ESA Climate Change Initiative Plus - Soil Moisture

Product Validation and Intercomparison Report (PVIR)

Supporting Product version v07.1

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Submitted by

EODC Earth Observation Data Centre for Water Resources Monitoring GmbH

in cooperation with

TU Wien, VanderSat, ETH Zürich, and CESBIO

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For more information on the CCI programme of the ESA see https://climate.esa.int/en/.

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Acronyms

ABS	Absolute values of soil moisture
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
ASCAT	Advanced SCATterometer
ATBD	Algorithm Theoretical Basis Document
CAL-VAL	Calibration and validation
CDF	Cumulative Distribution Function
CCI	Climate Change Initiative
CRDP	Climate Research Data Package
ECMWF	European Centre for Medium Range Weather Forecasts
ECV	Essential Climate Variable
ESA CCI SM	Soil moisture time series developed in the framework of ESA CCI
EO	Earth Observation
ERA	ECMWF Re-Analysis
ESA	European Space Agency
FY3	FengYun-3 satellites
IAA	Inter-annual anomalies of soil moisture
ISMN	International soil moisture network
LSM	Land surface model
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NH	Northern Hemisphere
PUG	Product User Guide
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RMSD	Root mean square difference
RMSE	Root mean square error
SAC-SMA	Sacramento Soil Moisture Accounting model
SM	Soil moisture
SMAP	Soil Moisture Active Passive mission
SMOS	Soil Moisture and Ocean Salinity mission
SSM	Surface soil moisture
TUW	Vienna University of Technology
ubRMSD	Unbiased root mean square difference
VWC	Volumetric water content
WMO	World Meteorological Office

1 Executive Summary

Within the framework of the European Space Agency (ESA) Climate Change Initiative (CCI) soil moisture project, an over 40-year (1978-2021) soil moisture time series (ESA CCI SM v07.1) is developed, which consists of three products: an ACTIVE data set, a PASSIVE data set and a COMBINED data set. It provides daily surface soil moisture with a spatial resolution of 0.25°. The merged product as well as its active and passive sources are publicly available to the user on the project webpage (https://climate.esa.int/en/projects/soil-moisture/data/) and also from the CCI Open Data Portal (https://climate.esa.int/en/odp/#/dashboard). Furthermore, the detailed description of its development [ATBD, RD-02], and a product user guide [PUG, RD-03] are publicly available on the project webpage (https://climate.esa.int/en/projects/soil-moisture/key-documents/)).

The validation of the public release of ESA CCI SM v07.1 is an important mechanism within the production process and is documented in this Product Validation and Intercomparison Report (PVIR). The guideline of the ESA CCI SM product validation is described in the Product Validation Plan [PVP, RD-05] and ensures that the validation meets the overall user requirements and that it is carried out in a transparent way. The established validation protocol is broadly accepted by the international soil moisture community. The validation is performed with in-situ or other appropriate global datasets (e.g., land surface models, land data assimilation systems, land reanalyses) that were not used for the production of the ESA CCI SM product. Additionally, the ESA CCI SM product releases undergo a basic "verification" as part of the production process, which is also documented in this PVIR.

The PVIR encompasses the following analyses (carried out independently by the indicated partners).

TU Wien: During the development of the ESA CCI SM product, verification and accuracy checks are undertaken to ensure that the product is made correctly and that the scientific developments implemented are positively impacting the product. The final results of these verification and accuracy checks are presented in this document (Section 5.1).

The verification checks include checking for completeness, i.e., spatial and temporal coverage for the new product and also with respect to the previous, approved (public), version of the product. These checks include ensuring the uncertainty data is provided with the product.

Basic validation is undertaken with respect to soil moisture from ECMWF's 5th generation atmospheric reanalyses of the global climate (ERA5); R (Pearson's correlation coefficient) and ubRMSD (unbiased root-mean-square-difference) are calculated and analysed. Validations are performed globally and after bias correction by matching the mean and standard deviation of each ESA CCI SM time series to that of the reference series. For inter-comparison between versions, only the common observations are used.

The evaluation of ESA CCI SM v07.1 shows differences in spatial and temporal coverage and in validation performance compared to the last public version. In terms of the former, the main differences stem from the extension of the dataset, both in time and with the addition of new sensors, and most noticeably from the newly added day-time observations. In terms of performance, a net improvement with respect to the previous version is visible when benchmarking against reanalysis data, especially in the Polar and Sub-Polar regions. As for v06.1, the break-adjusted COMBINED product is distributed with ESA CCI SM; the break-correction methodology is also found to improve the overall homogeneity and performance of the data set.

ETH Zürich: After Verification, the ESA CCI SM product is validated over four regions (North America, Europe, Sub-Saharan Africa, and Australia) and globally using in-situ observations from the ISMN and using the ERA5-Land and ERA-Interim/Land soil moisture reanalyses at 0.25° resolution (Section 5.2). In this validation process, the current release v07.1 is also set into perspective to previous major releases of ESA CCI SM from v0.1 up to v06.1. The evaluation uses the two top layers of the ERA soil moisture reanalyses (i.e., 0-7 cm and 7-28 cm depths) to compare the ESA CCI SM products, and the in-situ observations in 5 and 10 cm depth. In addition, the MERRA-2 reanalysis is used in the analysis of the long-term temporal trends.

The evaluation shows no clear regions where the ESA CCI SM products agree very well or very poorly with in-situ observations. However, the highest and most consistent correlations were found over Australia where the in-situ observations were located in the same climatic region. The ESA CCI SM products correlate higher with the observed in-situ soil moisture at 5 cm than at 10 cm depth. This depth dependency was less clear for the comparison with ERA5-Land. Over the US, the ESA CCI SM products show often higher correlation with the in-situ observations in areas of grassland than compared to areas of forest vegetation cover. This distinction for different vegetation types is less clear for the comparison with the ERA5-Land reanalysis and for the absolute values of the ESA CCI SM v07.1.

Overall, the ESA CCI SM product releases show increasing correlations with in-situ data with the evolution of the product pointing to the mature state of the product, and clear improvements between v07.1 and v06.1 are in particular visible for the more recent periods. However, remaining uncertainties exist in the representation of long-term temporal trends, which display distinct and partly diverging patterns among the ESA CCI SM COMBINED releases and the underlying ACTIVE and PASSIVE products, as well as compared to reanalysis products (Section 5.3).

2 Documents

2.1 Applicable documents

The documents outlined below detail the scope and focus for the work reported in this document.

[AD-1] ESA CCI+ PHASE 1 - NEW R&D ON CCI ECVS Soil Moisture Project Contract No: 4000126684/19/I-NB.

[AD-2] Climate Change Initiative Extension (CCI+) Phase 1 New R&D on CCI ECVs, Statement of Work, ESA Earth Observation Directorate, ESA-CCI-EOPS-PRGM-SOW-18-0118.

2.2 Reference documents

This section provides a list of reference documents either on which we base this document, or to which this document refers.

[RD-01] Product Validation and Intercomparison Report (PVIR), revision 3, version 2.6, 29 Nov. 2018

[RD-02] Algorithm Theoretical Basis Document (ATBD), v7.1, Mar. 2022

[RD-03] Soil Moisture CCI Product User Guide (PUG), v7.1, Apr. 2022

[RD-04] Climate Research Data Package (CRDP), v7.1, Apr. 2022

[RD-05] Product Validation Plan (PVP), version 3, Nov. 2021

2.3 Bibliography

A complete bibliographic list, detailing scientific texts or publications that support arguments or statements made in this document is provided in Section 7.

3 Introduction

3.1 Purpose of the document

The purpose of the PVIR is the final validation of the soil moisture time series, which is developed in the framework of the ESA CCI soil moisture project. It includes the verification and the validation of the product as outlined in the PVP.

3.2 Target audience

This document targets users of the soil moisture time series produced, as well as the scientific community. It demonstrates the value of an intercomparison between the ESA CCI SM product and other available soil moisture products.

3.3 Important documents

Detailed information on the ESA CCI SM v07.1 time series is provided in the Algorithm Development Document (ATBDv7.1), as well as the Product User Guide (PUGv7.1), produced in the framework of the ESA CCI soil moisture project. These documents are listed in Section 2 and are publicly available on the project webpage (https://climate.esa.int/en/projects/soil-moisture/key-documents/), and also from the CCI Open Data Portal (https://climate.esa.int/en/odp/#/dashboard).

4 Datasets overview

ESA CCI SM v07.1 validated in this PVIR covers the 1978-2021 time period in case of the COMBINED and the PASSIVE products, respectively the 1991-2021 time period in case of the ACTIVE product. It provides daily estimates of global surface soil moisture (i.e., top ~2-5 cm of the soil) at 0.25° spatial resolution. Data coverage is limited in the early years of the COMBINED product when only passive sensors are available. Microwave retrievals are impossible under snow and ice or when the soil is frozen, and complex topography, surface water, and urban structures have negative impacts on the retrieval quality [*Dorigo et al.*, 2017]. In addition, dense vegetation attenuates the microwave emission and backscatter from the soil surface and may mask the soil moisture signal. These limitations result in spatio-temporal data gaps of the product.

For the first time in the evolution of the ESA CCI SM product, a flag for barren ground has been introduced in v07.1 for the PASSIVE data sets with the aim of masking spurious effects introduced by subsurface scattering phenomena. Although the research concerning the flagging of such conditions has reached maturity, it was not clear until the production of version v07.1 how this would have affected important features of the products, such as the observational coverage and the trends in soil moisture. For this reason, the flag has been included in the PASSIVE and COMBINED product as optional, meaning that soil moisture has not been masked for barren grounds. For a fair comparison of the latest (v07.1) with the previous (v06.1) version of the products, the flag is never applied in the analysis presented here. For further details on the single ESA CCI SM product versions, please refer to the respective CRDP [RD-04].

The following table shows an overview of the datasets used for the validation of the ESA CCI SM product. Further details on these comparison datasets and the applied processing can be found in the respective parts of Sections 5.1 to 5.3.

Table 1: Overview of the products used for the ESA CCI SM validation.

Product	Producer	Data class	Description	Max. period used	Coverage
ISMN	Individual soil moisture networks, hosted at TU Wien	In-situ	In-situ soil moisture measurements	1991-2021	Global (but only few data in South America, Africa, and Asia)
ERA5-Land	ECMWF	Land surface model reanalysis	Reanalysis data for volumetric soil water at different levels of the soil profile	1988-2021	Global
ERA-Interim/Land	ECMWF	Land surface model reanalysis	Reanalysis data for volumetric soil water at different levels of the soil profile	1991-2010	Global
ERA5	ECMWF	Atmospheric reanalysis	Reanalysis data for volumetric soil water at different levels of the soil profile	2007-2020	Global
MERRA-2	NASA	Atmospheric reanalysis	Reanalysis data for volumetric soil water at different levels of the soil profile	1988-2020	Global

5 Verification and validation results

The following sections present the verification and validation results of the ESA CCI SM v07.1 product.

5.1 Verification and basic validation of the product

As part of the product generation, verification and basic validation activities are carried out throughout the development cycle and on the final product. The final generated dataset is evaluated here for completeness and to ensure the final products provide temporal and spatial patterns expected for soil moisture, through analysis of data statistics and soil moisture anomalies. The dataset is also compared to ERA5 to ensure the physical plausibility of the ESA CCI SM products generated and to ensure that the scientific developments have positively contributed to the product. The new break-adjusted product of ESA CCI SM v07.1 COMBINED [based on *Preimesberger et al.*, 2021] is also assessed for completeness and differences to the non-break-adjusted product.

5.1.1 Datasets

ESA CCI SM

In addition to the newly generated datasets of ESA CCI SM v07.1, the previous public release (v06.1) has been used[1]. All three respective products of ESA CCI SM (ACTIVE, PASSIVE, COMBINED) have been analysed, however, only a subset of these results are presented here. Further information is available upon request.

ERA5 soil moisture

ERA5 is a global reanalysis product provided by ECMWF [*Hersbach et al.*, 2020]. It provides global, sub-daily simulations of variables for land, atmosphere and ocean waves. The downloaded original 6-hourly (starting at 0:00 UTC) images of ERA5 Volumetric Soil Moisture and Soil Temperature with a spatial resolution of 0.25° Lat. x 0.25° Lon have been converted into a time series format of daily averages. The ERA5 dataset starts in 1979, however, in this comparison, a validation period of 2007-01-01 until 2020-12-31 is used.

5.1.2 Dataset completeness

Figure 1 shows the fractional coverage of ESA CCI SM COMBINED observations over time and latitude and Figure 2 shows the difference between the fractional coverage of v07.1 and v06.1. Note: the same plot is shown for the ACTIVE and PASSIVE products in Figure 5 and Figure 6

[1] Note that the v06.1 dataset runs to 2020-12-31 and therefore, comparisons to this dataset and the statistics presented here only use data up until that date with the exception of the Hovmöeller diagrams.

respectively at the end of this section for the benefit of data users along with the associated maps.

The data coverage is as expected, with greater fractional coverage in the later periods and seasonally varying coverage at extreme latitudes due to snow cover. In addition, around the equator, coverage is reduced due to high vegetation cover in many areas where soil moisture cannot be reliably retrieved. At several points in time, step changes in the number of observations correspond to the start of specific missions (e.g., the start of the AMSR-E mission as of June 2006 is visible in both the PASSIVE and COMBINED products). These comments are applicable to all data products (COMBINED, PASSIVE and ACTIVE; Figure 1, Figure 5 and Figure 6 respectively).

In terms of the difference to the previous product (shown in Figure 2), it can be seen that there is an increase in the fraction of valid observations where new datasets have been utilised, for example where the FY3C or the MetOP ASCAT C datasets have been added. However, the most noticeable increase is brought about by the inclusion of day-time observations in the passive sensors data, which has improved the coverage particularly in the earlier period, where many observational gaps existed. In the later periods, due to the relatively high observational density, the contribution of day-time acquisition has produced positive changes particularly in the equatorial and tropical regions. In the period 2015-2020, a slight decrease in coverage has occurred at the northern latitudes with seasonal patterns, likely due to differences in the flagging of frozen soil conditions (affecting both day- and night-time observations).

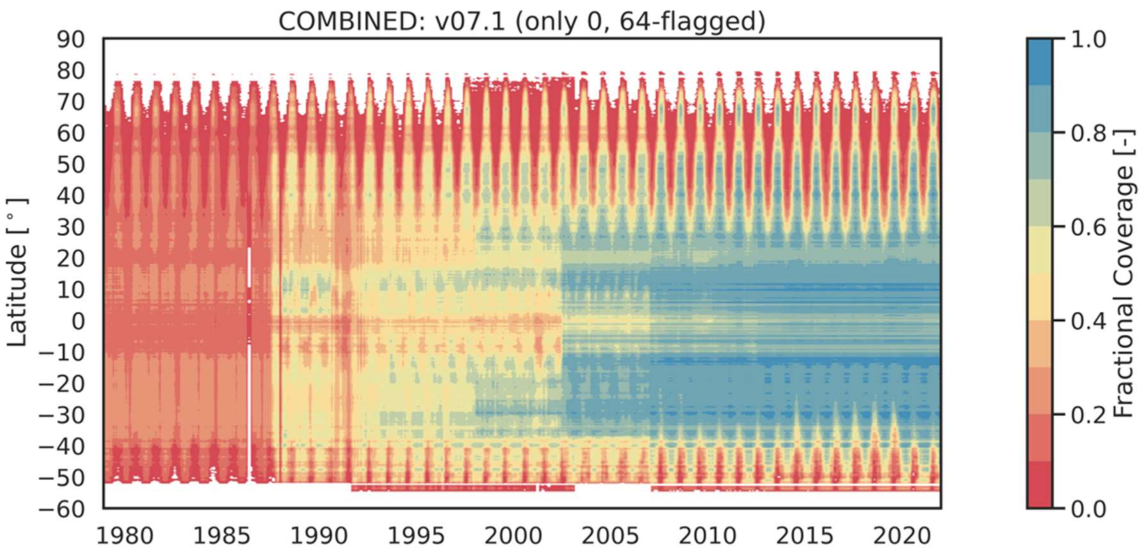

Figure 1: Hovmöller diagram of the fractional number of valid observations per month in the Soil Moisture variable of ESA CCI SM v07.1 COMBINED product. Note: areas of high vegetation are masked out from the monthly / latitude aggregation. 64-flagged values correspond to barren ground conditions.

