ESA Climate Change Initiative Plus - Soil Moisture

Product Validation and Intercomparison Report (PVIR)
D4.2 Version 1.0

Supporting Product Version v09.2

15/12/2025

Prepared by

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

in cooperation with

TU Wien, Transmissivity, CESBIO and UKCEH

This document forms the deliverable D4.2 Product Validation and Intercomparison Report (PVIR), Version 1.0, and was compiled for Phase 3 of the ESA Climate Change Initiative Plus Soil Moisture Project (CCN 4 to ESRIN Contract No: 4000126684/19/I-NB). For more information on the CCI programme of the European Space Agency (ESA) see https://climate.esa.int/.

Number of pages: 26 (including cover, preface and references).

Authors:	D. Duchemin, R Prajapati, N. Rodríguez-Fernández, A. Mialon
Circulation (Internal):	Project consortium and science partners
External:	ESA

Issue	Date	Details	Editor
0.1	19/02/2025	Created Based on approved deliverable D4.1, Version2, 20/06/2024	R. Kidd
0.1	02/09/2025	Initial version	D. Duchemin
0.2	30/09/2025	Reviewed. Updated Header and Document metadata	R. Kidd
0.2	30/09/2025	Edited section 5	D. Duchemin
0.3	01/10/2025	Moved i0.2 to Next Cloud for testing	R. Kidd
0.4	07/10/2025	Added subsections in 5.1.1, 5.1.2. Updated table of content/ figures/ table accordingly. Added coverage verification chapter	D. Duchemin W. Preimesberger
0.5	07/11/2025	Added content of subsection 5.3 Updated table of content/ figures/ table accordingly. Added Summary.	W. Preimesberger D. Duchemin
0.6	08/12/2025	Reviewed. Updated formatting, reformatted figures and cross references. To ESA for review	R. Kidd
0.7	15/12/2025	Updated Reference documents. Revised typo's in text, replaced wrt. with "with respect to"	R. Kidd

Document Change Record: For any clarifications please contact N. Rodríguez-Fernández. (nemesio.rodriguez-fernandez@cnrs.fr).

Project Partners

Prime Contractor, Project Management	**EODC**, Earth Observation Data Centre for Water Resources Monitoring (Austria)
Earth Observation Partners	**TU Wien**, Vienna University of Technology (Austria)
	TMS, Transmissivity BV (The Netherlands)
	CESBIO, Center of Spatial Studies for the Biosphere (France)
Climate Research Partner	**UKCEH**, UK Center for Ecology and Hydrology (United Kingdom)

Table of Content

List of Figures

List of Tables

Definitions, acronyms and abbreviations

AMI-WS	Active Microwave Instrument – Windscat (ERS 1 and ERS 2)
AMSR2	Advanced Microwave Scanning Radiometer 2
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System
ASCAT	Advanced Scatterometer (Metop)
ATBD	Algorithm Theoretical Basis Document
CCI	Climate Change Initiative
CDF	Cumulative Distribution Function
CF	Climate Forecast
DGG	Discrete Global Grid
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
ERA5	Fifth ECMWF ReAnalysis data set
ESA	European Space Agency
GLDAS	Global Land Data Assimilation System
LPRM	Land Parameter Retrieval model
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
PSD	Product Specification Document
PVP	Product Validation Plan
SM	Soil Moisture
SMAP	Soil Moisture Active Passive satellite mission
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal to noise ratio
SSMV	Surface Soil Moisture Volumetric
SSM/I	Special Sensor Microwave Imager
TC	Triple Collocation
TMI	TRMM Microwave Imager
UTC	Coordinated Universal Time
VOD	Vegetation Optical Depth
WACMOS	Water Cycle Multimission Observation Strategy
WARP	soil Water Retrieval Package
WindSat	WindSat Spaceborne Polarimetric Microwave Radiometer

1 Introduction

The document provides the validation and intercomparison of the ESA CCI SM products, version 9.2, with reference datasets and earlier products versions. It follows the validation strategy as described in the Product Validation Plan (PVP) D4.1.

1.1 Purpose of the document

This deliverable relates to the ESA CCI Surface Soil Moisture (SM) product version 9.2.

The document provides the following:

- Description of the datasets involved in the evaluation of the products
- Results of the verification steps following the data production
- Results of the validation of the products with respect to the reference datasets and the comparison with previous versions of the ESA CCI SM products.

1.2 Targeted audience

This document targets the following audience

- Users of the ESA CCI SM data product
- System Engineers for the ESA CCI SM product
- Other CCI ECV projects

2 Documents

2.1 Reference documents

This section provides a list of reference documents upon which this document is either based, or are required to be referenced by the reader in order to obtain the full information intended by the authors.

[RD-1] Dorigo, W., stradiotti, . pietro ., Preimesberger, W., Kidd, R., van der Schalie, R., Frederikse, T., Rodriguez-Fernandez, N., & Baghdadi, N. (2024). ESA Climate Change Initiative Plus - Soil Moisture Algorithm Theoretical Baseline Document (ATBD) Supporting Product Version 09.0. Zenodo. https://doi.org/10.5281/zenodo.13860922Product Validation Plan (PVP), Version 1.0, 2025, ESA Climate Change Initiative Plus - Soil Moisture, Phase 3, Supporting Product Version v09.2, 09/12/2025, Project Internal Documentation, available only on request

2.2 Bibliography

A complete bibliographic list, detailing scientific text or publications that support arguments or statements made within the current document is provided in Section 7.

3 Reference datasets

The ESA-CCI SM Products are evaluated with respect to Reference datasets. A short description of these is given hereunder, more details can be found in the Product Validation Plan (PVP) [RD-2].

3.1 ISMN in-situ measurements

The International Soil Moisture Network (ISMN) gathers in-situ Soil Moisture measurements, harmonizes the measures and their metadata, to provide a single access to the various validation campaigns, past and operational networks records (Dorigo et al., 2011). It provides SM measurements back to the 1950's, however only limited data are available in the earliest period. Therefore, the validation makes use of the dataset from 1990 to present, when the records provide a larger coverage in both time and space, which allow for a meaningful error evaluation. The SM variable is compared to the SM measurements of a maximum depth of 10 cm, from representative or very representative sites, with a "good" quality flag only.

3.2 Global reanalysis datasets

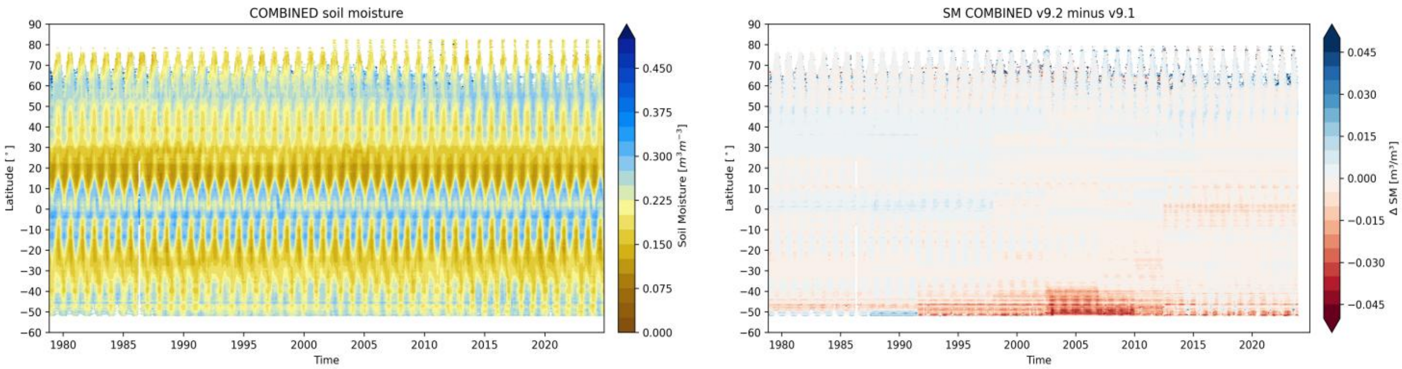
In order to evaluate the SM product on a large spatial and time scale, simulation datasets from land surface models are considered. The ERA5-Land model (C3S, 2019), developed by the ECMWF is used in its latest version. The variable *volumetric soil water layer 1*, which corresponds to the volume of water in the soil layer ranging from the surface to 7 cm depth, expressed in m^3m^{-3}, is employed in the following evaluation. It can be used as reference or as additional dataset, and if independent of the evaluation reference and the evaluated dataset, for the Triple Collocation Analysis (TCA).

4 Verification of the v09.2 ESA CCI SM productions

The verification occurs at the end of the production of the data records. The verifications encompass the validity of the format, the data completeness, and the comparison of aggregated SM statistics with those of the previous version to detect a potential significant deviation between the releases.

4.1 COMBINED

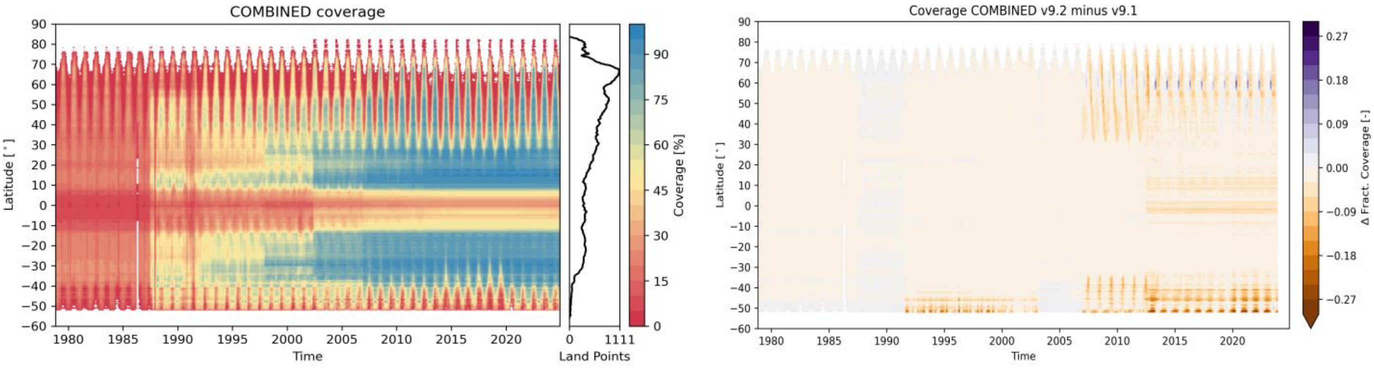
COMBINED v9.2 shows as expected similar global soil moisture pattern as the previous version (Figure 1). The largest differences are found in latitudes with sparse data coverage, either due to seasonal freeze/thaw dynamics (Northern Hemisphere) or due to a small number of (averaged) land points (Southern Hemisphere). Overall the detected differences compared to v9.1 are small (<0.05 m³/m³).



(a) (b)

Figure 1: Time-latitude diagram of absolute soil moisture values in the v9.2 COMBINED product (a), and difference with v9.1 (b).

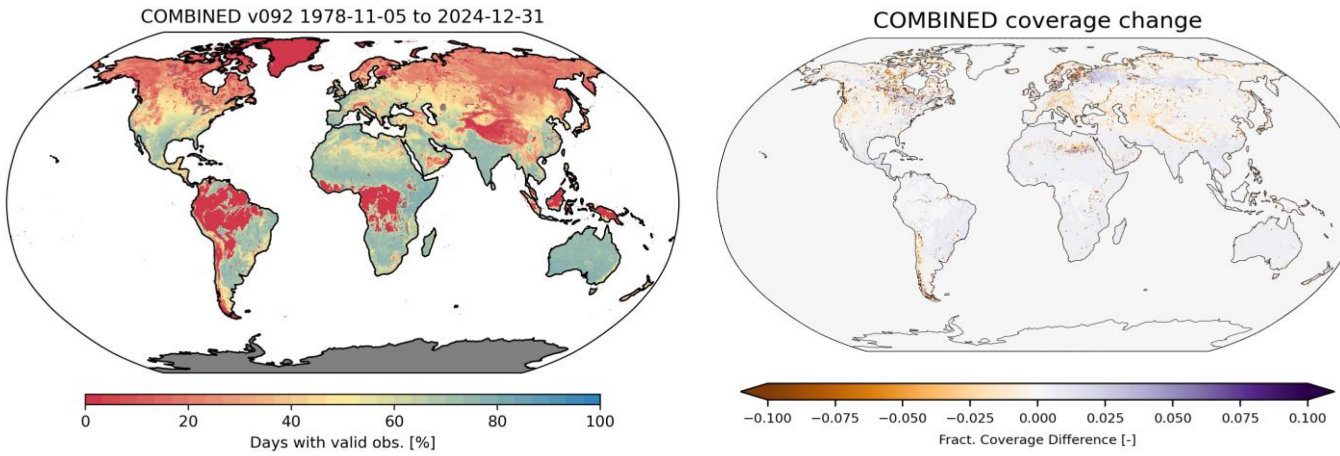
The same applies in terms of (fractional) data coverage (Figure 2). For some latitudes, data coverage is slightly lower in the v9.2, which is due to the exclusion of some pixels around water bodies and cities in the new version, which were not masked before (compare also Figure 3).



