Review of “Mid-Holocene ITCZ migration: Connection with Hadley cell dynamics and impacts on terrestrial hydroclimate”

By Bian et al.

I have previously reviewed the manuscript, and the authors have conducted substantial analysis to address the reviewers' concerns and enhance the study's novelty. They have largely revised the manuscript, making the storyline clearer and easier to follow. I find the paper interesting and valuable for publication. However, it still requires some revisions, as some of our concerns have not been fully addressed.

--We greatly appreciate the constructive comments and kind suggestions from the reviewer, which have significantly enhanced the quality of our manuscript. Please find our responses (in blue) to the reviewer’s comments (in black).

1. A clear knowledge gap needs to be clearly defined at the beginning of the introduction. The current introduction is not efficient at this point. I must say I only capture such a piece of information in the main context of lines 275-279. It would be very helpful if the author could write one or two sentences to address the question “What is new for the present study?”.

--Reply. Thanks for the suggestion. We have added related contents of knowledge gaps and creative points for this study to the second last paragraph of **Introduction**.

- **L85-93 in the revision with tracked changes**. Despite the many earlier studies, the complex interactions between the ITCZ, Hadley cell and hydrological changes during the mid-Holocene remain insufficiently understood. Therefore, a detailed quantitative evaluation of their dynamic interplay and multi-scale atmospheric processes involved is important, including changes in cross-equatorial energy flux transport by the stationary and transient eddies. This study addresses these gaps by focusing on three key aspects: (1) the dynamic connection between the northward ITCZ shift and Hadley cell changes during the mid-Holocene; (2) the joint influence of the ITCZ-Hadley cell evolution on the mid-Holocene hydrological cycle; and (3) the evaluation of consistency between proxy data and model simulations regarding terrestrial hydroclimate and land aridity in the mid-Holocene. Building on the recent advances in understanding the mid-Holocene global ITCZ by Bian and Räisänen (2024), this work specifically targets these critical research aspects.

2. In the abstract also in the conclusion, the authors have a strong statement of "Orbital forcing during the mid-Holocene does not directly drive the hemispheric asymmetry in annual atmospheric radiation balance." Why? The orbital forcing initialed all the changes in the solar radiation, and thereafter, drove changes in atmospheric circulation and further enhanced the hemispheric asymmetry in annual atmospheric radiation balance. Could you please make it more specific? What do you mean by "directly drive the hemispheric asymmetry in annual atmospheric radiation balance"? Maybe I just missed some key figures or results in the manuscript.

--Reply. To eliminate the risk of misunderstanding, we have rewritten the **L17-18** in the **Abstract** as: Although orbital forcing during the mid-Holocene was symmetric around the equator in the annual mean, it indirectly drove hemispherically asymmetric changes in annual atmospheric radiation balance.

- During the last round's revision, we have added three paragraphs in **Section 3.3** and two extra figures (**Figures A1, A2**) in the **Appendix A** to further clarify the changes in atmospheric radiation balance during the mid-Holocene.
- In the annual mean, orbital forcing is symmetric between the two hemispheres, while the change in the annual mean atmospheric radiation balance is asymmetric, with a slight positive anomaly ($\delta Ra > 0$) from 10°N to 30°N for land and ocean (**Figure 4b**), and 15°N to 40°N for land alone (**Figure 4d**). This suggests that factors other than the direct orbital forcing are also important.
- We further analyze the separate contributions of the shortwave (SW) and longwave (LW) flux components to the atmospheric radiation balance. Please see further details on **L384-393**.
- We further conducted analysis of the annual net surface energy budget ($\delta(Rs - SH0 - LE)$). Please see further details on **L394-401.**