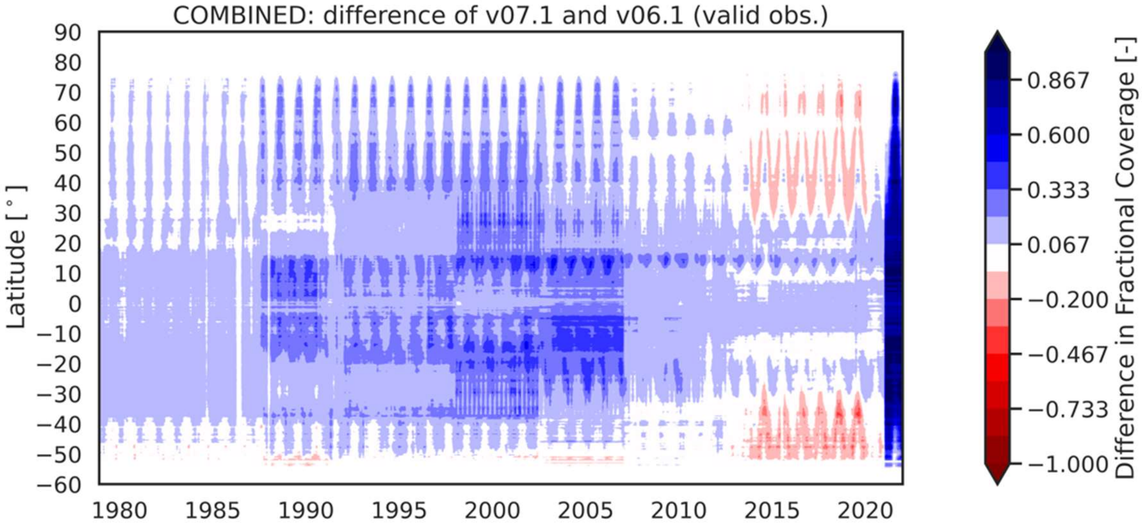

Figure 2: Hovmöller diagram of the difference in the fractional number of valid observations per month in the Soil Moisture variable of ESA CCI SM v07.1 COMBINED product compared to the ESA CCI SM v06.1 COMBINED product.

The spatial distribution of the coverage is provided in Figure 3 for the period 2007-01-01 to 2021-12-31 (i.e., post the introduction of soil moisture data from ASCAT sensors). As expected, there are fewer observations available in areas flagged for snow and vegetation cover. Although the observations flagged for barren grounds are included in the analysis, the coverage decreases naturally in desert and very dry areas for instance due to low weights obtained in the merging. This effect is also traceable to the impact of sub-surface scatter in barren soils.

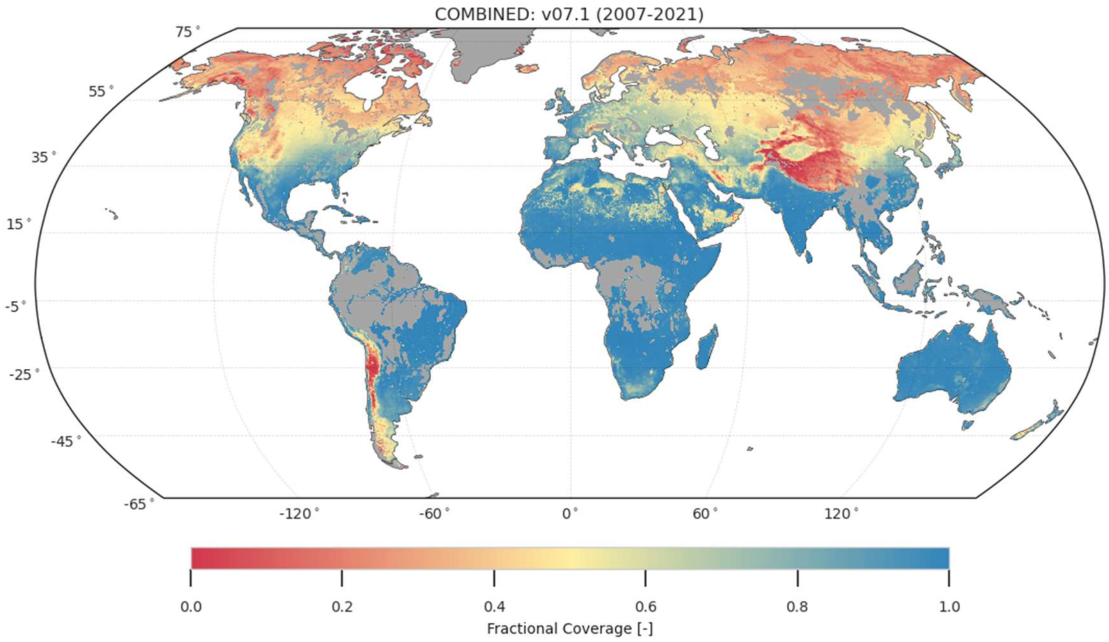

Figure 3: Spatial fraction of valid observations in the Soil Moisture variable of ESA CCI SM v07.1 COMBINED product for the period 2007-01-01 to 2021-12-31. Note: areas of high vegetation are masked out and appear in grey.

The use of day-time observations from passive sensors [RD-02] has produced a positive impact in the spatial coverage of the product (Figure 4). Although the period from 2007 onwards has generally a high observational density even in versions before v07.1, areas of difficult coverage between the tropics and in Oceania have experienced a net improvement. Small differences likely related to the flagging of the input products have caused a slight decrease in the coverage of the northern- and southern-most latitudes (e.g., Siberia and Patagonia). A localized decrease can be observed in the southern part of the Arabic peninsula; however, the exact cause is not yet identified.

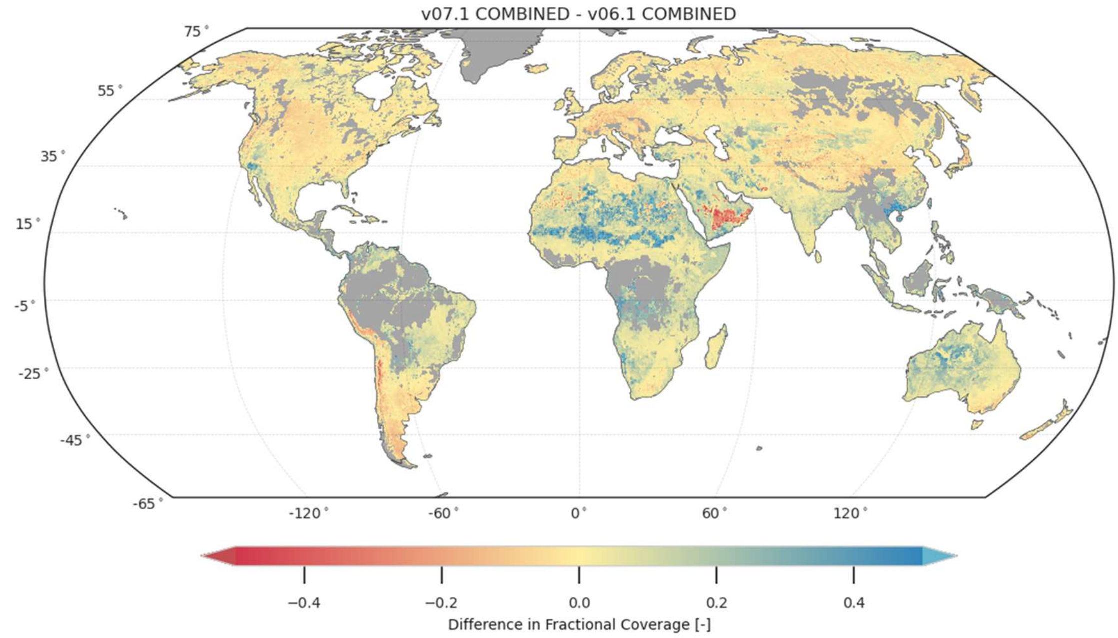

Figure 4: Difference in the spatial fraction of valid observations in the Soil Moisture variable of ESA CCI SM v07.1 COMBINED and v06.1 for the period 2007-01-01 to 2020-12-31. Blue represents an increase in valid observations in the new (v07.1) product.

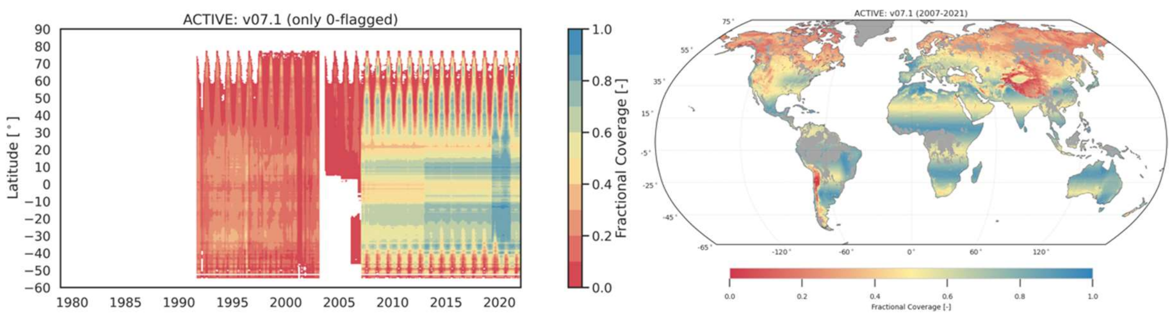

Figure 5: Hovmöller diagram of the fractional number of valid observations per month in the Soil Moisture variable of ESA CCI SM v07.1 ACTIVE product (left) with the spatial distribution of valid observations for the period 2007-01-01 to 2021-12-31 (right). Note: areas of high vegetation are masked out from the monthly / latitude aggregation

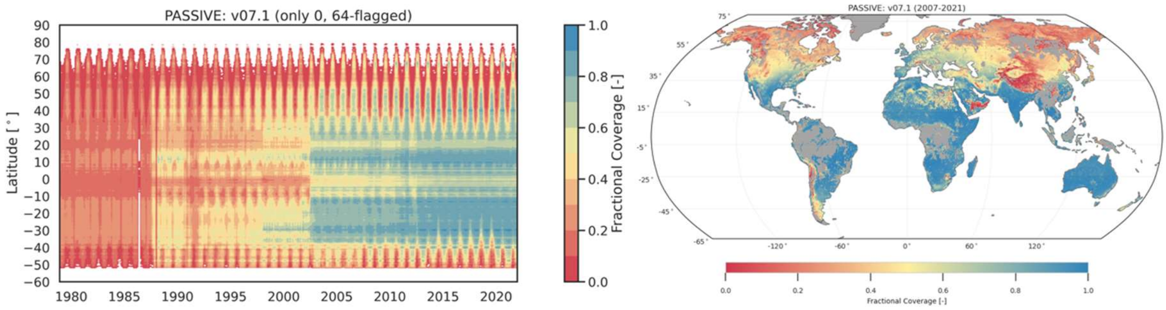

Figure 6: Hovmöller diagram of the fractional number of valid observations per month in the Soil Moisture variable of ESA CCI SM v07.1 PASSIVE product (left) with the spatial distribution of valid observations for the period 2007-01-01 to 2021-12-31 (right). Note: areas of high vegetation are masked out from the monthly / latitude aggregation.

5.1.3 Dataset uncertainty

Figure 7 shows changes in the uncertainty variable in ESA CCI SM v07.1 COMBINED over time / latitude. Uncertainty values are derived from the Triple Collocation (TC) process which can only be carried out when there are three independent soil moisture datasets available (an active, passive and modelled dataset are used in ESA CCI SM). For this reason, uncertainty values cannot be derived for SMMR and therefore, are only provided from the start of SSM/I (1987-07-09) onwards.

It can be seen from Figure 7 that the uncertainty (which is calculated per sensor period) reduces over time with the most recent periods showing uncertainty of below 0.01. This is due to the larger number of values from individual sensors used in the averaging and the optimality of the weighting. The uncertainty is also characteristic of the variability of soil moisture, with accuracy comparatively increasing in low-variability areas such as deserts (latitudes between 15° and 35° North).

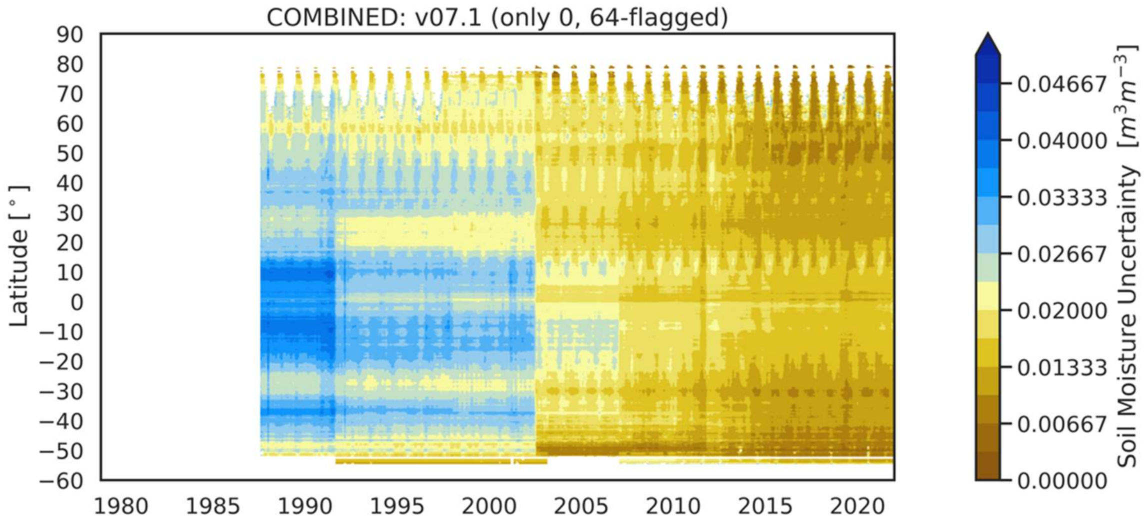

Figure 7: Monthly soil moisture uncertainty in ESA CCI SM v07.1 COMBINED. Note: areas of high vegetation are masked out from the monthly / latitude aggregation.

5.1.4 Soil moisture statistics

The mean and standard deviation of the ESA CCI SM v07.1 COMBINED product (Figure 8 and Figure 9) have been calculated for the period 2007-01-01 to 2020-12-31 and compared to the same results from the v06.1 COMBINED product (Figure 10).

The spatial patterns shown for both the mean and standard deviation are as expected, with regions of seasonal precipitation regimes showing high variability as opposed to low variability for instance in deserts and other arid areas. Looking at the comparison of the mean and standard deviation statistics on a per-point level, v07.1 and v06.1 do not differ significantly. The most outstanding result is a slight decrease of the soil moisture variability in the newest version (Figure 10, right). This likely comes as a result of the novel intra-annual scaling approach used, which has a better characterization of the time series extremes.