(a) (b)

Figure 2: Time-latitude diagram of relative daily data coverage (%) in the v9.2 COMBINED product (a), and difference with v9.1 (b).

This unintended exclusion of certain pixels (e.g., water bodies and urban areas) will be reverted to the previous behaviour in the next version. It occurs in locations where data are permanently masked for some sensors; however, at present, the remaining sensors are often not used to fill these gaps, as was done in earlier versions.



(a) (b)

Figure 3: Daily coverage of the v9.2 COMBINED product (a), and fractional coverage (%/100) difference compared to v9.1 (b).

The uncertainty field of the COMBINED product (Figure 4) shows the expected negative gradient over time, which is due to the additional of more (and more accurate) satellites over time, which reduce the total uncertainty level of the product. The found seasonal dynamics are due to the recent implementation of sub-seasonal error estimates (Stradiotti et al., 2025).

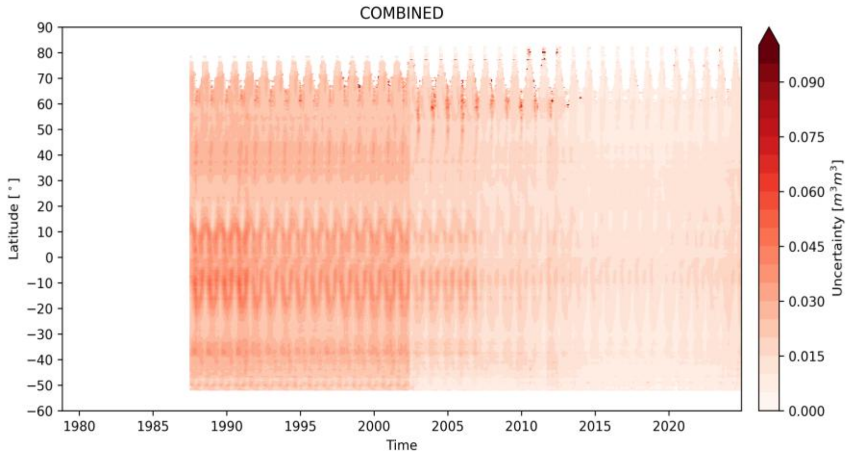
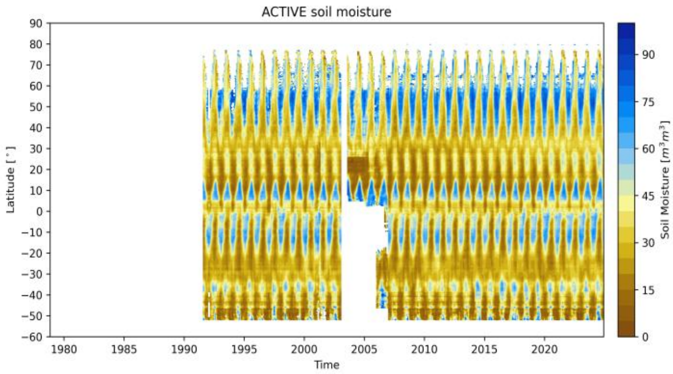


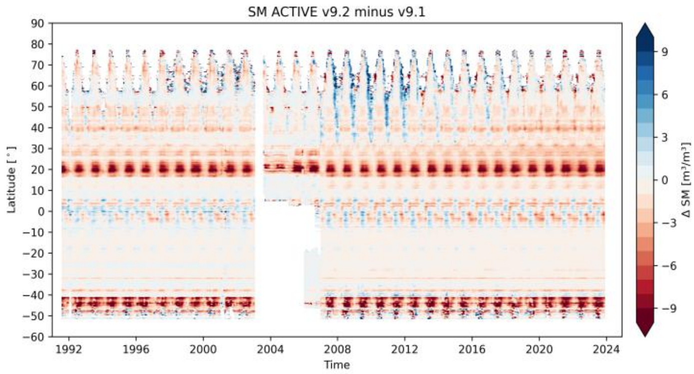
Figure 4: Time-latitude diagram of soil moisture uncertainty in the v9.2 COMBINED product

4.2 ACTIVE

Figure 5 shows the spatial-temporal soil moisture dynamics in the ACTIVE v9.2 product and the comparison to the previous version. ACTIVE shows similar seasonal dynamics as COMBINED but is scaled between 0-100 percent (soil moisture saturation). Some differences are found around the 20° latitude band, which is characterised by overall low data coverage as bare soil pixels are often masked out in the product. The active data can be driven by subsurface scattering features in these areas and are generally noisy and close to zero.



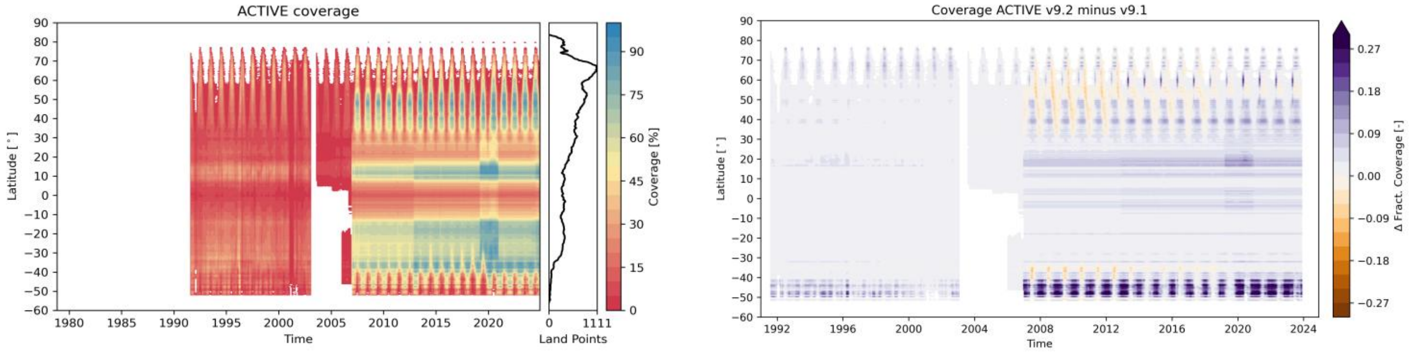
(a)



(b)

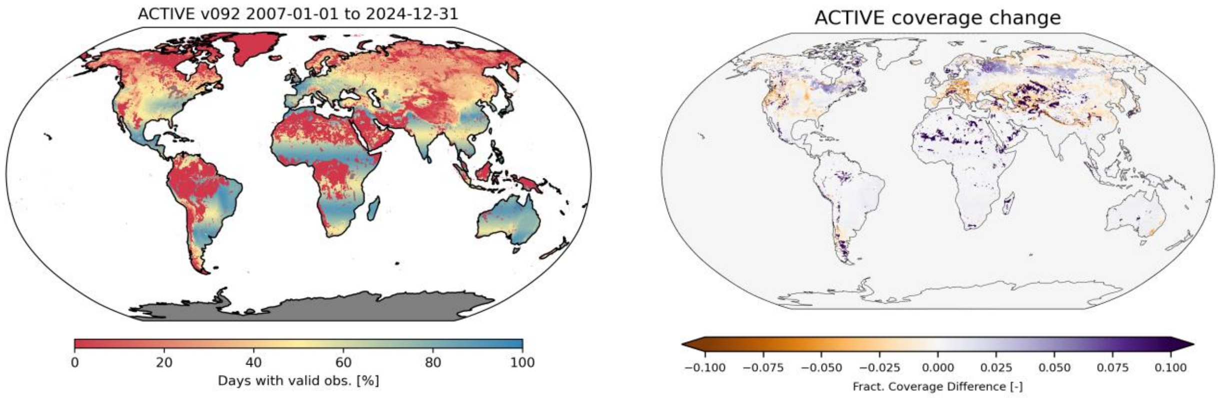
Figure 5: Time-latitude diagram of absolute soil moisture values in the v9.2 ACTIVE product (a), and difference with v9.1 (b).

Compared to v9.1, the coverage increased slightly, which some more observations included in most cases (Figure 6). The area around 20 °N shows some locations with increased data coverage, however, values there are often zero, which explains the lower average discussed before. This is also shown in Figure 7. Note also that the number of land pixels is very small below 40 °S, which may lead to an exaggerated effect in terms of fractional coverage change.



(a) (b)

Figure 6: Time-latitude diagram of relative daily data coverage (%) in the v9.2 ACTIVE product (a), and difference with v9.1 (b).



(a) (b)

Figure 7 - Daily coverage of the v9.2 ACTIVE product (a), and fractional coverage (%/100) difference compared to v9.1 (b) in the ASCAT period (after 01-2007).

In terms of uncertainty (Figure 8), the ACTIVE product does not show a trend as strong as the COMBINED product. In the ASCAT period the uncertainty level is overall constant, with some recently introduced seasonal features.

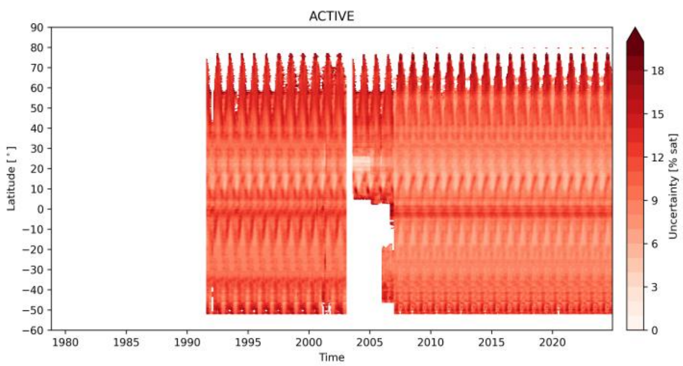
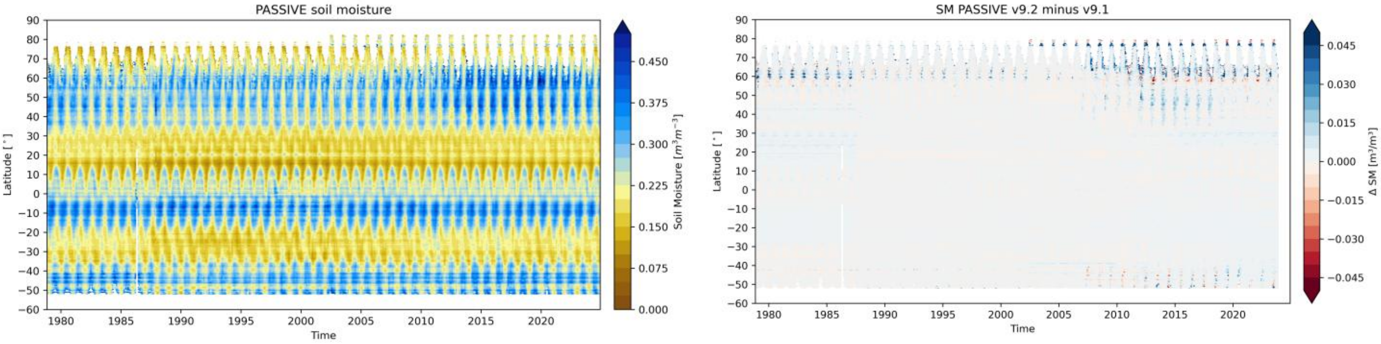


Figure 8: Time-latitude diagram of soil moisture uncertainty in the v9.2 ACTIVE product

4.3 PASSIVE

Other than the COMBINED product, which uses GLDAS Noah as the scaling reference, PASSIVE is scaled to AMSR-E/2 soil moisture retrievals. This leads to slightly different absolute values compared to COMBINED, but similar temporal dynamics (Figure 9).

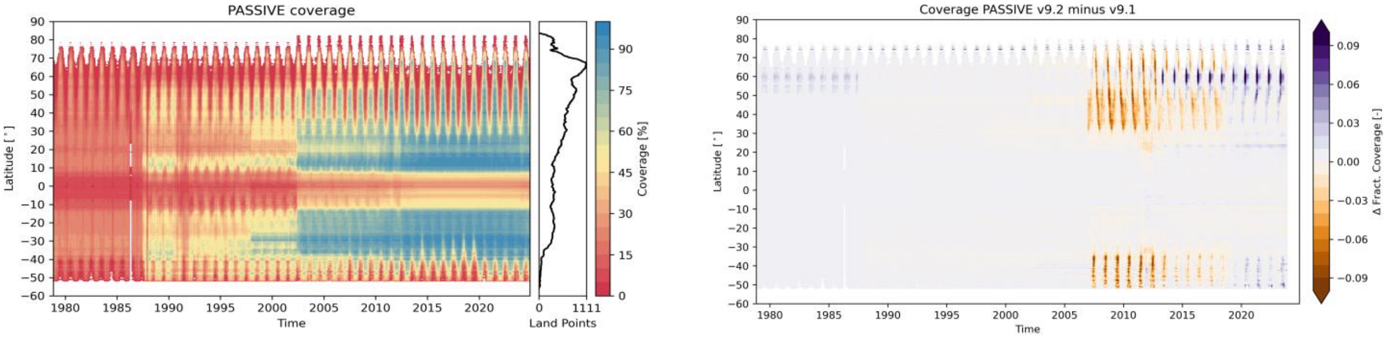
Compared to v9.1, the changes in v9.2 are minor, which is expected as the same input datasets were used.



