We thank Reviewer #1 for the constructive comments and suggestions, which greatly help to improve the quality of our manuscript. We have made revisions and replied to all the comments. Please find the point-by-point responses to the comments. Our responses are shown in "Blue" and the changes in the manuscript are shown in "Red".

Response to the comments from Reviewer #1

Comment#1:

Abstract: Please specify the reanalysis data you assimilate and improvements of soil moisture and temperature simulations.

Response:

Thank you for your suggestion. In response to your comment, we have clarified in the abstract that the assimilated data is derived from the Global Land Data Assimilation System (GLDAS) reanalysis (L18-21). Additionally, we have provided more specific details (L26-29) regarding the improvements resulting from our soil moisture and temperature assimilation. In terms of both soil moisture and temperature, the assimilation experiment outperforms the control simulation with reduced RMSE and higher temporal correlation in many regions, especially in South America, Central Africa, Australia, and large parts of Eurasia.

In light of your feedback, we have incorporated mentions of the specific "GLDAS" reanalysis (L18-21) and more detailed descriptions (L26-29) regarding the improvements in the Abstract.

L18-21: With an initial interest in providing initial conditions for decadal climate predictions, monthly mean anomalies of soil moisture and temperature from the Global Land Data Assimilation System (GLDAS) reanalysis from 1980 to 2016 are assimilated into the land component of E3SMv2 within the coupled modeling framework with a one-month assimilation window.

L26-29: In terms of both soil moisture and temperature, the assimilation experiment outperforms the control simulation with reduced RMSE and higher temporal correlation in many regions, especially in South America, Central Africa, Australia, and large parts of Eurasia.

Comment#2:

Sub-section 2.2: GLDAS dataset cannot actually be classified as a “observation dataset” since it is generally based on land surface models. Besides, soil moisture derived from different land surface models are systematically different (e.g., different soil moisture range and long-term mean value) which may introduce additional bias into the coupled data assimilation system. How do you handle this problem?

Response:

We agree that GLDAS data are land reanalysis data produced by models. Accordingly, we have revised our manuscript to replace the term "Observational Dataset" with "Land Reanalysis Dataset" on line 151.

We would like to clarify that our employed DRP-4DVar method does not input the full information of the GLDAS data into the initial conditions (ICs) of E3SM but rather, only incorporates part of the GLDAS information by fitting reanalysis data with historical samples produced by the model to form consistent forecast states (Wang et al., 2010). In light of your comment, we have further modified our experiment design to add bias correction before assimilation and conduct the anomaly assimilation for the weakly coupled land data assimilation (WCLDA) systems (L168-171). In our revised manuscript, we have updated all of the figures (Figures 3 to 10) along with their corresponding descriptions to represent the assimilation performance with bias correction.

L168-171: In this study, we conduct the anomaly assimilation for the WCLDA system with bias correction applied to GLDAS data before assimilation. For bias correction, the difference between GLDAS data and its long-term average is calculated as anomalies and then added to the simulated model climatology.

Comment#3:

Eq. (5): How to represent the cost function? Please add a string or symbol.

Response:

In the revised manuscript, we have added equations for "J_0" and "J_1" (L303) to represent the observational cost function before and after assimilation respectively in Eq. (8).

L303:

$$\begin{cases} \frac{J_1 - J_0}{J_0} \times 100\% \\ J_0 = \frac{1}{2}(y_{obs} - y_b)^T R^{-1}(y_{obs} - y_b) \\ J_1 = \frac{1}{2}(y_{obs} - y_a)^T R^{-1}(y_{obs} - y_a) \end{cases} \quad (8)$$

where J_0 and J_1 denote the observational cost function before and after assimilation respectively.

Comment#4:

Figure 3: How do you explain the temporal dynamics (maybe some seasonal cycles) of the cost function?

Response:

We have also noticed the cyclical behavior in the cost function. It has been noted that the assimilation performance diminishes during the spring maybe related to the "spring barrier" (Mu et al., 2007) and subsequently recovers in the summer. This phenomenon might be attributed to intrinsic model limitations. Further analysis is required to fully elucidate the underlying causes.

Comment#5:

Figure 4: The explanations summarized in sub-section 3.2 are inadequately for demonstrating

soil moisture degradation over many regions after the coupled data assimilation. It is suspiciously for me that Figure 4a, i and j show similar degradation spatial patterns while Figure 4b-h perform differently. If these degradations are related to GLDAS data quality, the off-line data assimilation results should be degraded over similar regions. I think more interpretations or experiments are necessary to figure out these issues.

Response:

Thank you for your thoughtful comments. In Figure 4, assimilation performance is degraded in the northern part of Russia and northern Africa. This is consistent with the findings in other studies that assimilation updates in northern Russia are limited due to the complexities of accurately representing frozen ground and snow processes in high latitudes (Edwards et al., 2007; Ireson et al., 2013). The surface soil moisture is highly susceptible to atmospheric conditions, subsequently affecting the assimilation performance. Furthermore, some degradations found in the deep layers could be attributed to the substantial influence of various terrestrial factors, such as subsurface runoff and interactions with groundwater, similar to the findings in previous studies (Liu and Mishra, 2017; Zeng and Decker, 2009).

In light of your suggestions, we have incorporated more detailed interpretations (L331-339) into the revised manuscript.

L331-339: However, assimilation performance is degraded in the northern part of Russia and northern Africa. This is consistent with the findings in other studies that assimilation updates in northern Russia are limited due to the complexities of accurately representing frozen ground and snow processes in high latitudes (Edwards et al., 2007; Ireson et al., 2013). As surface soil moisture is highly susceptible to atmospheric conditions, assimilation performance of surface soil moisture is limited by the accuracy of atmospheric forcing. Furthermore, some degradations found in the deep layers could be attributed to the substantial influence of various terrestrial factors, such as subsurface runoff and interactions with groundwater, similar to the findings in previous studies (Liu and Mishra, 2017; Zeng and Decker, 2009).

Comment#6:

I suggest adding a discussion section and focusing on the preconditions or theory basis for applying coupled data assimilation. For examples, if the land-atmosphere relationship is poorly represented, the improved land surface states may incorrectly influence the atmospheric process; for humid regions, the evaporative regime is typically energy-limited and the assimilation of soil moisture has very limited benefit while soil temperature may more effective. Vice versa for arid regions…

Response:

We agree with your opinion that the influence of the weakly coupled land data assimilation system on atmospheric processes may be limited in some domains due to uncertainties of the model parameterizations, particularly in representing land-atmosphere interactions (Zhou et al., 2023). For instance, in humid regions, where the evaporation process is predominantly regulated by energy, the assimilation of soil moisture tends to manifest a relatively small influence. In contrast, the assimilation of soil temperature may facilitate notable improvements within these regions. This underscores the importance of the unique characteristics and constraints presented by complicated regional conditions in the application of assimilation processes.

In response to your recommendation, we have incorporated this discussion (L450-457) in the revised manuscript.

L450-457: It is possible that the influence of the WCLDA system on atmospheric processes may be limited in some domains due to uncertainties of the model parameterizations, particularly in representing land-atmosphere interactions (Zhou et al., 2023). For example, in humid regions where the evaporation process is predominantly energy-limited, the assimilation of soil moisture tends to exert limited influence. Instead, the assimilation of soil temperature may yield more substantial improvements. This underscores the importance of the unique characteristics and constraints presented by complicated regional conditions in the application of assimilation processes.

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