RESPONSE TO REVIEWER #2 FOR GEOSCIENTIFIC MODEL DEVELOPMENT: MANUSCRIPT EGUSPHERE-2025-713

We sincerely thank Reviewer #2 for their thorough and insightful feedback on our manuscript, "Soil Parameterization in Land Surface Models Drives Large Discrepancies in Soil Moisture Predictions Across Hydrologically Complex Regions of the Contiguous United States." Your comments have been invaluable in helping us identify areas for improvement, and we outline below how we will address each point in the revised manuscript to enhance its clarity, robustness, and alignment with the standards of the hydrology and land surface modeling communities. Our responses to the suggestions are detailed below (in blue).

The authors present a comprehensive and methodologically rigorous study examining the influence of soil hydraulic and textural parameters on soil moisture simulations in CLM5, using soil parameter sets from the Soil Parameter Intercomparison Project (SP-MIP). Model outputs are compared against the ERA5-Land dataset as a benchmark. The study utilizes various analytical approaches, including means and variability assessments (Figures 4 and 5), as well as Empirical Orthogonal Function (EOF) analysis to investigate dominant spatial patterns and variability in soil moisture across the CONUS region. The findings suggest that soil parameterization has a substantial impact on CLM5 simulations, with notable discrepancies from ERA5-Land, particularly in hydrologically complex regions such as the Great Plains. The default CLM5 setup captures mean climatological patterns reasonably well but tends to underestimate interannual and seasonal variability.

Overall, the manuscript is well-structured, and the English is of generally high quality. The authors have executed a wide array of experiments that meaningfully contribute to our understanding of soil parameter sensitivities in land surface modeling. However, several critical issues remain that merit further investigation before the manuscript is suitable for publication. I recommend major revisions to address the following points:

1. Limited Benchmarking Against Reference Data:

The exclusive use of ERA5-Land as a benchmark is insufficient. While the authors acknowledge some of ERA5-Land's limitations, it remains a reanalysis product with inherent model dependencies and does not assimilate in-situ soil moisture observations directly. Prior studies [Koster et al., 2009] have demonstrated that soil moisture estimates are highly model-dependent. The validity of conclusions based solely on a single reference dataset is therefore limited.

To strengthen the analysis, I strongly recommend incorporating additional observation-based datasets, such as GLEM v3 *[Martens et al., 2017]*, SMERGE *[Tobin et al., 2019]*, and MERRA 2 [Reichle et al., 2017]. Each offers distinct advantages—GLEAM and SMERGE incorporate satellite-based observations, whereas MERRA-2 is a reanalysis-based soil moisture data. A recent study *[Duan et al., 2025]* has shown ERA5-Land's underperformance compared to these alternatives for sub-seasonal to seasonal forecast validations.

Response: We thank the reviewer for their thoughtful feedback regarding the use of ERA5-Land as the sole reference dataset. We respectfully clarify that the primary objective of our study was not to perform a formal validation of CLM5, but rather to assess the model's sensitivity to variations in soil hydraulic parameterizations. Our focus was on understanding whether the range of variability generated by CLM5 under different parameter configurations "brackets" the variability observed in ERA5-Land. The statistical tools we employed, such as EOF analysis, Euclidean distance, and Taylor diagrams, are commonly associated with model validation, but in our case, they were used as diagnostic tools to evaluate whether ERA5-Land's spatiotemporal variability could be reproduced through parameter perturbations alone.

We found that CLM5's parameter-driven variability consistently underestimated the amplitude of soil moisture variability compared to ERA5-Land, suggesting that the issue is not merely one of calibration but may reflect deeper structural limitations in how soil hydraulic properties are represented in the model. In this context, ERA5-Land serves as a physically consistent and spatially complete reference suitable for assessing relative variability patterns, rather than a ground-truth validation dataset. Although ERA5-Land does not assimilate in-situ soil moisture measurements (Muñoz-Sabater et al., 2021), its coherence and compatibility with CLM5's spatial and temporal scale make it well suited to this comparative framework.

We agree that incorporating additional observation-based datasets—such as GLEAM, SMERGE, or MERRA-2 could greatly benefit future studies aimed at model calibration. However, our current study is specifically focused on evaluating whether parameter variability alone can account for the structure of modeled soil moisture variability. Including multiple observational products at this stage would introduce additional complexity, potentially obscuring the sensitivity-based nature of our analysis. To address this, we have added clarifying text in Section 4 of the revised manuscript to better frame our work as a comparative sensitivity study. We also outline future directions that involve the integration of observational datasets for the purposes of model evaluation and calibration. Finally, we explicitly acknowledge the narrow scope of this study and emphasize the importance of using direct observational data in subsequent research focused on soil parameter calibration within global land models.