(a) (b)

Figure 9 - Time-latitude diagram of absolute soil moisture values in the v9.2 PASSIVE product (a), and difference with v9.1 (b).

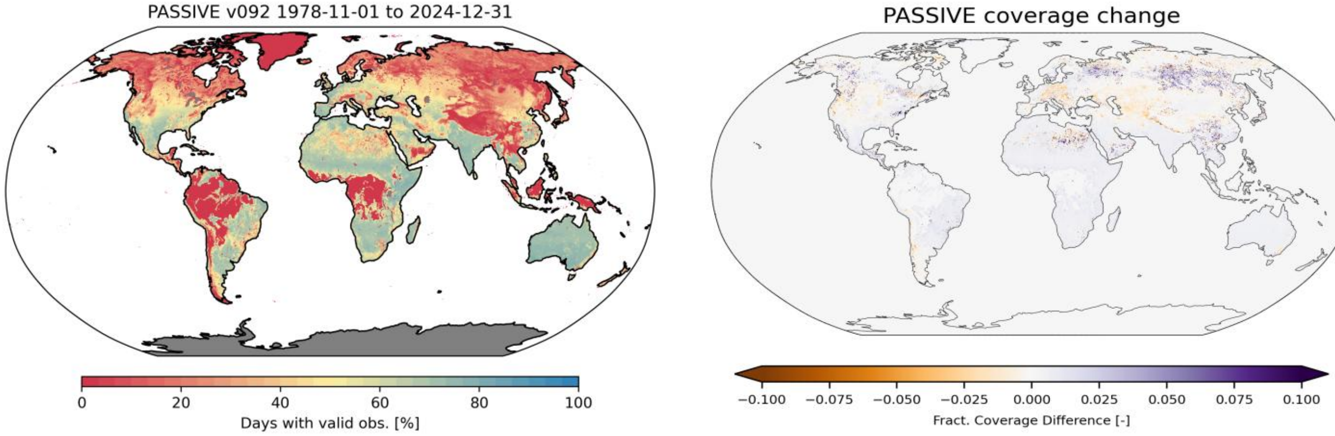
In terms of coverage, some differences are found in the ASCAT period, where – due to sensor cross-flagging – changes in active can also affect the coverage of PASSIVE (Figure 10). However, these differences are minor and do not affect the performance of the record.



(a) (b)

Figure 10: Time-latitude diagram of relative daily data coverage (%) in the v9.2 PASSIVE product (a), and difference with v9.1 (b).

Spatially, the patterns are the same as for the COMBINED product (Figure 11).



(a) (b)

Figure 11: Daily coverage of the v9.2 PASSIVE product (a), and fractional coverage (%/100) difference compared to v9.1 (b) in the period after 1978-11-01.

The PASSIVE uncertainty fields over time are shown in Figure 12 and show a similar pattern as for COMBINED.

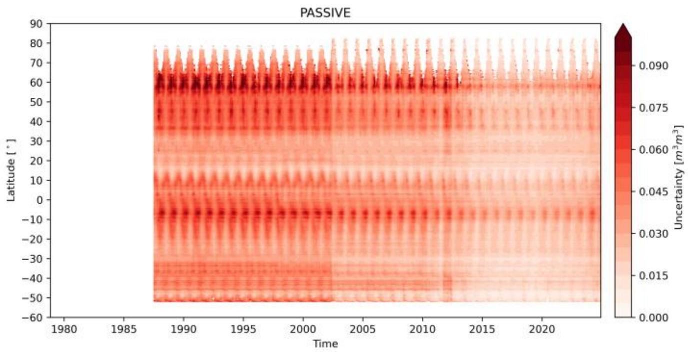


Figure 12: Time-latitude diagram of soil moisture uncertainty in the v9.2 PASSIVE product

5 Validation of the ESA CCI SM products v09.2

5.1 Comparison to reference datasets

5.1.1 Global level evaluation

5.1.1.1 Global level evaluation in 1991-2023

The Pearson's correlation coefficient (R) and the Unbiased Root Mean Squared Difference (UbRMSD) are evaluated with respect to the ISMN measurements for the ESA CCI SM Combined, Passive and Active products v9.2 over the 1991-2023 period. In the case of the active products, a CDF-matching based rescaling is applied with respect to the in-situ measurements to convert the saturation metric into the volumetric expression of the SM. The results can be put into perspective with those of version 9.1, as well as the ERA5-Land dataset, which are also evaluated in the same period. Figure 1 and Figure 2 provide the evaluation of the absolute values of the SM. Figure 3 and Figure 4 provide the same analysis for the SM anomalies, which are computed with respect to a climatology defined on the 2000-2022 period. The sites taken in consideration for the correlation are selected with respect to the p-values ($p<0.05$) to account for the significant correlations only.

The Inter quartile ranges (IQR) are represented with the vertical bars, the medians are provided as points (the medians of the upper and lower Confidence Intervals (CI) are shown with smaller points). Table 1 (respectively Table 2) provides the numerical values for the SM absolute, (resp. anomalies) values of the ESA CCI SM products, version 9.1 and 9.2.

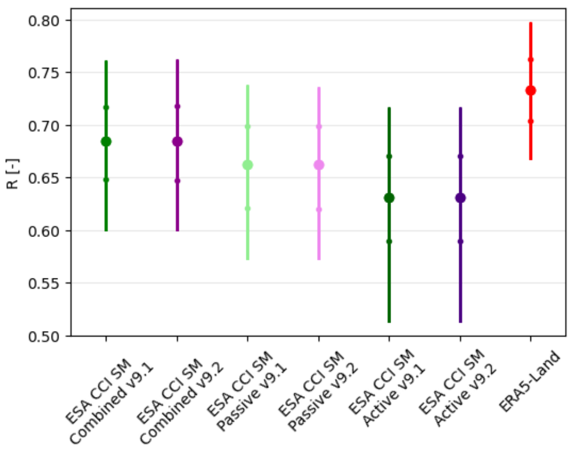


Figure 13 Correlation coefficients of ESA CCI SM Combined, Passive, Active v9.1, v9.2 products and of ERA5-Land (absolute values) with respect to ISMN measurements, in 1991-2023. (Median, IQR and CI of the median) Number of sites for passive, combined products and ERA5-Land evaluation: 1707; for active products: 1575

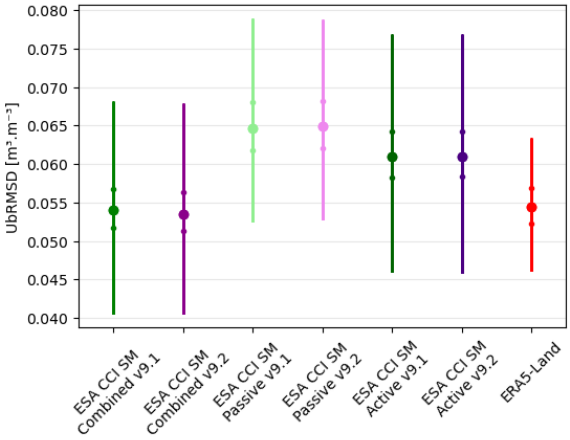


Figure 14 UbRMSD of ESA CCI SM Combined, Passive, Active v9.1, v9.2 products and of ERA5-Land (absolute values) with respect to ISMN measurements, in 1991-2023. (Median, IQR and CI of the median) Number of sites for passive, combined products and ERA5-Land evaluation: 1711; for active products: 1595

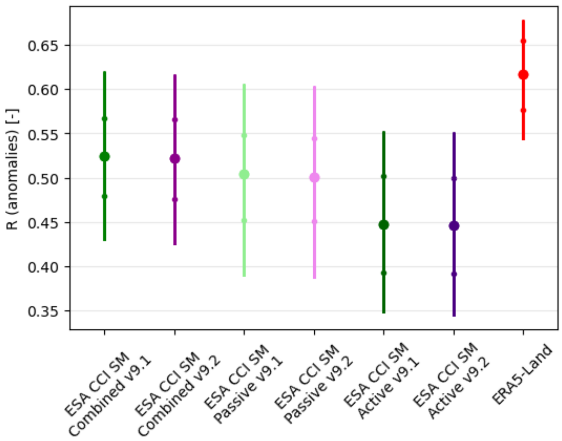


Figure 15 Correlation coefficients of ESA CCI SM Combined, Passive, Active v9.1, v9.2 products and of ERA5-Land (anomalies values) with respect to ISMN measurements, in 1991-2023. (Median, IQR and CI of the median). Anomalies are computed with respect to the 2000-2022 period. Number of sites for passive, combined products and ERA5-Land evaluation : 1670; for active products: 1536.

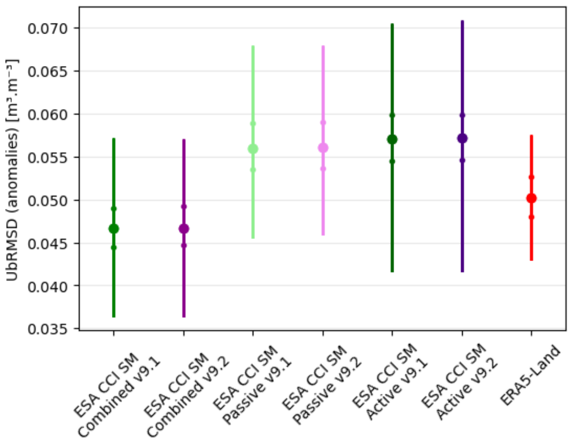


Figure 16 UbRSMD of ESA CCI SM Combined, Passive, Active v9.2, v9.1 products and of ERA5-Land (anomalies values) with respect to ISMN measurements, in 1991-2023. (Median, IQR and CI of the median). Anomalies are computed with respect to the 2000-2022 period. Number of sites for passive, combined products and ERA5-Land evaluation : 1695; for active products: 1580.

	COMBINED		ACTIVE		PASSIVE	
metric	v09.1	v09.2	v09.1	v09.2	v09.1	v09.2
Correlation [-]	0.684 [0.648; 0.717]	0.685 [0.647; 0.718]	0.631 [0.590; 0.670]	0.631 [0.590; 0.670]	0.662 [0.621; 0.699]	0.662 [0.620; 0.699]
UbRMSD [m3/m3]	0.054 [0.052; 0.057]	0.053 [0.051; 0.056]	0.061 [0.058; 0.064]	0.061 [0.058; 0.064]	0.065 [0.062; 0.068]	0.065 [0.062; 0.068]

Table 1: Correlation coefficient and UbRMSD (Median and CI) of the absolute values of ESA-CCI-SM Combined, Active and Passive products of version 9.1 and 9.2, with respect to ISMN, over the period 1991-2023.

	COMBINED		ACTIVE		PASSIVE	
metric	v09.1	v09.2	v09.1	v09.2	v09.1	v09.2
Correlation [-]	0.525 [0.479; 0.568]	0.522 [0.476; 0.566]	0.448 [0.393; 0.502]	0.446 [0.392; 0.500]	0.504 [0.452; 0.549]	0.501 [0.451; 0.545]
UbRMSD [m3/m3]	0.047 [0.045; 0.049]	0.047 [0.045; 0.049]	0.057 [0.054; 0.060]	0.057 [0.055; 0.060]	0.056 [0.053; 0.059]	0.056 [0.054; 0.059]

Table 2: Correlation coefficient and UbRMSD (Median and CI) of the anomalies of ESA-CCI-SM Combined, Active and Passive products of version 9.1 and 9.2, with respect to ISMN anomalies, over the period 1991-2023.The anomalies are computed with respect to the 2000-2022 period.

The two versions of the ESA CCI SM products provide, as expected, equivalent performances in all cases (absolute values/anomalies and R/UbRMSD). Indeed, the version 9.2 is an extension in time of version 9.1. For the correlation coefficients with respect to the ISMN measurements, the datasets show similar behaviours whether looking at the SM absolute values or the anomalies: ERA5-Land always has a median R higher than those of the ESA-CCI-SM products (by 5% or more). Among the ESA CCI SM products, the Combined product outperforms the others by 2 to 5 % (considering the median values again), highlighting the added value of merging both active and passive technologies into a single combined product. Comparing the correlation performances of the SM anomalies to the absolute values shows that the ranking of the datasets is unchanged. However, there is a strong performance decrease: the median R is reduced by around 16 % for the combined products, 18 % for the active ones, from 12 to 16 % for the passive products and 11 %for ERA5-Land.

For the UbRMSD metric, the Combined products show similar performances to the ERA5-Land in the case of the absolute values, with a median of 0.053 $m^3.m^{-3}$, slightly better in the case of the SM anomalies where the median goes down to 0.047 $m^3.m^{-3}$. It is close but however stays above the GCOS requirement for the SM uncertainty (0.04 $m^3.m^{-3}$ maximum). The Active and Passive products have even higher median UbRMSD (respectively 0.061 and 0.065 m^3/m^3 for the absolute SM values; 0.057 and 0.056 m^3/m^3 for the SM anomalies evaluation). Analysing the UbRMSD quartiles reveals that the GCOS requirement on SM uncertainty is verified for the Combined product for slightly more than 25% of the evaluation sites. For the Active and Passive products, the proportion of the evaluation sites that meet the GCOS SM uncertainty requirement is much smaller than 25%.

