Review of “Mid-Holocene ITCZ migration: impacts on Hadley cell dynamics and terrestrial hydroclimate” by Jianpu Bian, Jouni Räisänen, and Heikki Seppä.

This paper presents an analysis of the PMIP4 mid-Holocene (MH) simulations using a set of metrics to quantify changes in the ITCZ and Hadley Cell edge and extent. The paper also includes a broader discussion of the aridity and atmospheric circulation changes in the MH simulations and comparison with available proxy records. The paper is generally clearly written and describes the experiments and results thoroughly. There is a detailed comparison of different methods to define the Hadley Cell edge and strength and the MSE budget. The results will contribute to understanding of MH climate changes in climate model simulations. Overall the paper is a valuable contribution, presenting new and interesting results. I support publication subject to revisions addressing comments outlined below.

--We sincerely thank the reviewer for the thoughtful and constructive comments, which have significantly improved the quality of our manuscript. We have made substantial revisions and greatly extended the manuscript, with four new figures added for the analysis. Please find our point-to-point responses (in blue) to the reviewer comments (in black).

General comments:

My main concern is the focus on the annual mean changes. The key changes in the mid-Holocene are associated with seasonal shifts in insolation due to altered timing of perihelion, so that the seasonal mean anomalies will be larger and easier to interpret. Annual changes may involve offsetting summer and winter changes – for example, see Figure 6 of Brierley et al. (2020) mid-Holocene PMIP paper, where many changes in DJF and JJA precipitation are opposite in sign.

I suggest including analysis of the seasonal changes in addition to annual mean. As there is a clear seasonal change in insolation due to orbital changes, the resulting changes in atmospheric circulation and precipitation will be easier to interpret at seasonal time scales, e.g. for the summer monsoons in each hemisphere. It is also possible that MH minus PI Hadley cell changes will differ in Northern Hemisphere (NH) versus Southern Hemisphere (SH) winter given the strong seasonal orbital forcing anomalies.

--Reply. We agree with this comment and appreciate the suggestion. Although our study primarily focuses on annual changes in global and terrestrial hydroclimate, we acknowledge the importance of seasonal evolution in the hydrological cycle. We have rewritten **Section 3.3** and added three related paragraphs and two new figures (i.e. **Figures 5 and 6** in revised manuscript) to further analyze seasonal hydrological cycle changes and compare them with annual means. Additionally, we have further compared our results with Brierley et al. 2020, D'Agostino et al. 2019, 2020, and other related studies.

- During the mid-Holocene, seasonal anomalies are generally larger than annual changes**.** **L311-314**: The changes in perihelion precession and altered insolation patterns in the mid-Holocene influenced seasonal and inter-hemispheric thermal contrast between winter and summer, intensifying the seasonal variation in the cross-equatorial Hadley cell and ITCZ (Diaz and Bradley, 2004; Harrison et al., 2014; Claussen et al., 2017; Brierley et al., 2020; Lionello et al., 2024).
- We agree that the annual precipitation changes may involve offsetting summer and winter changes as mentioned in Brierley et al. 2020. In tropics and subtropics in both hemispheres, the global precipitation and P-E anomalies have reversed changes between winter and summer. Regarding the seasonal evolution over land and ocean separately, as shown in **Figure 5**, the marine areas also have contrasting precipitation and P-E anomalies between winter and summer, particularly in subtropics. Over land, annually averaged changes in the terrestrial hydrological cycle primarily reflect the changes in the summer season, with an amplified inter-hemispheric contrast during the mid-Holocene. Land areas in both hemispheres exhibit only minor changes in winter (**Figure 5**).
- **L323-334**: **Figure 5** further illustrates that the seasonal evolution in the hydrological cycle exhibits contrasting patterns between terrestrial and marine areas. Over land, key terrestrial hydrological components, including precipitation (**Figure 5a**), surface evaporation (**Figure 5c**), runoff (**Figure 5e**), and mid-tropospheric vertical motion (**Figure 5g**), show significant increases in the Northern Hemisphere during the mid-Holocene summer season (June-to-September; JJAS). This intensification is particularly evident in the West African and Asian Monsoon systems in the Northern Hemisphere, where monsoonal rainfall is greatly enhanced (Pausata et al., 2016; Claussen et al., 2017; D'Agostino et al., 2019; Brierley et al., 2020; Bian and Räisänen, 2024). In contrast, the Southern Hemisphere summer season (December-to-March;

DJFM) exhibits an opposite change of terrestrial hydrological cycle compared to the Northern Hemisphere, which is largely attributed to the suppression of subtropical monsoonal systems and reduced monsoonal precipitation (D'Agostino et al., 2020; Bian and Räisänen, 2024). Meanwhile, in their winter seasons, both hemispheres experience only minor alterations over land, emphasizing that terrestrial hydrological cycle changes are predominantly driven by summer season dynamics with an amplified inter-hemispheric contrast during the mid-Holocene.

