October 28, 2025

Re: Revised Manuscript essd-2025-410
(Fusing ERA5-Land and SMAP L4 for an Improved Global Soil Moisture Product)

Dear Editor:

Thank you very much for considering our revised manuscript as a potential contribution to *Earth System Science Data*. We have carefully addressed all comments provided by the two anonymous reviewers. We sincerely appreciate the time, effort, and constructive feedback that the reviewers have devoted to improving our work.

Below, we provide a point-by-point response to each comment (shown in *italics and blue font*), together with our revisions and clarifications. All changes in the revised manuscript are edited in revision mode for ease of reference.

Sincerely,

Wenhong Wang, Shiao Feng, Yonggen Zhang*, Zhongwang Wei, Jianzhi Dong, Lutz Weihermüller, and Harry Vereecken

Dear Reviewers,

We would like to note that the revisions of the manuscript were led by Wenhong Wang, as the original first author has since transitioned to the industry and is no longer actively involved in the work. Wenhong Wang not only independently reproduced the entire original work but also revised many rounds of iterative improvements to the manuscript. In addition, before the initial submission, Wenhong Wang had already contributed to roughly half of the research and analysis. Given the extent and depth of these contributions, which far exceed those typical of a secondary author, the original first author also has enthusiastically and happily agreed to swap positions in the authorship order, which was also approved by all co-authors and acknowledged by the editors.

Sincerely,

Yonggen Zhang on behalf of all co-authors

Replies to Reviewer #1

This paper presents a new gridded dataset, evaluation of multiple products based on a newly compiled set of in situ observations, and interesting results. It is also very well-written.

We thank the Reviewer for his/her positive assessment of our work.

The only major flaw seems to be the temporal coverage of the new product. The new dataset spans only 2015-2020, which is the same temporal coverage as SMAP L4. Yet the short temporal coverage of SMAP L4 is one of the reason to develop this new product. It should be straightforward to create a 1950-present (or whatever maximum feasible duration under storage and data download speed constraints) dataset using the current mean and variance scaling coefficients and ERA5-Land. The pre-SMAP period will be less accurate, but it has a good chance of being better than the original ERA5-Land when compared to pre-2015 in situ observations, and the expanded temporal coverage will make this new dataset a much more significant addition to the many gridded soil moisture datasets already available.

We thank the Reviewer for this valuable and constructive suggestion, which has significantly enhanced the scope of our study. Addressing the concern regarding the limited temporal coverage (2015-2020) of the adjusted ERA5-Land dataset, we have extended the dataset to span from 1950 to the present, as was recommended by the reviewer. This expansion is detailed in the revised Supporting Information S1, which now reads

> “Given that the SMAP L4 product is available only from 2015 onward, we sought to extend the adjusted ERA5-Land dataset to a longer temporal span while maintaining its reliability. To ensure that the bias correction parameters were temporally stable before applying them to earlier periods, we evaluated the stability of the mean and variance scaling coefficients, *m* and *n*, derived from the Mean-Variance Rescaling Method (Section 2.3.2) by comparing their distributions across two recent periods (2017-2020 and 2021-2024) using the Kolmogorov-Smirnov (KS) test, and further examined their spatial difference patterns to identify where deviations occur.
>
> The KS statistic is defined as
>
> $$D_{(N_1,N_2)} = \sup_x |F_{1,N_1}(x) - F_{2,N_2}(x)|,$$
>
> where $F_{1,N_1}(x)$ and $F_{2,N_2}(x)$ denote the empirical cumulative distribution functions (ECDFs) of the two samples with sizes N_1 and N_2 respectively. The value of $D_{(N_1,N_2)}$ ranges from 0 to 1, with smaller values indicating greater similarity between the two empirical distributions; a value close to 0 denotes nearly identical distributions (Massey, 1951). Here, N_1 and N_2 equals ~1.45 million for both *m* and *n* in this study.
>
> We obtained KS statistics of D_m = 0.0177 and D_n = 0.0108 when comparing the distributions of parameter *m* and *n* between the two periods. The critical D value for α = 0.05 is calculated as
>
> $$D_{0.05} \approx 1.36\sqrt{\frac{N_1 + N_2}{N_1 N_2}} \approx 0.00160$$
>
> where α is the significance level, representing the probability of incorrectly rejecting the null hypothesis of identical distributions when it is true (Type I error rate). Our observed statistcs (0.0177 for *m* and 0.0108 for *n*) exceed this threshold, indicating statistically significant differences ($p < 0.001$). This outcome is an expected artifact of the extreme

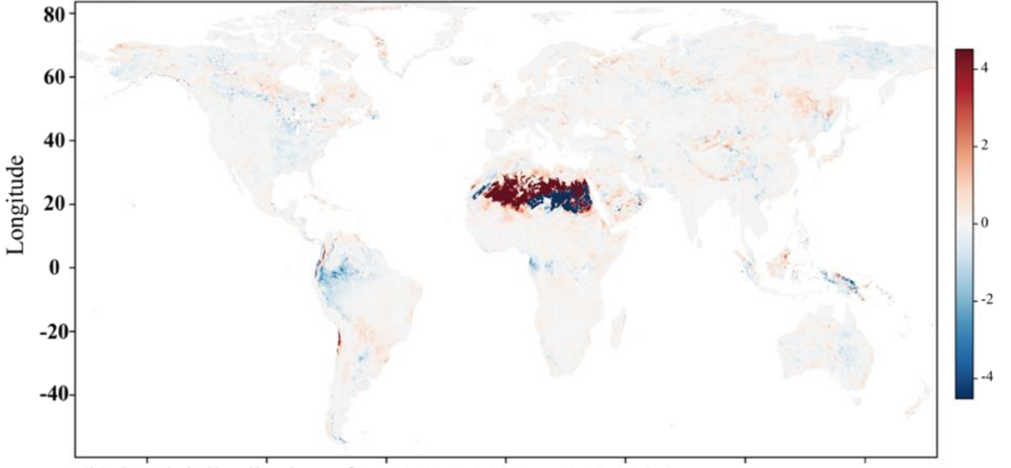
sensitivity for large samples in KS test ($N_1 = N_2 \approx 1.45 \times 10^6$ for both m and n in our study), where the test power becomes so high that it detects even trivial, non-substantive deviations that have no practical impact, making perfect identity virtually impossible (Lazariv and Lehmann, 2018; Makarov and Simonova, 2018).

Nevertheless, the magnitude of D itself is the key measure of practical similarity, quantifying the maximum absolute difference between the ECDFs. Our results show that this maximum difference is merely 1.77% for parameter m and 1.08% for n. We interpret these small magnitudes as strong evidence of temporal stability and practical similarity, consistent with previous applications using KS statistics to assess hydrologic and climatic distributional similarity, where small D magnitudes (e.g., on the order of 1-2%) are interpreted as negligible in practical terms (Kroll et al., 2015; Lanzante, 2021). Deviations less than these small magnitudes suggest that the bias correction parameters are sufficiently stable to be applied to earlier periods.

To complement this global assessment, we examined the spatial distribution of the differences in m and n (Fig. S1). The spatial patterns reveal that most regions remain stable, with notable deviations primarily over the Sahara Desert for m, and over the State of Amazonas in Brazil, northern Peru, and the northern Andes for n. These localized discrepancies suggest that future refinements could focus on these regions where persistent aridity or data scarcity might affect the robustness of the rescaling parameters. Overall, these results demonstrate that the parameters m and n maintain acceptable temporal consistency across the two analyzed periods.

Building on this stability and following the practice in bias correction for reanalysis data, where systematic differences (in mean and variance) between ERA5-Land and SMAP are assumed to remain relatively constant over historical periods when direct observations are limited, we therefore applied the coefficients derived from 2015-2020 to adjust the ERA5-Land data from 1950 to 2020. For the more recent extension, we calculated updated coefficients using 2021-2024 SMAP and ERA5-Land data to adjust the dataset from 2021 to the present. This approach has enabled us to create a continuous soil moisture dataset spanning 1950 to the present, which is now publicly available at https://doi.org/10.57760/sciencedb.30546."

