January 5, 2026

Re: Revised Manuscript essd-2025-410
(Fusing ERA5-Land and SMAP L4 for an Improved Global Soil Moisture Product (1950-2025))

Dear Editor:

Thank you very much for considering our revised manuscript for publication in *Earth System Science Data*. We have carefully revised the manuscript in response to all comments provided by the anonymous reviewer. We sincerely appreciate the time, effort, and constructive feedback that the reviewer devoted to further improving the quality and clarity of our work.

In the course of these substantial revisions, we would like to draw your attention to an update in the authorship list. The revision process benefited significantly from the assistance of Cong-Qiang Liu, who provided critical scientific input regarding additional independent historical data collection, dataset analysis, and revising the manuscript. Consequently, with the full agreement of all original co-authors, we have included him as a co-author in this revised version.

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, Cong-Qiang Liu, and Harry Vereecken

Replies to Editor's comment

The manuscript presents a valuable effort to generate a long-term soil moisture dataset by integrating satellite observations with reanalysis products. However, a major revision is needed to address concerns regarding the methodological justification for backward-extending SMAP–ERA5-Land relationships to earlier decades with potentially different climatological conditions. Clarifications are also required on the organization and scientific accuracy of the sensor descriptions, as well as the rationale for separating overlapping calibration/validation periods. In addition, statistical tests should be included to support statements about "high correlations" used throughout the manuscript. Addressing these issues will substantially strengthen the scientific rigor and reliability of the dataset and its interpretation.

We sincerely thank the Editor for the constructive and insightful comments. In response, we have thoroughly revised the manuscript to address all raised concerns.

Specifically, regarding the methodological justification for backward extension, we have strengthened the justification for the backward extension of the SMAP L4 and ERA5-Land relationship through three specific actions. Firstly, we adopted a single continuous calibration period (April 2015-October 2025) to derive robust scaling parameters *m* and *n* in the mean-variance rescaling method, which maps the original ERA5-Land soil moisture to match SMAP L4 (see Section 2.3.2). Secondly, we conducted an additional independent historical validation using ISMN in situ observations dating back to 1960 until March 2015. Finally, to ensure the stability of our adjustment parameters under different climatologies, we identified the three wettest and three driest years based on global annual mean soil moisture derived from SMAP L4 data and calculated the mean-variance adjustment parameters for these contrasting conditions. The results (now presented in the new Section 3.3.4) demonstrate that the parameters remain statistically stable regardless of extreme wet or dry conditions, justifying their application to historical periods with potentially different climatologies (Please refer to our detailed response to the general comment from Reviewer #2 for the complete analysis).

Regaring the sensor descriptions, we have also reorganized and refined the descriptions of remote sensing sensors to improve clarity and logical flow, and scientific accuracy (Please refer to the detailed response to the Specific Comment #3 from Reviewer #2 for the results).

In addition, we have explicitly quantified all statements regarding “high correlation” by incorporating exact correlation coefficients (r) throughout the manuscript. This ensures that all qualitative claims are supported by precise quantitative evidence (Please refer to the detailed response to the Specific Comment #5 from Reviewer #2 for the results).

We believe that these revisions substantially enhance the soundness, transparency, and reliability of the proposed dataset, and we sincerely appreciate the Editor’s constructive comments in improving the quality of this work.

Replies to Reviewer #2

General Comments: The authors have most of my comments well addressed. One major concern is using the existing relationships between ERA5-Land and SMAP to backward extend the soil moisture data for 65 years (1950–2014), during which the climatology could be very different from that of 2015–2025. This application needs further justifications.

We thank the Reviewer for this valuable and constructive comment. To address this concern and following the suggestion in Detailed Comment #4, we first updated our methodology to derive the adjustment parameters m and n in the mean-variance rescaling method (see Section 2.3.2) using the single, continuous period from April 2015 (marking the start of SMAP L4 data availability) to October 2025. We then applied these coefficients to adjust the historical ERA5-Land soil moisture data from 1950 to October 2025. To further justify the backward extension of the adjusted ERA5-Land soil moisture dataset and ensure that these coefficients remain valid under historical climatological conditions, we conducted two rigorous new assessments:

1) Historical Validation: We conducted evaluations using ISMN soil moisture observations spanning 1960 - March 2015 to assess the performance of the adjusted ERA5-Land dataset relative to the original ERA5-Land product. ISMN was used exclusively for this analysis because it is the only network with sufficient historical records dating back to the mid-20th century; other networks used in the main analysis (CMA, Cemaden, SONTE-China, and COSMOS-Europe) lack adequate coverage during this historical period. Due to the extremely sparse station availability prior to 1970, statistical evaluation metrics were calculated for the

period 1970 - March 2015 only. While the adjusted product extends back to 1950, and limited ISMN records are available for the 1960s, these early records were insufficient for robust and meaningful evaluation.

2) Assessment of Parameter Stability under Contrasting Climatic Conditions: We examined the sensitivity of the adjustment parameters (*m* and *n*) in the mean-variance rescaling method to varying climatic conditions. To this end, we identified the three wettest and three driest years during the SMAP L4 availability period (2015-2025) based on global annual mean soil moisture levels. The adjustment parameters were then calculated and compared for these contrasting conditions to ensure that the coefficients remain statistically stable and robust against interannual climate variability.

These analyses demonstrate that the adjustment parameters are temporally stable and that the adjusted product consistently outperforms the original ERA5-Land throughout the historical period. Accordingly, we have updated Section 2.1.1 (“In situ Datasets”) to explicitly describe the collection of this independent historical ISMN dataset (1960 - March 2015), which now reads,

> “In addition to this primary dataset, all available ISMN soil moisture records spanning the period January 1960 - March 2015 (2,173 in situ stations providing an independent set of approximately 1.9 million soil moisture measurement records) were separately collected and retained. This dataset enables an independent evaluation of the reliability of the temporally extended ERA5-Land dataset. The spatial distribution of these historical stations is provided in Supporting Information Fig. S1.”