2. Underestimation of Interannual and Seasonal Variability

Figures 5 and 7 clearly indicate that all CLM5 configurations substantially underestimate soil moisture variability relative to ERA5-Land. Notably, Figure 5 reveals a tight clustering of CLM5 experiments, suggesting low variability in contrast to the wider spread of ERA5-Land data. However, this important point is underexplored in the manuscript. For instance, lines 284–285 state: "Despite these discrepancies, … broad agreement," which downplays the observed discrepancies. This variability gap warrants a deeper investigation and further supports the need for multiple observational references (as per Comment 1).

Response: We appreciate the reviewer's careful observation regarding the underrepresentation of soil moisture variability in CLM5 simulations compared to ERA5-Land, as illustrated in Figures 5 and 7. We fully agree that this discrepancy merits deeper treatment in the manuscript, both to reflect the limitations of the CLM5 parameterizations and to reinforce the case for additional benchmarking with observation-based datasets. To address this, we have made the following changes in the revised manuscript:

- Interannual Variability (Section 3.2 – Interannual Soil Moisture Anomalies):
  We have added a new discussion to explicitly highlight the tight clustering of CLM5 experiments and their muted anomaly spread relative to ERA5-Land. We interpret this as a systemic underestimation of interannual variability by the model, likely driven by diffusive parameter settings or limited responsiveness to hydrological extremes. The sentence previously beginning with "Despite these discrepancies..." (lines 284–285 in the original version) has been revised to emphasize that while CLM5 and ERA5-Land align in anomaly phase, they diverge significantly in magnitude. We also added supporting literature (e.g., Muñoz-Sabater et al., 2021), noting ERA5-Land's enhanced responsiveness to meteorological forcing due to its reanalysis design.

- Seasonal Variability (Section 3.3 – Seasonal Variability of Soil Moisture):
  We have inserted a new paragraph discussing the systematic underestimation of seasonal amplitude in CLM5 simulations, especially during the spring-summer transition. This observation, now clearly stated and referenced (e.g., Stahl and McColl, 2022), complements the interannual findings by showing that modeled soil moisture dynamics are dampened not only year-to-year but also within seasonal cycles. We interpret this underestimation as a likely artifact of overly conservative or static soil hydraulic properties in the parameter sets.

These additions enhance the manuscript's clarity and transparency regarding model limitations. We believe the revised text now better contextualizes the role of parameter choices in limiting model variability and strengthens our case for including multiple observational references in future work. We thank the reviewer again for bringing this important issue to our attention.

3. Neglect of Irrigation Effects:

The authors identify significant differences between CLM5 and ERA5-Land EOF modes in agriculturally intensive areas, particularly the central U.S. (Figure 11b). These "hotspots" overlap spatially with known heavily irrigated regions, including the Ogallala Aquifer and Mississippi Valley [McDermid et al., 2023]. However, the manuscript does not clarify:

- Whether Irrigation was included in CLM5 simulations.

- How Irrigation may affect soil moisture in ERA5-Land.

This omission weakens the attribution of model-observation discrepancies solely to soil parameterization. Explicit discussion on irrigation modeling and its inclusion or exclusion is essential to substantiate the attribution claims made (e.g., Lines 14–15).

Response: We thank the reviewer for this important comment regarding irrigation and its potential influence on the soil moisture discrepancies observed between CLM5 and ERA5-Land, particularly in the agriculturally intensive regions of the central U.S. We clarify that irrigation was not included in any of the CLM5 simulations used in this study. All experiments were conducted under naturalized conditions to isolate the influence of soil hydraulic parameterizations without additional confounding from anthropogenic water inputs. This decision aligns with our study's objective, which is to examine the intra-model sensitivity of CLM5 to soil parameter settings under consistent and climatically driven boundary conditions. We now explicitly state this in Section 2.2.1 (Experimental Designs):

"....Importantly, irrigation processes were not represented in any of the CLM5 simulations, as all experiments were conducted under naturalized conditions to isolate the influence of soil hydraulic parameterizations without additional anthropogenic water inputs."