(a) Spatial distribution of Δm (2021-2024 – 2017-2020)



(b) Spatial distribution of Δn (2021-2024 – 2017-2020)

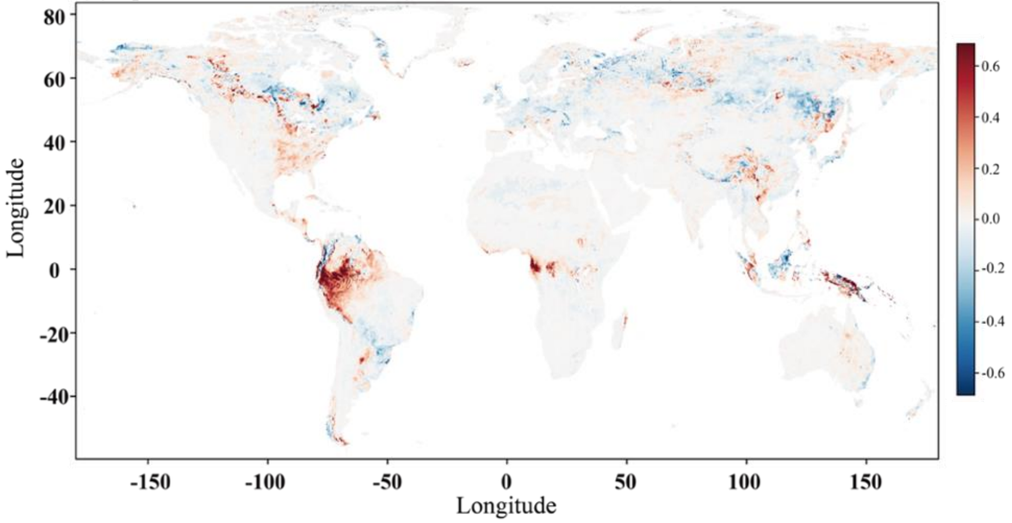


Figure S1. Spatial distribution of variations in the adjustment parameters (a) *m* and (b) *n* from the Mean-Variance Rescaling Method between 2017-2020 and 2021-2024.

New references added:

Massey, F. J.: The Kolmogorov-Smirnov Test for Goodness of Fit, Journal of the American Statistical Association, 46, 68–78, https://doi.org/10.1080/01621459.1951.10500769, 1951.

Lazariv, T. and Lehmann, C.: Goodness-of-Fit Tests for Large Datasets, https://doi.org/10.48550/arXiv.1810.09753, 23 October 2018.

Makarov, A. A. and Simonova, G. I.: Comparative Analysis of the Powers of the Two-Sample Kolmogorov–Smirnov and Anderson–Darling Tests Under Various Alternatives, J Math Sci, 228, 495–500, https://doi.org/10.1007/s10958-017-3638-3, 2018.

Kroll, C. N., Croteau, K. E., and Vogel, R. M.: Hypothesis tests for hydrologic alteration, Journal of Hydrology, 530, 117–126, https://doi.org/10.1016/j.jhydrol.2015.09.057, 2015.

Lanzante, J. R.: Testing for differences between two distributions in the presence of serial correlation using the Kolmogorov–Smirnov and Kuiper's tests, International Journal of Climatology, 41, 6314–6323, https://doi.org/10.1002/joc.7196, 2021.

Furthermore, in Section 2.3.2, we have added the following clarification to emphasize the extended temporal span:

> "To extend the temporal coverage beyond the availability of SMAP L4 (which begins in 2015), we verified the stability of the mean and variance scaling coefficients by comparing them between 2017-2020 and 2021-2024, as shown in Supporting Information S1. Leveraging this stability, we applied the 2015-2020 coefficients to adjust historical ERA5-Land data from 1950 to 2020 and used updated coefficients from 2021-2024 to extend the ERA5-Land dataset from 2021 to the present, resulting in a continuous adjusted ERA5-Land product spanning 1950 to the present. Note that all analyses presented in this study are based on the 2015-2020 period, during which SMAP L4 data are available for direct fusion and validation."

Minor Comments

1. *line 20-21: The 5%, 20%, and 15% number are hard to infer for the readers from Fig. 11 or Table 1. Please either give accompanying percentages in Table 1, or give absolute values in the abstract. Also, please spell out the NNSE abbreviation.*

We thank the reviewer for this valuable comment. We acknowledge that the improvement (~5% for correlation coefficient (r), ~20% for RMSE reduction, and ~15% for normalized Nash-Sutcliffe efficiency (NNSE) improvement) in the original abstract were approximate values and not easily inferable from Figure 11 or Table 1. Additionally, the comparison was based solely on the Part 1 dataset (where ESA-CCI data are available), and the term "original products" was unclear, as it referred to ERA5-Land and SMAP L4.

To address these issues and enhance clarity, we have now included the corresponding percentage improvements in the updated Table 1. For a fairer and more comprehensive evaluation, we have revised Table 1 to reflect comparisons against the entire in situ dataset (combining Part 1 and Part 2), rather than limiting it to Part 1. This update better highlights the overall performance of each product and reduces redundancy with Figure 11, which remains focused on stratified results. Accordingly, both the abstract and relevant sections of the main text have been revised to incorporate these changes and ensure consistency throughout the manuscript. The revised abstract now reads,

> "Validation against in situ measurements demonstrates a reduction in RMSE of 24.6% and an improvement in normalized Nash-Sutcliffe Efficiency (*NNSE*) of 30.6% compared to the original ERA5-Land product."

The corresponding text in Section 3.3.1 now reads

> "The combined metrics from all stations are presented in Fig. 10, where results are shown separately for regions with and without available ESA-CCI data. In contrast, Table 1

> provides the overall mean improvement and percentages across all stations without differentiating ESA-CCI data availability, highlighting the general performance of each product.”

and

> “Adjusted ERA5-Land integrates the strengths of ERA5-Land and SMAP L4, achieving notable improvements across the performance metrics. Specifically, the adjusted ERA5-Land dataset achieves a mean correlation coefficient (*r*) of 0.687 (0.01% improvement over ERA5-Land, 3.01% over SMAP L4, and 4.41% over ESA-CCI), a mean *RMSE* of 0.087 cm^3/cm^3 (24.61% reduction compared to ERA5-Land, 0.80% over SMAP L4, and 2.46% over ESA-CCI), a mean *NNSE* of 0.423 (30.57% improvement over ERA5-Land, 1.46% over SMAP L4, and 12.54% over ESA-CCI), and a mean Bias of -0.001 cm^3/cm^3 (closest to zero among all products). These results, particularly the substantial *RMSE* reduction of 24.6% and *NNSE* improvement of 30.6% relative to the original ERA5-Land, demonstrate the fusion method’s effectiveness in enhancing accuracy while preserves or slightly improves correlation compared to SMAP L4.”

The updated Table 1 now reads:

Table 1. Mean and median values for evaluation metrics of the four soil moisture products compared against the in situ measurements. Bold data in the table represent the best performance results among the products for each metric.

Metrics	*r*		*RMSE* (cm^3/cm^3)		*NNSE*		*Bias* (cm^3/cm^3)
Products	mean	Impr. (%)	mean	Impr. (%)	mean	Impr. (%)	mean
ERA5-Land	0.6865	+0.01	0.1158	-24.61	0.3238	+30.57	0.0734
ESA-CCI	0.6583	+4.41	0.0895	-2.46	0.3757	+12.54	0.0325
SMAP L4	0.6672	+3.01	0.0880	-0.80	0.4167	+1.46	-0.0018
adjusted ERA5-Land	**0.6873**	-	**0.0873**	-	**0.4228**	**-**	**-0.0010**

In addition, in the revised manuscript, we have now spelled out the abbreviation *NNSE* at its first appearance as normalized Nash–Sutcliffe Efficiency (*NNSE*).

2.line 93: Cheng et al. 2017 did not discuss ERA5-Land. Please delete.

Corrected. We removed the mention of ERA5-Land in relation to Cheng et al. (2017).

3. Fig. 6 The comparison is for a single day. It will be more informative if the comparison can be over all days - perhaps showing the per grid RMSE during the entire overlapping period.

We thank the Reviewer for this suggestion. The purpose of Fig. 6 is to highlight the spatial differences between the original and fused products. We agree that RMSE is an important evaluation metric. However, RMSE is especially meaningful when evaluated against a reference dataset (i.e., in situ measurements). A direct RMSE comparison between the two products themselves could be misinterpreted by readers as a measure of their relative differences, rather than an indicator of their accuracy in representing actual soil moisture conditions, potentially leading to confusion about their true performance.

Regarding the RMSE during the entire overlapping period, we have already provided RMSE evaluations of multiple products against in situ measurements in Figure 10 of the revised manuscript.

4. Fig. 7 The ESA-CCI and SMAP L4 rows are reversely labelled. Also, the monochrome colorbar makes it difficult to see seasonality - please change it to something easier to read.

We thank the Reviewer for pointing this out. In the revised manuscript, we have corrected the mislabeling of ESA-CCI and SMAP L4 in Fig. 7. In addition, we have modified the color scheme by replacing the previous monochrome colorbar with a more distinguishable and visually clear colormap, which makes seasonal variations easier to identify. This figure is updated in the revised manuscript.