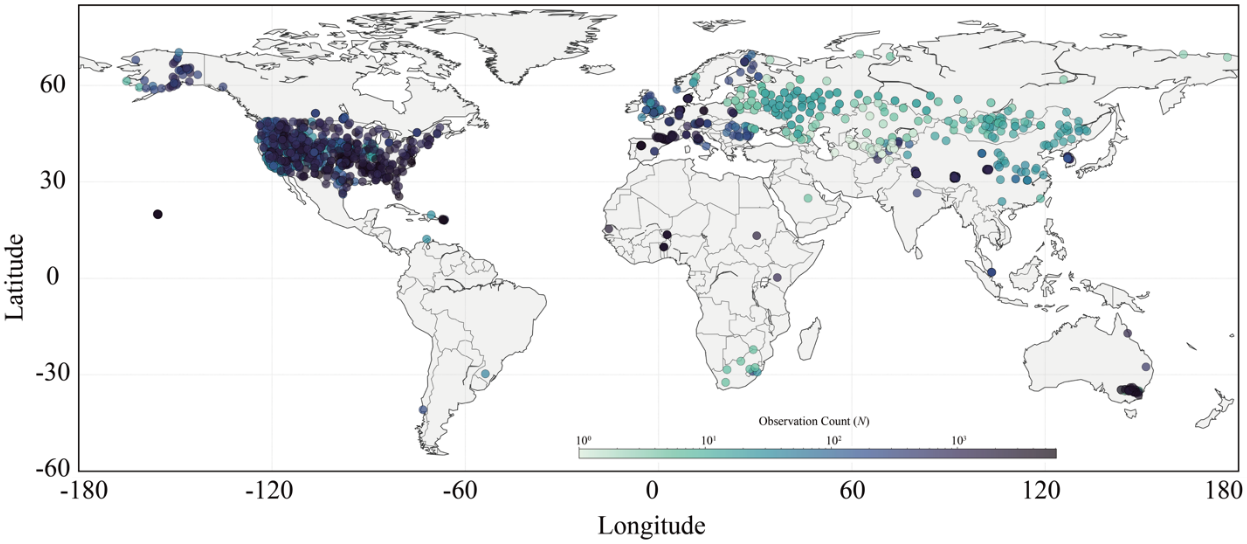


Figure S1. Spatial distribution of the 2,173 independent ISMN in situ stations collected for the historical validation of the adjusted ERA5-Land dataset (1960 - March 2015). The color gradient represents the data density available at each station, ranging from sparse records (light green) to dense time series (dark blue).

In addition, we have updated Section 2.3.2 (“Mean-Variance Rescaling Method”) to clearly describe the temporal extension procedure. The revised text now reads:

> “To extend the temporal coverage of the soil moisture product, the scaling coefficients were derived using a single, continuous reference period from April 2015 (marking the start of SMAP L4 data availability) to October 2025 and subsequently applied to adjust the ERA5-Land soil moisture data from 1950 to October 2025, thereby generating a continuous adjusted ERA5-Land dataset spanning 1950 to October 2025. To further justify the backward extension of the adjusted ERA5-Land soil moisture dataset and to ensure that the derived scaling coefficients remain valid under historical climatological conditions, two complementary assessments were conducted as follows:
>
> 1. Historical Validation: we conducted evaluations using ISMN soil moisture observations spanning 1960 - March 2015 to assess the performance of the adjusted ERA5-Land dataset relative to the original ERA5-Land product. ISMN was used exclusively for this analysis because it is the only network with sufficient historical records dating back to the mid-20th century; other networks used in the main analysis (CMA, Cemaden, SONTE-China, and COSMOS-Europe) lack adequate coverage during this historical period. Due to the extremely sparse station availability prior to 1970, statistical evaluation metrics were calculated for the period 1970 - March 2015 only. While the adjusted product extends back to 1950, and limited ISMN records are available for the 1960s, these early records were insufficient for robust and meaningful evaluation.
>
> 2. Assessment of Parameter Stability under Contrasting Climatic Conditions: we examined the sensitivity of the adjustment parameters (m and n) in the mean-variance rescaling method to varying climatic conditions. To this end, we identified the three wettest and three driest years during the SMAP L4 availability period (2015-2025) based on global annual mean soil moisture levels. The adjustment parameters were then calculated and compared for these contrasting conditions to ensure that the coefficients remain statistically stable and robust against interannual climate variability (detailed results are discussed in Section 3.3.4).”

The detailed results of these analyses and related discussions have been added to a new Section 3.4 of the revised manuscript, which now reads as follows:

> **“3.4 Evaluation of the Extended Adjusted ERA5-Land Dataset against the Original ERA5-Land using ISMN Observations (1960 - March 2015) and Stability Assessment of Mean-Variance Adjustment Parameters under Wet and Dry Conditions**
>
> This section employs a multi-metric evaluation framework to systematically compare the performance of the original ERA5-Land and the adjusted ERA5-Land datasets against 2,173 ISMN in situ stations over the period 1960 - March 2015 with approximately 1.9 million soil moisture measurement records. The validity and effectiveness of extending the adjusted ERA5-Land dataset to the historical period are assessed in Fig. 13. In these density scatter plots, each data point represents an individual station, with the color gradient indicating the observation count available for that site.
>
> Overall, compared with the original ERA5-Land, the adjusted ERA5-Land exhibits consistent performance improvements across all evaluation metrics. In terms of correlation

coefficient *r* (Fig. 13a), the adjusted ERA5-Land shows slightly higher station-based correlation coefficients (mean *r* increases from 0.6225 to 0.6230), indicating that it effectively preserves the temporal variability characteristics of the original ERA5-Land soil moisture data. For the bias (Fig. 13b), the distribution of the adjusted ERA5-Land is more strongly centered around zero (mean *Bias* reduced from 0.0561 cm^3/cm^3 to -0.0158 cm^3/cm^3), reflecting a substantial reduction in systematic bias and demonstrating that the adjustment procedure effectively mitigates long-term biases present in the original ERA5-Land dataset. Regarding error magnitude (Fig. 13c), the adjusted ERA5-Land exhibits markedly lower *RMSE* values at the majority of stations, with the mean *RMSE* decreasing from approximately 0.0999 cm^3/cm^3 for the original ERA5-Land to approximately 0.0835 cm^3/cm^3 after adjustment, indicating an overall improvement in–absolute accuracy. Meanwhile, the *NNSE* metric (Fig. 13d) shifts upward following adjustment, with the mean *NNSE* increasing by approximately 30% relative to the ERA5-Land, further demonstrating a significantly enhanced ability of the adjusted dataset to explain observed soil moisture variability at the station scale.

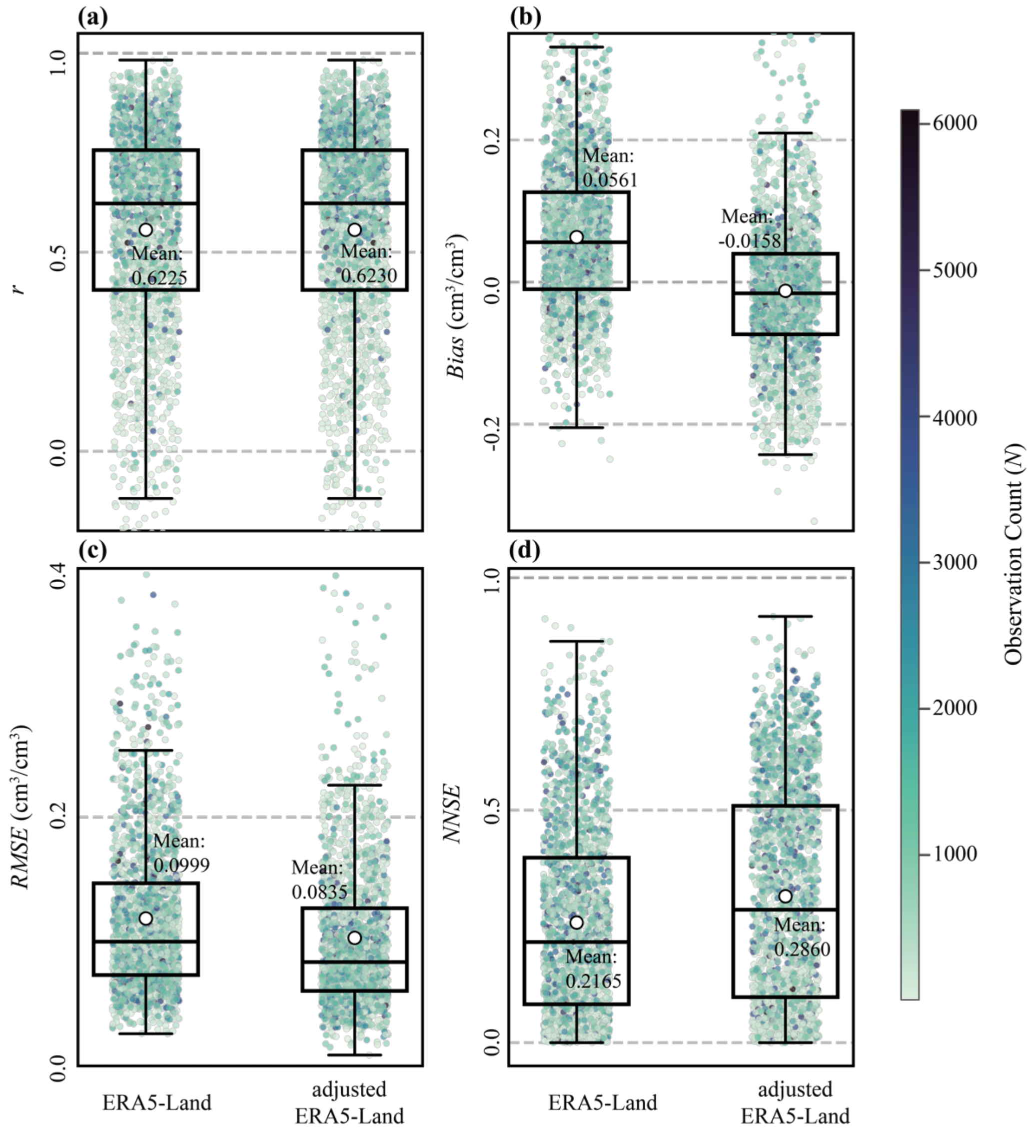


Figure 13. Comparative evaluation of the extended adjusted ERA5-Land soil moisture dataset versus the original ERA5-Land against ISMN in situ observations for the historical period (1960 - March 2015). The panels display the distributions of four performance metrics: (a) Pearson correlation coefficient (r), (b) *Bias* (cm^3/cm^3), (c) *RMSE* (cm^3/cm^3), and (d) *NNSE*. In the density scatter plots, each point represents a single ISMN station with more than 10 valid observations ($N > 10$) throughout the entire historical period, colored according to the available observation count as shown in the color bar. The overlaid boxplots summarize the statistical distribution: the box spans the interquartile range (25th to 75th percentiles), and the central line marks the median. The white circles and numerical labels indicate the mean value of each distribution.