5.1.1.2 Global level evaluation until 2024

The figures 17 to Figure 21 provide the evaluation metrics of the ESA CCI SM Products v9.2, which were evaluated against the ISMN datasets from 1978 (or 1991 for Active product) until 2024. In practice, the number of collocated samples is too low in the earliest period, and the results of the evaluation are representative of the 1996-2024 period only. The figures 17 and 18 depict the distribution of the correlation coefficients and the UbRMSD. The maps shown in Figure 19, Figure 20, and Figure 21 represent the different evaluation metrics per ISMN site. The Table 3 provide the numerical values of the medians, including upper and lower CI, for correlation coefficients and the UbRMSD.

metric	COMBINED v09.2	ACTIVE v09.2	PASSIVE v09.2
Correlation [-]	0.681 [0.647; 0.715]	0.629 [0.586; 0.667]	0.656 [0.618; 0.693]
UbRMSD [m3/m3]	0.0537 [0.052; 0.057]	0.062 [0.060; 0.065]	0.0658 [0.063; 0.069]

Table 3: Correlation coefficient and UbRMSD (Median and CI) of the absolute values of ESA-CCI-SM Combined, Active and Passive products of version 9.2, with respect to ISMN, over the period 1996-2024.

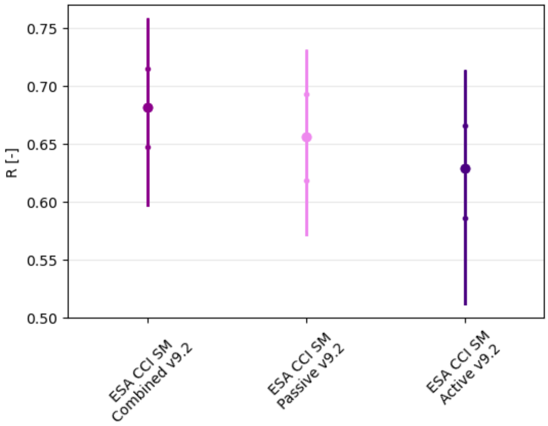


Figure 17: Correlation coefficients of ESA CCI SM Combined, Passive, Active v9.2 products (absolute values) with respect to ISMN measurements, in 1978-2024. (Median, IQR and CI of the median) Number of sites for passive, combined products evaluation: 1718; for active products: 1626

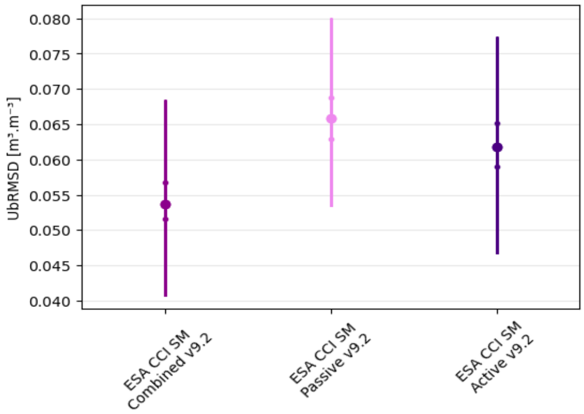


Figure 18: UbRMSD of ESA CCI SM Combined, Passive, Active v9.2 products (absolute values) with respect to ISMN measurements, in 1978-2024. (Median, IQR and CI of the median) Number of sites for passive, combined products evaluation: 1720; for active products: 1651

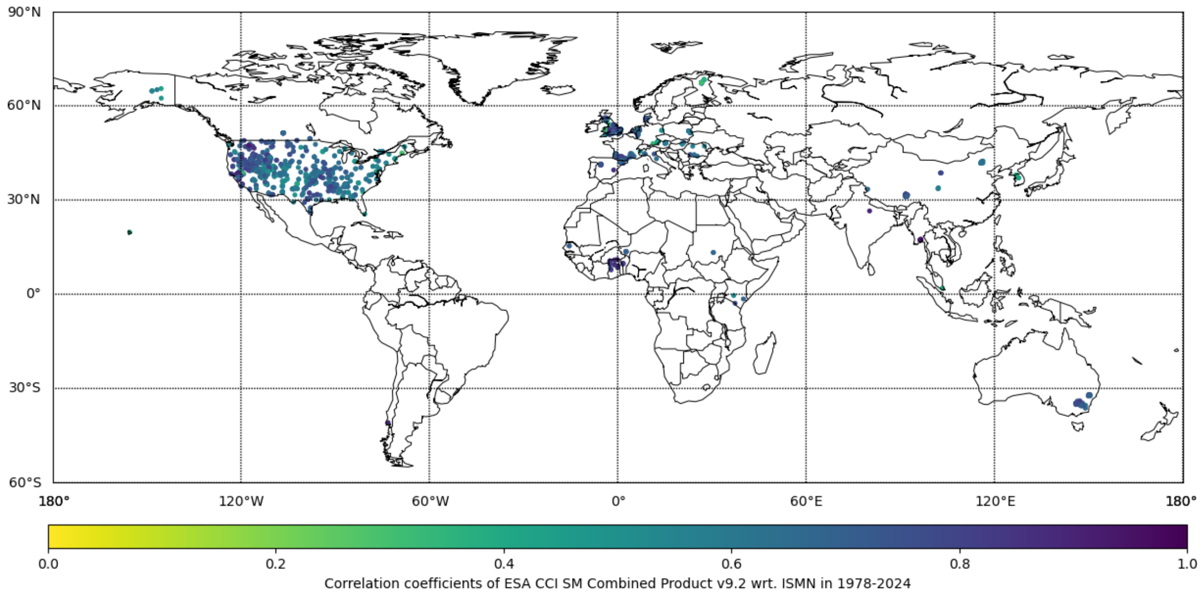


Figure 19:Correlation Coefficients of ESA CCI SM Combined product v9.2 with respect to ISMN in 1978-2024 on the ISMN sites

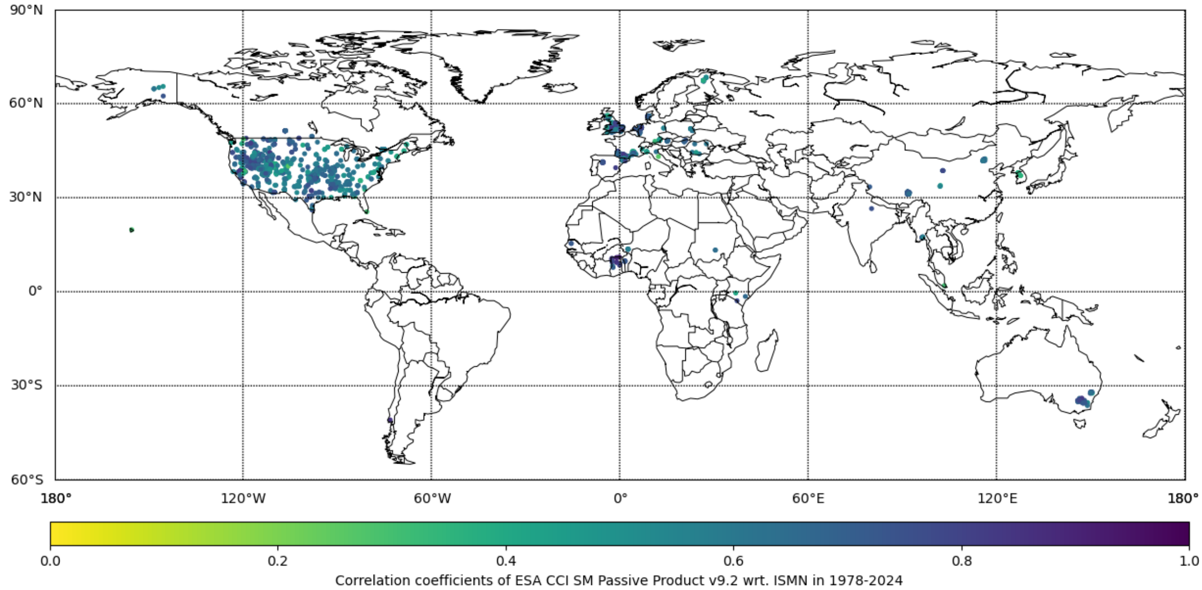


Figure 20: Correlation Coefficients of ESA CCI SM Passive product v9.2 with respect to ISMN in 1978-2024 on the ISMN sites

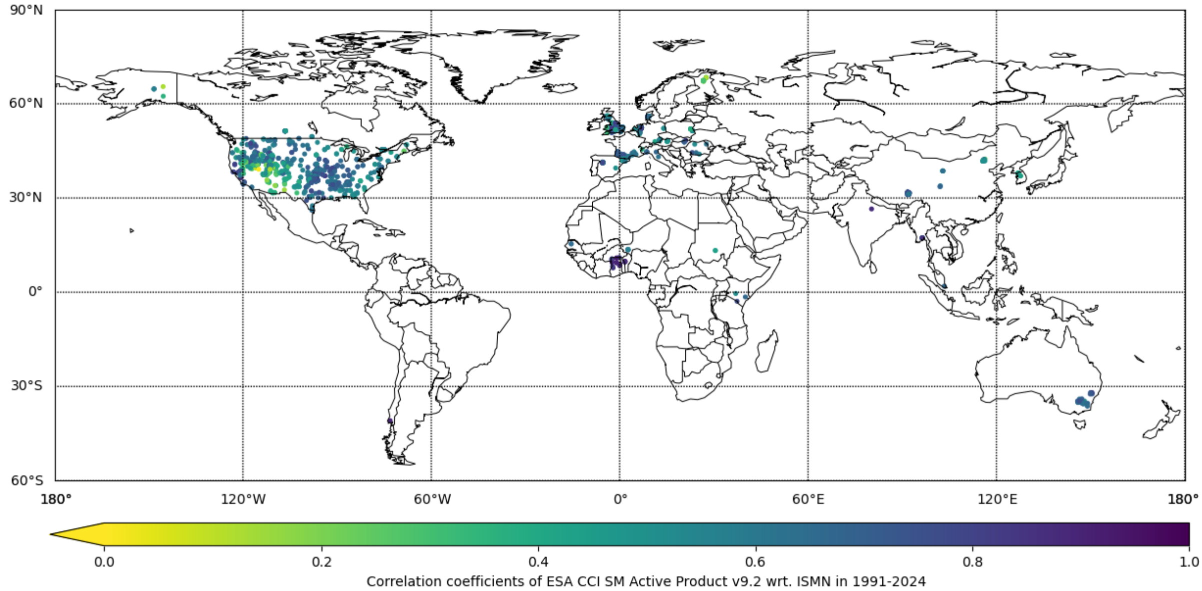


Figure 21:Correlation Coefficients of ESA CCI SM Active product v9.2 with respect to ISMN in 1978-2024 on the ISMN sites

The maps shown in Figure 19, Figure 20, and Figure 21 show similar spatial patterns for all products. The metric value is generally high for sites in the west of Europe, India, Myanmar, Australia. It is more contrasted in Africa (with the highest R in Ghana) and in the USA (the Great lakes region as well as the southwest of the USA have lower R values compared to the rest of the country, especially for the Active product). The sites located in the highest latitudes (Alaska, Scandinavia) show lower performances.

5.1.2 Stability evaluation

5.1.2.1 Stability evaluation in 1991-2023

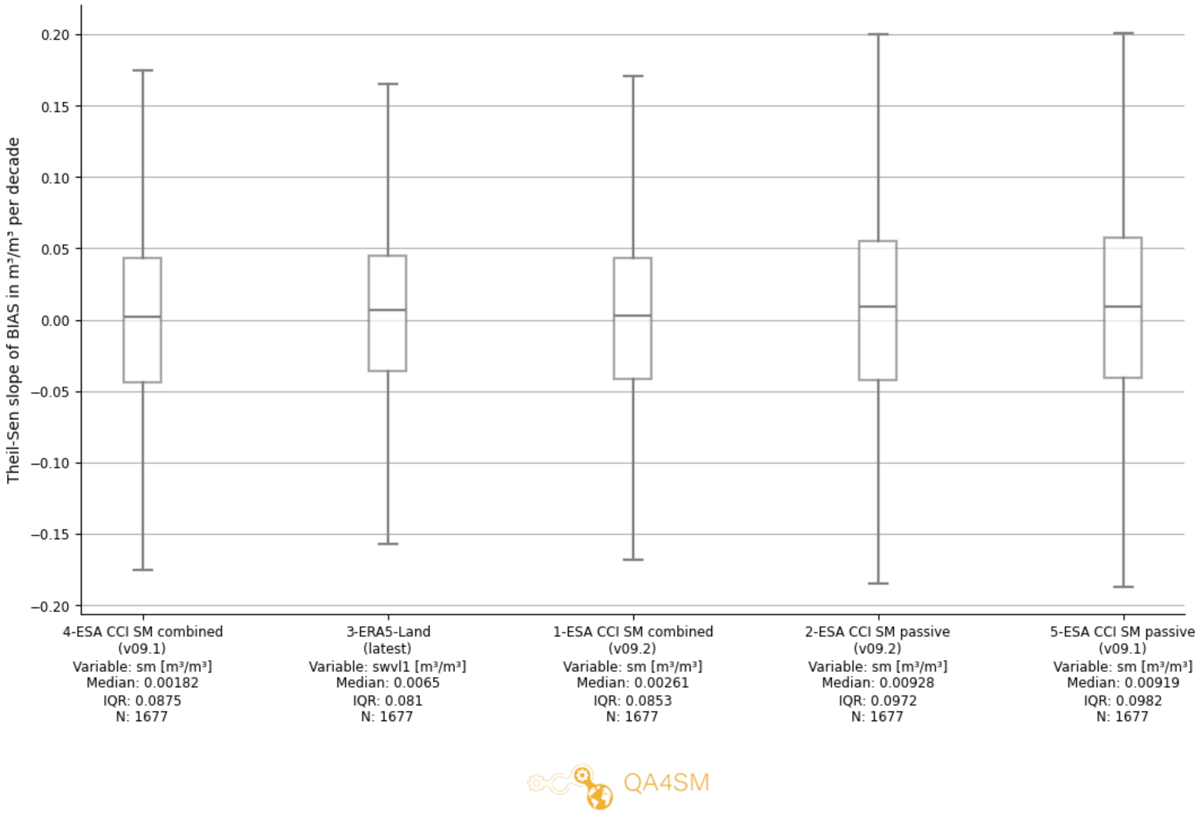


Figure 22 Theil-Sen slopes of the bias per decade for ESA-CCI SM Combined, Passive products v9.2, v9.1 and ERA5-Land with respect to ISMN measurements in 1991-2023

The Theil-Sen slopes of the Bias are rather equivalent among the different datasets; the most stable products are the combined with a median value around 0.002 m^3/m^{-3} per decade, while the passive products median is 0.009 m^3/m^{-3} per decade and the ERA5-Land datasets median is ~0.007 m^3/m^{-3} per decade. The IQR and the spread of the whiskers show that the GCOS requirement on stability (max 0.1 m^3/m^{-3} per decade) is fulfilled for the large majority of the evaluated sites.