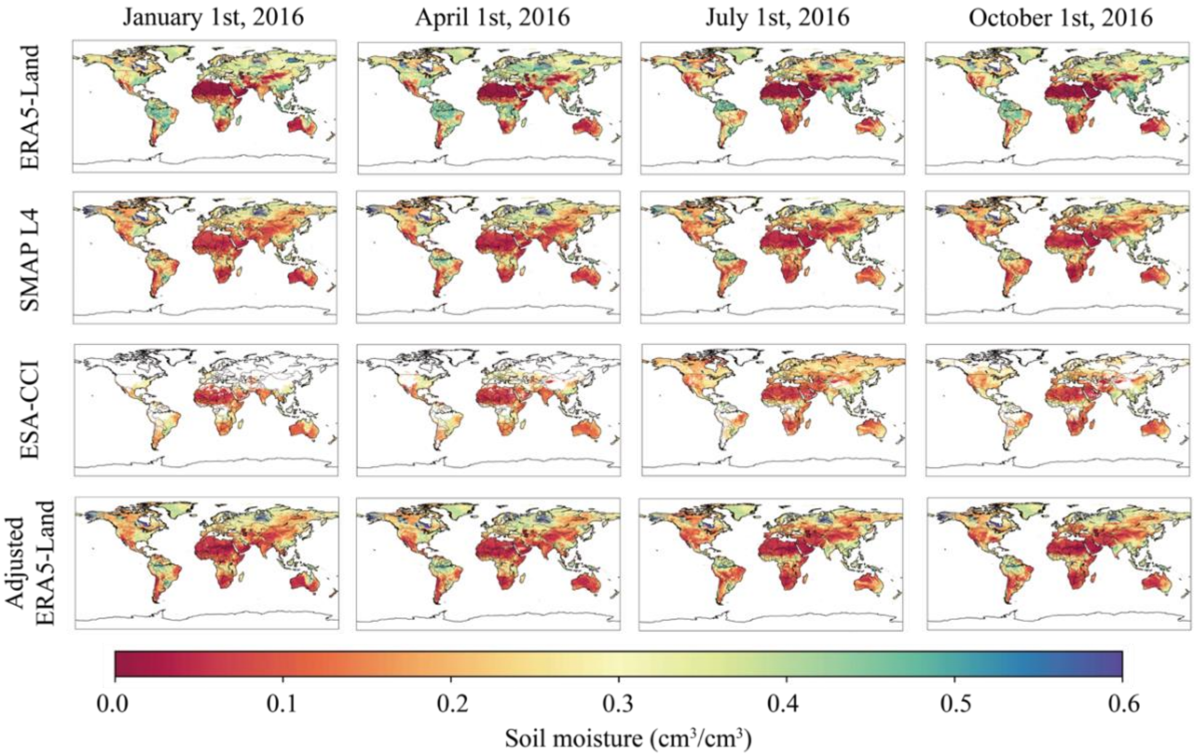


Figure 7. Global spatial distribution of soil moisture from four products in different rows: ERA5-Land, SMAP L4, ESA-CCI, and the adjusted ERA5-Land dataset, shown for the first day of January, April, July, and October 2016 in different columns.

5. The discussion on ESA-CCI data gaps around lines 420-430 is unnecessarily long. The nature of the gaps - high latitudes, vegetated zones, and alpine regions - is well-reported in the original ESA-CCI paper and understood to be related to microwave sensor limitations. The authors should condense the text substantially and either remove Fig. 8, or replace the 2015 information with more comprehensive information such as the percentage of available days in each season during *the entire 2015-now period. Fig. 9 and its related description are okay, because they adds new information based on the new in situ dataset provided in this study.*

Thank you for this insightful comment. We agree that the discussion on the nature of the ESA-CCI data gaps was overly detailed and largely reiterated well-known limitations already covered in the literature. To address this, we have substantially condensed the text (now around 70 words, reduced by over 70% from the original paragraph) while retaining key messages on data availability across climate zones. The revised text in Section 3.2 now reads:

> "Gaps in ESA-CCI are well-documented in high-latitude, densely vegetated, and alpine regions due to microwave sensor limitations (Dorigo et al., 2017; Gruber et al., 2019). Data availability is the highest in temperate regions, such as Europe and parts of the United States, under favorable conditions. In contrast, tropical and semi-arid regions in Africa and South America, crucial for the global hydrological cycle and transpiration (Wang et al., 2017), exhibit substantial seasonal gaps in the moisture dataset."

In addition, we have removed the original Figure 8 entirely.

6. Fig. 12 - it is very difficult to see regional variations due to overlapping dots. Perhaps summary graphs can be made for each continent (North America, Europe, Asia, South America, Africa) mentioned in the text description of this figure.

We appreciate this constructive suggestion. To address the difficulty of discerning regional variations due to overlapping dots, we have added enlarged regional maps in Supporting Information S3. These supplementary figures show the spatial variations more clearly and complement the global overview shown in Fig. 11 of the updated manuscript.

We make it clear in Section 3.3.2 of the revised manuscript that

> "To further clarify the regional variations obscured by overlapping dots in the global map, enlarged regional maps for North America, Europe, Asia (primarily China), South America (mainly Brazil), and Africa are provided in Supporting Information S3, offering a detailed view of spatial performance across these continents."

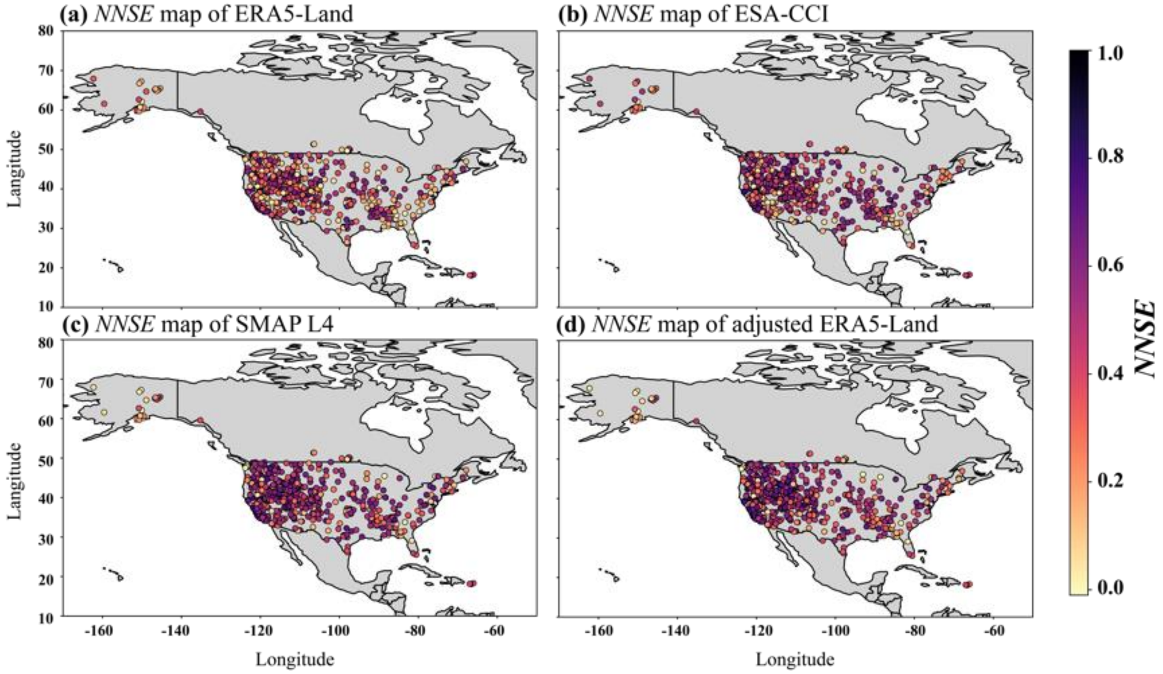


Figure S3.1. Regional NNSE evaluation results for North America. The four panels show NNSE values for (a) ERA5-Land, (b) ESA-CCI, (c) SMAP L4, and (d) adjusted ERA5-Land, compared with in situ measurements.