- **L336-342**. Compared to terrestrial hydrological cycle changes, the seasonal evolution of hydrological changes over ocean shows no pronounced inter-hemispheric asymmetry during the mid-Holocene (**Figures 5b, 5d, 5f, and 5h**). In the marine tropics, both precipitation and runoff decline throughout the annual cycle (**Figures 5b, 5f**). Meanwhile, in both the northern and southern subtropical oceans, precipitation and runoff increase during DJFM but decrease in JJAS (**Figures 5b, 5f**), resulting in a small positive annual-mean anomaly driven by enhanced water vapor convergence (**Figure 4c**; Bian and Räisänen (2024)). Another notable land–ocean contrast lies in evaporation: while terrestrial evaporation exhibits marked inter-hemispheric differences, oceanic evaporation declines across the annual cycle in both hemispheres (**Figures 5c, 5d**).
- **L344-354**. Further analysis of the seasonal evolution of moisture budget between land and ocean indicates that the dynamic term (δDY) is the primary driver of terrestrial precipitation changes in the Northern Hemisphere during JJAS (**Figure 6a**), particularly in the NH monsoonal regions as discussed in D'Agostino et al. (2019). Strengthened mean atmospheric flow (i.e. δDY) increases moisture convergence, thereby reinforcing NH monsoons and monsoonal rainfall during the mid-Holocene (D'Agostino et al., 2019; D'Agostino et al., 2020; Bian and Räisänen, 2024). Conversely, the dynamic term (δDY) is also the dominant factor in the reduction of terrestrial precipitation in the Southern Hemisphere during DJFM (**Figure 6b**). Unlike the annual moisture budget variations depicted in **Figure 4c**, the transient eddy flux term (δTE) plays a compensatory role in the NH summer terrestrial precipitation changes. Moreover, both hemispheres exhibit relatively minor changes in terrestrial moisture budgets during winter seasons (**Figures 6a, 6b**), indicating that shifts in the terrestrial hydrological cycle are primarily driven by summer dynamics during the mid-Holocene.
- **L314-319** From an energetic constraint and eddy-mediated view, monsoons as integral components of the large-scale tropical overturning circulations of the Hadley cell and

ITCZ (Bordoni and Schneider, 2008; Schneider et al., 2014; Geen et al., 2020; Biasutti et al., 2018; Hill, 2019), further exhibited pronounced seasonal migration and contrast with significantly modulated monsoonal rainfall patterns during the mid-Holocene (Claussen et al., 2017; Tierney et al., 2017; D'Agostino et al., 2019; D'Agostino et al., 2020; Geen et al.,2020; Kang, 2020; Lionello et al., 2024).

- Our work in preparation for the mid-Holocene asymmetric evolution of Hadley cells shows that the cross-equatorial winter Hadley cell becomes much stronger with increased width during the mid-Holocene, while the summer Hadley cell weakens and shifts northward. The enhanced seasonal contrasts in Hadley cell dynamics further influence hemispheric monsoon patterns as noted in D'Agostino et al., 2019, 2020.

There is also some apparent confusion regarding the annual mean insolation change due to orbital differences at 6ka relative to pre-industrial. For example, in the abstract it is stated that "orbital forcing increased radiative heating in the Northern Hemisphere" and at line 318, the paper mentions "increased solar radiation in the Northern Hemisphere driven by orbital forcing". While this is true for the NH spring/summer, the paper presents annual mean results only.

Obliquity changes at 6ka cause annual mean heating at high latitudes versus tropics in both hemispheres, whereas precession of perihelion causes anomalies in seasonal heating in both NH and SH which cancel out for the annual average. It is therefore confusing to present annual mean results but refer to orbital increases in NH insolation and heating.

There may be an annual mean increase in NH temperature in some models – but there is no figure showing this, and it is not evident in the PMIP4 ensemble mean temperature as shown in Brierley et al. (2020) Figure 1: the NH is mainly cooler except for high northern latitudes. Given this, I cannot see how the results show "increased radiative heating in the Northern Hemisphere" for annual averages. Please clarify this.