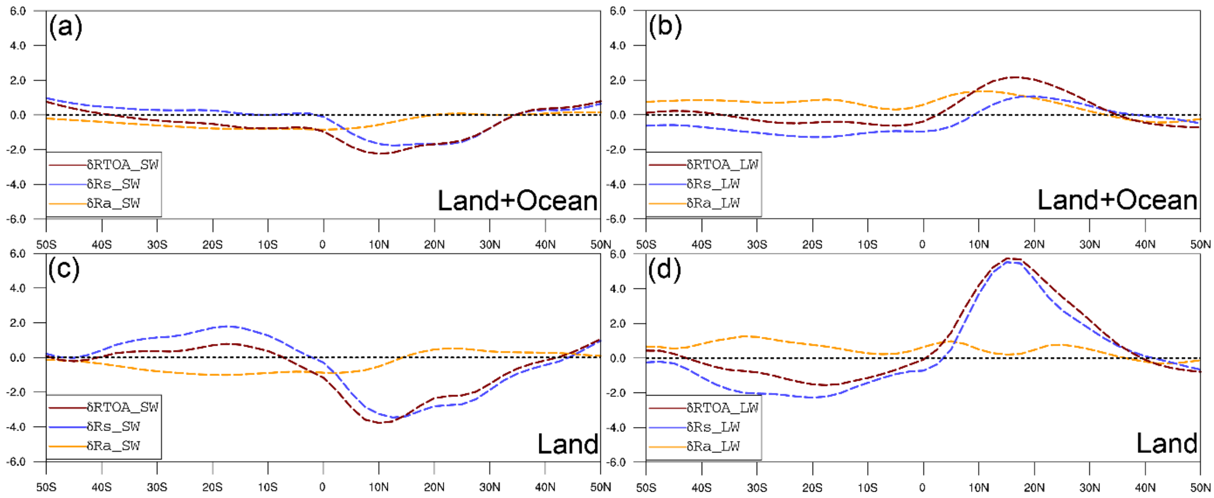

Figure A1. Individual contributions of the shortwave (a) and longwave (b) flux components to the changes of annual atmospheric radiation balance from the PI to the MH period. (c), (d) are as (a), (b) respectively, but for land only. The unit is W m^{-2}. All results are based onPMIP4-CMIP6 multimodel averages.

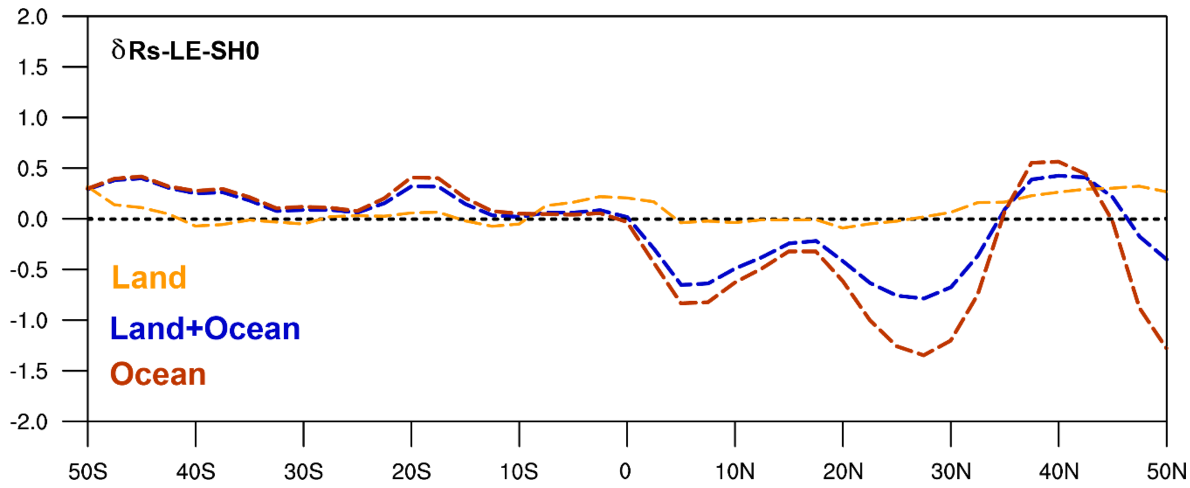

Figure A2. Changes in the annual net surface energy budget ($\delta(Rs - SH0 - LE)$) from the PI to the MH period (unit: W m^{-2}). All results are based on PMIP4-CMIP6 multimodel averages.