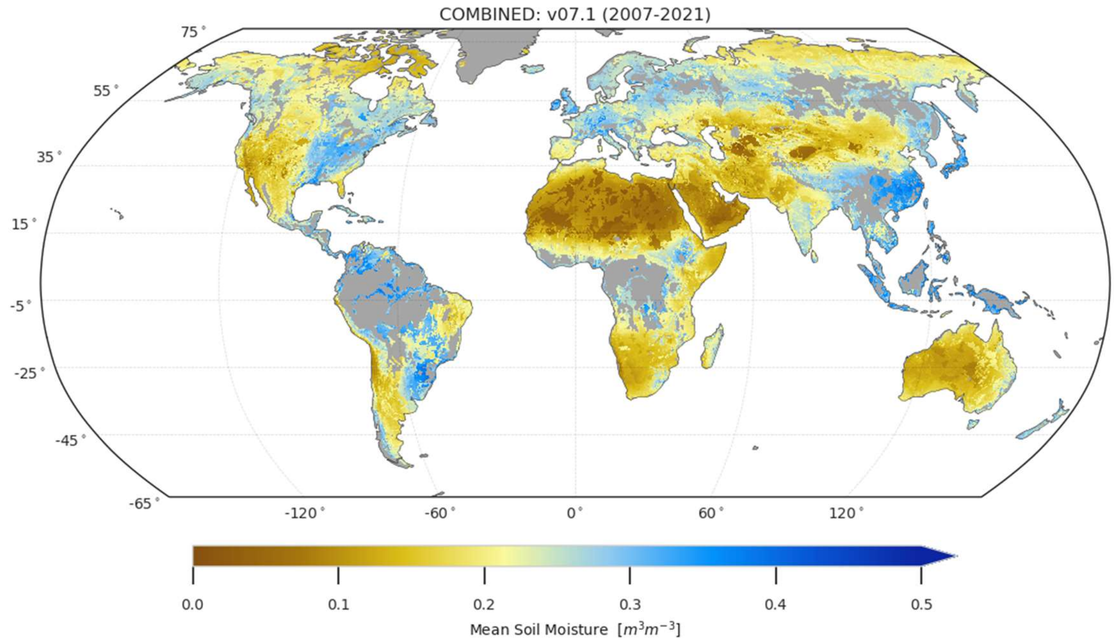

Figure 8: Mean soil moisture for the ESA CCI SM v07.1 COMBINED product for the period 2007-01-01 to 2021-12-31.

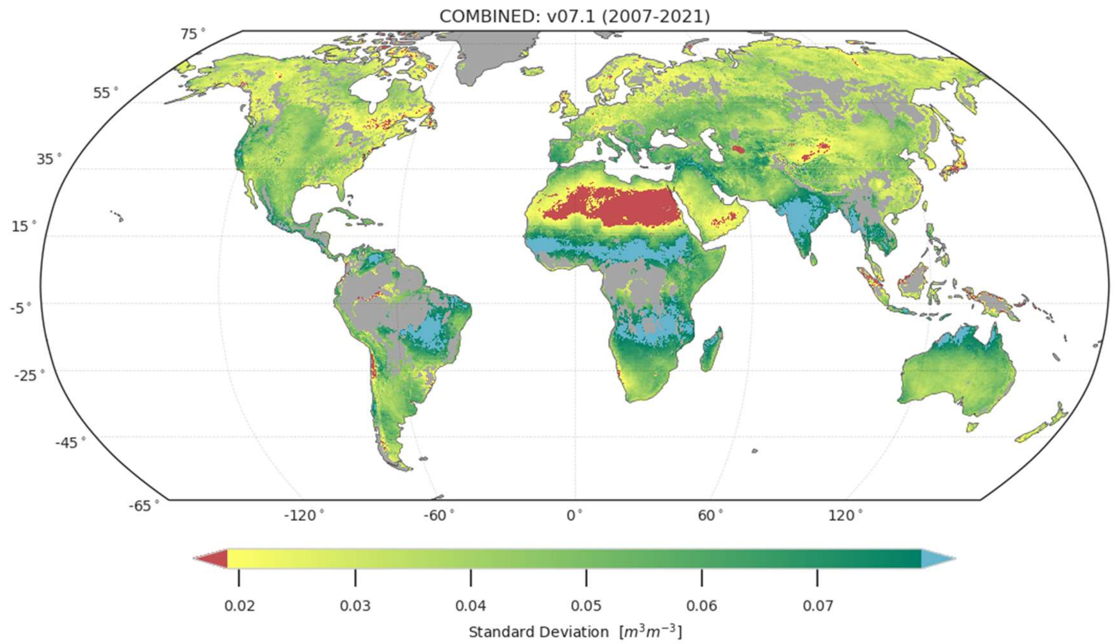

Figure 9: Standard deviation of soil moisture for the ESA CCI SM v07.1 COMBINED product for the period 2007-01-01 to 2021-12-31. Highlighted are the values below (red) and above (cyan) the 5th and 95th percentile, respectively.

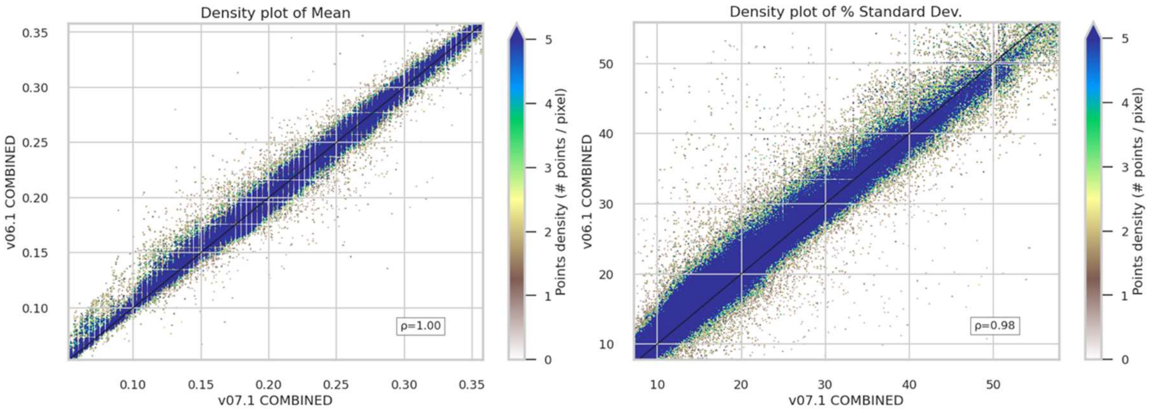

Figure 10: Comparison of the mean (left) and standard deviation (expressed in percentage units with respect to the mean, right) of the ESA CCI SM v07.1 and v06.1 COMBINED datasets. Relative to the period 2007-01-01 to 2020-12-31.

5.1.5 Soil moisture anomalies

Soil moisture anomalies are generated for each ESA CCI SM product version and used in the BAMS State of the Climate (SotC) report [e.g., *Preimesberger et al.*, 2020]. For the verification of the product, simple visual inspection of the anomalies provides a quick check of how the product is performing compared to previous products (i.e., do the anomalies provide the same spatial patterns) and can be easily verified using knowledge of the extreme drought and rainfall events in the period analyzed.

Figure 11 shows the anomalies for the year 2021 for Europe for the ESA CCI SM v07.1 COMBINED product. The same is shown in Figure 12 for the v06.2 COMBINED product (Note: v06.2 is used here as it is the temporally extended version of v06.1 and therefore can be used to compare anomalies from 2021; this version has not been publicly distributed at the time of writing of this report).

The patterns coincide well between the two product versions, with strong negative anomalies in Southern Brazil, North America and around the Caspian Sea, and strong positive anomalies in Northern China, India and South-East Australia. The most noticeable difference in this sense regards the region of North Africa and the (sub-) Saharan desert, where slight negative anomalies in v06.2 differ from slight and strong positive anomalies in v07.1. Looking at Figure 4, this area has particularly benefitted from a large increase in observations, which will have yielded an overall more robust climatology (and better correlation, Figure 14) and contributed to different estimation of the anomalies for 2021. In terms of absolute values, the anomalies (both negative and positive) are less extreme in several regions, including India, South America and Australia.

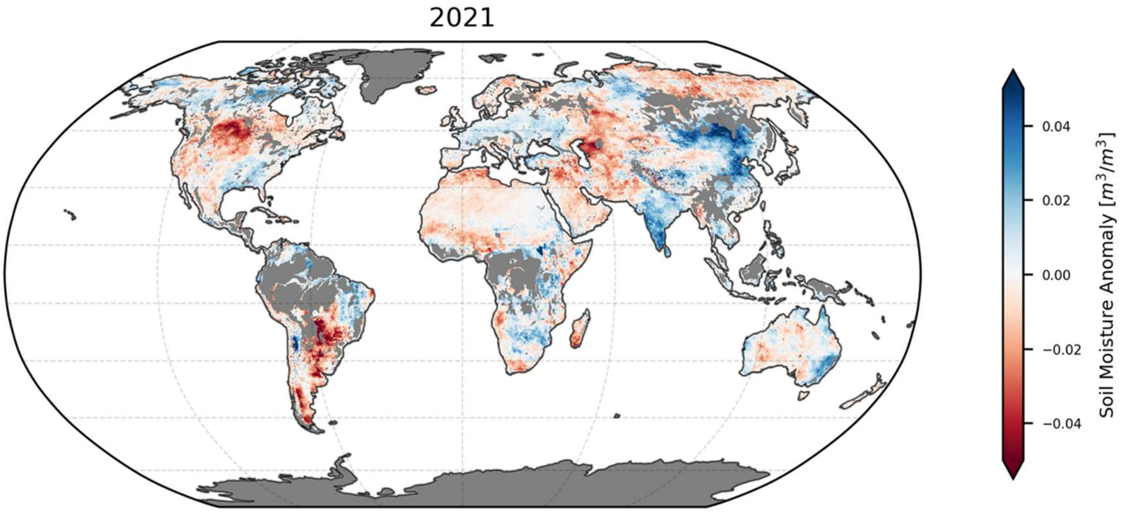

Figure 11: Soil moisture anomalies for the year 2021 from the ESA CCI SM v07.1 COMBINED product (reference period 1991-2020).

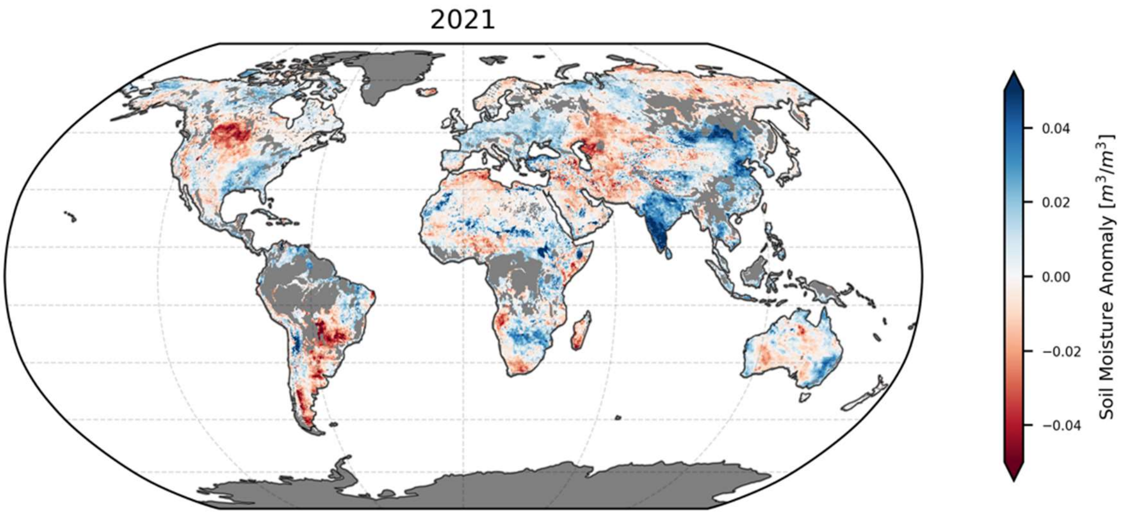

Figure 12: Soil moisture anomalies for the year 2021 from the ESA CCI SM v06.2 COMBINED product (reference period 1991-2020).

5.1.6 Basic validation against ERA5 soil moisture

Validation of ESA CCI SM v07.1 COMBINED against ERA5 soil moisture has been undertaken using the QA4SM framework (www.qa4sm.eu) run locally to allow the inclusion of v07.1. An inter-comparison (i.e., common observations only) was undertaken using v07.1 COMBINED, v06.1 COMBINED and ERA5 soil moisture for the period 2007-01-01 to 2020-12-31.

This period has been chosen as there are more observations available in this period (see Figure 1) and the majority of the changes made at v07.1 affect this period. This means that that the validation results provide clearer information about how the product has changed between v06.1 and v07.1.

Mean – standard deviation scaling has been undertaken to reduce systematic biases between the datasets prior to validation and spatial matching is undertaken using nearest neighbor resampling (CCI is matched to the nearest ERA5 point and results are presented on the ERA5 grid). Temporal matching is also undertaken using nearest neighbor resampling (i.e., the ERA5 observation closest to the midnight UTC timestamp of CCI is used).

The correlation between ERA5 soil moisture and ESA CCI SM v07.1 COMBINED is shown in Figure 13. As expected, good correlations are achieved in areas where the landcover characteristics are more optimal for retrieval, for instance in the sparsely vegetated plains and croplands in the Midwestern United States. Processes that affect the observational quality, e.g., frozen or barren soils (note that the flag for barren grounds is not applied to the data set), are associated with areas of low correlation at northern latitudes or on deserts.

Figure 14 shows the difference in correlation with ERA 5 between v07.1 and v06.1. Large improvements can be noticed particularly in areas where the correlation is typically low, as in the polar and subpolar zones, and in the sub-Saharan region, where a large coverage improvement was noticed. Other regions with net improvements are south-east Asia and south-western Brazil. The only regions showing a slight deterioration are north of the Black Sea and in the southern Arabic peninsula. The latter corresponds to a decrease in the coverage as observed in Figure 4.

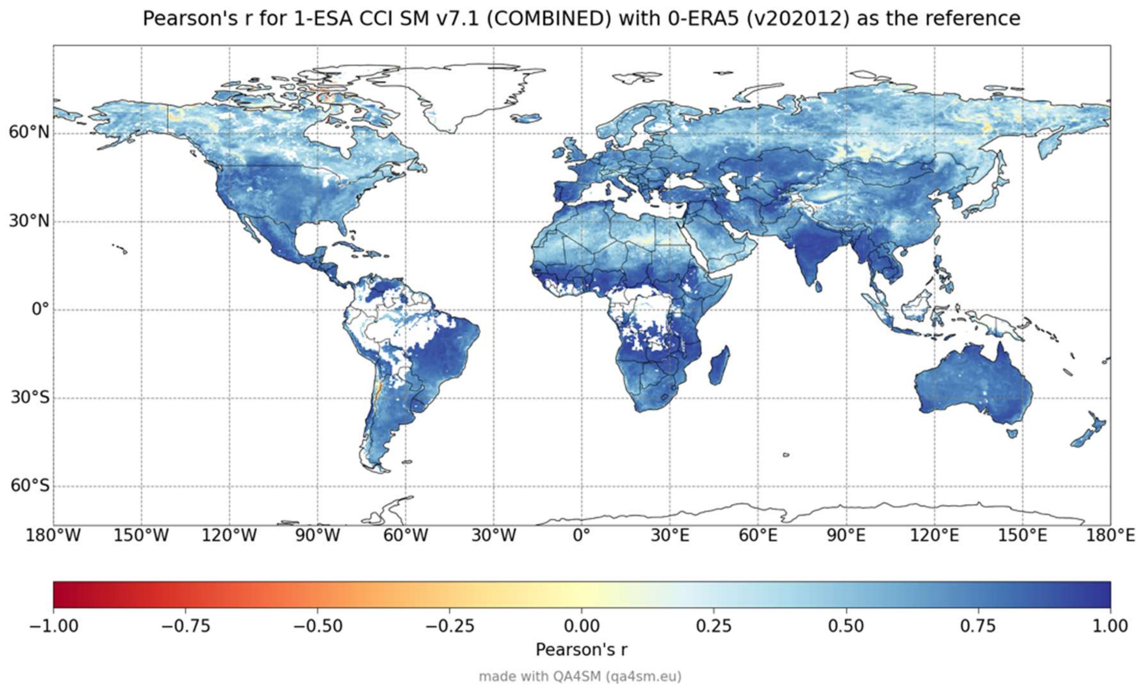

Figure 13: Pearson's correlation between ESA CCI SM v07.1 COMBINED and ERA5 soil moisture for the period 2007-01-01 to 2020-12-31.