To further reinforce the dataset performance characterized by the site-scale evaluations and to provide a comprehensive assessment over the long-term historical period, we conducted an aggregated validation using the independent 2,173 ISMN stations available for the period 1960 - March 2015 and their complete time series. The corresponding validation statistics comparing the adjusted ERA5-Land with the original ERA5-Land are summarized in Table 2. The aggregated results show that the adjusted ERA5-Land consistently outperforms the ERA5-Land across all evaluation metrics. Specifically, the mean *RMSE* decreases from 0.137 cm^3/cm^3 to 0.110 cm^3/cm^3, representing a reduction of 19.7% and indicating improved absolute accuracy; the mean *NNSE* increases from 0.398 to 0.504 (an improvement of approximately 26.6%), indicating a substantially enhanced ability of the adjusted dataset to explain observed soil moisture variability. In addition, the mean Bias is reduced to approximately -0.003 cm^3/cm^3, which is markedly closer to zero than that of the ERA5-Land (0.075 cm^3/cm^3), demonstrating that the adjustment procedure utilized in this study effectively mitigates long-term systematic biases.

Table 2. Aggregated validation statistics comparing the performance of the original ERA5-Land and the Extended Adjusted ERA5-Land datasets against observations from 2,173 ISMN stations for the period 1960 - March 2015. The Improvement (Impr.) column represents the relative percentage improvement of the Adjusted ERA5-Land compared to the original ERA5-Land.

Metrics	*r*		*RMSE* (cm^3/cm^3)		*NNSE*		*Bias* (cm^3/cm^3)
Products	mean	Impr. (%)	mean	Impr. (%)	mean	Impr. (%)	mean
ERA5-Land	0.506	+1.98	0.137	-19.71	0.398	+26.63	0.075
Adjusted ERA5-Land	0.516	-	0.110	-	0.504	-	-0.003

To further examine the temporal robustness of the adjusted ERA5-Land dataset, we analyzed the interannual variations of the validation metrics. ISMN station observations were aggregated on an annual basis, and yearly validation metrics were calculated for both the adjusted ERA5-Land and the original ERA5-Land relative to the ISMN sites. We focused the analysis on the period 1970 - March 2015, as the period 1960-1969 was excluded due to insufficient statistical representativeness. Across the entire 1960-1969 period, there were only 20 soil moisture observations in total (with a maximum of 4 observations in any single year). Such extreme data scarcity precludes the calculation of robust or meaningful evaluation metrics (see the temporal evolution of available soil moisture observations in Supporting Information Fig. S8). Furthermore, even within the retained analysis period, the data distribution remains highly skewed; the period from 1998 to March 2015 accounts for approximately 99% of the validation dataset.

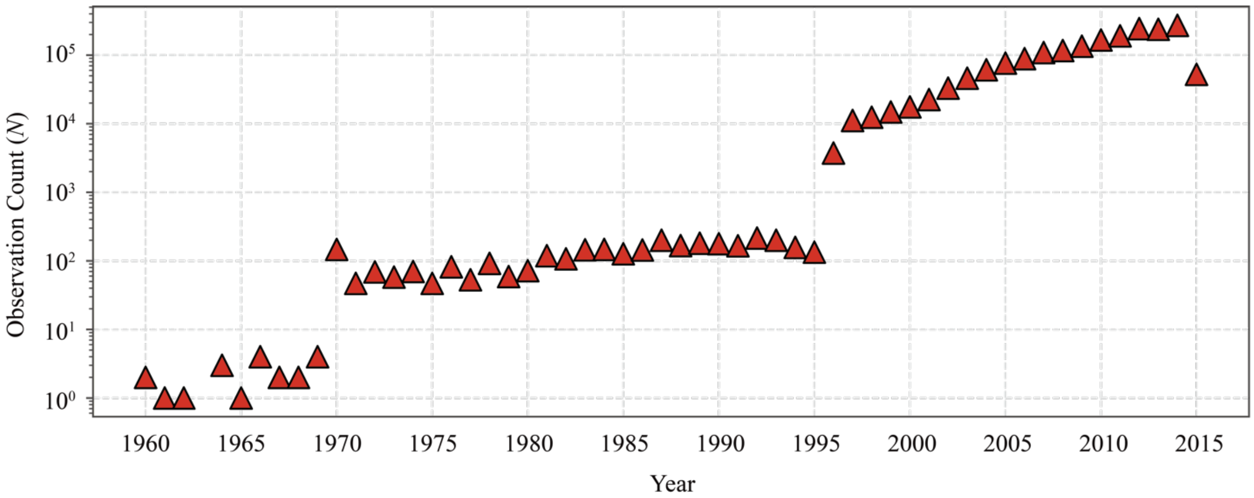


Figure S8. Temporal evolution of the number of available ISMN in situ soil moisture observations used for the historical validation (1960-2015). The period 1960-1970 was excluded from the aggregated statistical analysis in Table 2 due to the extremely sparse data coverage (fewer than 4 observations annually), which prevents robust assessment.

As shown in Fig. 14, the adjusted ERA5-Land (red circles) consistently outperforms the ERA5-Land (blue triangles) across all four evaluation metrics throughout the analysis period 1970 - March 2015, demonstrating sustained and stable improvements over time. In terms of correlation (Fig. 14a), the adjusted ERA5-Land exhibits systematically higher *r* values than the ERA5-Land. This improvement is observed both in the earlier sparse data period (prior to 1998) and the later data-rich period (after 1998), indicating a stable ability to capture interannual soil moisture variability across periods of varying observational density.