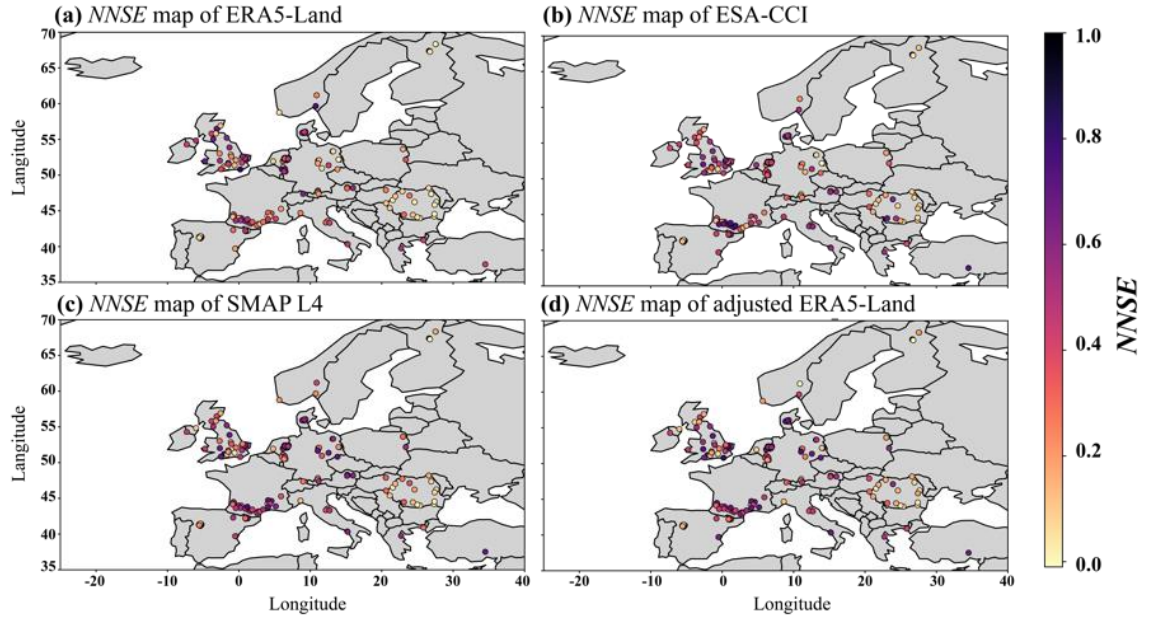


Figure S3.2. Regional NNSE evaluation results for Europe, showing NNSE values for (a) ERA5-Land, (b) ESA CCI, (c) SMAP L4, and (d) adjusted ERA5-Land, compared with in situ measurements.

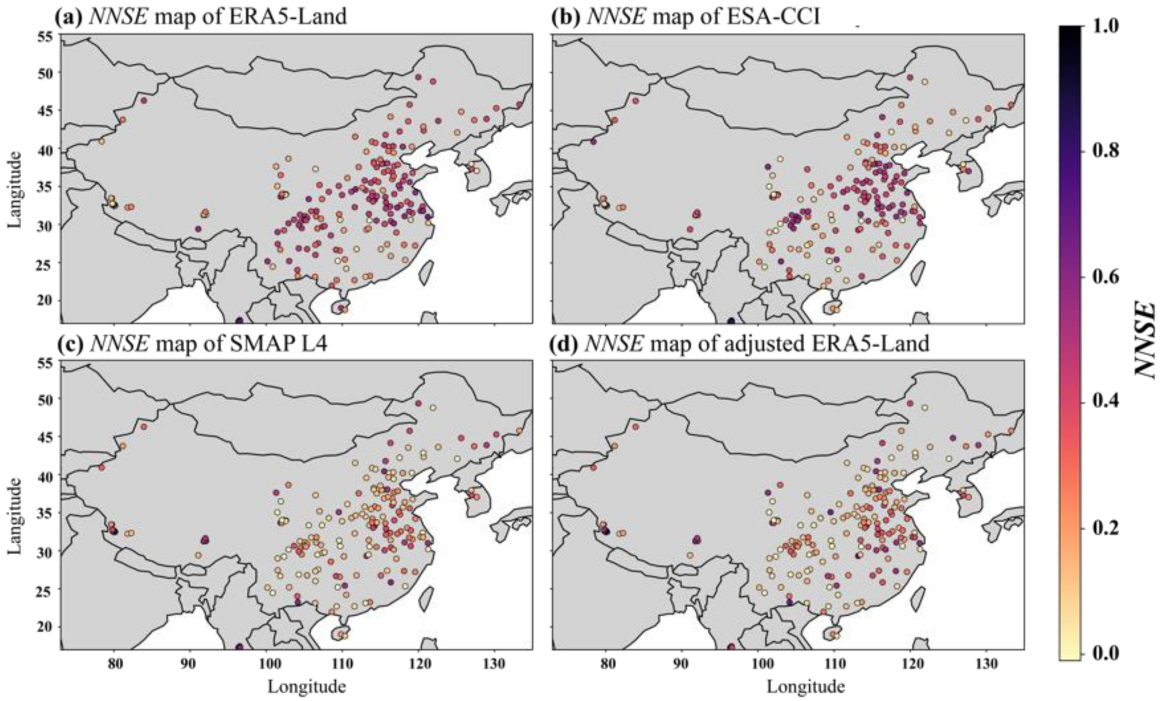


Figure S3.3. Regional *NNSE* evaluation results for Asia, mainly covering China and surrounding temperate zones.

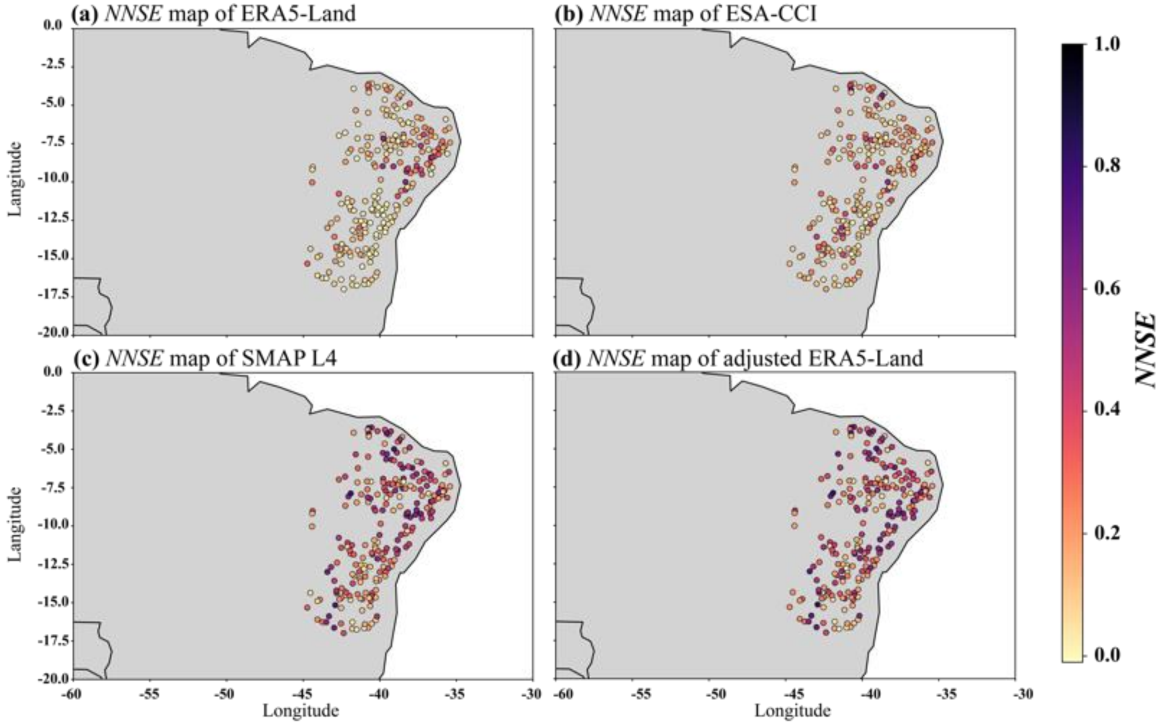


Figure S3.4. Regional *NNSE* evaluation results for South America, primarily focusing on Brazil.