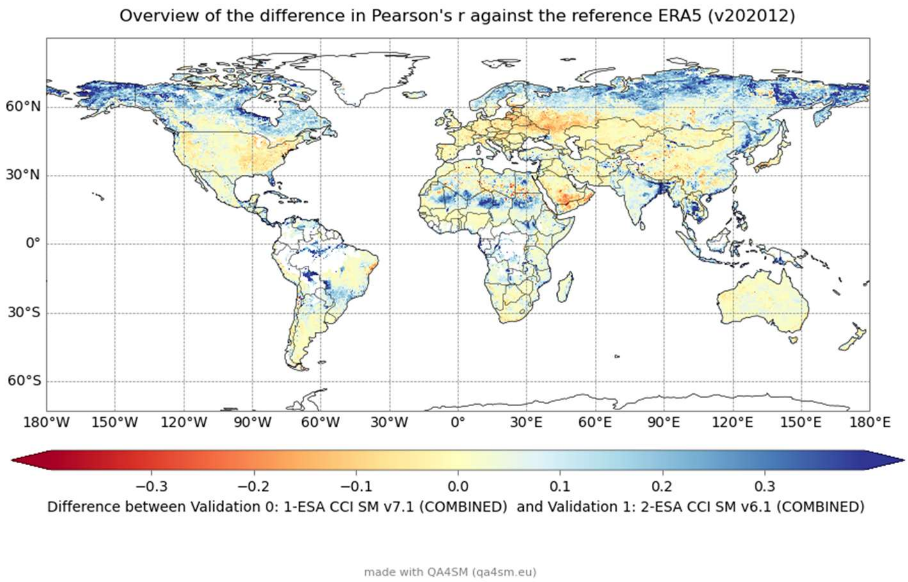

Figure 14: Difference in Pearson's correlation against ERA5 soil moisture between ESA CCI SM v07.1 COMBINED and v06.1 COMBINED for the period 2007-01-01 to 2020-12-31.

5.1.7 Break-adjusted COMBINED product

As with version v06.1, the break-adjusted COMBINED product is produced in v07.1 using the methodology set out in [*Preimesberger et al.*, 2021; also described briefly in the ATBD [RD-02]].

The basic quality checks for data completeness have also been applied to this dataset and the coverage is the same as those shown for the COMBINED product in Figure 1 and Figure 3, which is as expected. No uncertainty field is provided with the break-adjusted product as the method for estimating how uncertainties change through the break correction procedure has not yet been developed.

The correction algorithm is applied to points where breaks in mean or variance were detected, based on the methods described by *Su et al.* [2016]. The reference data set for break detection and correction is ERA5. Figure 15 shows the break detection results for 2 out of a total of 8 sensor transition dates (1987-07-09, 1991-08-05, 1998-01-01, 2002-06-19, 2007-01-01, 2010-01-15, 2012-07-01, 2015-03-31) corresponding to changes in the constellation of merged sensors. Some sensor transitions are excluded to guarantee subperiods with more than one year in length.

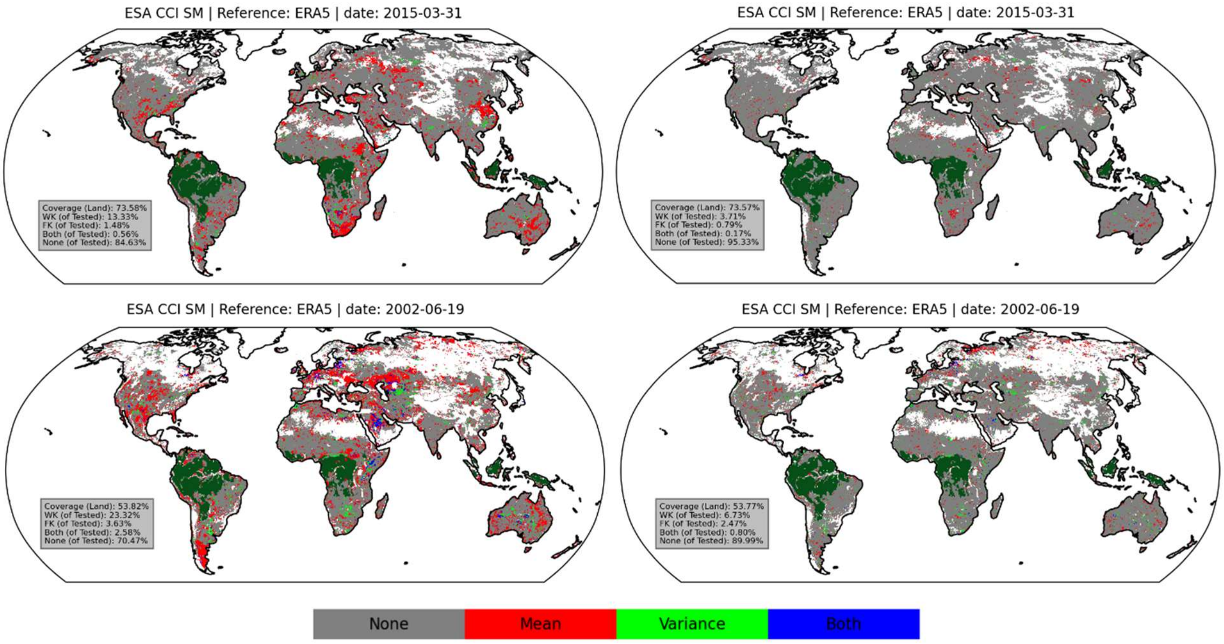

Figure 15: Break detection for ESA CCI SM v07.1 (COMBINED) between subperiods before / after the sensor transitions at 2015-03-31 (top) and 2002-06-19 (bottom). Bright green points indicate variance breaks while red points indicate breaks in mean. Results for the remaining 6 transition dates are not shown.

Figure 16 shows the change in the longest period without breaks before and after the correction is applied. The period length increases the more breaks for a single grid point are removed. Areas in the North are almost never affected, as due to insufficient data only low or insignificant correlation with ERA5 is achieved, and therefore no testing can be performed.

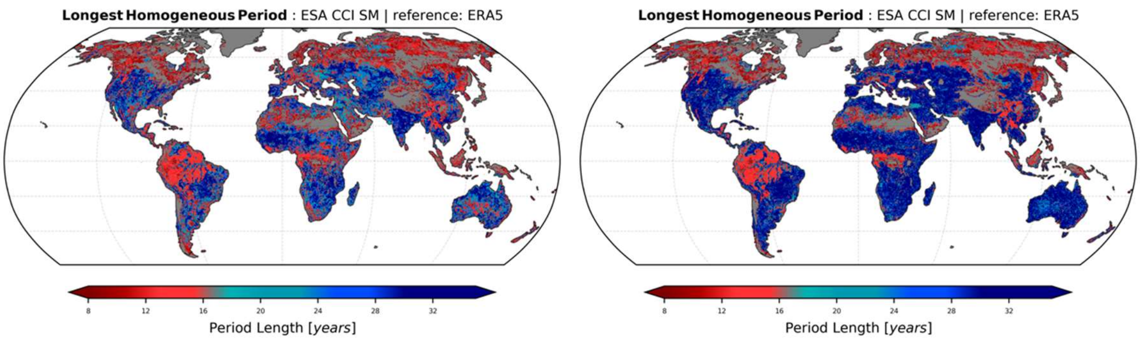

Figure 16: Comparison of the longest homogeneous period before (left) and after (right) correction for soil moisture breaks in the COMBINED product.

The difference Hovmöller diagram, with the original product subtracted from the break-adjusted product, is shown in Figure 17. The largest effect is in the Southern hemisphere in the period 2002 to 2011 (i.e., the AMSR-E period) where the break adjusted product provides lower values than the original product. In the northern hemisphere differences can be seen prior to 2002 where the break adjusted product provides higher values than the original product. These differences can also be seen in the monthly averaged time series Figure 17.

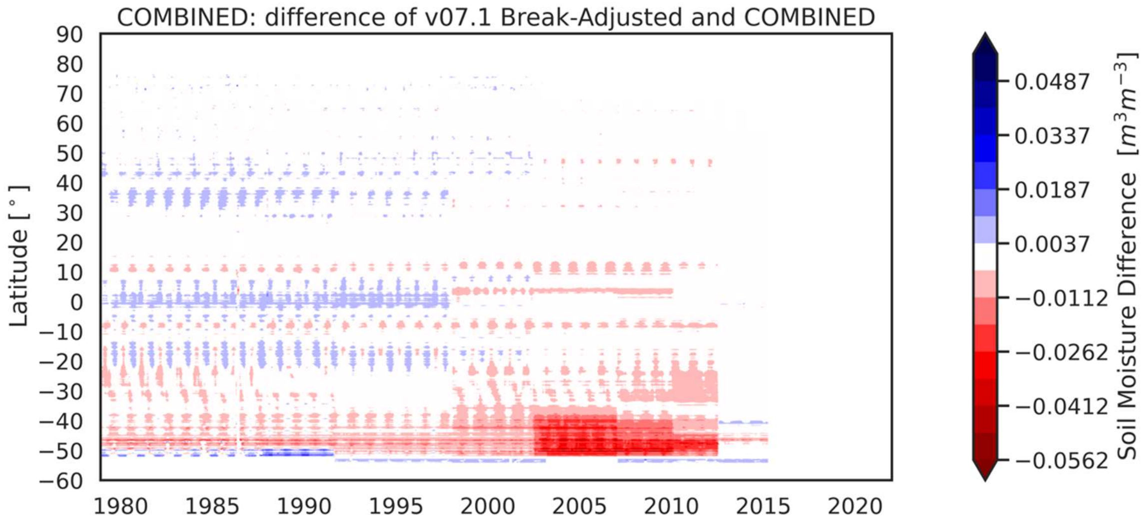

Figure 17: Differences in soil moisture Hovmöller for the ESA CI SM v07.1 COMBINED break-adjusted product vs. the original, non-break-adjusted original ESA CCI SM v07.1 COMBINED product. Soil moisture is averaged per month and per latitude. Note: areas of high vegetation are masked out from the monthly / latitude aggregation. Red (negative) means that the break-adjusted product provides lower soil moisture values than the original product.

Figure 18 shows that the break-adjusted product improves almost univocally the correlation to reanalysis data in large parts of the Southern and Northern Hemispheres, with patterns well matching the soil moisture change shown in Figure 17. While many regions benefit from the correction of temporal breaks, the largest improvement is observed in the very south of South America and around the Middle-East and Black Sea.

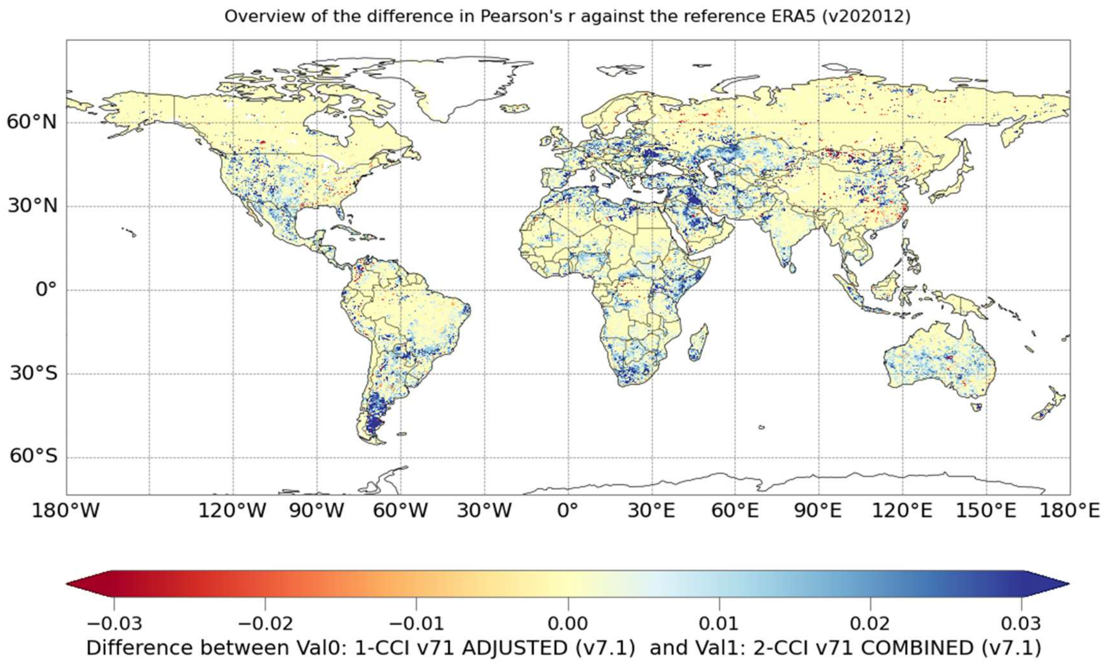

Figure 18: Comparison of Pearson's correlation of COMBINED with ERA5, after and before adjustment of the breaks, globally for the period 1980-2021.

5.1.8 Summary

The following points summarize the conclusions of the above sections:

- The ESA CCI SM v07.1 product provides increased spatial and temporal coverage with respect to previous versions due to the inclusion of FY3D, ASCAT C and the day-time observations from all passive sensors.
- The uncertainty provided with the ESA CCI SM v07.1 product is complete and realistic.
- The general statistics of the data are as expected, and in line with previous versions, with a slight reduction in the standard deviation for ESA CCI SM v07.1 COMBINED compared to v06.1.
- The soil moisture anomalies for 2021 in v07.1 COMBINED are in line with the previous v06.2 version, with patterns coinciding almost everywhere. Regional changes in the sign and absolute values of anomalies are likely related to coverage-driven differences in the calculation of the climatology.
- A large improvement and only few areas of localized decrease characterize the correlation of v07.1 to ERA5, with respect to v06.1. The improvements are primarily in the polar and sub-polar zones and in parts of the tropical zones.
- The break-adjusted product provides the largest changes in soil moisture absolute values predominantly at the start of the AMSR-E period. Breaks are removed globally and improve the correlation of the COMBINED product with reanalysis data in various regions.

5.2 Comparison to in-situ observations from ISMN and global land reanalysis products

5.2.1 Datasets and data processing

ESA CCI SM

To date various versions of the ESA CCI SM product are available. We use here v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and the newest v07.1 release of the COMBINED product derived from the collocated C-band scatterometer data set and the collocated multi-frequency radiometer data set. These represent the major releases of the different product generations [as represented by the evolution of the merging algorithm; see *Gruber et al.*, 2019 for an overview on the ESA CCI SM product evolution]. Additionally, the ACTIVE and PASSIVE products of ESA CCI SM v07.1 and v06.1 are used for some of the analyses, as well as a break-adjusted version of the v07.1 COMBINED product [*Preimesberger et al.*, 2021]. The spatial resolution of ESA CCI SM is 0.25°, with daily temporal resolution. Data is presented in $m^3 m^{-3}$ and represents soil moisture in the top few millimeters to centimeters of the soil [*Kuria et al.*, 2007]. The quality and availability of the data has increased over time, as the number of available satellites has increased [*Dorigo et al.*, 2017; *Dorigo et al.*, 2015; *Dorigo et al.*, 2010].

ISMN

In-situ soil moisture measurements are obtained from the International Soil Moisture Network (ISMN). The ISMN database consists of measurements from various networks. If needed the data is transformed so that it is consistent in units (m^3 m^{-3}), then quality checked and flagged [*Dorigo et al.*, 2011]. The analyses are based on a full download from 4 February 2022. All data is aggregated to daily averages, considering only values with quality flag "G" (see https://ismn.geo.tuwien.ac.at/en/data-access/quality-flags/). This implicitly also masks soil temperatures < 0°C.