5.1.2.2 Stability evaluation until 2024

Figure 23 provides the distribution of the Theil-Sen slopes of the bias per decade for ESA CCI SM Combined and Passive products v9.2 with respect towith respect to ISMN measurements in 1996-2024. It compares well with Figure 22. The spatial distributions are shown on Figure 24, Figure 25 for the Combined, resp. Passive product. They confirm that the products fulfil the GCOS recommendation on stability for most of the sites. The comparison of the maps shows that the evolution of the Bias is similar in the products for a large majority of ISMN sites.

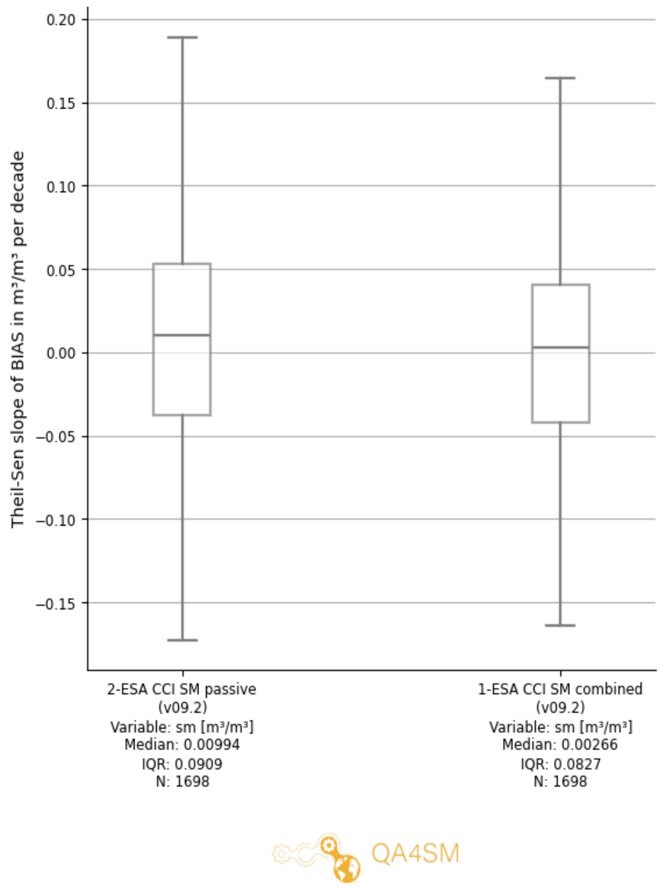


Figure 23: Theil-Sen slopes of the bias per decade for ESA-CCI SM Combined, Passive products v9.2 with respect to ISMN measurements in 1996-2024

Figure 23 shows the absolute values of the slope of the Bias evaluated on a given site as a function of the number of samples in its evaluation time series, and the threshold of the GCOS recommendation is represented by the horizontal black line. One can observe that the values above the threshold, especially the largest slope values, are found for sites with a low number of observations. Moreover, Figure 27 shows the Theil-Sen slope bias of the Passive product as a function of the Theil-Sen slope of the bias of the Combined product for each ISMN site. The black circle represents the GCOS recommendation threshold. The figure shows that some sites have a quite large difference in bias slope between the products (if the point is far from the X=Y line), and some also have a changing slope sign (if within the top-left or bottom-right corners). Those variations seem also linked to a low number of observations in the evaluation time series.

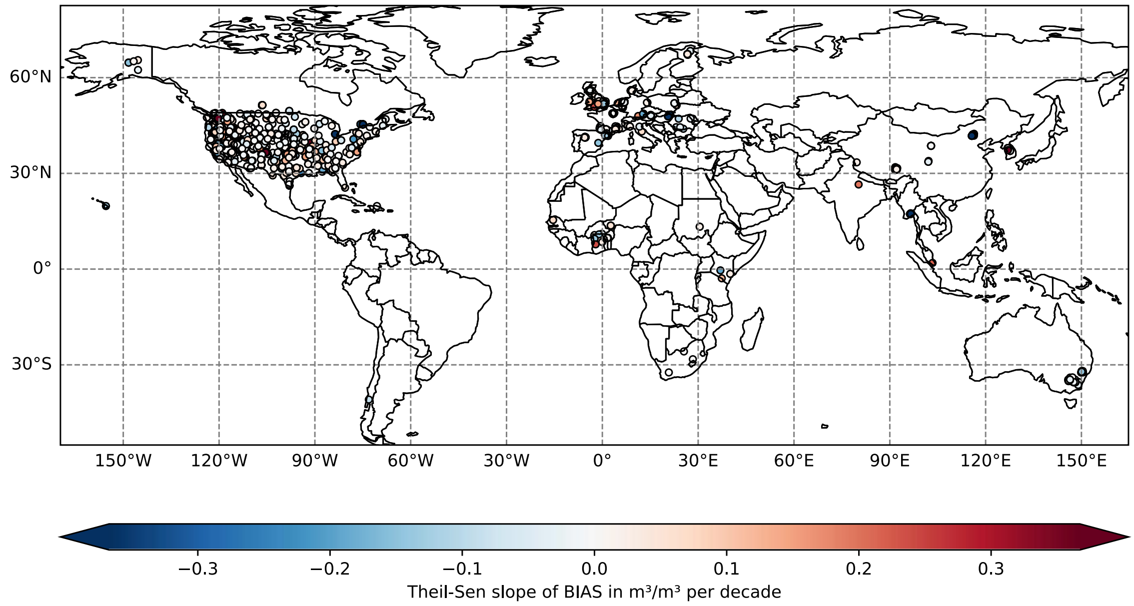


Figure 24:Theil-Sen slope of the bias per decade for ESA-CCI SM Combined product v9.2 with respect to ISMN measurements in 1996-2024 for each ISMN sites

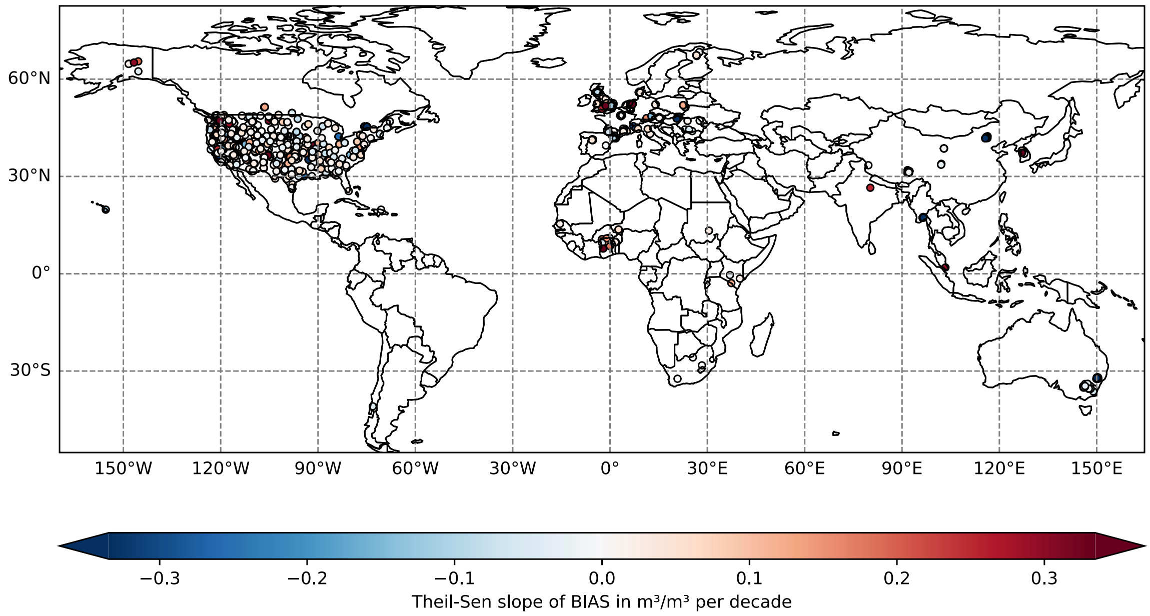


Figure 25:Theil-Sen slope of the bias per decade for ESA-CCI SM Passive product v9.2 with respect to ISMN measurements in 1996-2024 for each ISMN sites

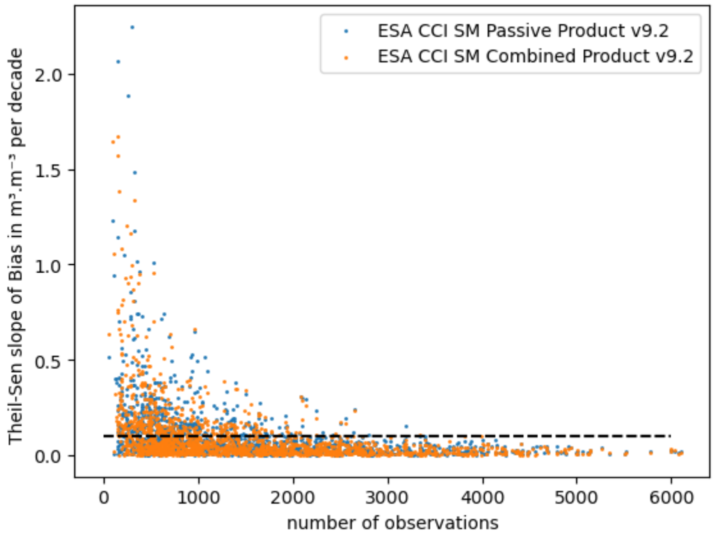


Figure 26: Absolute values of Theil-Sen slope of the bias per decade for ESA CCI SM Combined and Passive products v9.2 with respect to ISMN measurements in 1996-2024 for each ISMN sites depending on their number of observations. The threshold value of the GCOS recommendation on stability is shown with the black line.

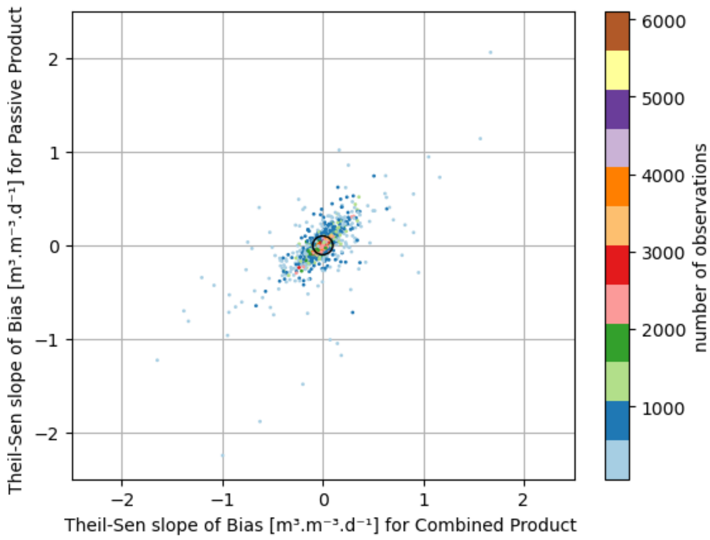


Figure 27: Theil-Sen slope of the bias per decade for ESA CCI SM Passive product v9.2 as a function of the Theil-Sen slope of the bias per decade for ESA CCI SM Combined product v9.2, for each ISMN sites. The colour of the point represents the number of observations of the time series used in the evaluation with respect to ISMN measurements in 1996-2024.