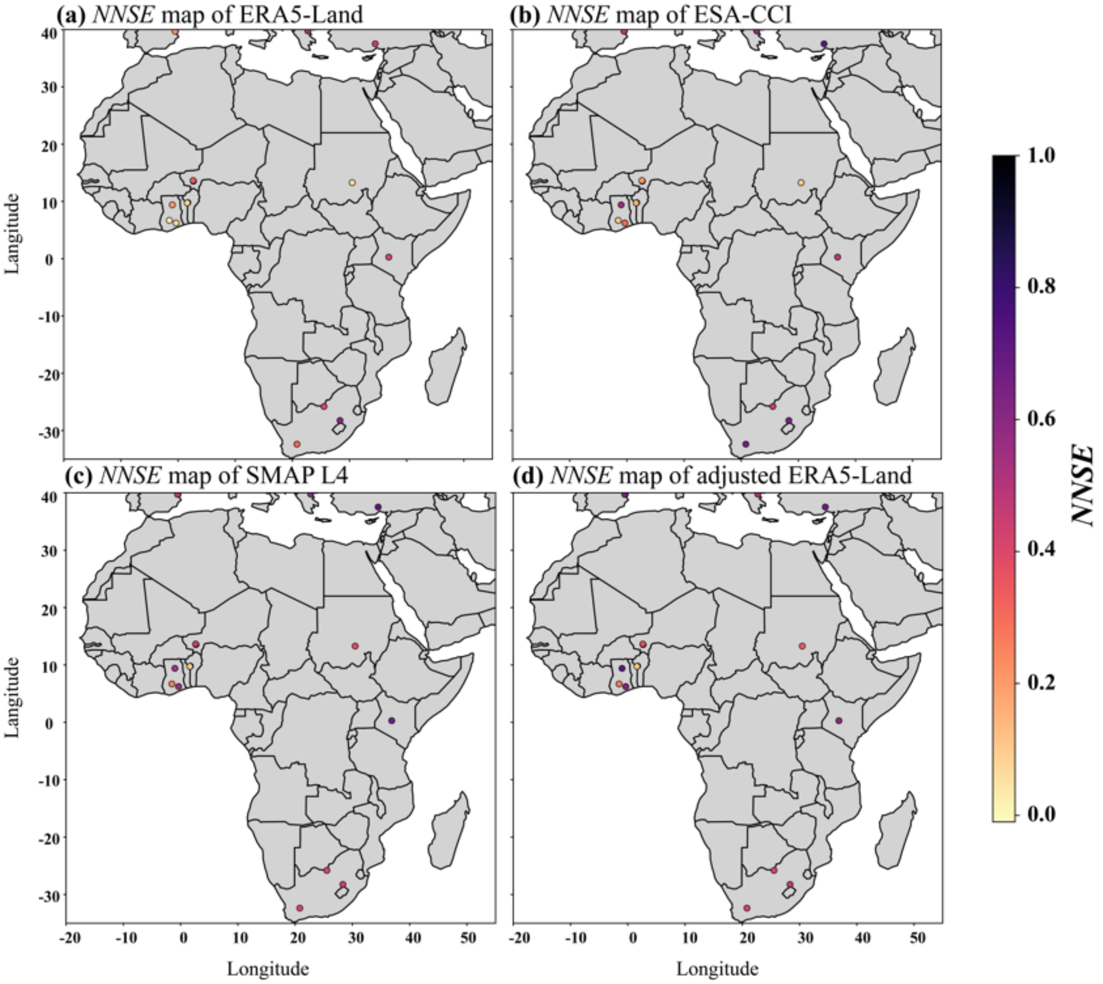


Figure S3.5. Regional *NNSE* evaluation results for Africa, with limited in situ coverage.

Replies to Reviewer #2

By using soil moisture from ERA-Land, SMAP L4, and in-situ measurements from four different network sources, this study has developed a soil moisture data product at the 0.1 degree and daily spatiotemporal resolution for 2015–2020. Including ESA-CCI provides readers the limitations of ESA-CCI, which are not helpful for the data fusion. In other words, the investigation of ESA-CCI is a parallel storyline alongside the ERA5-Land and SMAP data fusion. Performing a similar analysis for SMAP L2/L3 is more beneficial for the understanding of the features and limitations of the SMAP L4 data. The short period of the data record (2015–2020) hinders the decadal scale investigation of soil moisture dynamics. Besides statistical analysis, the performance of the new data product in capturing soil moisture dynamics under drought conditions is more of interest as the authors mentioned in the Abstract Section that this product could benefit drought monitoring. Additionally, a workflow representing data processing and fusion is needed.

We thank the Reviewer for his/her positive assessment of our work.

Detailed Comments:

1. L23: what are the specific decision-making activities? How can a six-year dataset (2015-2020) at 0.1 degree spatial resolution benefit decision-making activities given the spatial heterogeneity of landscapes?

We thank the reviewer for this comment. We have removed “decision-making” in the revised abstract. In addition, as was reponsed to the later comments and the also the comments from previous reviewer, we have extended the dataset from 1950 to present .

2. L27-29: “the water cycle” and “the hydrological cycle” cover some same processes, making this sentence redundant.

We appreciate these suggestions. In the revised manuscript, we have replaced “the hydrological cycle” with “hydrological processes” to avoid redundancy with “the water cycle.”

3. L34-35: in this case, I’d include “the carbon and nitrogen cycles” in the topic sentence along with references.

We have expanded the topic sentence by including *“biogeochemical cycles”* (covering the carbon and nitrogen cycles) and added appropriate references. The revised sentence now reads:

> “Soil moisture is a critical driver of water and energy cycles across Earth’s spheres, playing a foundational role in coupling land-atmosphere interactions, regulating regional hydrological and biogeochemical processes, and sustaining ecosystem services (McColl et al., 2017; Humphrey et al., 2021; Dorigo et al., 2017; Li et al., 2025; Hao et al., 2025).”

New references added:

Li, W., Wang, G., Mu, Z., Qi, S., Zhou, S., and Xiang, D.: Microbially-Mediated Soil Carbon-Nitrogen Dynamics in Response to Future Soil Moisture Change, Earth’s Future, 13, e2024EF005521, https://doi.org/10.1029/2024EF005521, 2025.

Hao, Y., Mao, J., Bachmann, C. M., Hoffman, F. M., Koren, G., Chen, H., Tian, H., Liu, J., Tao, J., Tang, J., Li, L., Liu, L., Apple, M., Shi, M., Jin, M., Zhu, Q., Kannenberg, S., Shi, X., Zhang, X., Wang, Y., Fang, Y., and Dai, Y.: Soil moisture controls over carbon sequestration and greenhouse gas emissions: a review, npj Clim Atmos Sci, 8, 16, https://doi.org/10.1038/s41612-024-00888-8, 2025.

4. L79: the ESA-CCI soil moisture also has limitations in the tropical regions due to the dense coverage of trees, which is shown in Gruber et al. (2019) and is only mentioned in the next paragraph. I'd update the logic and structure of these two paragraphs by introducing each data type individually, with the advantages and limitations of each data type discussed at the same time. To further address this comment, the authors might want to discuss the limitations of soil moisture measurements/datasets across regions (e.g., tropical vs high-latitude regions).

Thank you for this helpful suggestion. We have revised the ESA-CCI description to present both its strengths and limitations within the same paragraph. In addition, we have substaintily revised these two paragraphs. The first paragraph acts as an overview of different remote sensing techniques, and by empysizing each remote sensing approach individually, with the advantages and limitations of each remote sensing appraoch, without introduing specific soil moisture products. The second paragraph shifts to evaluation and limitations of specific products. The revised text now reads:

> "On the other hand, remote sensing is mainly based on microwave and optical/thermal sensors to estimate soil moisture over larger areas, each type offering distinct advantages and limitations across regions. Passive microwave sensors, such as those of the Soil Moisture Active Passive (SMAP) mission (gridded to ~36 km for Level-2 soil moisture products; Entekhabi et al., 2010; Reichle et al., 2019), Soil Moisture and Ocean Salinity (SMOS) (yielding ~30-50 km resolution, averaging ~40 km for Level-2 soil moisture products, depending on incidence angle and processing; Kerr et al., 2010; Zhang et al., 2021b), and Advanced Microwave Scanning Radiometer 2 (AMSR2) (footprint of ~22-35 km, gridded to ~25 km for Level-2 products; Imaoka et al., 2010; Zhang et al., 2021a), provide resolutions suitable for global soil moisture monitoring but are limited to explore small scale soil moisture variability either due to processing or used frequency bands. In contrast, products derived from data assimilation, such as the SMAP L4 dataset, provide soil moisture estimates at a ~9 km resolution through the direct assimilation of passive microwave observations (e.g., SMAP radiometer brightness temperature) into the NASA Catchment land surface model using an ensemble Kalman filter (EnKF) (Reichle et al., 2019), offering lower bias and an unbiased root-mean-square error against in situ measurements. By comparison, active microwave sensors such as radars, employed for example in Sentinel-1, provide higher resolution (1-10 km) but are more sensitive to vegetation and surface roughness impacts, leading to challenges in densely vegetated tropics and heterogeneous landscapes (Babaeian et al., 2019; Mohanty et al., 2017; Bauer-Marschallinger et al., 2019). Optical and thermal sensors (e.g., MODIS, Landsat) complement microwave data by capturing surface conditions but are limited to shallow depths and moreover are only capable to sense the Earth surface only at cloud-free conditions (Babaeian et al., 2018; Zhang and Zhou, 2016). To take advantage of different sensing approaches, multi-sensor fusion, such as in the European Space Agency's Climate

> Change Initiative (ESA-CCI), enhances soil moisture prediction accuracy. However, it suffers from data gaps and reduced accuracy in tropical forests and snow/ice-covered high-latitude regions, due to microwave signal attenuation (Dorigo et al., 2017; Gruber et al., 2019). These methodological strengths and limitations highlight the global soil moisture products derived from them, revealing persistent opportunities for improvement despite notable advances in observation techniques.
>
> Despite these advances in remote sensing techniques, global soil moisture products, such as ERA5-Land, ESA-CCI, SMAP L4, SMOS, AMSR2, and GLDAS, still face ongoing obstacles in delivering consistent, accurate, and comprehensive global soil moisture datasets. ERA5-Land, a widely recognized reanalysis product, provides extensive temporal coverage (1950-present) at 0.1° resolution and, with advanced land surface modeling, complements its fine-scale detail that makes it particularly valuable for capturing long-term trends (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). However, ERA5-Land exhibits…"

In addition, to further address the reviewer's suggestion to discuss the limitations of soil moisture datasets across regions, we have added the following paragraph:

> "Overall, these soil moisture datasets exhibit region-dependent limitations: satellite-based products such as SMAP L4 and ESA-CCI tend to show higher uncertainties in dense tropical or forested regions due to vegetation effects (Gruber et al., 2019; Fan et al., 2020; Hirschi et al., 2025), while reanalysis data such as ERA5-Land may be less reliable in high-latitude or arid regions where model parameterizations struggle to capture frozen or sparse-moisture conditions (Muñoz-Sabater et al., 2021). These complementary strengths and weaknesses highlight the need for an integrated dataset that combines the extensive coverage of ERA5-Land with the high accuracy of SMAP L4. "

5. L86: the essential role of soil moisture is discussed in the pervious paragraphs. I'd not repeat this.

We appreciate the reviewer's comment. In the revised manuscript, we have removed the repeated description of the essential role of soil moisture.