Measurements from both the 5 cm and the 10 cm depths are considered since near-surface sensors appear to be more prone to errors [*Mittelbach et al.*, 2012].

ERA5-Land, ERA-Interim/Land, MERRA-2

To determine the influence of soil depth on soil moisture variability, we use ECMWF's ERA5-Land reanalysis soil moisture [*C3S*, 2019; *Munoz-Sabater et al.*, 2021]. ERA5-Land is available as a re-gridded 0.25° soil moisture product, corresponding to the ESA CCI SM resolution, and has global coverage. Here we use the top two soil layers, which represent 0-7 cm and 7-28 cm soil depths. Data is aggregated from the original hourly temporal resolution to daily averages. Moreover, the forerunner of ERA5-Land, ERA-Interim/Land [*Balsamo et al.*, 2015; *Dee et al.*, 2011] is used for comparison and as previous reanalysis benchmark in some of the analyses. For the analysis of the long-term temporal trends, also surface soil moisture of the atmospheric reanalysis MERRA-2 is included [*Gelaro et al.*, 2017].

Data selection

We consider ISMN soil moisture measurements that have at least one year of data (i.e., 365 days with valid data) and focus the main analyses on the US, Europe, Africa and Australia (see Figure 19) as well as the time period 1991-2010 when considering all major ESA CCI SM product releases. This selection results in 302 individual soil moisture time series from 18 different networks. Soil moisture time series from the grid cells in which the stations fall are extracted from ESA CCI SM, ERA5-Land and ERA-Interim/Land for this comparison. Thus, depending on the spatial and temporal overlap with ESA CCI SM, less time series might be used in the actual validation process.

Moreover, an extended time period is used for the global validation of the last two product releases (see Section 5.2.2) and the evaluation of the product evolution over time (see Section 5.2.3). This, depending on the temporal subset under investigation, considers the extended set of currently available ISMN data with up to 1000 stations.

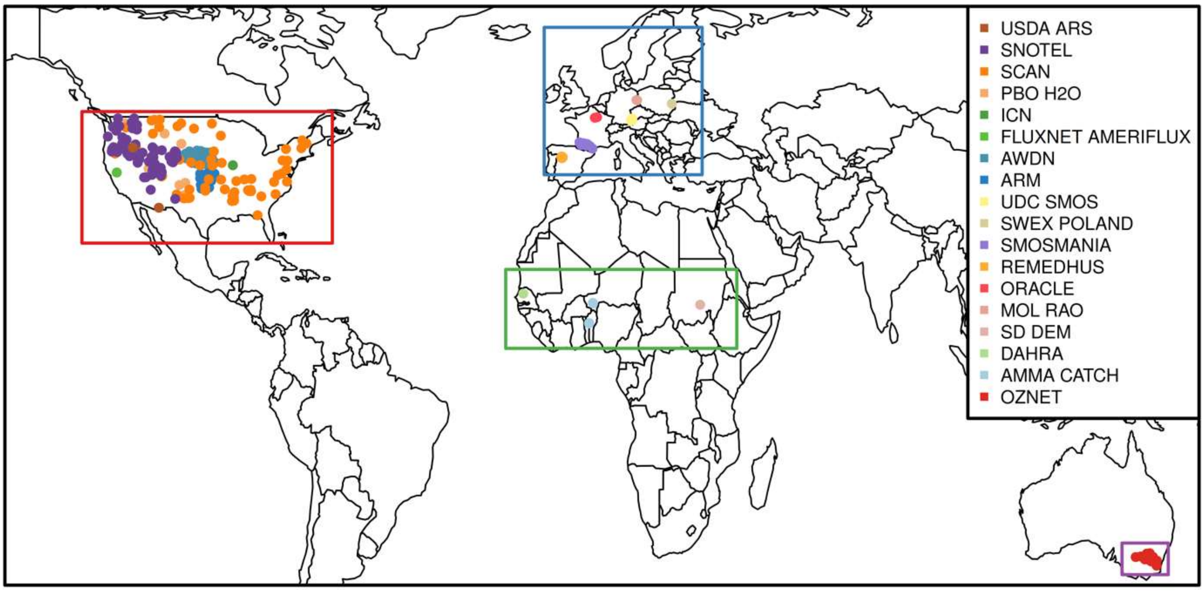

Figure 19: Overview of the spatial coverage of the stations considered in this section, rectangles indicate the four focus areas of the comparison, i.e., the United States (US, red), Europe (EU, blue), Africa (AF, green), and Australia (AUS, purple). Stations are color coded by network, see Figure 20 for the legend.

Comparisons of the products

We focus on the evaluation of ESA CCI SM v07.1 COMBINED and compare it to its forerunners v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 as well as to ERA5-Land and ERA-Interim/Land layer 1 and layer 2 soil moisture. Additionally, the ACTIVE and PASSIVE products of v07.1 and v06.1 are use in some of the comparisons. All considered data sets have a different temporal coverage, and we account for this by masking for common data availability (unless specified otherwise; see Figure 20).

To account for the different units and dynamic ranges of the products, and to remove systematic differences between the products, the ESA CCI SM, ERA5-Land and ERA-Interim/Land soil moisture time series are scaled to the respective in-situ time series using a CDF matching approach. Then, the long-term inter-annual anomalies are calculated based on subtracting the long-term mean using a 11-day window.

Agreement between in-situ data and ESA CCI SM, ERA5-Land and ERA-Interim/Land is determined by the Pearson correlation and by the unbiased root mean square difference (ubRMSD) between the in-situ time series and the corresponding time series from the gridded product. Note that because data availability varies among locations, the time period (and amount of data) used to calculate the statistical metrics may differ between locations. Also, most of the available in-situ data is from the US, so a general global conclusion cannot be made. All analyses are performed on mean daily soil moisture, and results are shown for both the absolute scaled data, as well as the inter-annual anomalies.

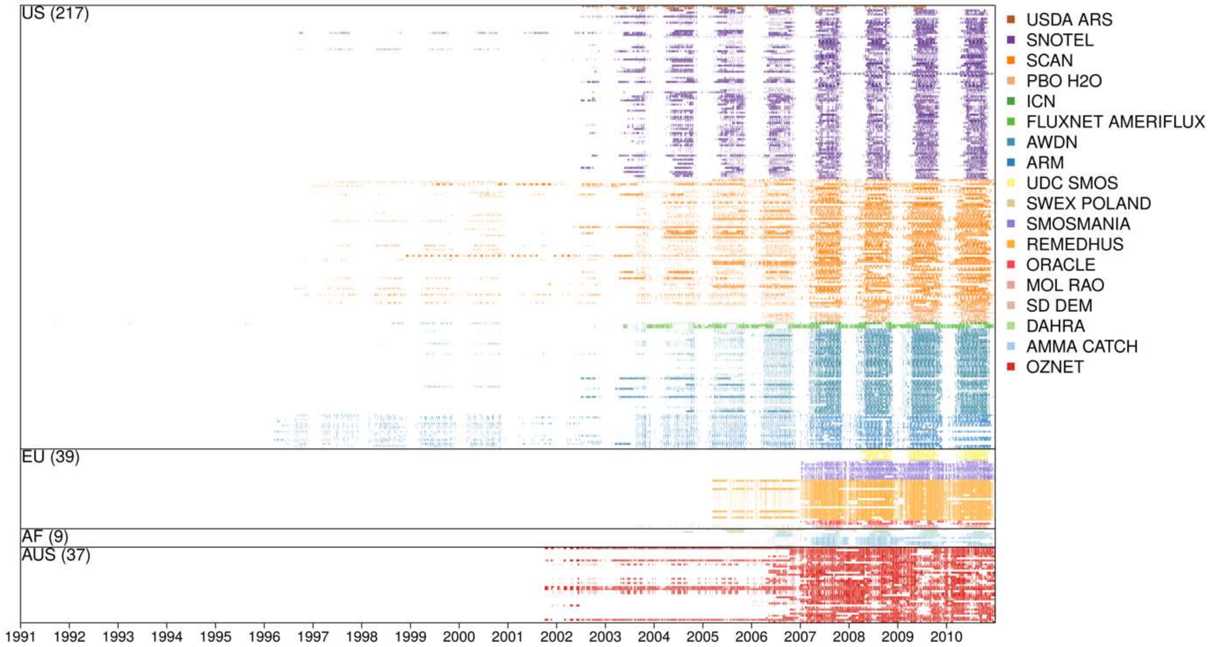

Figure 20: Overview of the temporal coverage of the stations considered in this section, after masking for common data availability, split per region. The number of stations per region is indicated in brackets.

5.2.2 General findings

Figure 21 shows the distribution of the correlation and ubRMSD values from the comparison of ESA CCI SM v06.1 and v07.1 (COMBINED, ACTIVE, PASSIVE) with respect to the full set of ISMN stations (i.e., up to 800 stations, 5 cm measuring depth) over the common 1992-2020 time period. Both absolute soil moisture values as well as the inter-annual anomalies are analyzed. The corresponding median values of the metrics and the corresponding confidence intervals are displayed in Table 2 and Table 3.

For the COMBINED product, higher correlations can be observed for v07.1 as compared to v06.1 with an increase in the median correlation from 0.631 to 0.673 for the absolute soil moisture values and from 0.517 to 0.536 for the inter-annual anomalies. Such an increase in the skill between v06.1 and v07.1 is less clearly visible for ubRMSD (based on the confidence intervals of the median estimates, Table 2 and Table 3). As expected, the PASSIVE and in particular the ACTIVE products show lower skill compared to the COMBINED products for both releases, showing the benefit of the applied merging approach for ESA CCI SM.

Overall, ERA5-Land shows better agreement with the in-situ data as compared to the ESA CCI SM releases, which is in line with other product inter-comparison studies [e.g., *Beck et al.*, 2021].

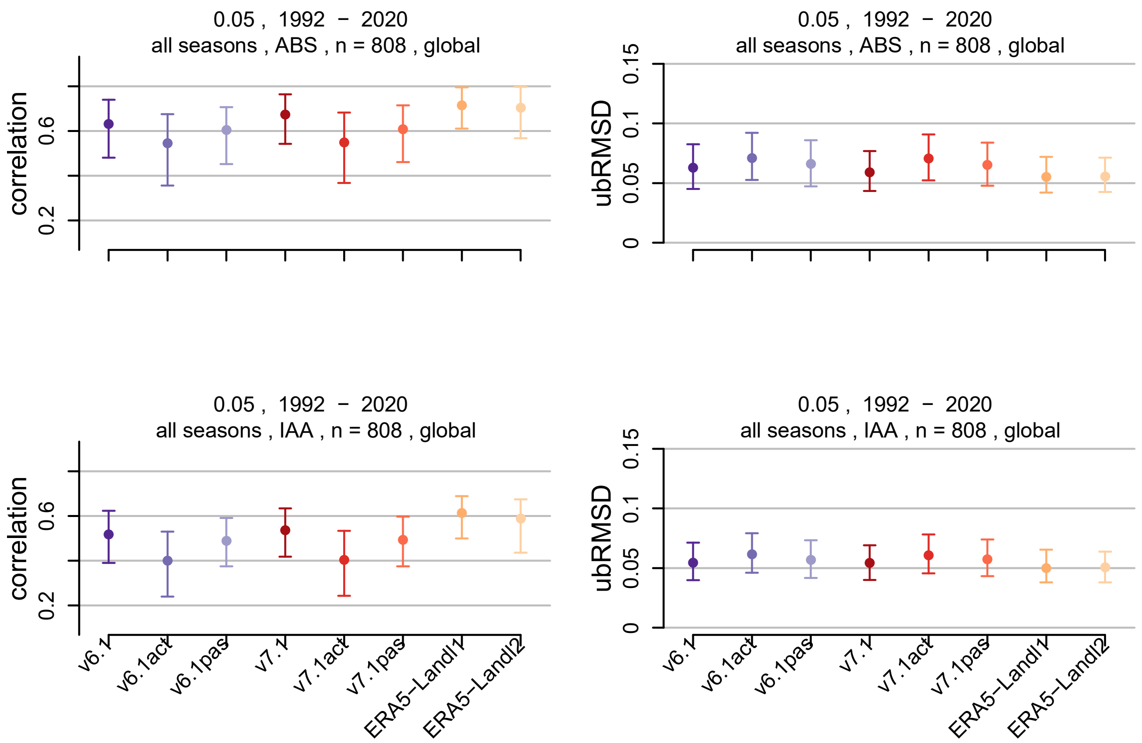

Figure 21: Correlation (left) and ubRMSD (right) of the last two releases of ESA CCI SM (v06.1 and v07.1 COMBINED, ACTIVE and PASSIVE; the latter two denoted as vX.Yact and vX.Ypas) as well as of ERA5-Land (layers 1 and 2)) as compared to the full set of ISMN in-situ station observations (5 cm measurement depth) for absolute soil moisture (ABS, top) and the inter-annual anomalies (IAA, bottom).

Table 2: Median (and corresponding 95% confidence intervals derived from a non-parametric bootstrap) of correlation and ubRMSD derived from the comparison ESA CCI SM v06.1 and v07.1 COMBINED, ACTIVE and PASSIVE to the full set of ISMN stations (measurements at 5 cm depth). Values are displayed for the absolute soil moisture.

Metric	COMBINED		ACTIVE		PASSIVE	
	v06.1	v07.1	v06.1	v07.1	v06.1	v07.1
Correlation [-]	0.631 [0.609;0.650]	0.673 [0.661;0.687]	0.545 [0.523;0.570]	0.548 [0.526;0.571]	0.604 [0.590;0.625]	0.608 [0.597;0.626]
ubRMSD [m^3/m^3]	0.063 [0.061;0.066]	0.059 [0.057;0.061]	0.071 [0.069;0.074]	0.071 [0.069;0.073]	0.066 [0.064;0.069]	0.065 [0.063;0.067]

Table 3: As Table 2 but for the inter-annual anomalies of soil moisture.

Metric	COMBINED		ACTIVE		PASSIVE	
	v06.1	v07.1	v06.1	v07.1	v06.1	v07.1
Correlation [-]	0.517 [0.498;0.532]	0.536 [0.522;0.549]	0.399 [0.383;0.420]	0.403 [0.388;0.425]	0.489 [0.473;0.503]	0.493 [0.478;0.507]
ubRMSD [m^3/m^3]	0.055 [0.053;0.056]	0.054 [0.053;0.057]	0.062 [0.059;0.064]	0.061 [0.058;0.063]	0.057 [0.056;0.059]	0.057 [0.055;0.059]

For different climate zones (Figure 22 and Figure 23), the correlations and ubRMSDs also often indicate better agreement of ERA5-Land with the in-situ data compared to different ESA CCI SM COMBINED releases, i.e., considering the first public version of the product (v0.1) and the respective major releases of the main product generations [as represented by the evolution of the merging algorithm; see *Gruber et al.*, 2019]. The overall skill of ESA CCI SM appears to be slightly better for arid climate zones (i.e., BSx), both for absolute values and anomalies. A slight increasing tendency in the skill is visible for the subsequent major ESA CCI SM releases, with the COMBINED product reaching similar skill as ERA-Interim/Land in the latest v07.1 release.