5.1.3 TCA-based STD error estimation

By means of TCA, the Error standard deviation (STD) of the product can be estimated. This metric accounts for the uncertainty relative to the random errors of a target dataset only (i.e. the 1st and 2nd order bias components are corrected for) if the 2 additional datasets are *independent* (their random errors are not correlated). To retrieve the error STD of the ESA CCI SM products, the TCA is applied with respect to both the ISMN and the ERA5-Land datasets in 1991-2023.

Table 4 reports the median and IQR of the error STD for the Combined, Passive and Active products, version 9.1 and 9.2. Again, no significant differences are shown by the 2 successive releases of the products. Furthermore, although the Combined products seem to benefit from a relatively large margin with respect to the GCOS recommendations regarding the uncertainty for satellite SM products (0.04 $m^3.m^{-3}$), this is not the case for the Active and Passive products. Their median uncertainties are close to the threshold value, meaning that for half of the evaluated sites these products fail to meet the uncertainty recommendation, even without accounting on the systematic errors. It also confirms the results of the UbRMSD, and suggests that the 2^{nd} order component of the bias (included in the UbRMSD) would be quite significant, especially in the case of the Combined product, as it would be responsible for the reduction of the proportion of the dataset fulfilling the GCOS requirements to only a quarter.

	COMBINED		ACTIVE		PASSIVE	
metric	v09.1	v09.2	v09.1	v09.2	v09.1	v09.2
Median Error STD [m^3/m^3]	0.020	0.021	0.044	0.044	0.041	0.041
IQR Error STD [m^3/m^3]	0.008	0.008	0.024	0.024	0.024	0.024

Table 4: Standard Deviation of the error in 1991-2023 (estimated from TCA-based RMSE, with the ISMN and ERA5-Land datasets as independent references)

5.1.4 Impact of Land Covers

When differentiating on the land cover classes of the ISMN sites, we can observe in Figure 28 a shift of the bias median towards 0 for the ESA CCI SM Combined and Passive products compared to the ERA5-Land (orange) in the two main cases of Cropland and Grassland. For the tree cover class, the Passive products present the worse performances in terms of both median and IQR spreading due to this particularly challenging land cover condition for SM retrievals. Nevertheless, the Combined products show much better bias median and dispersion, even lower (resp. shorter) than the ERA5-Land metrics. The origin of this compensation could be due to the integration of active SM signals of a higher quality (in terms of bias, which would be lower in this case) and/or to a combination of the two passive and active signals with a scaling reference adding value to the resulting signal. However, the hypotheses cannot be verified since the Active products are provided in percent of saturation, their evaluations require a prior rescaling to the in-situ measurements such as a CDF matching, which artificially cancels the bias with the scaling reference, thus preventing from analysing the bias metric.

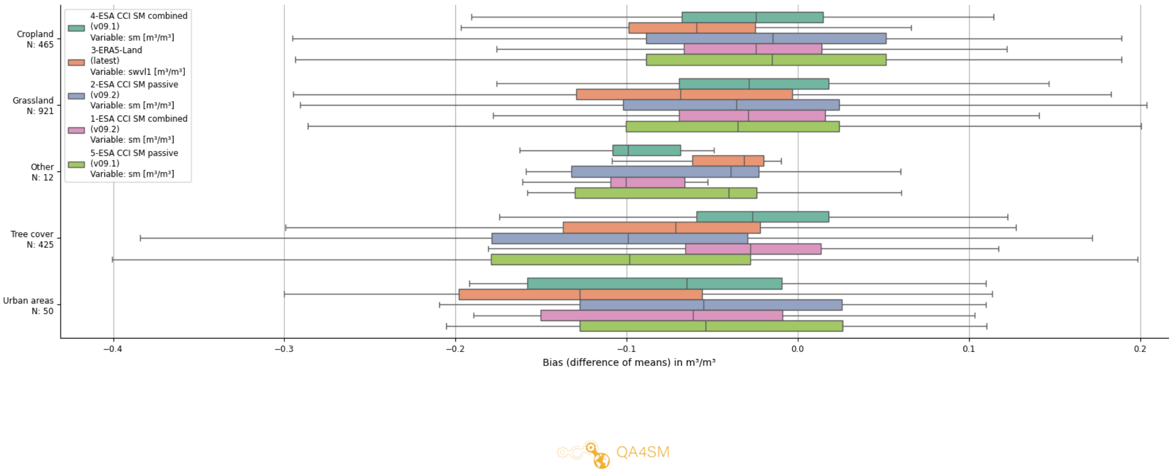


Figure 28 Bias of ESA CCI SM Combined, Passive products v9.2, v9.1 and ERA5-Land with respect to ISMN measurements per land cover class

The variation of the Pearson's correlation coefficients depending on the land cover is shown in Figure 29 and Figure 30. It confirms the observation of Figure 14 about the ERA5-Land dataset (light green in Figure 29, blue in Figure 30), which has a superiority in temporal similarity with the in-situ measurements, for the three main land covers compared to all the ESA CCI SM products. For the Croplands, Grasslands and Tree covers, the Combined and Passive products have similar performances within each class, while the Combined is always slightly better. The active product, in Figure 30, shows the lowest median R, as observed in Figure 14 and Table 1. Again, the Tree cover class provide the worse performances for all products. Here, we do not observe a particular improvement for the Combined product, thus the latter do not benefit from a higher temporal similarity while preserving a reduced bias through variation of the SM around a coherent mean with respect to the in-situ measurements. The Active products also show the lowest performances in the Tree cover class, where almost half of the sites have a correlation below 0.5.

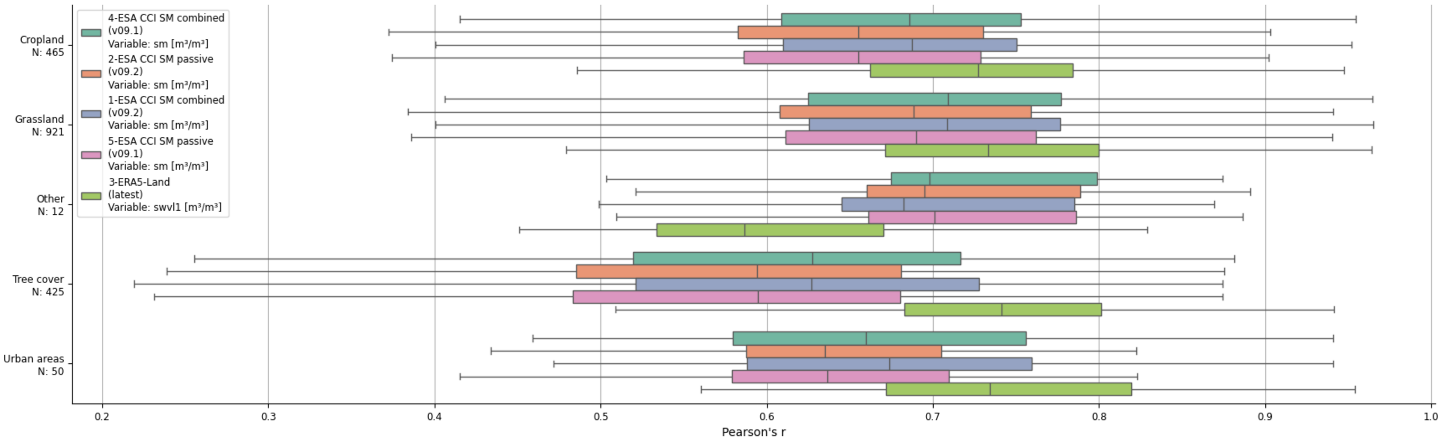


Figure 29 Pearson's correlation coefficients of ESA CCI SM Combined, Passive products v9.2, v9.1 and ERA5-Land with respect to ISMN measurements per land cover class

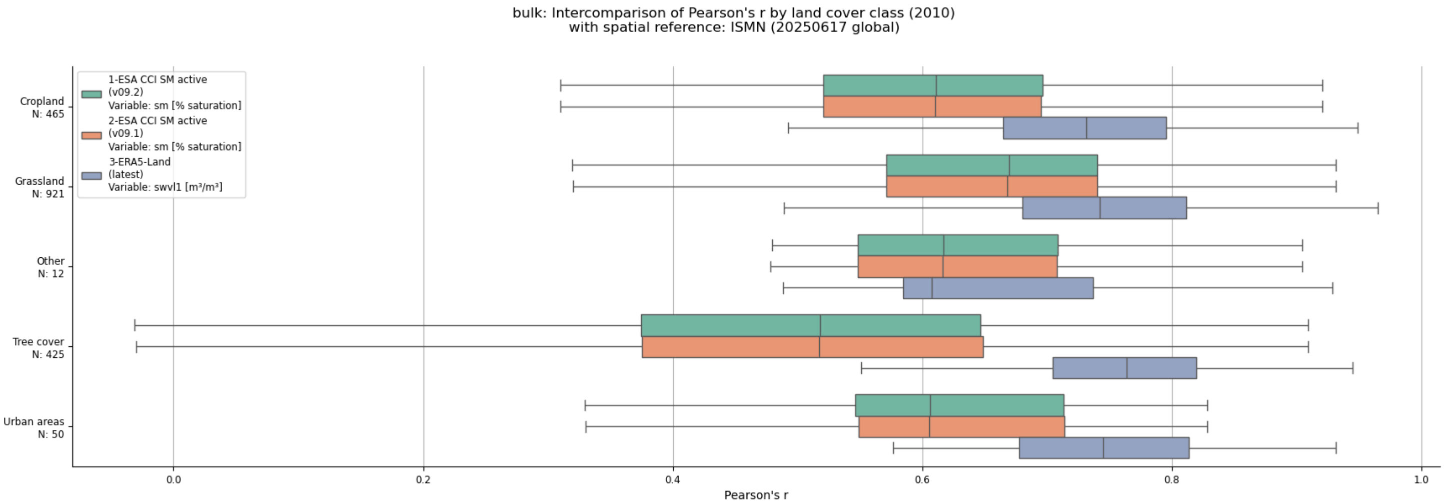


Figure 30 Pearson's correlation coefficients of ESA CCI SM Active product v9.2, v9.1 and ERA5-Land with respect to ISMN measurements per land cover class

5.1.5 Impact of Climate conditions

The Pearson correlation coefficients of each product and version are provided by climate conditions as defined by the Koeppen-Geiger classification, and with respect to the ISMN measurements, in Figure 31 (Combined and Passive products) and in Figure 32 (Active products). It can be observed that the performances of the Passive and Combined products are similar for the Continental and the Temperate climates (resp. with a median R >0.6 and around 0.7) while the Combined have a clear improvement for the sites with the Arid, Polar or Tropical climates, compared to the Passive product. The Combined product even outperforms ERA5-Land for sites under Polar or Tropical climates, which are the classes where the Active product also performs best with the median R> 0.7 and 0.8 respectively. However, this comparison must be taken with care as the latter classes gather less than 100 sites each.

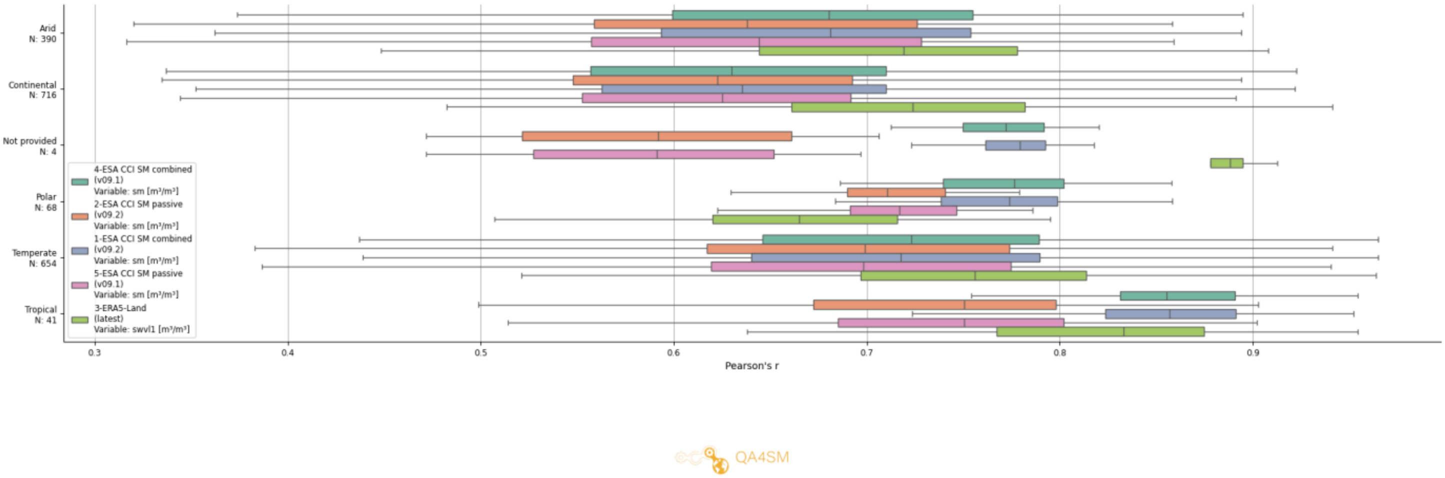


Figure 31 Pearson's correlation coefficients of ESA CCI SM Combined, Passive products v9.2, v9.1 and ERA5-Land with respect to ISMN measurements per Koeppen-Geiger climate class