6. L87-89: Many other soil moisture datasets have been used for similar purposes, e.g., land model evaluation and water management. This discussion is not necessary.

Thanks for the comments, we have deleted the unnecessary discussion of dataset applications (L87–89) in the revised manuscript. The revised text highlights ERA5-Land's advantages relative to other datasets, which now reads,

> "ERA5-Land, a widely recognized reanalysis product, provides extensive temporal coverage (1950-present) at 0.1° resolution and, with advanced land surface modeling, complements its fine-scale detail that makes it particularly valuable for capturing long-term trends."

7. L98 vs L125: The short time frame is also a limitation of this study, which develops soil moisture data for the period 2015–2020. I'd rephrase this sentence. In other words, it is not necessary mean that this study can address all the limitations discussed in Introduction.

We thank the Reviewer for this insightful comment. We acknowledge that, due to the limited temporal coverage of our original dataset (2015-2020), this study does not fully address all the limitations discussed in the Introduction. In the revised version, we have extended the dataset to cover the period 1950-present, which helps overcome this limitation and provides a more comprehensive temporal representation.

8. L145: Does the "1.9 million soil moisture content" refer to 1.9 million measurement record? The authors might want to mention the temporal resolution of the measurements (i.e., hourly) in the main context (rather than only mentioning it in the figure legend).

We thank the Reviewer for this constructive suggestion. The "1.9 million soil moisture content" refers to approximately 1.9 million in situ measurement records. These measurements have a daily temporal resolution, and this information has been explicitly added to the revised text to improve clarity and completeness.

> "After this step, 1,615 of around 3,500 in situ stations meeting our criteria were obtained, providing a total of approximately 1.9 million soil moisture measurement records (with daily temporal resolution), and their global spatial coverage and temporal characteristics are illustrated in Fig. 1."

9. L142 vs L188: The SONTE-China dataset has the measurement depths of 5, 10, 20, and 40 cm. While L124 mentioned the data retrieval of the 0-10 cm depth, how did the authors handle the inconsistency of layer depths? For the data fusion purpose, did the authors calculate the arithmetic mean between the 5 cm and 10 cm layers, or else?

We thank the Reviewer for this insightful question. Yes, for the SONTE-China dataset, we calculated the arithmetic mean of the 5 cm and 10 cm layers to represent the 0–10 cm soil moisture, ensuring consistency with the depth range used for other datasets in the fusion process. We make it clear in Section 2.2.1 of the revised manscript that

> "To ensure consistency with the 0-10 cm depth range used across other datasets in the fusion process, the soil moisture values from the SONTE-China dataset at 5 cm and 10 cm depths were averaged arithmetically to represent the 0-10 cm layer."

10. L239-240: this part is redundant.

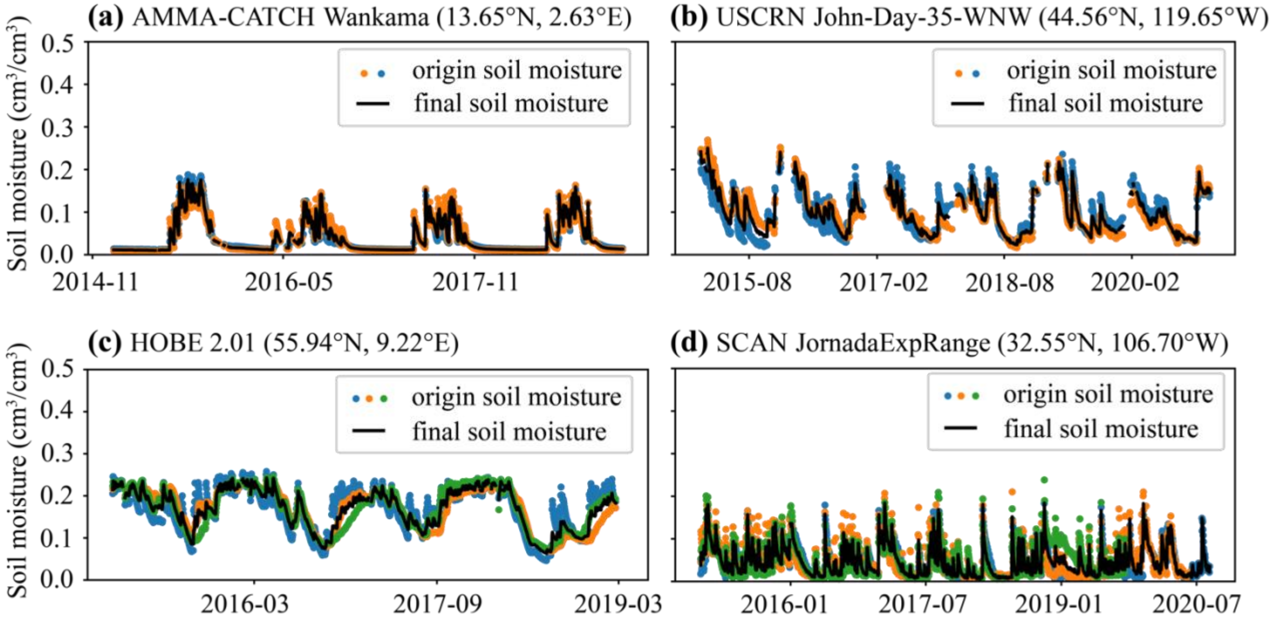
We agree. The redundant sentence "In the following, the preprocessing steps for the in situ datasets are described" has been removed in the revised manuscript.

11. Figure 2: This study has developed soil moisture data for 2015–2020, and the plots show time series of soil moisture of different periods. Additionally, it's not clear to me the reason for showing of the four sites among all the ISMN sites globally. Are they four sites representing locations under four different climatological conditions or else?

We thank the reviewer for the insightful comment. The four sites shown in Figure 2 were randomly selected for demonstration purposes and we make it clear in section 2.2 of the revised manuscript that

> "Figure 2 demonstrates the effectiveness of the screening and quality control procedure, featuring time series from four randomly selected ISMN sites, which are distributed globally and represent diverse climatological conditions."

To make it clear of the location of the four sites, we have added the latitude and longitude coordinates of each site in the revised figure (Wankama: 13.65°N, 2.63°E; John Day: 44.56°N, 119.65°W; Hobe: 55.94°N, 9.22°E; Jornada Experimental Range: 32.55°N, 106.70°W).


(a) AMMA-CATCH Wankama (13.65°N, 2.63°E)