Regarding ERA5-Land, we also confirm that irrigation is not represented in the ERA5-Land land surface simulations. The H-TESSEL model used to produce ERA5-Land does not include irrigation schemes or anthropogenic water management processes, as noted in previous studies (Wipfler et al., 2011; Lavers et al., 2022; Tang and McColl, 2023). We have incorporated this clarification into the revised Section 2.2.2 (Reference Dataset), noting that while ERA5-Land is a high-quality benchmark for pattern-oriented analysis, both CLM5 and ERA5-Land effectively simulate non-irrigated soil moisture dynamics. Therefore, the attribution of observed differences in EOF structure over agricultural "hotspots" to parameterization effects remains valid within the assumptions of this framework.

That said, we agree that in heavily irrigated areas such as the Ogallala Aquifer region or parts of the Mississippi Valley, the exclusion of irrigation from both datasets may limit interpretability, as true soil moisture conditions in these areas are influenced by human water use. We have included a statement to this effect in the revised Discussion, emphasizing that future work should incorporate irrigation modeling or use observation-driven products (e.g., SMERGE, GLEAM) that account for such influences, especially in agriculturally dominated landscapes. We appreciate the reviewer's guidance on this issue and believe the revised manuscript now provides a clearer and more transparent account of irrigation-related limitations and assumptions.

4. Initial Conditions Not Explained:

The setup of initial conditions in the model simulations remains unclear. Since each experiment involves different soil parameter settings, it is essential that the model reaches equilibrium separately for each case [Kennedy et al., 2024]. Without spin-up or appropriate initialization, differences in the initial soil moisture state could propagate and bias the results.

Please clarify whether each experiment was initialized to equilibrium independently, and if so, provide methodological details.

Response: We thank the reviewer for highlighting the importance of proper initialization and the potential impact of non-equilibrated soil moisture conditions. In response to this comment, we have revised Section 2.2.1 (Experimental Designs) to explicitly describe the spin-up procedure used for all CLM5 simulations.

As now clarified in the manuscript, each experiment (EXP1, EXP3, EXP4a–4d) was independently initialized using the standard CLM5 spin-up protocol. This approach involves running the model through an accelerated decomposition (AD) mode followed by a normal mode with repeated cycling of GSWP3 meteorological forcing. The spin-up process was conducted until key state variables such as total water storage, soil carbon, and vegetation biomass reached quasi-equilibrium, ensuring that each simulation began from a stable baseline (Lawrence et al., 2019). Spin-up followed SP-MIP protocol guidelines to ensure equilibrium prior to the 1980 to 2010 simulation period (Gundmundsson and Cuntz, 2017).

These updates now make it clear that any differences observed between experiments are attributable to the imposed soil parameter configurations and not to transient effects or inconsistencies in the initial conditions. We appreciate the reviewer's suggestion, which helped improve the clarity and methodological rigor of the manuscript.

Minor Comments:

- Line 32: The phrase "such as artificial neural networks" requires a reference. A citation demonstrating the use of ANN as PTFs would be appropriate. - We have included two citations: da Silva et al. 2023 and Schaap et al. 1998, to support the use of neural network-based PTFs.

- Line 77: Parentheses are inconsistent in references; e.g., fix "Ji et al……, Zeng et al., (2021)" to consistent formatting. - We have corrected this.

- Line 132: Typo: "PFTS" should be corrected to "PTFs."

  We have corrected the typo to refer to pedotransfer functions accurately.

- Lines 160–179 (Section 2.3): Consider revising for clarity. There are some repetitions, e.g., "dominant variability modes and their temporal patterns"…" spatial and temporal patterns"…

  We have streamlined the text to eliminate redundancies and enhance the description of the EOF analysis methodology.

- Line 193: The term "demeaned" could be clarified or rephrased for general readability.

  We have rephrased the sentence to read "... where the mean at each grid point has been removed to highlight variability."

- Figure 5: Further explanation is needed regarding the variability difference between ERA5-Land and CLM5 simulations.

  Response: We thank the reviewer for pointing out the need to clarify the variability difference between ERA5-Land and CLM5 simulations. In the revised manuscript, we have significantly expanded the "Interannual Soil Moisture Anomalies" subsection to address this issue. We now quantify the amplitude discrepancy, noting that ERA5-Land anomalies reach up to ± 40k\ m², while CLM5 anomalies are generally confined to a ± 20 kg\m² range. This underestimation reflects a muted response in CLM5, which we attribute to structural limitations such as static soil parameterization, overly diffusive vertical redistribution, and the absence of data assimilation factors that have been shown to reduce variability in land surface models (Koster et al., 2009; Muñoz-Sabater et al., 2021). We further discuss how this dampened variability may impact key hydrological processes like evapotranspiration, runoff, and land–atmosphere coupling (Koster et al., 2004; Berg and Sheffield, 2018). In addition, the caption for Figure 5 has been revised to clearly state the contrast in anomaly range between CLM5 and ERA5-Land, helping guide the reader's interpretation. These revisions directly respond to the reviewer's concern and enhance both the clarity and analytical depth of the section.