With respect to bias (Fig. 14b), distinct behaviors are observed. The original ERA5-Land exhibits a persistent positive bias (systematic overestimation across nearly the entire record. In contrast, the adjusted ERA5-Land successfully mitigates this systematic offset. While interannual fluctuations exist, particularly during the data-sparse period (1970-1998), where limited station sampling leads to higher variability, the magnitude of the bias in the adjusted ERA5-Land product is generally smaller. Crucially, in the data-rich period after 1998, the bias of the adjusted product stabilizes near zero. This suggests that the adjustment procedure effectively removes systematic bias, resulting in a more balanced error distribution in which local over- and underestimations tend to cancel out at the global scale, in contrast to the consistent overestimation observed in the original ERA5-Land dataset. Regarding error magnitude (Fig. 14c), the adjusted ERA5-Land demonstrates improved absolute accuracy, yielding lower *RMSE* values in the vast majority of analyzed years. While isolated instances of slightly higher *RMSE* occur in the early sparse period (e.g., 1972 and 1977), likely due to the limited spatial representativeness of the few available stations, the performance becomes highly consistent in the data-rich period. Specifically, during the period with robust station coverage (after 1998), the adjusted product consistently exhibits lower *RMSE* than the original ERA5-Land. These findings support the temporal stability of the accuracy gains, demonstrating sustained improvements, most clearly evident during periods with sufficient in situ observational coverage. The *NNSE* metric (Fig. 14d) further corroborates these findings. Compared with the ERA5-Land, the adjusted ERA5-Land maintains consistently higher *NNSE* values throughout nearly the entire analysis period. The only deviation occurs in 1977, an isolated case within the data-sparse period, which likely reflects limited sampling dataset. Beyond this single year, the sustained improvement in *NNSE* confirms the enhanced ability of the adjusted dataset to capture soil moisture dynamics. Overall, the results presented in Fig. 14 demonstrate that the adjusted ERA5-Land dataset achieves stable and sustained performance improvements, with accuracy that remains consistent throughout the backward-extended historical period.

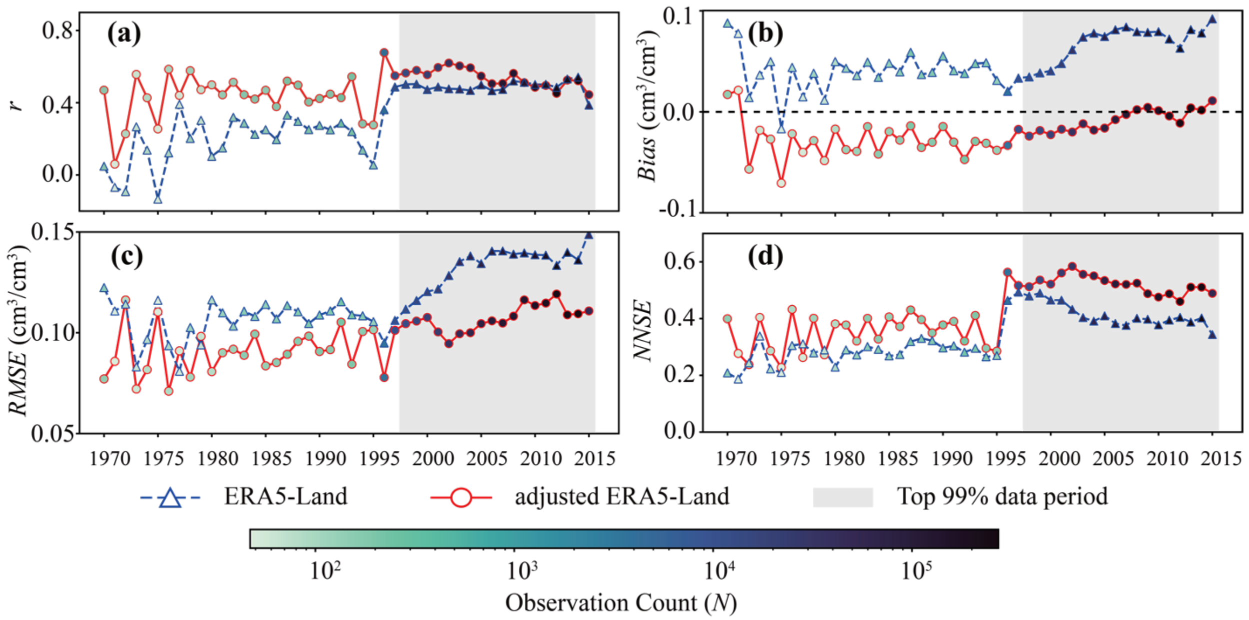
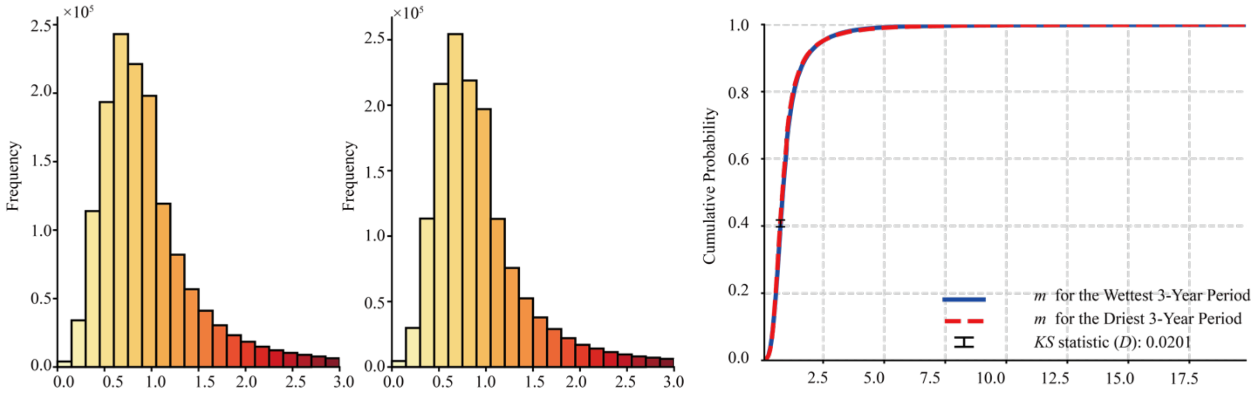