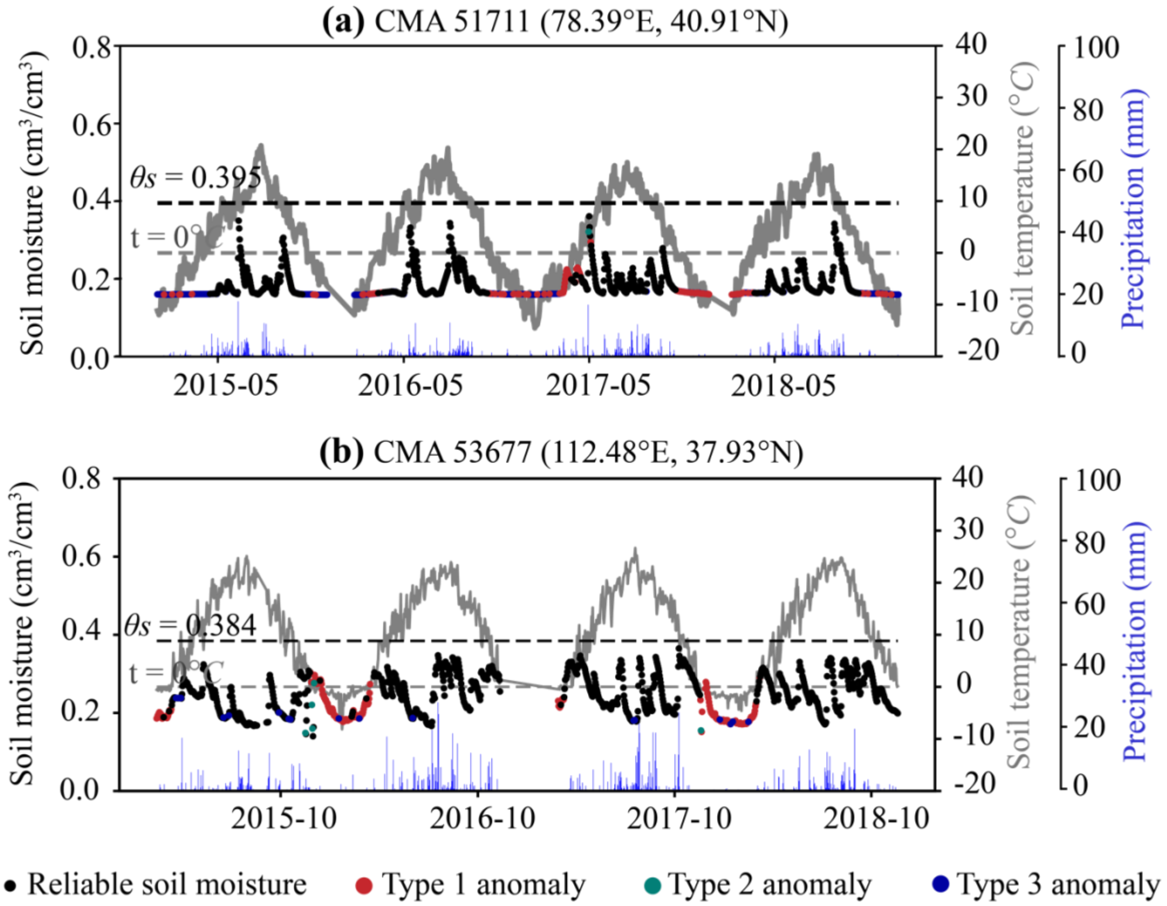
(b) USCRN John-Day-35-WNW (44.56°N, 119.65°W)

(c) HOBE 2.01 (55.94°N, 9.22°E)

(d) SCAN JornadaExpRange (32.55°N, 106.70°W)

12. Figure 3: I'd use more contrasting colors to represent "Type 2" and "Type 3". For the selected sites (for Figure 2 as well), I'd include the latitude and longitude information.

We thank the Reviewer for this helpful suggestion. In the revised version, we have (i) modified the colors for Type 2 and Type 3 to be more contrasting and thus easier to distinguish, and (ii) added the latitude and longitude information for the selected sites in both Figure 2 and Figure 3.



13. L285-287: Is this statement based on the analysis of the authors or existing studies? If it is the latter, what are the references? Is it true for everywhere globally or are there differences in terms of correlation and accuracy across space?

We appreciate the Reviewer's insightful comment. This statement is supported by existing studies rather than solely our own analysis. In the revised manuscript, we have clarified this point and added appropriate references.

> "Based on these considerations and prior studies (Reichle et al., 2019; Muñoz-Sabater et al., 2021), ERA5-Land and SMAP L4 were preliminarily selected for their potential complementary strengths, with ERA5-Land offering a long time series, high correlation with in situ data, and extensive spatial coverage, while SMAP L4 providing low bias and high accuracy as evidenced by the lowest RMSE values, though spatial variations exist, as detailed in Section 3."

Regarding whether these strengths hold true globally or if there are spatial differences in correlation and accuracy, we have reviewed previous research in Section 4.2, which demonstrates that performance metrics vary across regions and climates. These findings align with our analysis and highlight that the statement is not uniformly true globally but exhibits spatial differences. In our study, we explicitly address these spatial differences through a comprehensive evaluation in

Sections 3.3. To further emphasize this, we have revised the manuscript text in Section 2.3.1 to include:

> "Although these complementary strengths of ERA5-Land and SMAP L4 are reported as global averages in the literature, spatial differences exist, varying across diverse geographical regions and climatic zones, as confirmed by our regionally differentiated validation."

This ensures the context is clear and supports the fusion rationale by focusing on overall synergies while acknowledging variability.

14. L290-293: If ESA-CCI has issues over dense forests, why is it selected for data evaluation? Is it only because of the multi-sensor feature? The obstacles of optical measurements in the tropics are well recognized. However, choosing a dataset with better spatial coverage could still help improve uncertainty estimates in the tropics given that this study spans the entire globe.

We appreciate the opportunity to clarify our rationale for including ESA-CCI in the evaluation while excluding it from the fusion process. First, ESA-CCI (v09.1 Combined) is primarily based on multi-sensor microwave data (active and passive), rather than optical measurements (Dorigo et al., 2017; Gruber et al., 2019), if we understand the reviwer's comment correctly. The challenges observed in tropical and densely vegetated regions mainly arise from microwave signal attenuation caused by high-biomass vegetation canopies, which leads to retrieval difficulties and data gaps, rather than limitations of optical sensors. To avoid possible misunderstanding, we have revised the corresponding text in the manuscript to more accurately describe the underlying causes of this issue.

> *"*ESA-CCI integrates active and passive microwave data, thereby achieving high performance as shown by high temporal correlations with independent data and low estimated random errors. However, the product suffers from significant data gaps, mainly due to frozen conditions and dense vegetation causing microwave signal attenuation, which limits its applicability in certain global modeling applications (Dorigo et al., 2017; Gruber et al., 2019)*"*

Regarding the selection for evaluation: ESA-CCI was included not solely for its multi-sensor integration, but because it is one of the most widely recognized and utilized global soil moisture products, serving as a key benchmark in the literature for climate studies, hydrological modeling, and validation exercises (e.g., Dorigo et al., 2017; Gruber et al., 2019; Hirschi et al., 2025; Li et al., 2025b). Its long temporal coverage (1978-present) and fusion of diverse satellite sources make it valuable for comparative assessment, allowing us to highlight its strengths (e.g., reasonable RMSE where data are available, as shown in Table 1 and Figure 10 in the revised manuscript) alongside its limitations.

To enhance the clarity of why ESA-CCI was used for data evaluation in the manuscript, the revised text in section 2.3.1 now reads

> "ESA-CCI was included in the evaluation as a comprehensive benchmark, given its status as a widely recognized global soil moisture product with long temporal coverage and multi-sensor integration, which enables meaningful comparisons despite its known data gaps. These gaps were then explicitly accounted for in our analysis in section 3.3."

Regarding the comment “However, choosing a dataset with better spatial coverage could still help improve uncertainty estimates in the tropics given that this study spans the entire globe”, we fully agree on the importance of better spatial coverage for improving uncertainty estimates in the tropics, especially given the global scope of our study and the datasets with fewer gaps could indeed refine uncertainty quantification in these challenging environments (e.g., by enabling more robust validation against sparse in situ measurements). However, after careful consideration of available alternatives, we opted not to replace ESA-CCI in the evaluation for the following reasons. For example, alternative datasets with potentially better tropical coverage, such as GLDAS (Rodell et al., 2004; Beaudoing and Rodell, 2020) or AMSR2-based products (Imaoka et al., 2010; Zhang et al., 2021a), were reviewed during the study design (as briefly noted in Lines 85-105 of the original manuscript). While these offer more consistent spatial coverage in vegetated areas, they come with trade-offs that made them less suitable for our comparative evaluation: GLDAS, for instance, has coarser resolution (0.25°-1°) and model-driven biases that limit its utility for high-resolution benchmarking, whereas AMSR2 is sensitive to vegetation at its frequency band, often resulting in higher uncertainties in dense tropical forests compared to L-band products, such as SMAP L4. In contrast, ESA-CCI’s multi-sensor fusion provides a unique perspective on microwave-based retrievals, allowing us to contextualize its performance against ERA5-Land and SMAP L4 in a balanced manner. In addition, ESA-CCI was excluded from the fusion process precisely due to its gaps (as detailed in Section 2.3.1), with our adjusted ERA5-Land product relying instead on the complementary strengths of ERA5-Land (seamless coverage) and SMAP L4 (low bias), which together yield improved global consistency.

To address potential impacts on tropical uncertainty estimates, we stratified our validation to explicitly handle data gaps (Section 3.3.1), computing metrics separately for periods with and without ESA-CCI availability. In the revised manuscript, we have expanded the discussion in *Section 4.1* to more explicitly address tropical uncertainties, noting that

> “Although in situ data in tropical regions remain sparse (only ~7% of our 1,615 stations are in tropical zones, primarily from the Cemaden dataset), the evaluation still indicates a notable improvement in the tropical regions, where the RMSE decreased from 0.1475 in the ERA5-Land product to 0.0702 in the adjusted ERA5-Land dataset (a reduction of ~50%), and the NNSE increased from 0.1365 to 0.3482 (an improvement of 150%), as shown in Fig. 12.”