--Reply. We appreciate the suggestion and agree that the orbital forcing was discussed in a potentially misleading way in the original manuscript. We have revised those places accordingly in the revision. Furthermore, we have added three paragraphs in **Section 3.3** and two extra figures in the **Appendix** to further clarify the changes in atmospheric radiation balance during the mid-Holocene.

- **L360-367:** We agree that changes in radiative forcing due to orbital parameters result in increased net radiation (δRa > 0) in the Northern Hemisphere during spring and summer (Brierley et al., 2020). 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 (δRa > 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.
- **L368-377**. We further analyze the separate contributions of the shortwave (SW) and longwave (LW) flux components to the atmospheric radiation balance (**Figure A1**). In the Northern Hemisphere, enhanced atmospheric absorption of SW radiation (δRs_SW), which is primarily due to increased atmospheric water vapor and cloudiness, contrasts with reduced SW absorption in the Southern Hemisphere (**Figures A1a, A1c**). Additionally, changes in cloudiness and water vapor could affect the rate of longwave cooling and then lead to changes in radiative transfer and heating process. During the mid-Holocene, reduced atmospheric LW cooling (i.e. −δRa_LW; **Figures A1b, A1d**) further increases the atmospheric radiation balance (δRa) in the Northern Hemisphere, though this effect plays a secondary role in creating the hemispheric asymmetry. Therefore, the combination of reduced surface SW radiation (δRs_SW; **Figures A1a and A1c**) and increased δRa_SW (i.e. δRTOA_SW −δRs_SW; **Figures A1a, A1c**) in the Northern Hemisphere suggests that increased cloudiness and water vapor play an important role.
- **L378-384**. Furthermore, changes in the annual net surface energy budget (δ(Rs −SH0 −LE)) over land are minimal due to the small heat capacity of the land surface, but over the ocean, shifts in heat transport disturb this balance (**Figure A2**). Specifically, the negative anomalies of δ(Rs−SH0−LE) in the Northern Hemisphere tropics seem much larger than the positive anomalies in the Southern Hemisphere tropics (**Figure A2**). This disparity suggests that ocean currents are transferring more heat from the Southern Hemisphere to the Northern Hemisphere, thereby amplifying the inter-hemispheric asymmetry in the ocean-to-atmosphere energy transfer and annual atmospheric radiation balance during the mid-Holocene.
- **L384-385**. Additionally, inherent geographic differences between the hemispheres, particularly in land-sea distribution, may further contribute to this asymmetry, although delineating the precise processes involved remains challenging.

Specific comments:

Abstract, line 16: Clarify that the wetter NH and drier SH is mainly over land. (Note that this also may vary when considering seasonal changes – see General Comment above).

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

Line 59: Use of bilinear interpolation – it is normally better to use conservative regridding for fields such as precipitation and mass streamfunction. Please confirm the choice of regridding does not significantly alter the results.

--Reply. We agree with this comment. We further tested the conservative interpolation method for precipitation and streamfunction metrics and compared them with bilinear methods. The differences among these results are generally small and non-significant. We have revised and confirmed this issue in Section 2.1. Please find further details in **L103-105**.

Line 130: As discussed in General Comment above, there would be some benefit to also including seasonal mean results, e.g. for DJF and JJA seasons.

--Reply. We agree with this comment. We have rewritten **Section 3.3** and added three related paragraphs for the analysis of seasonal results. Please find further details in **L311-354**.

Line 131: Make clear that you are comparing the CMIP6-PMIP4 PI simulations with observations here. This should also be stated in the caption for Figure 1.

--Reply. We agree with this comment and have revised it.

Line 135: According to the legend, Figure 1c shows the multi-model *median* not the mean – if you are using this to argue that the multi-model mean should be used elsewhere, I suggest modify Figure 1c to show the multi-model mean not median.

--Reply. Thanks for noticing this typo, which we have corrected in the revised manuscript. The figure indeed shows the multi-model mean result, not the multi-model median.

Line 159-161: Note that some of the discussion in Reeves et al. (2013) of changes towards wetter/drier conditions is expressed relative to the early Holocene, not to the late Holocene or pre-industrial. It may also be worth including comparison with Petherick et al. (2013) paper about temperate Australian records:

Petherick, L., Bostock, H., Cohen, T. J., Fitzsimmons, K., Tibby, J., Fletcher, M. S., ... & Dosseto, A. (2013). Climatic records over the past 30 ka from temperate Australia–a synthesis from the Oz-INTIMATE workgroup. Quaternary Science Reviews, 74, 58-77.

--Reply. We agree with this comment and have added Petherick et al. (2013) work in the analysis.