Figure 14. Interannual evaluation of the adjusted ERA5-Land (red circles) and the original ERA5-Land (blue triangles) soil moisture products against ISMN in situ observations over the period 1970 - March 2015. The panels display time series of the spatially aggregated (a) Pearson correlation coefficient (*r*), (b) *Bias* (cm^3/cm^3), (c) *RMSE* (cm^3/cm^3), and (d) *NNSE*. The color intensity of the data points corresponds to the number of available in situ observations for each year, as indicated by the color bar. The gray shaded region marks the period (1998-2015) where station density is the highest, accounting for approximately 99% of the total validation data records.

To investigate the influence of climatic variability, particularly differences between wet and dry conditions, on the mean-variance rescaling parameter (*m* and *n*), we identified the three wettest non-consecutive years (2016, 2017, and 2022) and the three driest years (2019, 2021, and 2024) from the period 2016-2024 based on global annual mean soil moisture derived from SMAP L4 data. Given that the SMAP data record begins in April 2015 and extends to October 2025, both 2015 and 2025 were excluded from this selection as they represent incomplete calendar years. Based on these selected years, the corresponding *m* and *n* parameters were calculated, and their distributional characteristics and empirical cumulative distribution functions (ECDFs) were analyzed, as shown in Fig. 15.

The distributional analysis indicates a high degree of similarity between the wettest three-years period and the driest three-years for both *m* (Figs. 15a-c) and *n* (Figs. 15d-f). Both the histogram shapes and the ECDF curves exhibit strong consistency across the two climatic regimes, with no evident systematic shift. A quantitative comparison was further conducted using the Kolmogorov-Smirnov (*KS*) test, yielding a *KS* statistic (*D*) of 0.0201 for parameter *m*, with a comparable result obtained for *n*. Under large-sample conditions ($N = 1.45 \times 10^6$), standard statistical tests often yield low *p*-values for even negligible differences due to high statistical power. Therefore, we interpret the magnitude of the *KS* statistic *D*, which quantifies the maximum absolute difference between the two ECDFs, rather than relying solely on significance testing. The results show that this maximum difference amounts to only 2.01% for parameter *m* and 1.32% for parameter *n*. Previous hydrological and climatological studies have demonstrated that *D* values on the order of 1-2% can be regarded as practically negligible and indicative of highly similar distributions (Kroll et al., 2015; Lanzante, 2021). Accordingly, these results suggest that the adjustment parameters (*m* and *n*) exhibit strong temporal stability across contrasting the wettest and driest climatic conditions, with limited sensitivity to interannual climate variability. This stability provides a robust physical and statistical justification for applying the derived bias-correction parameters to the earlier historical periods.

(a) *m* Histogram for the Wettest 3-Year Period **(b) *m* Histogram for the Driest 3-Year Period** **(c) ECDF Comparison of Parameter *m* Distributions**



(d) *n* Histogram for the Wettest 3-Year Period **(e) *n* Histogram for the Driest 3-Year Period** **(f) ECDF Comparison of Parameter *n* Distributions**

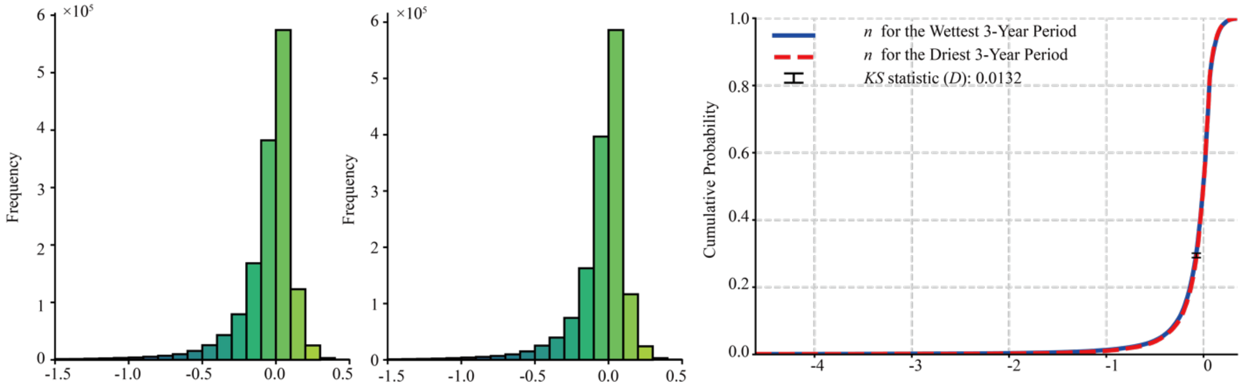


Figure 15. Assessment of the temporal stability of the mean-variance adjustment parameters *m* (top row) and *n* (bottom row) under contrasting climatic conditions. The distributions are derived from (a, d) the three wettest non-consecutive years and (b, e) the three driest non-consecutive years selected from 2015-2024. Panels (c) and (f) present the comparison of the Empirical Cumulative Distribution Functions (ECDFs), where the blue solid line represents the wettest period and the red dashed line represents the driest period. The black markers indicate the Kolmogorov-Smirnov (KS) statistic (*D*), which quantifies the maximum vertical divergence between the two distributions (0.0201 for *m* and 0.0132 for *n*).”