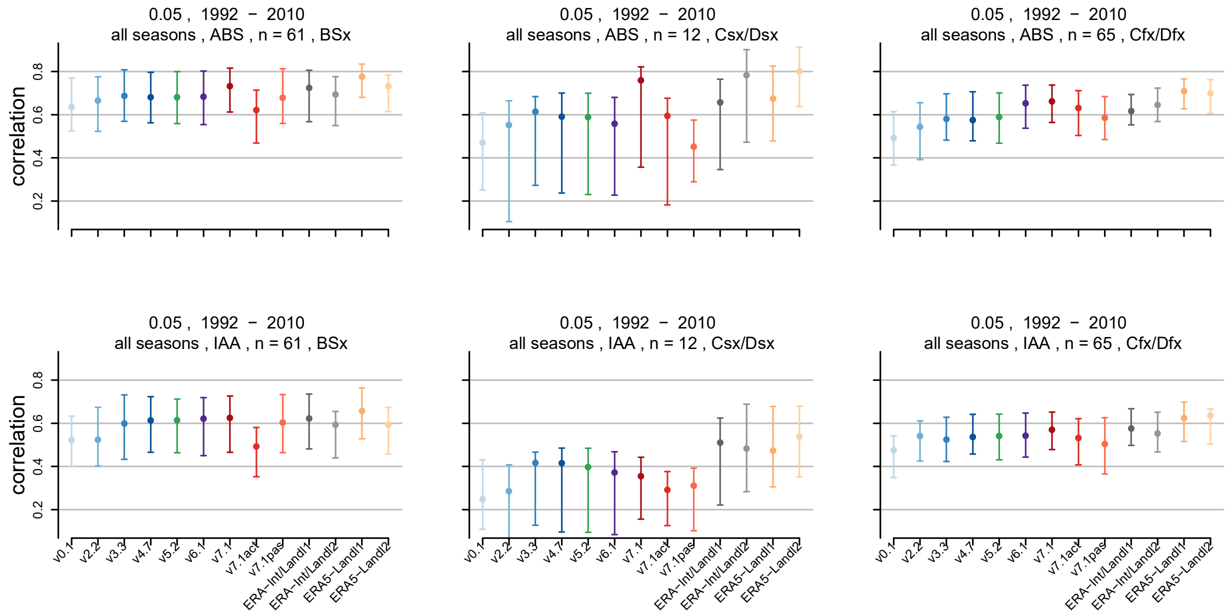

Figure 22: Correlation of the gridded soil moisture products (ESA CCI SM v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1 COMBINED, as well as ERA-Interim/Land and ERA5-Land (layers 1 and 2)) as compared to in-situ station observations (5 cm depth) for three combinations of Köppen-Geiger classes (BSx - arid, Csx/Dsx - temperate/continental summer dry, Cfx/Dfx - temperate/continental without dry season). (Top row) Absolute values of soil moisture (ABS); (bottom row) inter-annual anomalies (IAA). Shown is the median and IQR of the correlations, n denotes the number of stations underlying the distributions.

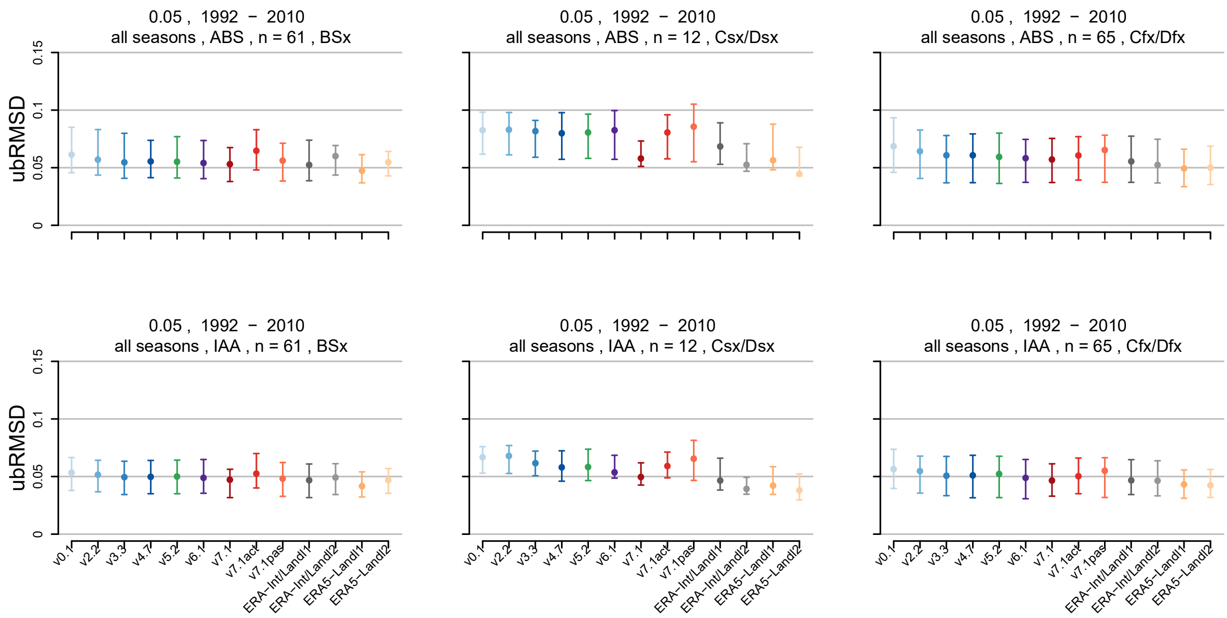

Figure 23: As Figure 22, but showing ubRMSD.

Focusing on the US only where spatial coverage with in-situ stations is most dense (Figure 24), correlation is highest for the absolute values and drops considerably for the anomalies. We find that the spatial pattern of the ESA CCI SM COMBINED correlations is rather scattered for the absolute values, and there are no clear areas in which the product agrees either very well or very poorly with in-situ soil moisture. Also, no pronounced difference in performance can be found between networks (not shown). For the anomalies, the ESA CCI SM correlations appear lower in the north-eastern of the region, which is likely related to complex topography. This is not the case for ERA5-Land layer 1.

There is a slight increase in correlation for each subsequent ESA CCI SM release, most notable when comparing v0.1 to v07.1. ERA5-Land layer 1 shows better agreement with in-situ soil moisture than ESA CCI SM, for both absolute values and anomalies.

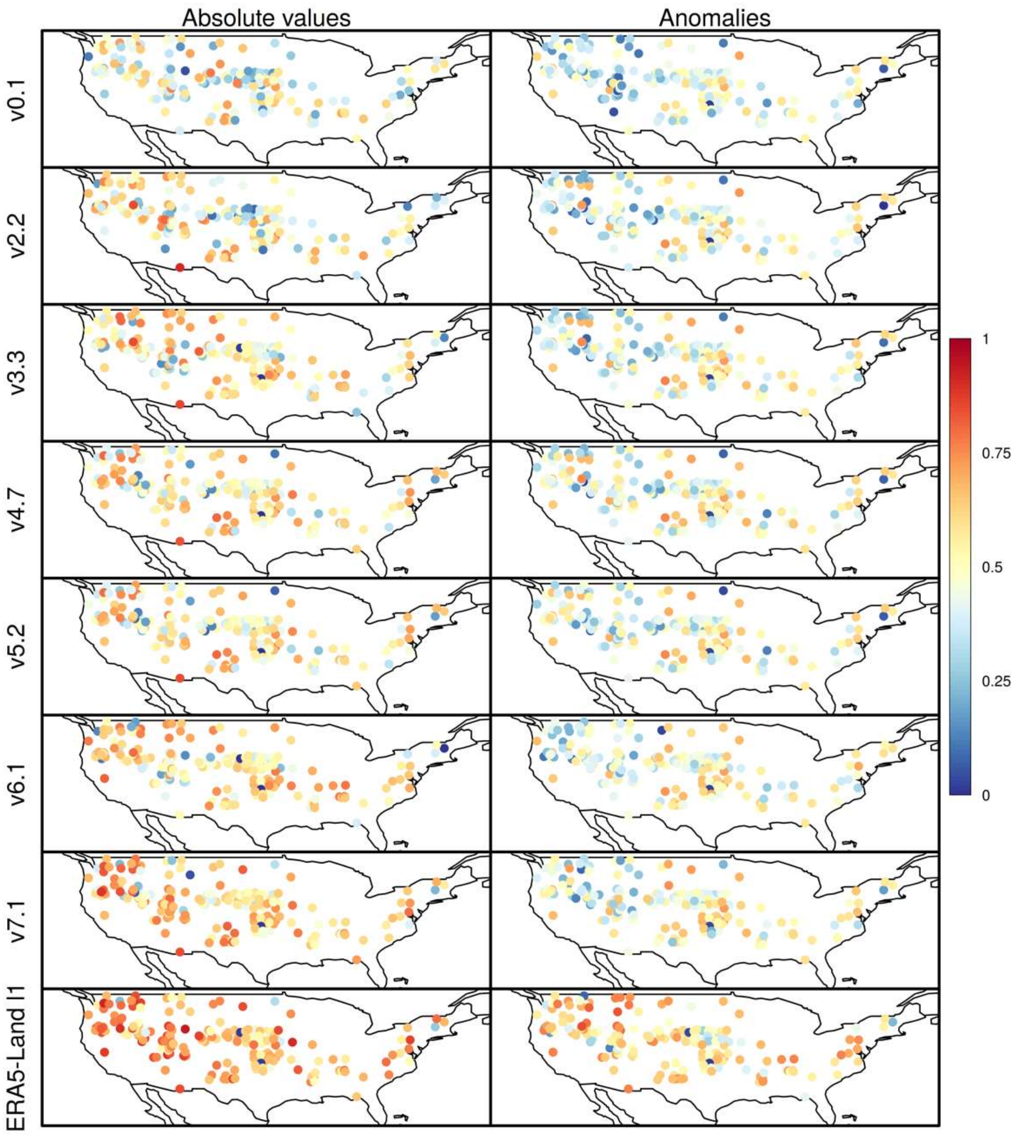

Figure 24: Correlation between in-situ soil moisture and ESA CCI SM for versions v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1 COMBINED, as well as ERA5-Land soil moisture layer 1 (ERA5-Land l1, 0-7 cm), for absolute soil moisture (left) and the anomalies (right) and the period 1991-2010.

5.2.3 Temporal subsets and product evolution

Figure 25 shows the (significantly positive, $p < 0.05$) correlations of the different ESA CCI SM releases, as well as ERA5-Land and ERA-Interim/Land layer 1 compared to in-situ stations (extended set of stations, see Section 5.2.1) in the US for different temporal subsets (i.e., 1998-2001, 2002-2005, 2006-2009, 2010-2013, 2014-2017 and 2018-2021, as well as 1998 up to the end of the individual time series).

The overall correlations for ESA CCI SM appear higher in the earliest period, with a drop during 2002-2005 and subsequent increase towards later periods. This behaviour is in particular visible for summer (not shown). The correlations of ERA5-Land are more stable over time, while ERA-Interim/Land also displays a drop in 2002-2005. The ESA CCI SM releases show a general increase in performance with data releases, pointing to the increasing maturity of the product. This is in particular the case for the periods after 2005 and is also visible in clear improvements from v06.1 to v07.1 for these later time slices. As for the global validation with ISMN, the PASSIVE and ACTIVE products of v07.1 often show lower skill compared to the COMBINED product. Exceptions are the two first time slices, where the ACTIVE product of v07.1 shows clearly better agreement with in-situ observations than the COMBINED and PASSIVE products.

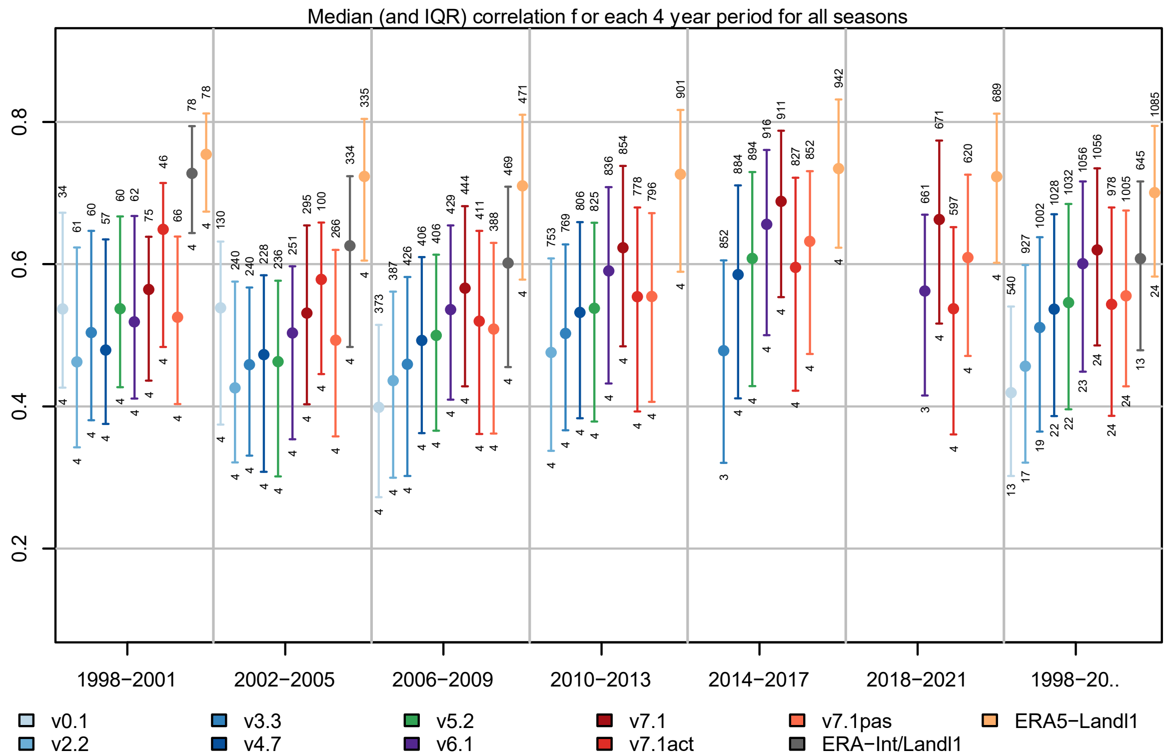

Figure 25: Correlation of the gridded soil moisture products as compared to in-situ station observations in 5 and 10 cm depth for the full year for the US. Subdivided in consecutive 4-year periods (1998-2001, 2002-2005, 2006-2009, 2010-2013, 2014-2017 and 2018-2021) as well as for the longest period data is available (1998-20.., end date would e.g. be 2010 for CCI v0.1, but is 2021 for e.g. CCI v07.1). Note that in this case, data is not masked for common data availability. Whiskers show the median and the IQR. Above indicated the number of stations correlations were calculated for that comply to the following criteria: at least 10% of the time-series is not NA, p-value < 0.05, and the calculated correlation is positive. And below indicated the number of years considered. In addition to the major

releases of ESA CCI SM COMBINED, the ACTIVE and PASSIVE products are also shown in case of v07.1 (denoted v7.1act and v7.1pas).

5.2.4 The influence of measuring depth

ESA CCI SM represents soil moisture in only the top few millimeters to centimeters of the soil [*Dorigo et al.*, 2012; *Dorigo et al.*, 2017]. To determine the influence of measuring depth on the correlation we differentiate between in-situ measurements at 5 and 10 cm depth, see Figure 26. As noted above, the near-surface measurements may be more prone to errors due to their vicinity to air [*Mittelbach et al.*, 2012]. Considering also the 10 cm measurements increases the robustness of the comparisons and may help to detect systematic degradations of the 5 cm sensors. For each major release of ESA CCI SM COMBINED as well as for ERA5-Land (layers 1 and 2), we distinguish between three different regions (US, EU, and AUS) and show the results for the absolute values (top) as well as the anomalies (bottom). Circles denote correlations with in-situ measurements taken at 5 cm depth, and triangles at 10 cm depth.

ESA CCI SM: For the US and Europe, there is a large spread in the derived correlations, likely due to the large spread in climate conditions that the stations are located in. For Australia, the spread is much smaller, there are far fewer stations here and they are all located in the south-eastern part of the continent. For the US, the absolute values show correlations for the ESA CCI SM releases ranging between 0.1 to over 0.9 for the comparison with the 5 cm in-situ measurements, and between 0.1 to 0.7 for the 10 cm measurements, with the median correlation for the shallower 5 cm in-situ measurements being consistently higher. For Europe, the correlations are higher with a median value over 0.6 for 5 cm depth for ESA CCI SM v0.1, and over 0.7 for v07.1. Again, the correlation with in-situ measurements at 10 cm depth is lower, though there are also less measurements available at this depth. The overall highest correlations are found in Australia, with up to 0.8 for the median. Again, the correlations are lower for 10 cm depth.