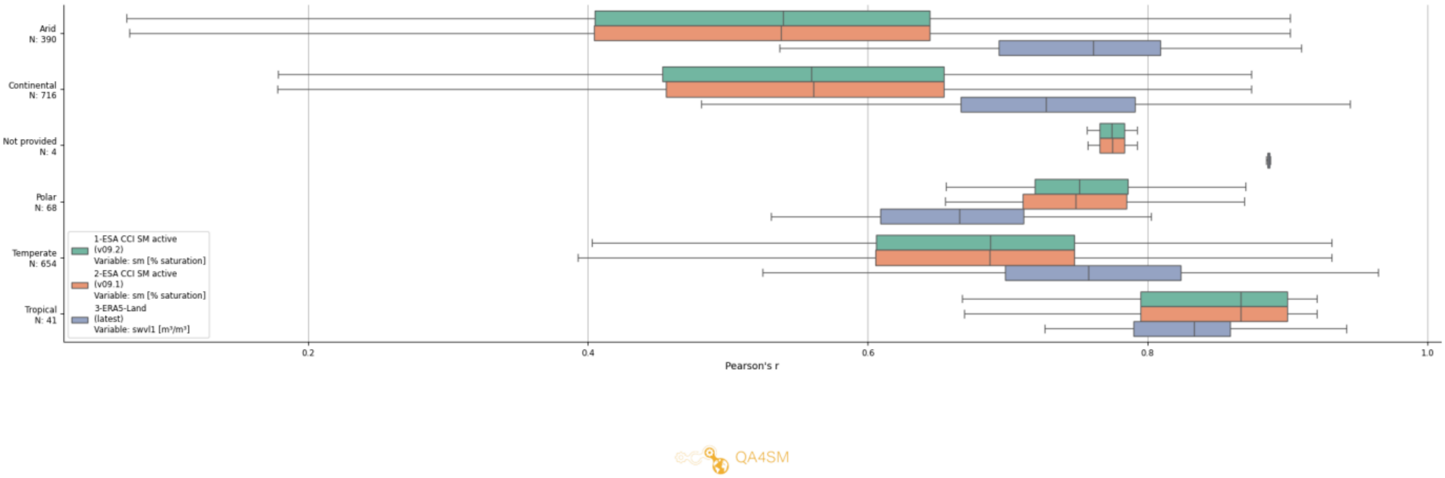


Figure 32 Pearson's correlation coefficients of ESA CCI SM Active product v9.2, v9.1 and ERA5-Land with respect to ISMN measurements per Koeppen-Geiger climate class

5.2 Intercomparison and evolution over time

In this subsection, the Combined product version 9.2 is compared to the earlier releases v9.1, 8.1 and 7.1. ERA5-Land dataset is also included in the comparisons which are realised with respect to the ISMN measurements, in terms of Pearson's correlation coefficient (R) in Figure 33 and UbRMSD in Figure 34. The comparison is performed on time intervals of 5 years, to evaluate the evolution of the products' skills throughout the 1990-2020 time period. In Figure 11, the sites taken in consideration for the correlation are selected with respect to the p-values ($p<0.05$) to account for the significant correlations only. Their number N within each period is indicated below the dates. For the two following figures, the IQR are represented with the vertical bars, the medians are provided as points (the smaller points represent the upper and lower CI).

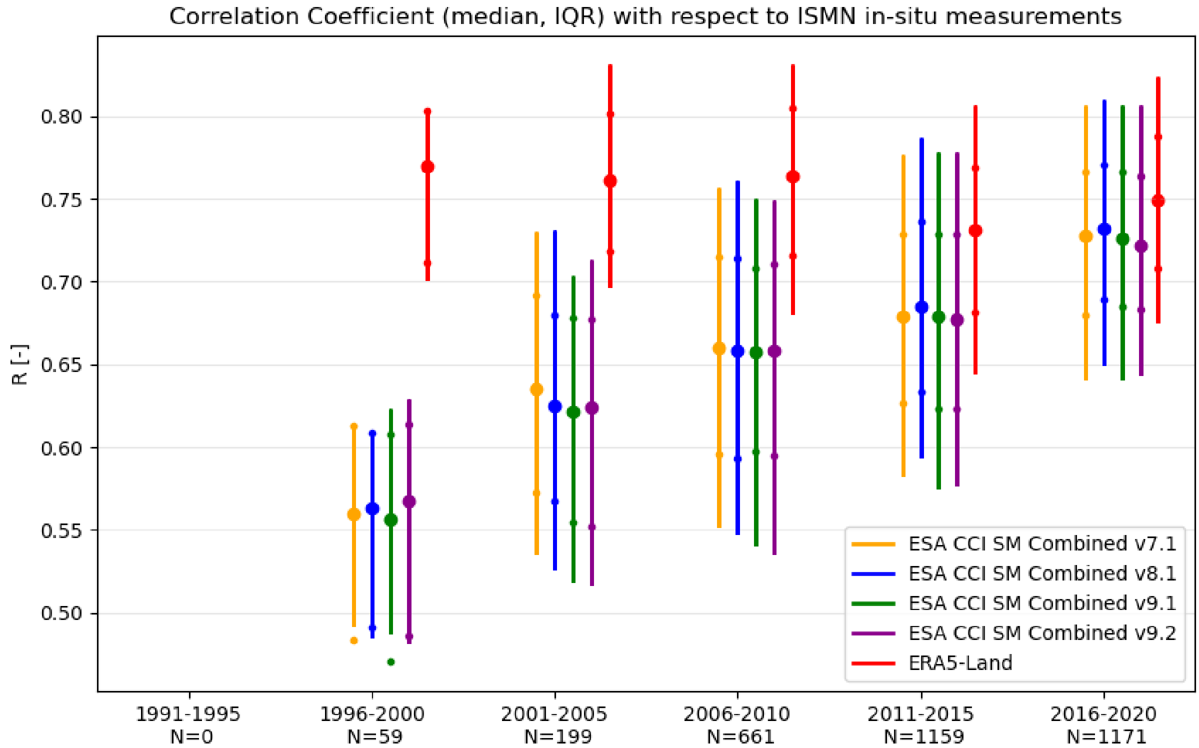


Figure 33 Pearson's correlation coefficients of ESA CCI SM Combined product v9.2, v9.1, v8.1, v7.1 and ERA5-Land with respect to ISMN measurements between 1991 and 2020, per 5 years time windows. N is the number of ISMN sites for which the statistics are computed in each time windows. A selection for sites with significant correlation coefficients is realised based on their associated p-values (p<0.05).

In Figure 33, the skills of the different releases are equivalent in each evaluated time window. It can be noted a strong increase of the correlation of the combined products throughout the years, with a median R ranging from 0.55 in 1996-2000 to ~0.72 in 2016-2020. It should however be noted that the number of sites in the earliest period is quite low (N<200), in contrast to the latest time intervals where N> 1000. In the latest period (2016-2020), the combined performs thus almost as well as ERA5-Land, having a stable skill around 0.75. This improvement emphasizes the interest of integrating an increasing number of missions into the Combined product.

If similar median and IQR UbRMSD can also be observed for the different releases in each time interval from Figure 34, the UbRMSD of the Combined product shows a less continuous improvement over time, compared to the correlation metric. For instance, the UbRMSD is the lowest in the earliest period (1996-2000) with a median value below 0.045 $m^3.m^{-3}$ (outperforming the ERA5-Land dataset with a large margin) and reaches its highest level on the following time interval, where the medians of the different releases, as well as ERA5-Land, are ~0.055 $m^3.m^{-3}$, while the Combined products have a much larger spreading among the sites than ERA5-Land. From this time interval to 2020, the UbRMSD has a decreasing trend; the last two periods show similar results for the ESA-CCI-SM Combined product on the one hand (having a median UbRMSD slightly below 0.05 $m^3.m^{-3}$) and for ERA5-Land on the other hand, whose median UbRMSD is slightly above 0.05 $m^3.m^{-3}$.

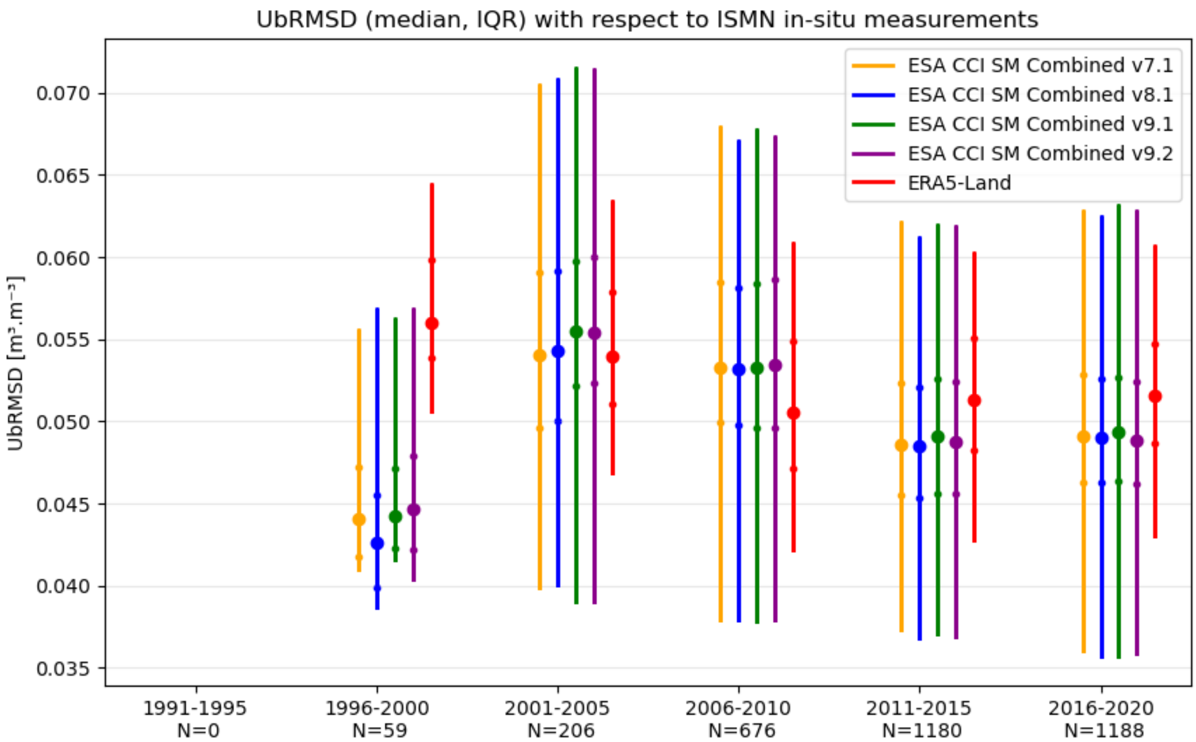


Figure 34 UbRMSD of ESA CCI SM Combined product v9.2, v9.1, v8.1, v7.1 and ERA5-Land with respect to ISMN measurements between 1991 and 2020, per 5 years time windows. N is the number of ISMN sites for which the statistics are computed in each time windows.

5.3 Trends analysis

In this section, we compare long-term trends (linear increases or decreases) in ESA CCI SM products across different versions, as well as with other related soil moisture model and reanalysis datasets (ERA5-Land, MERRA-2, and GLDAS Noah v2.1).

Trends for the science products (GAPFILLED and RZSM) are reported in their respective PVIRs. For trend estimation, the Theil–Sen estimator is used. This method calculates the median of all pairwise slopes between data points over time at each location to estimate the long-term increase or decrease. Trends are computed from annual mean soil moisture values over the periods 1988–2010 and 1992–2020, respectively.

Where only statistically significant trends are shown, significance is assessed using the Mann–Kendall test (p-value < 0.05 for significant increases or decreases).

5.3.1 Results

Figure 35 shows the 1988–2010 trends of the COMBINED product across the five most recent ESA CCI SM versions (v6–v9.2). Trends are consistent between v9.1 and v9.2, as the latest version primarily represents a temporal extension. Accordingly, and in line with the other validation results presented here, most dataset statistics are expected to remain unchanged.

However, differences between major releases have been observed in the past. Notably, a pronounced wetting trend over Patagonia has emerged since version 7, when daytime retrievals and seasonal CDF matching were introduced. Trends in Europe shifted from wetting to drying after v6, with more recent versions showing widespread drying across large parts of the continent. Similar drying patterns are evident along the U.S. East and West Coasts. Negative trends over extensive areas of western Russia have also been present since v9. In contrast, northern Australia shows stronger positive trends from v7 onward compared to earlier releases. A pronounced drying trend is found in East Asia, consistent with large-scale drying in ERA5-Land and MERRA-2 over the same region.

Both ERA5-Land and MERRA-2 exhibit strong drying trends over Central Africa. This pattern is not apparent in ESA CCI SM, likely because large portions of the region are masked due to dense vegetation. Similarly, the negative trend over central South America in ERA5-Land may be partially masked in the satellite data: some subtropical regions show decreasing trends in ESA CCI SM, though these are less pronounced than in the reanalysis products.