In addition, Discussion 4 has been carefully revised to synthesize these new analyses and to further strengthen the justification and validation of the backward extension of the adjusted ERA5-Land product. The revised text now reads as follows:

> L769: "…regional systematic biases. Beyond the primary validation period (2015-2020), this study further verifies the product's performance against historical in situ observations dating back to 1960. The high consistency observed between the adjusted ERA5-Land and these long-term soil moisture measurements (Section 3.4), together with the stability of scaling parameters tested under contrasting wet and dry conditions, provides observational evidence supporting the reliability of the data extension. These characteristics ensure that the dataset is not only accurate for present-day applications but also supports the analysis of multi-decadal climate trends, making it suitable for applications demanding regional water balance and global consistency, such as water resource management and long-term climate modeling. Nevertheless…"
>
> L820: "…the results presented here. However, a key distinction of our work is the rigorous validation of the backward extension. Methodologies for long-term reconstruction often rely on the assumption that statistical relationships established in the satellite period remain consistent over time (e.g., Li et al., 2022); however, verifying this consistency has historically been difficult due to the scarcity of independent pre-satellite observations. By compiling and utilizing the comprehensive ISMN archive dating back to 1960, our study provides rare, independent evidence supporting the temporal transferability of the mean-variance rescaling method, providing a quantitative assessment of historical performance that is often constrained by data availability in global soil moisture reconstruction efforts."

Accordingly, we have revised the Abstract and Conclusions to consistently reflect these updates and to clearly highlight the historical validation and its implications. The revised text now reads as follows:

Abstract:

> L15: "…compilation to date, comprising approximately 3.8 million records, organized into a primary dataset for modern validation (2015-2020) and an independent historical dataset (1960-2015). It is found that during the primary validation period (2015-2020), ERA5-Land…"
>
> L24: "…ERA5-Land products. Crucially, the reliability of the backward extension was verified against independent historical observations spanning 1960 to 2015, demonstrating sustained improvements over ERA5-Land with 19.7% *RMSE* reduction and 26.6% *NNSE* increase. This confirms the robustness of the adjustment parameters in the mean-variance rescaling method. The …"

Conclusions:

> L850: "To ensure a rigorous assessment, we collected in situ measurements from networks including ISMN, CMA, Cemaden, COSMOS-Europe, and SONTE-China. To the best of out knowledge, this collection represents the most comprehensive in situ soil moisture

> compilations available to date, comprising approximately 3.8 million records in total. These records are organized into two distinct subsets to support specific evaluation objectives, i.e., a primary dataset for the validation analysis (2015-2020) containing 1.9 million records, and an independent historical dataset (1960-2015) containing an additional 1.9 million records."
>
> L863: "Furthermore, we extended the temporal coverage to span 1950 to October 2025 by applying scaling coefficients derived from the calibration period (2015-2025). To justify this backward extension, we conducted a rigorous historical validation using the independent ISMN dataset spanning 1960 to 2015. The adjusted ERA5-Land consistently outperformed the original ERA5-Land throughout this historical period, achieving a 19.7% reduction in *RMSE* and a 26.6% improvement in *NNSE*, demonstrating robustness even in the extended timeframe. This was further supported by a climate sensitivity analysis, which confirmed that the adjustment parameters in the mean-variance rescaling method remain stable under contrasting wet and dry climatic conditions. These findings provide rare observational evidence verifying the assumption that statistical relationships established in the calibration period remain consistent over time."

In addition to the validation efforts described above, we have included a cautionary note in the Discussion section regarding the earliest segment of the dataset. We explicitly acknowledge the lack of in situ observations during this decade and advise users to interpret regional trends and extreme events in this early period with appropriate caution. The added text is as follows:

> "While this study provides a systematic validation spanning more than six decades (1960-2025), it is important to acknowledge the limitations concerning the earliest segment of the reconstructed record. Due to the complete unavailability of reliable in situ observations prior to 1960 and the extreme sparsity of station data between 1960 and 1970, a direct quantitative validation for the 1950 -1960 period was not feasible. Consequently, although the proven stability of the adopted mean-variance adjustment parameters under contrasting climatic conditions supports the methodological transferability, users are advised to interpret the data with caution when analyzing specific regional trends or extreme events during the unvalidated 1950-1960 decade and the subsequent data-sparse early years. Future efforts will focus on "data archaeology" to recover and digitize historical records, which could enable the retroactive validation of these early years and enhance the reliability of the long-term product."

Detailed Comments:

1. L69: "…processing or used frequency bands". This is unclear to me. Is it "processing or used frequency of spectral bands"? Additionally, what does "processing" mean? Data processing? Retrieval algorithms?

We thank the Reviewer for pointing out this ambiguity. We agree that the original wording was unclear. In this context, "used frequency bands" refers to the physical diffraction limits imposed by the low microwave frequencies (e.g., L-band) used by passive sensors. These long wavelengths require very large antennas to achieve high resolution; consequently, with current satellite antenna sizes, the native sensor footprints are relatively coarse (e.g., ~36-40 km). The term "processing" refers to the subsequent product-level data processing steps required to convert these raw footprints into a gridded product. This includes spatial aggregation, regridding, and noise-reduction smoothing, all of which can further smooth out small-scale spatial heterogeneity. The revised text now reads:

> "…but are limited in capturing small-scale soil moisture variability. This limitation arises from the coarse sensor footprints inherent to the low-frequency microwave bands and the spatial aggregation applied during data processing (e.g., regridding and noise-reduction smoothing), which further degrade spatial details."