For the anomalies, the distinction between the 5 cm and the 10 cm correlations appears less pronounced, in particular in the US (where v0.1 even shows a reversed behavior, i.e., slightly higher 10 cm median correlation).

ERA5-Land: Consistent with ESA CCI SM, absolute values of ERA5-Land layer 1 (l1) and layer 2 (l2) show higher correlations with in-situ measurements at 5 cm depth than at 10 cm depth for the US and Europe. For Australia, the correlation is less dependent of the measuring depth, both for absolute values and the anomalies. For ERA5-Land l2, correlation with measurements taken at 10 cm are slightly higher in this region. For the anomalies, the results are comparable, though here the median correlation for 10 cm is also higher over Europe for ERA5-Land l2 and l2. The range of the correlations of ERA5-Land is similar to ESA CCI SM v07.1 (i.e., also going up to over 0.9 for the absolute values), and with overall mostly higher median correlations.

Overall, these results are according to expectations and do not indicate widespread or systematic degradations of the 5 cm compared to the 10 cm in-situ measurement.

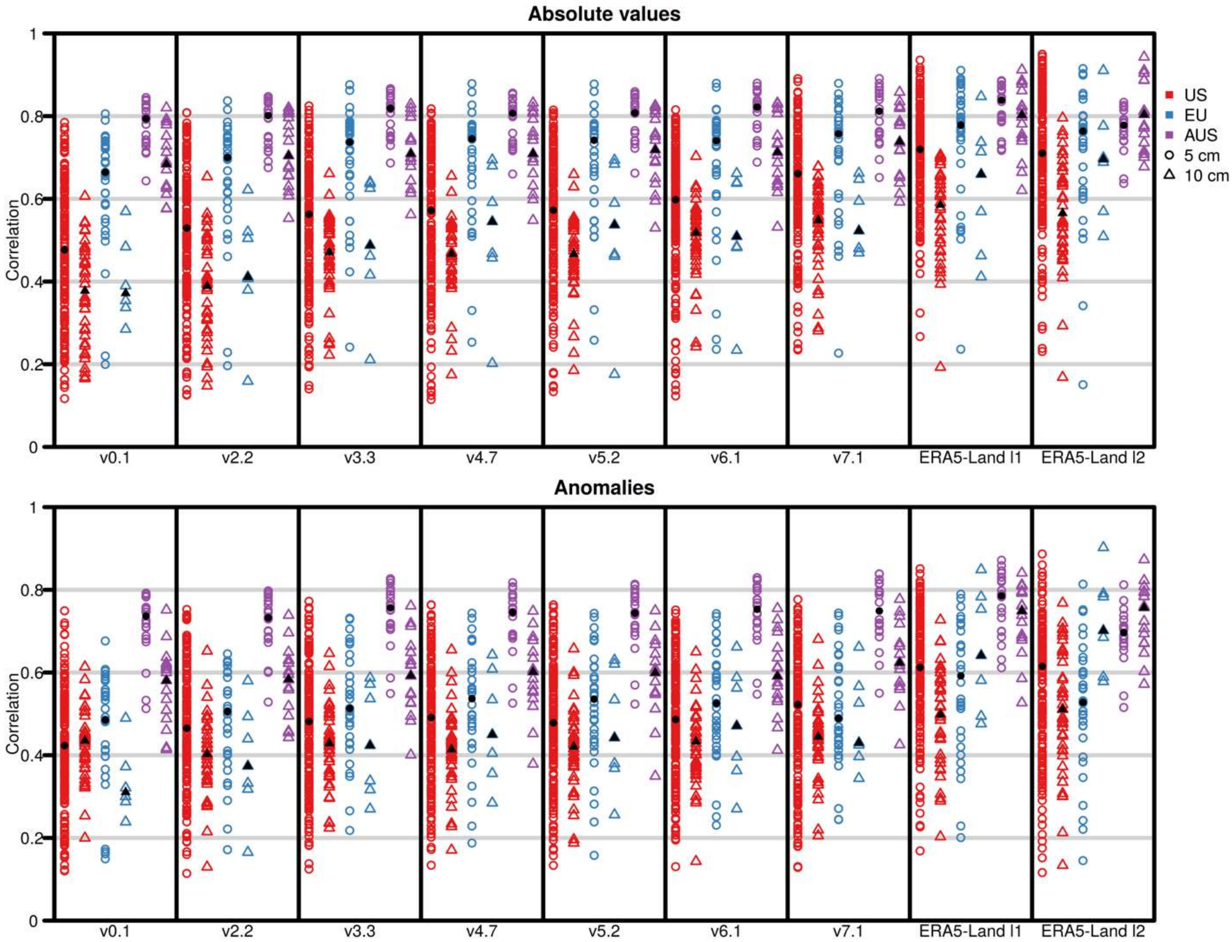

Figure 26: Correlation between in-situ measurements and ESA CCI SM v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1, as well as ERA5-Land soil moisture layer 1 and 2 for the absolute soil moisture values (top) and the anomalies (bottom). For each product, we distinguish between 3 regions US, EU, and AUS (red, blue and purple, AF has insufficient data coverage), and the correlation at 5 cm depth (circles) and 10 cm depth (triangles) over the 1991-2010 time period. The same number of stations is taken into account for the individual distributions of the top and bottom panels. The black circles/triangles represent the respective median values.

5.2.5 The influence of land cover

Figure 27 shows the correlations of ESA CCI SM v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1 (COMBINED products), as well as ERA5-Land layer 1 with the in-situ measurements over the US for absolute values and their inter-annual anomalies, differentiating between grassland (orange) and forest (green) sites (based on the land-cover information of the ISMN stations). As above, correlations for the anomalies are lower compared to the absolute values for all products. For ESA CCI SM, there is mostly a notably higher correlation for grassland sites than for forest sites, both for the absolute values as well as the anomalies. This is related to the reduced retrieval quality over more densely vegetated areas. The only exception is v07.1, where the median correlation for the absolute values is similar for grassland and forest sites, which may possibly result from algorithm improvements (e.g., accounting for seasonal vegetation trends and variable vegetation scattering). For ERA5-Land, such a distinction in the skill between the two land cover types is not visible.

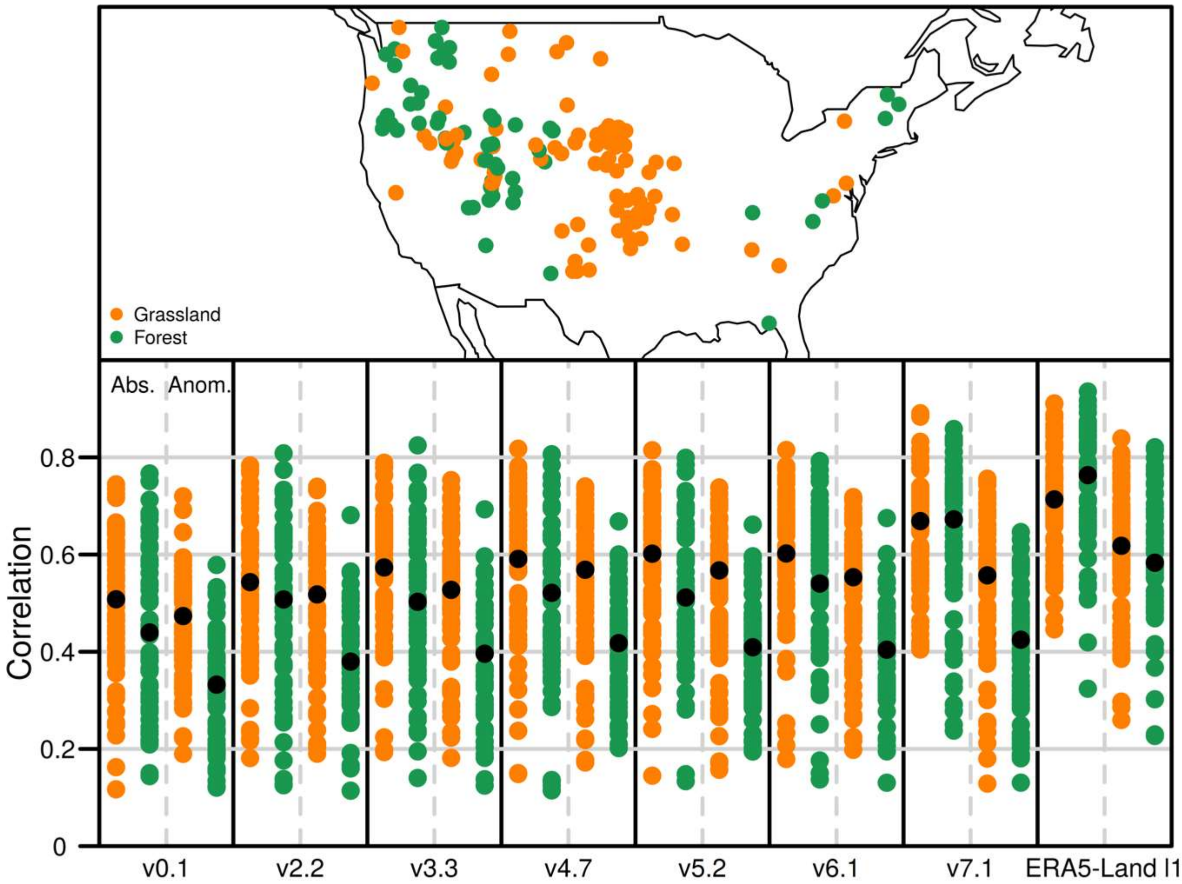

Figure 27: Correlation between in-situ measurements at 5 cm depth and ESA CCI SM v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1, as well as ERA5-Land soil moisture layer 1 over the 1991-2010 time period, differentiating between grassland (orange) and forest (green) sites for absolute soil moisture values and anomalies. Black dot denotes the median value.

5.2.6 Summary

- Spatially scattered pattern in correlations, no clear areas in which the ESA CCI SM products agree either very well or very poorly with in-situ soil moisture. Though, highest correlations are found in Australia, which corresponds to overall higher correlations and lower ubRMSDs in arid climate.
- ESA CCI SM clearly shows a higher correlation with in-situ measurements at 5 cm depth than at 10 cm depth. For ERA5-Land this distinction is less clear.
- Also, ESA CCI SM often shows higher correlations with in-situ measurements over grassland sites than over forest sites, except for the absolute soil moisture values of v07.1. For ERA5-Land this difference is not visible.

- In particular ERA5-Land reanalysis soil moisture on the average shows better agreement with the in-situ data compared to ESA CCI SM. However, ESA CCI SM shows a general increase in skill with subsequent major releases, pointing to the increasing maturity of the remote sensing product. Also, ESA CCI SM v07.1 shows a clear improvement over v06.1, which is most pronounced for recent time periods.

5.3 Long-term trends

5.3.1 Datasets and trend calculation

In this section, temporal trends of aggregated yearly mean soil moisture are analysed for different time periods. As in previous sections, the major product releases of ESA CCI SM are considered and compared to the ERA5-Land and the MERRA-2 reanalysis soil moisture (surface layer). In addition, also the break-adjusted version of ESA CCI SM v07.1 COMBINED is included in this analysis [*Preimesberger et al.*, 2021]. Theil-Sen trend estimates for the 1988-2010, 1992-2020 and 2007-2020 time periods are presented (Figure 28 - Figure 30), and significance is determined using Mann-Kendall trend tests (p-value < 0.05 for significant trends).

5.3.2 Results

Significant trends in the different product versions (COMBINED products of ESA CCI SM v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1) are only partly consistent (Figure 28). In particular, a large-scale tendency for more widespread positive trends in the northern mid-latitudes is visible with later product versions, while the partly negative trends in Siberia (most pronounced in v04.7 and v05.2) partly turn into positive trends. Also, the original significant wetting trend in southern Africa disappears with the latest product releases, while Patagonia starts to experience wetting trends. Over Australia, the widespread drying trend present in v0.1 also mostly disappears and partly turns into a wetting trend in v07.1.

Comparing the last two product releases of ESA CCI SM (v07.1 and v06.1, COMBINED products), significant trends appear more similar. However, ESA CCI SM v07.1 shows less pronounced positive trends in the northern mid-latitudes (true for all considered time periods, see also Figure 29 and Figure 30). The break-adjusted product of v07.1 displays very similar trend patterns compared to the non-adjusted version (Figure 29 and Figure 30).

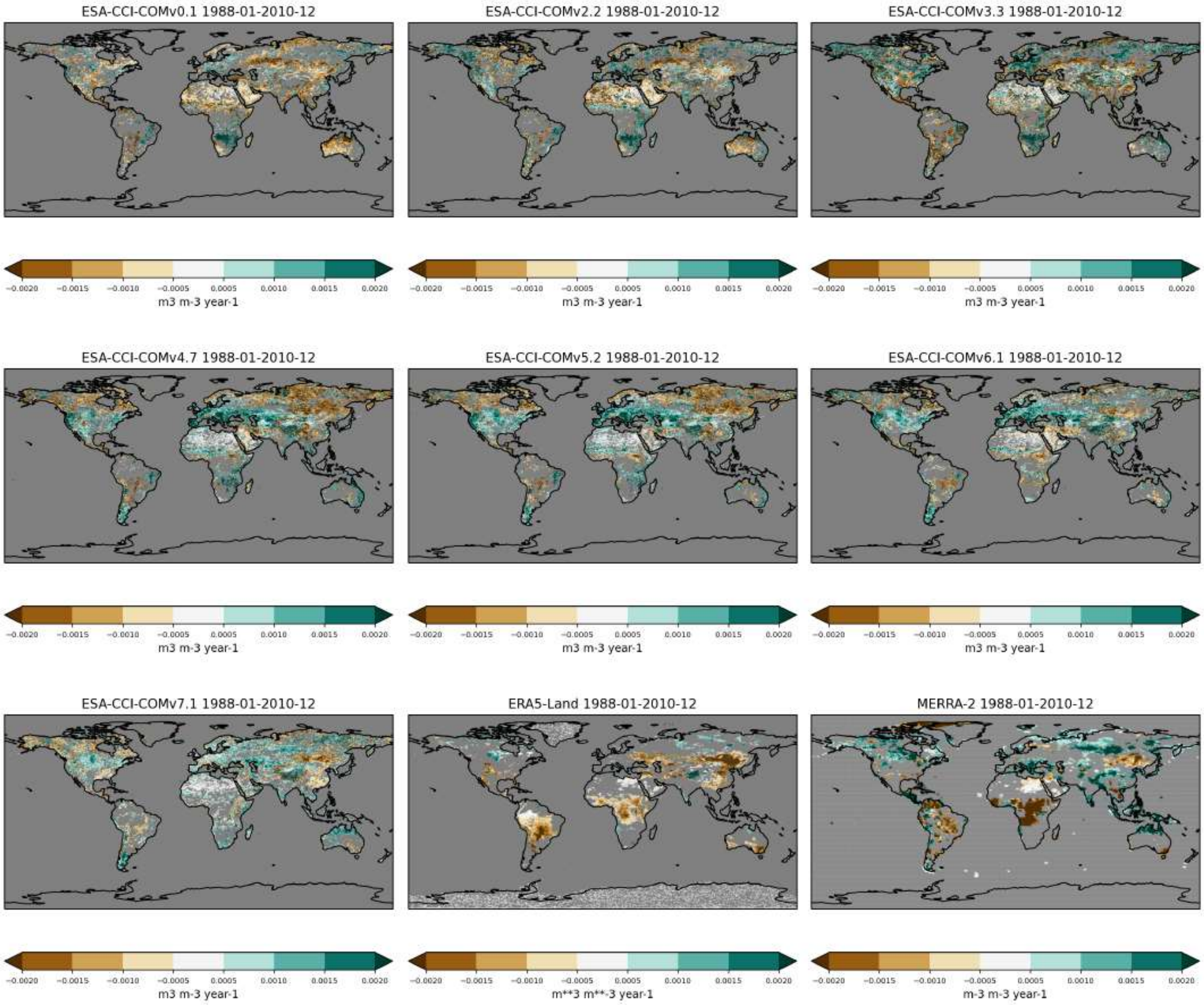

Figure 28: Evolution of 1988-2010 trends with the major product releases ESA CCI SM (v0.1, v02.2, v03.3, v04.7, v05.2, v06.1 and v07.1 COMBINED products), and in comparison to ERA5-Land and MERRA-2. Theil-sen trend estimate based on yearly mean surface soil moisture (m^3 m^{-3} per year). A Mann-Kendall test with a false rejection rate (or alpha value) of 0.05 was performed to mask out regions where no significant trend is present.

