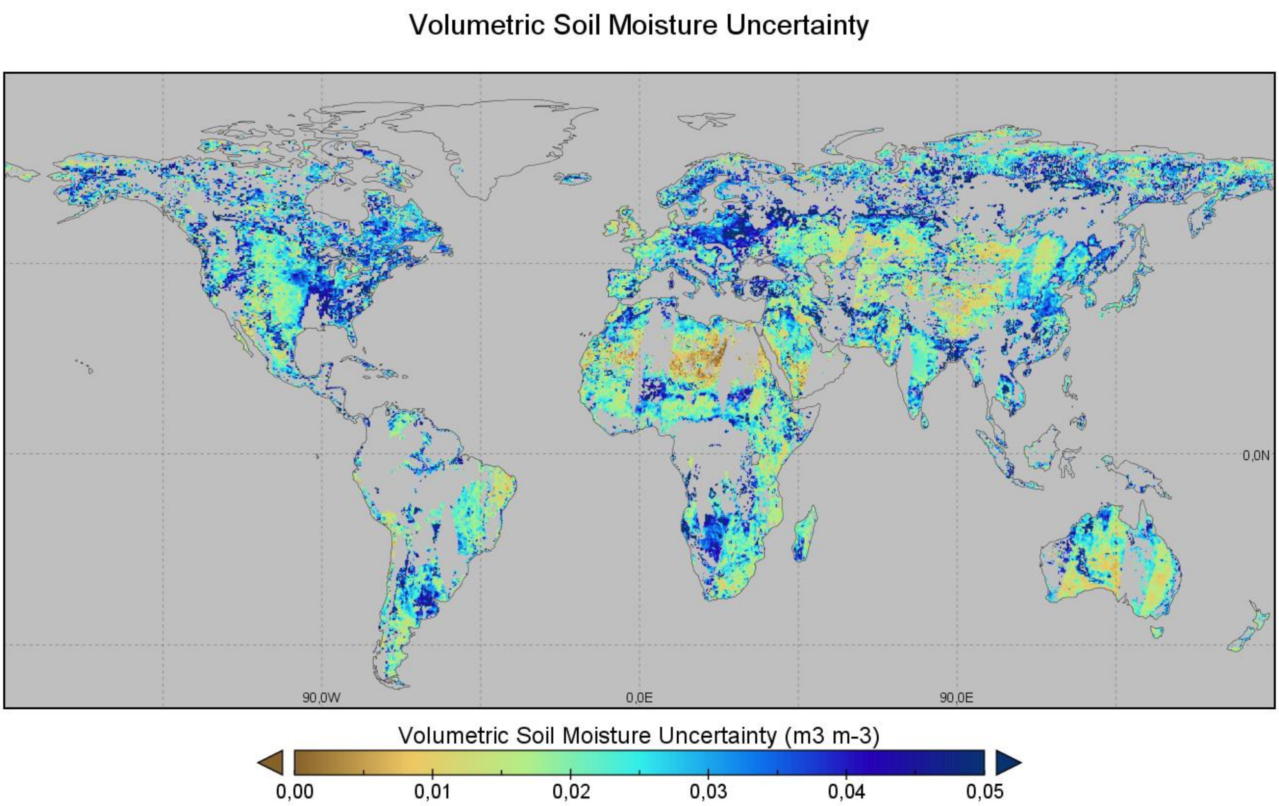

Figure 8 “sm_uncertainty” for day 2017-07-07 from the COMBINED ICDR product.

t0 (Daily)

The original observation timestamp is stored within the NetCDF variable t0 (t-zero). 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.”

Table 22 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>
_CoordinateAxes	lat lon time
_FillValue	-9999.0; type: double

5. Overview of EO and modelled data used to create the C3S products

Table 23: Major characteristics of passive and active microwave instruments and model products

	Passive microwave products							Active microwave products				Model product	
	SMMR	SSM/I	TMI	AMSR-E	AMSR2	Windsat	SMOS	AMI-WS	AMS-WS	ASCAT-A	ASCAT-B	GLDAS-1-Noah	GLDAS-2-Noah
Platform	Nimbus 7	DMSP	TRMM	Aqua	GCOM-W1	Coriolis	SMOS	ERS1/2	ERS2	MetOp-A	MetOp-B	---	---
Time period used	Jan 1979 – Aug 1987	Sep 1987 – Dec 2007	Jan 1998 – Dec 2013	Jul 2002 – Oct 2011	May 2012 – Dec 2017	Oct 2007 – Jul 2012	Jan 2010 – Dec 2017	Jul 1991 – Dec 2006	May 1997 – Feb 2007	Jan 2007 – Dec 2017	Nov 2012 – Dec 2015	Jan 2000 – Dec 2017	Jan 1948 – Dec 2010
Algorithm Product version	LPRM v05	LPRM v05	LPRM v05	LPRM v06	LPRM v06	LPRM v05	LPRM v06	WARP 5.4 P1R1	WARP 5.5 P1R1	WARP 5.5 P2R2	WARP 5.5 P2R2	V1	V2.0
Channel used for soil moisture	6.6 GHz	19.3 GHz	10.7 GHz	6.9/10.7 GHz	6.925/10.65 GHz	6.8/10.7 GHz	1.4 GHz	5.3 GHz	5.3 GHz	5.3 GHz	5.3 GHz	---	---
Original spatial resolution* (km^2)	150×150	69 × 43	59 × 36	76 × 44	35 x 62	25 x 35	40 km	50 × 50	25 x 25	25 × 25	25 × 25	25 × 25	25 × 25
Spatial coverage	Global	Global	N40° to S40°	Global	Global	Global	Global	Global	Global	Global	Global	Global	Global
Swath width (km)	780	1400	780/897 after boost in Aug 2001	1445	1450	1025	600	500	500	1100 (550×2)	1100 (550×2)	---	---
Equatorial crossing time	Descending: 0:00	Descending: 06:30	Varies (non polar-orbiting)	Descending: 01:30	Descending 01:31	Descending 6:03	Ascending 6:00	Descending: 10:30	Desending 10:30	Descending: 09:30	Descending: 09:30	---	---
Unit	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	Degree of saturation (%)	Degree of saturation (%)	Degree of saturation (%)	Degree of saturation (%)	kg m^{-2}	kg m^{-2}

*For passive and active microwave instruments, this stands for the footprint spatial resolution.

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