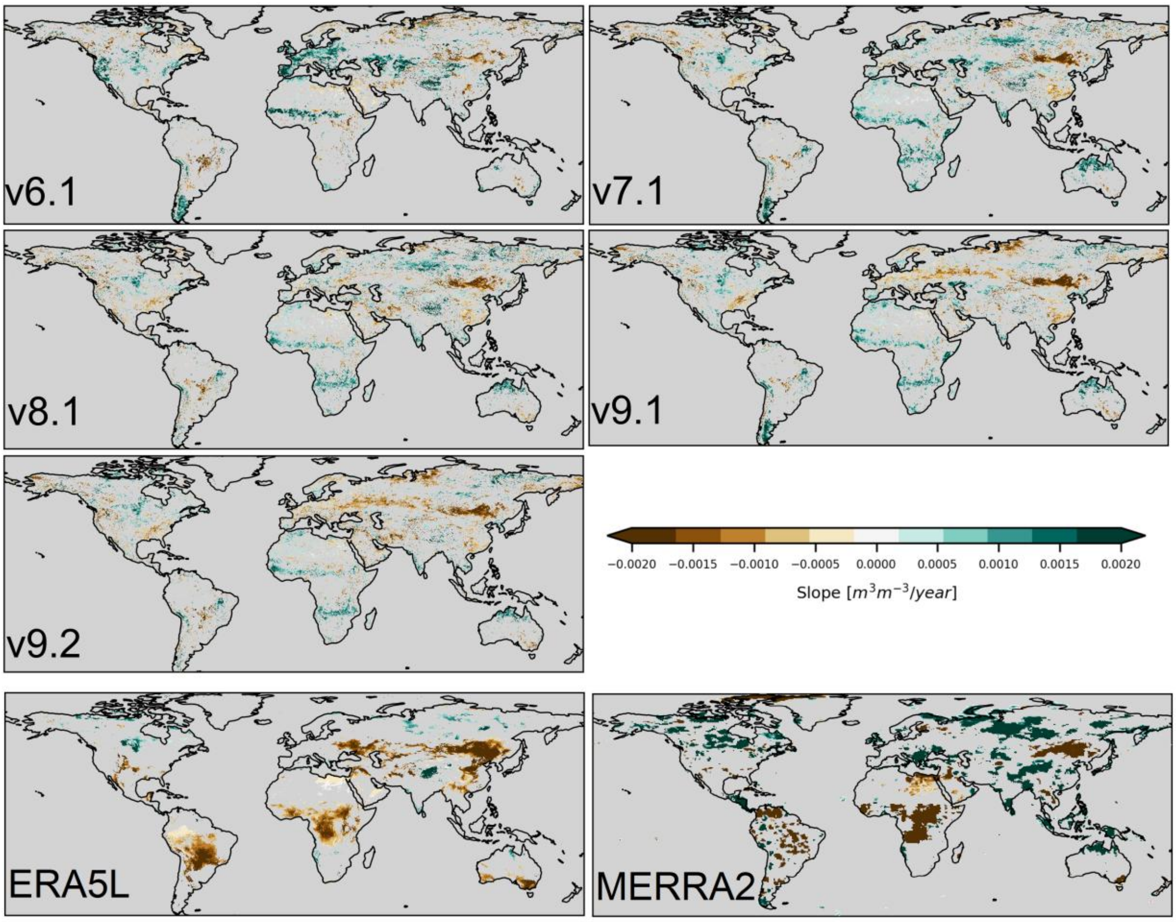


Figure 35: Significant (p<0.05) annual soil moisture trends over the period 1988-2010 in ESA CCI SM COMBINED across versions, and in ERA5-Land and MERRA2.

Trends between the ACTIVE, PASSIVE and COMBINED v9 products are compared in Figure 36. Note that no significance mask is applied here.

The (artificial) wetting trend caused by long-term land cover changes not accounted for in the retrieval of H SAF ASCAT, and reported in previous PVIRs, is still present in v9. However, a new version of the H SAF ASCAT SSM product (H121) has since been released, which is expected to correct this issue and will be implemented in ESA CCI SM v10.

As expected, the absolute trend magnitude differs between the PASSIVE and COMBINED products due to the use of different scaling references, although several regional patterns are consistent between the two. Trends across North and South America are largely similar, except in Central America, where the PASSIVE product shows a positive trend and the COMBINED product a negative one. For Europe, both products indicate a negative trend. The pronounced band of negative trends over Central Asia appears only in the PASSIVE product and not in the COMBINED one; however, similar features are evident in ERA5-Land and GLDAS. Both PASSIVE and COMBINED show consistent wetting trends over the Tibetan Plateau, as well as parts of East China and central to southern Africa. In contrast, over South Africa and Namibia, the COMBINED product shows drying trends, while the PASSIVE product indicates consistent wetting. To a lesser extent, this also applies to northern Australia.

ERA5-Land shows predominantly drying trends globally, whereas MERRA-2 tends to exhibit wetter conditions overall. GLDAS Noah serves as the scaling reference for the COMBINED product. While there are some regional similarities between the two (e.g., in South America, the Middle East, East China, and parts of Australia), the GLDAS trends are not directly inherited by the COMBINED product. It should be noted, however, that GLDAS Noah v2.1 is only available after 2000; consequently, the period over which trends were computed here is considerably shorter than for the other datasets.

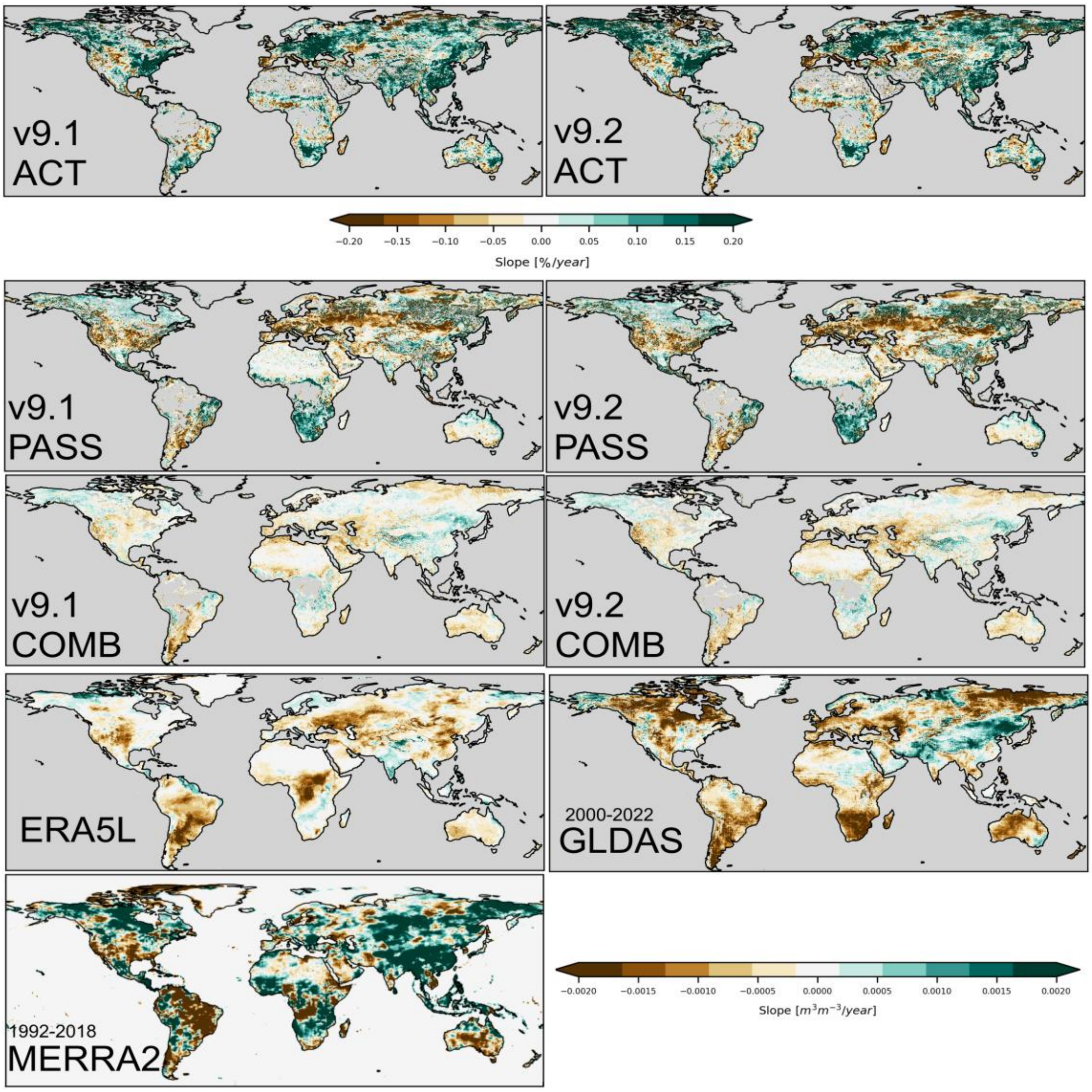


Figure 36: Annual soil moisture change (trend) over the period 1992-2022. MERRA2 was computed from 1992-2018, and GLDAS from 2000-2022 instead. No significance mask is applied.

6 Summary

The results of the verification with respect to previous releases as well as results of the validation with respect to the reference datasets show as expected a high consistency of the products from release 9.2 with version 9.1.

The increase of fractional data coverage over time is associated to a decrease of SM uncertainty, which goes below 0.03 $m^3.m^{-3}$ in the last years for the COMBINED product, 0.06 $m^3.m^{-3}$ for the PASSIVE i.e. a higher value but with the same trend, while the uncertainty remains constant (< ~15%) for the ACTIVE product. Seasonal patterns are visible for all products, due to the introduction of sub-seasonal merging weights to account for the seasonal dynamic of retrieval errors.

The median correlation coefficient with respect to ISMN varies between 0.63 and 0.69 depending on the product, the highest score is found for COMBINED. The median UbRMSD with respect to ISMN ranges from 0.05 m^3/m^3 to 0.06 m^3/m^3. Performances are in line with previous version.

The estimation of the error standard deviation based on TCA shows that COMBINED product fulfills the GCOS requirement on uncertainty with a median error STD below the recommended threshold (0.02 <0.04 $m^3.m^{-3}$). However, the PASSIVE and ACTIVE products have a median error STD slightly above the threshold, meaning that for half of the evaluated sites, the requirement is not met. This analysis shows once more the improved capability of the COMBINED product compared to the PASSIVE and ACTIVE ones to provide a robust SM dataset following the needs of the climate community.

The evaluation of the Theil-Sen slopes of the bias shows that the GOCS requirement regarding the product stability is fulfilled for a large majority of the evaluated locations of the ISMN.

The intercomparisons of the COMBINED product of the previous releases with respect to ISMN show very similar skills among the most recent versions. It also shows a clear improvement of the performances over time with the median correlation coefficient almost reaching that of ERA5-Land (around 0.72 and 0.75 resp.), while the median UbRMSD for the COMBINED products of all evaluated releases is below ERA5-Land (below and above 0.05 $m^3.m^{-3}$ resp.), in the most recent years.

The trend analysis confirms the expected consistent results between COMBINED v9.1 and v9.2. The evaluation performed over the period 1988-2010 also shows the similarity with ERA5-Land and MERRA-2 in East Asia with a pronounced drying trend. Another drying trend is detected across Eurasia in CCI product, which is also partially found in ERA5-Land.

On the contrary, the strong drying trends found in Central Africa and South America for the two reanalysis datasets are not found in the CCI COMBINED product v9.2 : it is mainly masked due to dense vegetation, and for South America only partially and less pronounced, while the rest of these regions shows either no significant or an opposite trend.

Among the different CCI products of releases 9.1 and 9.2, the trends in 1992-2022 are contrasted and partly consistent. The ACTIVE product has a predominant artificial wetting trend which is caused by unaccounted land cover changes in one of the integrated datasets. This issue is expected to be fixed for the future release using the recently distributed new version of the latter dataset. The CCI PASSIVE and COMBINED products are more in line with each other, though the different scaling references cause different trend magnitudes. Consistent trends are found for instance in North and South America, as well as in Europe where a drying trend is detected. Wetting trends are found for both products in the Tibetan Plateau, East China and Central to Southern Africa. However, in South Africa and Namibia, the detected trends are different since the PASSIVE product shows a pronounced wetting trend and the COMBINED shows drying trends. North Australia also has diverging trends among products.

7 Bibliography

Dorigo, W. A.; Wagner, W.; Hohensinn, R.; Hahn, S.; Paulik, C.; Xaver, A.; Gruber, A.; Drusch, M.; Mecklenburg, S.; van Oevelen, P.; Robock, A.; Jackson, T. The International Soil Moisture Network: A Data Hosting Facility for Global in Situ Soil Moisture Measurements. Hydrology and Earth System Sciences 2011, 15 (5), 1675–1698. https://doi.org/10.5194/hess-15-1675-2011.

Copernicus Climate Change Service (C3S)(2019): ERA5-Land hourly data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.e2161bac

Stradiotti, P., Gruber, A., Preimesberger, W. and Dorigo, W. (2025) 'Accounting for seasonal retrieval errors in the merging of multi-sensor satellite soil moisture products', ***Science of Remote Sensing***, 12, p. 100242. doi: 10.1016/j.srs.2025.100242.