The significant trend signals of ESA CCI SM v07.1 COMBINED, and the ERA5-Land and MERRA-2 reanalysis products are also diverse and only partly consistent. In particular, ERA5-Land shows predominantly negative trends for the 1988-2010 and 1992-2020 time periods, while MERRA-2 and ESA CCI SM v07.1 COMBINED show larger fractions of positive trends (Figure 28 and Figure 29). Differences in the distribution of significant trends over the 1992-2020 time period are also visible between the COMBINED, ACTIVE and PASSIVE products of both ESA CCI SM v07.1 and v06.1. In particular, the PASSIVE products display widespread negative trends in Europe, western USA and parts of Asia (though partly less pronounced in v07.1 as compared to v06.1), while the COMBINED and ACTIVE products display no significant or positive trends in these regions (Figure 29). On the other hand, the significant positive 1992-2020 trends in southern Africa appear more widespread in the PASSIVE products. For recent 2007-2020 time period, trend magnitudes become intensified in the COMBINED and the ACTIVE products of both versions compared to the 1992-2020 time period. The PASSIVE products display less widespread significant trends for this recent time period.

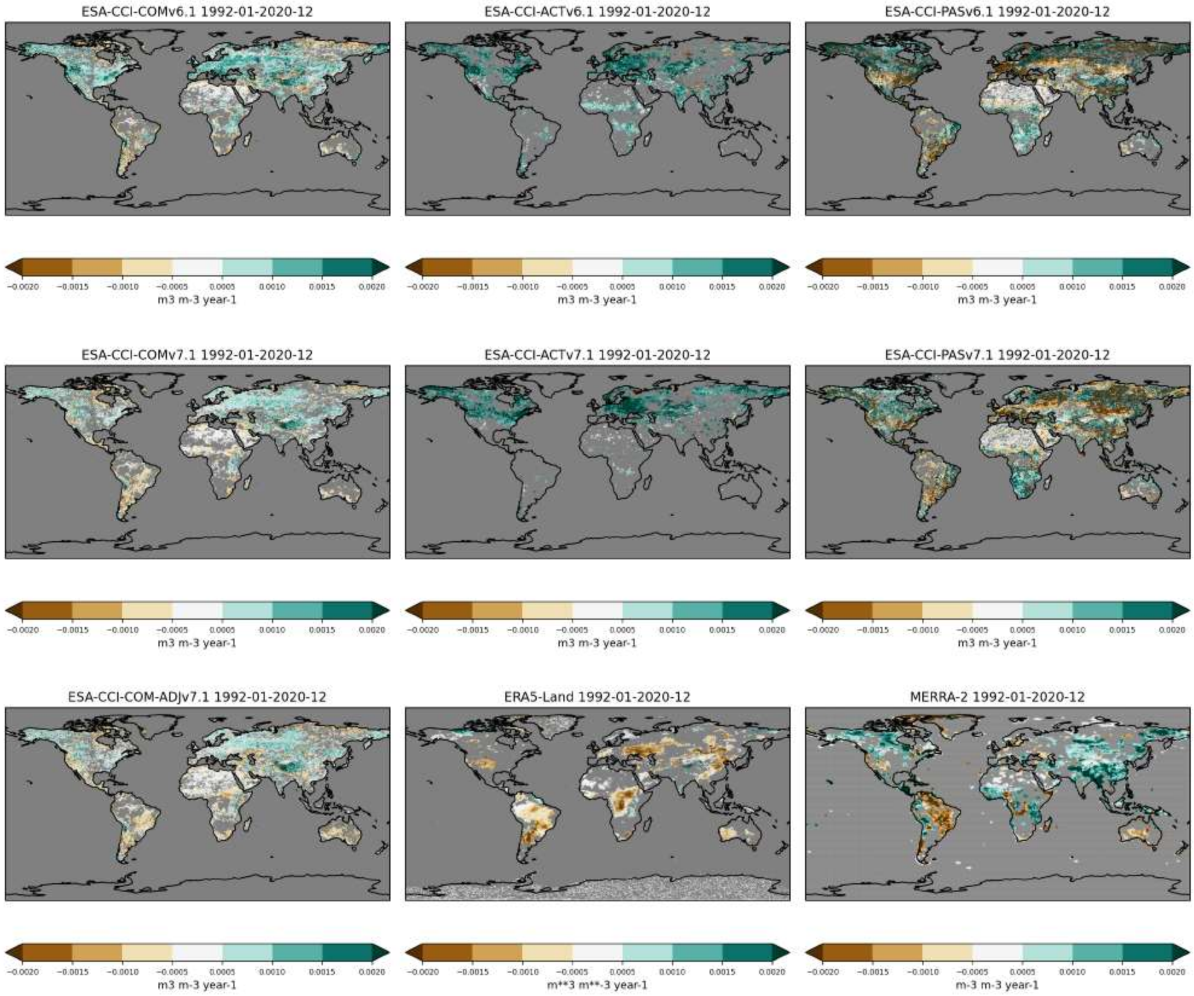

Figure 29: As Figure 28, but for the long-term 1992-2020 trends of v07.1 and v06.1 COMBINED, ACTIVE and PASSIVE, as well as including the break-adjusted product of v07.1, and in comparison to ERA5-Land and MERRA-2.

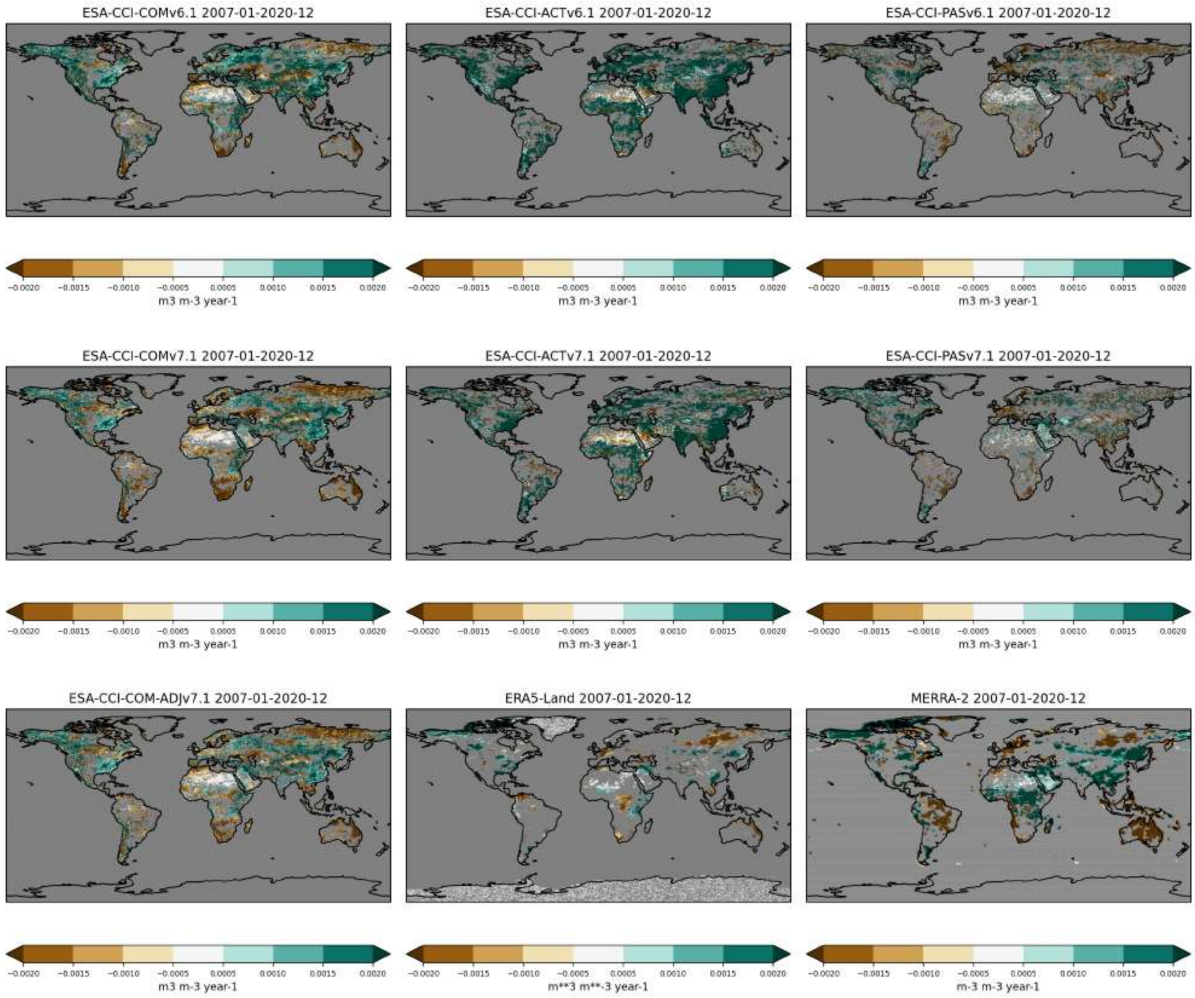

Figure 30: Figure 29, but for the recent 2007-2020 trends.

5.3.3 Summary

- The representation of long-term significant trends over the common 1988-2010 time period shows changes with the evolution of ESA CCI SM (COMBINED product).
- Significant trend patterns partly diverge between the ESA CCI SM COMBINED, and the underlying ACTIVE and PASSIVE products, as well as compared to reanalysis products.
- Trends in the last two product releases of ESA CCI SM COMBINED (v07.1 vs. v06.1) appear more similar, though v07.1 shows less pronounced positive trends in the northern mid-latitudes.

6 Conclusions

Based on the various verification and validation activities described in this PVIR, the current ESA CCI SM v07.1 product is generally suitable for representing the spatio-temporal evolution of surface soil moisture (in particular, its temporal dynamics). When compared to in-situ measurements, the product shows a general increase in skill with subsequent major data releases, which points to the increasing maturity of the ESA CCI SM product.

The agreement of ESA CCI SM with in-situ measurements appears slightly better for arid climate. Moreover, previous validation activities further showed that the ESA CCI SM product suffers shortcomings at northern high latitudes (northward of 60ºN, though improving from earlier products), over regions with complex topography and regions with dense vegetation, all areas well known to be difficult to monitor from remote sensing platforms.

Within the ESA CCI SM v07.1, the COMBINED product performs best in terms of all considered metrics, which clearly shows the benefit of merging active and passive remote sensing for global surface soil moisture.

Uncertainties remain in the representation of long-term temporal trends, which display distinct and partly diverging patterns among the major product releases of ESA CCI SM COMBINED and the underlying ACTIVE and PASSIVE products, as well as when compared to reanalysis products.

Finally, the potential of data assimilation for adding value to the ESA CCI SM product has been noted in previous PVIRs, e.g., by providing soil moisture information at higher spatial resolution in the horizontal, and in the vertical (e.g., providing information on root zone soil moisture). This is especially relevant for regions where high-quality precipitation data sets are lacking, here the ESA CCI SM product can provide valuable additional information of the state of the land surface. Various workshops and meetings within the ESA CCI for soil moisture have identified the importance of root zone soil moisture information for studies of the climate system, including the hydrological and carbon cycles.

7 Bibliography

Balsamo, G., et al. (2015), ERA-Interim/Land: a global land surface reanalysis data set, *Hydrology and Earth System Sciences*, *19*(1), 389-407, doi:10.5194/hess-19-389-2015.

Beck, H. E., et al. (2021), Evaluation of 18 satellite- and model-based soil moisture products using in situ measurements from 826 sensors, *Hydrology and Earth System Sciences*, *25*(1), 17-40, doi:10.5194/hess-25-17-2021.

C3S (2019), C3S ERA5-Land reanalysis. Copernicus Climate Change Service., edited, https://cds.climate.copernicus.eu/cdsapp#!/home.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553-597, doi:10.1002/qj.828.

Dorigo, W., R. de Jeu, D. Chung, R. Parinussa, Y. Liu, W. Wagner, and D. Fernandez-Prieto (2012), Evaluating global trends (1988-2010) in harmonized multi-satellite surface soil moisture, *Geophysical Research Letters*, *39*(18), doi:10.1029/2012gl052988.

Dorigo, W., et al. (2017), ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions, *Remote Sensing of Environment*, *203*, 185-215, doi:10.1016/j.rse.2017.07.001.

Dorigo, W. A., et al. (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.

Dorigo, W. A., K. Scipal, R. M. Parinussa, Y. Y. Liu, W. Wagner, R. A. M. de Jeu, and V. Naeimi (2010), Error characterisation of global active and passive microwave soil moisture datasets, *Hydrology and Earth System Sciences*, *14*(12), 2605-2616, doi:10.5194/hess-14-2605-2010.

Dorigo, W. A., et al. (2011), The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, *Hydrology and Earth System Sciences*, *15*(5), 1675-1698, doi:10.5194/hess-15-1675-2011.

Gelaro, R., et al. (2017), The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), *Journal of Climate*, *30*(14), 5419-5454, doi:10.1175/jcli-d-16-0758.1.

Gruber, A., T. Scanlon, R. van der Schalie, W. Wagner, and W. Dorigo (2019), Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology, *Earth System Science Data*, *11*(2), 717-739, doi:10.5194/essd-11-717-2019.

Hersbach, H., et al. (2020), The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999-2049, doi:10.1002/qj.3803.

Kuria, D. N., T. Koike, H. Lu, H. Tsutsui, and T. Graf (2007), Field-supported verification and improvement of a passive microwave surface emission model for rough, bare, and wet soil surfaces by incorporating shadowing effects, *IEEE Transactions on Geoscience and Remote Sensing*, *45*(5), 1207-1216, doi:10.1109/Tgrs.2007.894552.

Mittelbach, H., I. Lehner, and S. I. Seneviratne (2012), Comparison of four soil moisture sensor types under field conditions in Switzerland, *Journal of Hydrology*, *430*, 39-49, doi:10.1016/j.jhydrol.2012.01.041.

Munoz-Sabater, J., et al. (2021), ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, *Earth System Science Data*, *13*(9), 4349-4383, doi:10.5194/essd-13-4349-2021.

Preimesberger, W., A. Pasik, R. van der Schalie, T. Scanlon, R. Kidd, R. A. M. de Jeu, and W. A. Dorigo (2020), Soil Moisture [in: "State of the Climate in 2019"], *Bulletin American Meteorological Society*, *101*(8), S56-S57, doi:10.1175/BAMS-D-20-0104.1.

Preimesberger, W., T. Scanlon, C.-H. Su, A. Gruber, and W. Dorigo (2021), Homogenization of Structural Breaks in the Global ESA CCI Soil Moisture Multisatellite Climate Data Record, *IEEE Transactions on Geoscience and Remote Sensing*, *59*(4), 2845-2862, doi:10.1109/tgrs.2020.3012896.

Su, C. H., D. Ryu, W. Dorigo, S. Zwieback, A. Gruber, C. Albergel, R. H. Reichle, and W. Wagner (2016), Homogeneity of a global multisatellite soil moisture climate data record, *Geophysical Research Letters*, *43*(21), 11245-11252, doi:10.1002/2016gl070458.