15. L409-417: This part belongs to Discussion.

We thank the reviewer for this comment, which has helped us refine the manuscript’s structure for better clarity and logical flow. In the revised manuscript, we have relocated lines 409–415 (encompassing the citation to Zheng et al. (2023) on ESA-CCI data gap proportions, along with the explanations of gap causes and their potential implications for data reliability and fusion outcomes) to the Discussion section (now integrated into Section 4.1 in the revised manuscript). This move is indeed appropriate, as these elements involve interpretive analysis and broader contextualization of the gaps’ origins and consequences, which align more closely with the Discussion’s role in interpretating results and addressing limitations. The corresponding added text in Section 4.1 regarding ESA-CCI now reads as follows. We have also revised the text slightly to ensure a smooth logical flow.

> “ESA-CCI, on the other hand, is widely recognized for its superior integration of multi-source satellite data and high precision (Hirschi et al., 2025; Li et al., 2025b). It demonstrates robust performance across various regions and climate zones worldwide. However, ESA-CCI suffers from limitations in data coverage, with notable gaps in high-latitude and high-altitude regions, as well as densely vegetated areas (Ortet et al., 2024; Xie et al., 2024). Quantitatively, Zheng et al. (2023) reported that the proportion of daily missing data in ESA-CCI ranged from 21.8 to 94.9% between 2000 and 2020, with an average of 58.2%. Even after 2007, when available satellite data increased, the smallest proportion of missing data relative to the global land area (excluding Antarctica) still reached 21.8%. These gaps primarily result from unstable satellite coverage, challenges in data retrieval under specific conditions (e.g., dense vegetation, frozen soil, or snow), and rigorous quality control (Babaeian et al., 2019; Dorigo et al., 2017; Li et al., 2021b; Mu et al., 2022). Consequently, such issues may lead to spatial and temporal data discontinuities, introduce biases, and undermine the reliability of the fusion outcomes (Li et al., 2021b; Zhang and Zhou, 2016). These characteristics make it more suitable for applications requiring high accuracy rather than continuous coverage, such as regional drought monitoring and hydrological modeling.”

However, we have retained lines 415–417 (“In contrast, SMAP L4 shows missing data in only a few areas globally, including Greenland and parts of rivers, lakes, and other open-water bodies, with no substantial changes in these areas over time.”) in the Results section. This sentence provides a direct, factual description of the observed spatial coverage patterns in SMAP L4, derived from our analysis of the year 2016 data and Figure 7. As such, it serves as an objective presentation of the results, complementing the preceding descriptions of ERA5-Land and ESA-CCI coverage, and ensuring a balanced comparison within the spatiotemporal coverage subsection (Section 3.2). Moving this descriptive element to the Discussion might disrupt the sequential reporting of findings, but we believe its placement here enhances readability and maintains the Results section’s focus on empirical observations. If the reviewer prefers further adjustments, we would be happy to reconsider.

16. Figure 8: Given the small numbers of day with data availability in the tropics and in high-latitude regions (for 2015; the coverage in 2016 might be similar?), how do the authors get the global coverage of ESA-CCI in Figure 7?

Thank you for your comment and for highlighting this potential inconsistency. We acknowledge that the discrepancy between Figures 7 and 8 is due to an error on our part. As also noted by Reviewer 1, the rows for ESA-CCI and SMAP L4 in Figure 7 were inadvertently reversed in the original manuscript. We have now corrected the labels in the revised Figure 7, which swaps the rows to accurately reflect each product’s characteristics. We believe this resolves the issue and appreciate your feedback in improving the clarity of the manuscript.

17. Section 3.3.1: How about the performance of datasets in agricultural regions, which are largely affected by food demands and human activities, which are not sufficiently represented by the process-based models of the reanalysis systems, i.e. ERA-Land here.

Thank you for your comment regarding the performance of the product compared with ERA-Land in agricultural regions. The comparision of the adjusted ERA5-Land and the original ERA5-Land datasets based on in-situ measurement sites located in agricultural areas (accounting for approximately 15% of all in-situ measurement sites; see Figure 2) are included in the Supporting information S2, which now reads

> "To further assess the product's applicability in human-managed environments, we evaluated the performance of the two datasets at in-situ measurement sites located within agricultural regions. The comparison between the adjusted ERA5-Land and the original ERA5-Land datasets in these regions is shown in Fig. S2.
>
> The results show that the fused product also performs well in agricultural regions, where soil moisture dynamics are more strongly influenced by irrigation, cropping cycles, and other human interventions that are typically underrepresented in reanalysis models such as ERA5-Land. Specifically, the fused dataset reduces the RMSE by about 10% and increases the NNSE from 0.354 to 0.366 compared with the original ERA5-Land, indicating improved reliability and consistency of soil moisture representation in these human-managed landscapes."

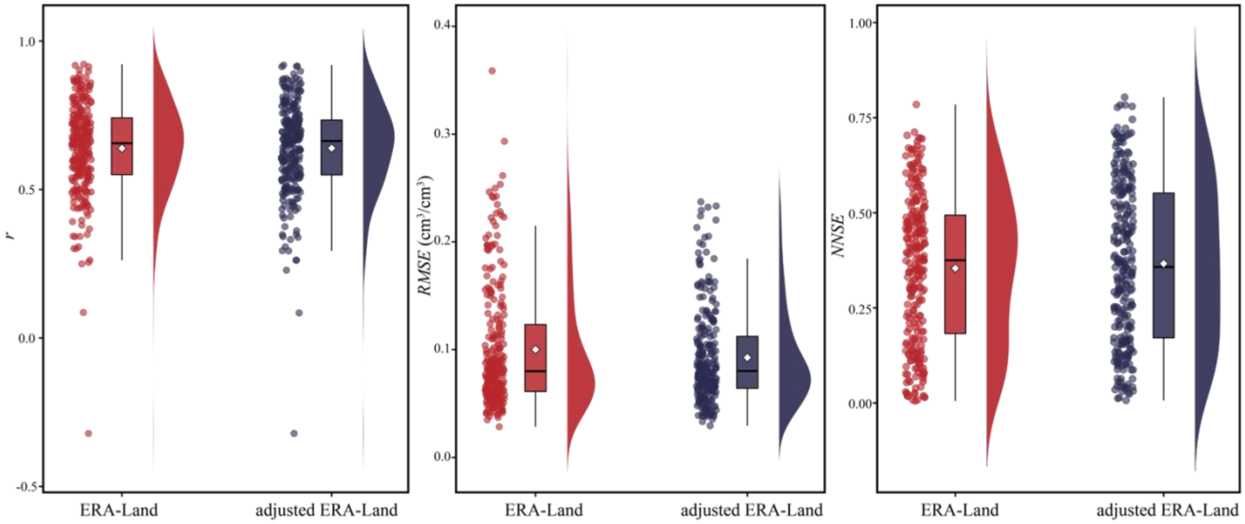


Figure S2. Distribution of three performance metrics for two soil moisture products over **agricultural regions**, including (a) Pearson correlation coefficient (r), (b) RMSE, and (c) NNSE.

18. L585-588: Compared to the time frame of SMAP products, April 2015–present, this study (adjusted ERA-Land) has the limitation in representing soil moisture over the long-term. I'd at least develop a data for 2015-2024.

As previously addressed in our response to the first reviewer, we have extended the temporal coverage of our adjusted ERA5-Land dataset from 1950 to the present. Please refer to our detailed reply to the first comment from the first reviewer for further information.

19. L604-612: this part shows that various soil moisture datasets show different accuracy across space, i.e., CONUS vs Europe. In this case, why not combine SMAP L4 and ESA-CCI to adjust ERA5-Land in regions with reasonable ESA-CCI coverages.

Thank you for this insightful suggestion. We agree that combining SMAP L4 and ESA-CCI to adjust or bias-correct ERA5-Land in regions with reasonable ESA-CCI coverage (e.g., where microwave retrievals are reliable and data gaps are minimal) is technically feasible and promising. This approach could potentially leverage the complementary strengths of these datasets, such as SMAP L4's assimilation-based root-zone estimates and ESA-CCI's multi-sensor microwave observations, and improve overall accuracy in spatially variable regions, such as CONUS and Europe. However, implementing this combination is beyond the scope of the current study, which primarily focuses on evaluating and comparing existing datasets rather than developing a new merged product.

Such an extension would require additional methodological development (e.g., optimal weighting schemes and selection of the optimal benckmark dataset) and extensive re-analysis, which would significantly expand the manuscript's focus. Instead, in the revised manuscript, we have added a brief sentence in the third paragraph in the Conclusions section of the revised manuscript to acknowledge this as a promising direction for future research:

> "Future efforts could explore fusing SMAP L4 and ESA-CCI to bias-correct ERA5-Land in regions where ESA-CCI provides sufficient coverage and demonstrates superior accuracy, taking advantage of their spatial accuracy differences to yield more robust global estimates."

We appreciate the feedback from the reviewer for inspiring this forward-looking addition.