2. L74–76: I've updated this sentence as "By comparison, active microwave sensors, such as radars used in Sentinel-1, provide higher resolution (1–10 km) but are more sensitive to vegetation and surface roughness, posing challenges in densely vegetated tropical regions and heterogeneous landscapes."

Thank you for the suggestion. We have revised the sentence in Lines 74-76 to improve clarity and precision. The sentence has been updated to:

> "By comparison, active microwave sensors, such as radars used in Sentinel-1, provide higher resolution (1-10 km) but are more sensitive to vegetation and surface roughness, posing challenges in densely vegetated tropical regions and heterogeneous landscapes."

3. L76–80: the limitations of optical/thermal sensors are supposed to be discussed after the introduction of these sensors (e.g., after the discussion of AMSR2). Additionally, I am not sure the reasons for including MODIS and LandSat here, since neither of these instruments have soil moisture data products.

For this updated paragraph, starting from L62, I'd first introduce the limitations and advantages of different sensors, and then discussion the multi-sensor integrated datasets and DA-based datasets, to indicate observations, sensor integration, and DA still have limitations from different perspectives.

Thank you for this helpful comment regarding the logical flow and the classification of sensor limitations. We have reorganized the paragraph to follow the suggested logical sequence:

1). Single Sensors: We now discuss passive microwave, active microwave, and optical/thermal sensors in sequence, highlighting their specific strengths and limitations.

2). Integrated Approaches: We follow this with a discussion on multi-sensor fusion (ESA-CCI) and data assimilation (SMAP L4).

Regarding MODIS and Landsat, we agree that citing specific missions without direct soil moisture products was potentially confusing. We have removed these specific names. Yet, we kept a general description of optical/thermal sensors to clarify that they are valuable for complementing microwave data (e.g., by providing high-resolution spatial information for downscaling) rather than measuring soil moisture directly.

Finally, we concluded the paragraph by synthesizing these points to highlight the significant evolution of soil moisture estimation strategies, which now encompass a broad range of independent sensor retrievals, multi-sensor fusion products, and data assimilation systems.

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 offering distinct advantages and limitations. 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. However, they are limited in capturing small scale soil moisture variability. This limitation arises from the coarse sensor footprints inherent to the low-frequency microwave bands and the spatial aggregation applied during data processing (e.g., regridding and noise-reduction smoothing), which further degrade spatial details. By comparison, active microwave sensors, such as radars used in Sentinel-1, provide higher resolution (1-10 km) but are more sensitive to vegetation and surface roughness, posing challenges in densely vegetated tropical regions and heterogeneous landscapes (Babaeian et al., 2019; Mohanty et al., 2017; Bauer-Marschallinger et al., 2019). Distinct from microwave observations, optical and thermal sensors complement microwave data by capturing surface conditions; however, they are limited to shallow depths and are restricted to observing the surface only under 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. Yet, these still suffer 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). Furthermore, 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). While SMAP L4 offers lower bias and unbiased root-mean-square error against in situ measurements, its performance naturally relies on the spatiotemporal availability of the assimilated observations. These methodological strengths and limitations highlight the significant evolution of soil moisture estimation strategies, which now encompass a broad range of independent sensor retrievals, multi-sensor fusion products, and data assimilation systems."

4. L350–355: The periods 2017–2020 and 2021–2024 are next to each other, and I do not understand why the authors used two separate periods instead of one continuous period (2015–2024/25). Please clarify this. Additionally, the climatology during 2015–2025 might be very different from the climatology before 2000. Thus, the ERA5-Land and SMAP (if it was launched earlier) relationship may not be the same for the time periods before 2000. Thus, I'd justify the *use of these relationships to backward extend the data. In other words, the authors need to show the consistency of the relationship over time before applying it to the ERA5-Land data under different climatology.*

Thank you for this valuable and constructive comment. Following the Reviewer's suggestion, we have updated the methodology to use a single continuous period (April 2015–October 2025), corresponding to the availability of reliable SMAP soil moisture observations beginning in April 2015 and the most recent ERA5-Land data release available at the time of revision (October 2025), to derive the adjustment coefficients, which are then applied to the full historical ERA5-Land record. Further details are provided in the General Comments.

Regarding to the justification for backward extension and the temporal stability of the relationship, we fully agree that establishing the consistency of the relationship is crucial before applying it to historical periods. To address this, we have conducted two rigorous new assessments: (1) an independent historical validation using ISMN in situ observations dating back to 1960, and (2) a Climate Sensitivity Analysis to test the stability of the adjustment parameters under contrasting climatic conditions (specifically, comparing the wettest and driest years). The results demonstrate that the relationship remains robust and stable over time. Please refer to our detailed response to the "General Comments" section above for the complete methodology, statistical evidence, and supporting figures.

5. The authors have mentioned "high correlation" in many places of the manuscript. I'd perform statistic tests to justify this statement.

Thank you for this helpful suggestion. We agree that statements referring to "high correlation" should be supported by appropriate statistical tests. In response, we have clarified the statistical basis of the reported correlations and revised the relevant text accordingly as follows:

> L17 in the Abstract: "It is found that during the primary validation period (2015-2020), ERA5-Land exhibits high correlation (with correlation coefficient of 0.69) between measured and predicted soil moisture but the data also shows significant bias."
>
> L319 in Section 2.3.1: "… with ERA5-Land offering a long time series, high correlation with in situ data with correlation coefficient of 0.69, and extensive spatial coverage…"
>
> L878 in the Summary and Conclusions section: "… high temporal coverage, which exhibited high correlation against measurements with r of 0.69, but stronger…"