- **L221-227**: For northern Australia, recent studies indicate that the contraction of the local ITCZ contributed to reduced monsoon activity and precipitation (Reeves et al., 2013; Proske et al., 2014; Field et al., 2017; Lowry and McGowan, 2024), which aligns with PMIP4 simulation results (**Figures 1b, 1f**). For temperate Australia, some sites of pollen reconstructions and paleo-hydrologic records of the Oz-INTIMATE series in southeastern Australia indicate wetter conditions with enhanced river discharge and increased precipitation during the mid-Holocene (Petherick et al., 2013; Lowry and McGowan, 2024), while PMIP4 simulations do not consistently capture those robust changes in **Figure 1b**.

Figure 1: (c) Caption should cite Adler et al. 2003 for GPCP. (f) Are different dot sizes significant? Explain in caption if so. I also suggest reversing the colour scheme as red is usually dry and blue is usually wet for precipitation anomaly plots.

--Reply. We agree with this comment and have revised the caption accordingly. Large dots represent significant changes of reconstructed annual precipitation, and small ones are not significant, following the similar plotting method in Bartlein et al. (2011). Additionally, to keep the same color scale meaning in Figures 1b, 1e, and 1f (red colors denote positive anomalies, blue colors denote negative anomalies), we keep the color scheme unadjusted in Figure 1.

Table 1: Table caption should be expanded to define all abbreviations used in table and distinguish between Method I and Method II – remind the reader how these differ (using streamfunction values at 500 hPa versus average over 200-900 hPa).

--Reply. Thanks for the suggestion and we have revised the caption of **Table 1**.

Line 167-168: The methods used to define the ITCZ location need to be briefly described in the Methods section, not just in the Supplement.

--Reply. We agree with this comment and have added a new **Section 2.3** for defining ITCZ position metrics. Please see further details in **L133-141** and Eqs. (3)-(4).

Figure 2: What are the red and blue line colours in (a) and (b) panels? Define in caption.

--Reply. Red is for positive and blue for negative changes. We have revised the caption accordingly.

For panel c, either include full names (inner edge, southern edge etc.) or define the abbreviations in the figure caption: "southern edge of Hadley Cell (Edge_S)" etc.

--Reply. Thanks for the suggestion. We have revised the caption.

Figure 3: Please either label the models on the x-axis of figures or ensure the order of models in the legend matches the order in the plots. Otherwise, any colour-blind reader will not be able to interpret this figure.

--Reply. Thanks for the suggestion. We have revised the order of the legend to be the same as the order on the x-axis.

Line 196: Previous studies of global warming – clarify whether these are model or observational studies and whether focused on historical period or future projections or both.

--Reply. We agree with the comment and have revised it with clarification for future projections. **L259-262**: Previous studies of global warming based on observations and climate simulations reveal that the deep-tropics squeeze and the projected northward migration of ITCZ tend to influence the changes in the width and strength of tropical overturning circulation (Hadley cell) (Kang and Lu, 2012; Lau and Kim, 2015; Byrne et al., 2018; Watt-Meyer and Frierson, 2019; Lionello et al., 2024).

Figure 4 a-f: It is difficult to distinguish the lines based on the colour alone. I suggest using different dot and dash patterns as well as different colours.

--Reply. We agree with the comment and have used different line types and markers to make the identification of the individual lines in this figure easier.

Section 4, paragraphs 2 and 3: In this section, you should also compare your results with D'Agostino et al. (2019) and (2020) studies on NH and SH monsoon changes in PMIP mid-Holocene simulations. These studies make use of MSE budget analysis so they are highly relevant. You may also want to mention these studies in the introduction in the section discussing the MH monsoon changes (lines 35-40).

D'Agostino, R., Bader, J., Bordoni, S., Ferreira, D., & Jungclaus, J. (2019). Northern Hemisphere monsoon response to mid-Holocene orbital forcing and greenhouse gas-induced global warming. *Geophysical Research Letters*, *46*(3), 1591-1601.

D'Agostino, R., Brown, J. R., Moise, A., Nguyen, H., Dias, P. L. S., & Jungclaus, J. (2020). Contrasting southern hemisphere monsoon response: MidHolocene orbital forcing versus future greenhouse gas–induced global warming. *Journal of Climate*, *33*(22), 9595-9613.

--Reply. We agree with this comment and appreciate the suggestion. We have rewritten **Section 3.3** and further compared our results with D'Agostino et al. 2019, 2020, and other related studies. Please see **L311-354** for further details.

References:

Line 472: Publisher details missing from Nicholson book reference.

--Reply. Thanks for noticing this. We have added the publisher details.

References

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