3. The discussion in the conclusion section of lines 538-556 is very interesting and important. I take the conclusion that “the contributions from transient and stationary eddies are not negligible in mid-Holocene”, as a key new finding of the present study. However, the discussion here only provides reviews on the debate on the importance of eddy fluxes from previous studies. I would suggest the authors add some findings from your results. What do we learn from your analysis in the mid-Holocene? You have done a comprehensive dynamic analysis to draw a conclusion here.

--Reply. Thanks for the suggestion. We agree that contributions from transient and stationary eddies are not negligible in the mid-Holocene, as shown by both multiple previous studies and our own comparison results. We have added analysis of this in **Section 3.2** and **Appendix B**.

- Our results identified that the annual cross-equatorial energy flux exhibits negative anomalies ($\delta F < 0$) in the deep tropics as well as the Northern Hemisphere, indicating reduced northward energy transport from the Southern Hemisphere during the mid-Holocene. This imbalance shifts the energy flux zero-crossing latitude northward, resulting in a corresponding northward migration of the ITCZ (**Eq. B1** and **Figure B1**). However, as shown in **Eqs. B2-B3** and **Figure B1**, the contributions from the SE and TE eddies changes are not negligible during this period. These complexities highlight the limitations of the energetic constraint framework in fully explaining ITCZ shifts and their nonlinear relationship with Hadley cell dynamics during the mid-Holocene. Please see further details on **L280-296** and **L556-575**.

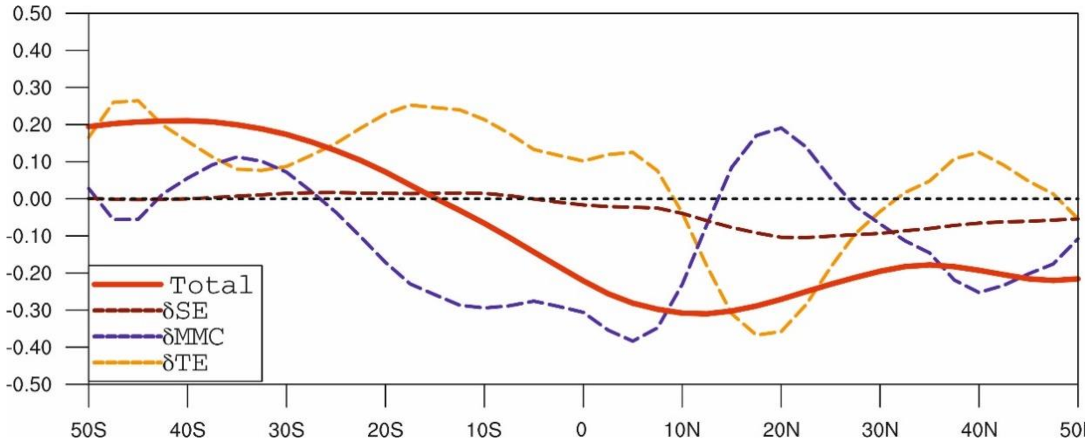

Figure B1. Changes in the annual atmospheric meridional energy transport by the mean meridional circulation (MMC), stationary eddies (SE), and transient eddies (TE) from the PI to the MH period (unit: PW). See Eqs. B2-B3 in Appendix B for further details. All results are based on PMIP4-CMIP6 multimodel averages.

4. Figure 4 requires efforts to improve, and the same for Figure 6. There are busy figures. The colors and marks make the figures difficult to read. In the legend, the change in precipitation is solid red, but it is dash red in the figure, and the change in P-E is solid blue, but it is dash blue in the figure. My suggestions would be to only use different colors for the terms, darker and thick lines for the key information of the figure, and lighter colors for the less important information.

--Reply. We agree with this comment and have revised them accordingly.