- Lines 218–319: The statement about 5 cm in-situ sensors vs. ERA5-Land's 0–7 cm integration is not directly relevant when the analysis uses 0–1 m averaged soil moisture. Clarify or remove.

  We have removed the statement to focus on the relevant depth.

- Figure 7: Please explain the significant differences between EAR5-Land variability and CLM5 cluster, except for Exp4-a.

  Response: We thank the reviewer for this helpful observation. In response, we have revised the Seasonal Variability of Soil Moisture *s*ubsection to provide a more detailed analysis of the differences between ERA5-Land and the CLM5 simulations (EXP1–EXP3), and to highlight the unique behavior of EXP4a. Specifically, we now explain that EXP1, EXP2, and EXP3 form a tightly clustered group with relatively flattened seasonal cycles that substantially underestimate the amplitude of variability observed in ERA5-Land. These configurations fail to capture the sharper rise in spring and pronounced decline in late summer exhibited by the reanalysis data. In contrast, EXP4a stands out as it more closely aligns with ERA5-Land in both phase and amplitude during the active seasonal months, which we attribute to its loamy sand texture and low water retention capacity. These additions clarify the model–reanalysis discrepancy, reinforce the role of soil texture in amplifying seasonal dynamics, and directly address the reviewer's request. We also revised the Figure 7 caption to highlight these findings more clearly.

- Figures 9 and A2: Clarify whether maps show EOF loadings or correlation coefficients. If correlation coefficients are used, explain the meaning and implications, e.g., correlation with respect to what?

Response: We thank the reviewer for raising this important point regarding the interpretation of the spatial patterns in Figures 9 and A2. We confirm that both sets of maps depict correlation coefficients, not raw EOF loadings. Specifically, the values represent correlation coefficients between the time series of each grid point's soil moisture anomalies and the corresponding principal component (PC) time series associated with the EOF mode. To address this comment and improve clarity for the reader, we have made the following revisions in the manuscript:

- Section 3.4.2 (Spatial and Temporal Analysis of EOF Modes) now explicitly states that the figures show correlation maps, not EOF loadings. We describe that the correlation coefficient quantifies the strength and direction of association between local soil moisture anomalies and the temporal evolution of each mode. A new sentence has also been added to explain that positive correlations indicate regions that vary in phase with the PC time series, while negative correlations reflect anti-phase behavior, thus providing insight into the regional expression of each mode.
- The caption of Figure 9 has been revised to clarify that the shading indicates correlation coefficients, and we have explained the interpretation of positive and negative values in the context of EOF-PC relationships.
- The caption of Figure A2 has been similarly updated to ensure consistency and interpretive transparency. It clearly states that the maps show correlation coefficients and describes what those correlations represent in terms of spatial coherence with the temporal EOF modes.

We believe these changes address the reviewer's concerns and improve the manuscript's clarity regarding the meaning and implications of the spatial EOF visualizations. We appreciate the reviewer's suggestion, which has helped us strengthen both the technical accuracy and readability of the manuscript.

- Table 3: Please include a total cumulative variance explained by the first 10 EOF modes for each experiment.

We have updated Table 3 to include the total cumulative variance explained.

EOF Mode	EXP1 %Expl. Var.	EXP2 %Expl. Var.	EXP3 %Expl. Var.	ERA5-Land %Expl. Var.
EOF-1	11.45	11.66	10.84 ↓[2]	17.5 ↓[2]
EOF-2	10.40	10.60	9.85 ↑[1]	8.48 ↓[3]
EOF-3	8.81	8.25	9.08	7.83 ↑[1]
EOF-4	5.69	5.83	5.73	5.75
EOF-5	4.37	4.59	4.48	5.61
EOF-6	3.49	3.56	3.48	3.64
EOF-7	3.26	3.23	3.24	3.10
EOF-8	2.51	2.53	2.63	2.86
EOF-9	2.14	2.16	2.22	2.76
EOF-10	1.96	1.99	1.95	2.22
Total Cumm. %Expl. Var.	54.07	54.4	53.49	59.77

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