Overview:

This study investigates the effects of the northward migration of the Intertropical Convergence Zone (ITCZ) on the Hadley cell and global hydrological patterns during the mid-Holocene, around 6,000 years ago. This period, known as the "Green Sahara," experienced significant climatic changes, with increased precipitation in typically arid regions. The study utilizes simulations from the PMIP4-CMIP6 archive to analyze shifts in the ITCZ and changes in Hadley cell characteristics, revealing a contraction and weakening of the northern Hadley cell and an expansion and strengthening of the southern cell. These dynamics contributed to wetter conditions in the Northern Hemisphere and drier conditions in the Southern Hemisphere. This study underscores the complex interactions among orbital forcing, ITCZ migration, Hadley cell dynamics, and terrestrial aridity during the mid-Holocene. While climate models provide valuable insights, recognizing their limitations and the uncertainties in simulations and reconstructions is crucial. Continued research and model development are necessary to enhance our understanding of past climate changes and their implications for future climate scenarios. In general, I find the paper is well written and could be published after revision.

--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).

My main concerns:

What are the new findings of the study? The change of Hadley cell, ITCZ, and precipitation patterns in the Mid-Holocene were well reported in previous studies, and especially the Mid-Holocene ITCZ migration and precipitation patterns have been reported in the authors' previous published paper of Bian et al. (2024). Maybe the moisture static energy budget could be interesting to understand the dynamics of changes in Hadley cells. The author should clearly state what is new in the introduction.

Bian, J., Räisänen, J. Mid-Holocene changes in the global ITCZ: meridional structure and land–sea rainfall differences. Clim Dyn 62, 10683–10701 (2024). https://doi.org/10.1007/s00382-024-07470-1

--Reply. Thanks for the suggestion. In the revision, we have made substantial updates to better clarify our study focus and key findings.

- We have added a short paragraph to the end of the Introduction to clarify our main scientific goals in this study. **L91-95**: This work expands over earlier research in Bian and Räisänen (2024) by quantitatively addressing 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) proxy evidence alongside physical regimes modulating terrestrial hydroclimate and land aridity during this period.
- As summarized on **L489-498**: The northward migration of ITCZ is accompanied by a northward movement of the inner HC edge, resulting in a contracted and weakened northern HC, while the southern HC expands and intensifies in the mid-Holocene. Specifically, the northern HC width contracted by 1.1° and 0.5°, with strength reductions of 3.7% and 4.1%, while the southern HC expanded by 1.2° and 0.6° and strengthened by 2.9% and 1.8%, according to the two streamfunction metrics.
- Seasonal analysis (**L323-354 and Figs. 5-6**) indicates that the terrestrial hydrological cycle changes are primarily due to summer dynamics with an amplified inter-hemispheric contrast and asymmetry during the mid-Holocene, while there are minor changes during winter seasons for both hemispheres.
- Orbital forcing does not directly drive the hemispheric asymmetry in annual atmospheric radiation balance during the mid-Holocene, and enhanced cloudiness and water vapor in the Northern Hemisphere tropics play key roles. See **L364-377** and **Figs. A1-A2**.
- Moist static energy budget analysis reveals that stronger rising motion significantly promotes vertical MSE advection over land in the Northern Hemisphere, enhancing moist convection and precipitation, while reduced rising motion weakens vertical MSE advection in the Southern Hemisphere, suppressing moist convection and precipitation over land (cf. paragraph on **L385-393**)
- As summarized on **L526-535 and discussed in more detail on L437-467**: The northward ITCZ migration and the associated changes in Hadley cell significantly influence regional climates by altering terrestrial dryness across the tropics and subtropics. Both simulations and reconstructions generally agree on reduced terrestrial

aridity and drylands contraction in the Northern Hemisphere, while the Southern Hemisphere has enhanced aridity and drylands expansion.

Why is the ITCZ migration leading to the change of Hadley Cells? It could also be the Hadley cell leads the ITCZ migration. Where I can see the evidence of ITCZ migration leading to the changes in Hadley Cells?

--Reply. We agree with the comment and acknowledge that this is indeed a very important question. The ITCZ is co-located with the rising branch of Hadley cell, and the northward migration of ITCZ is accompanied by a northward movement of the inner HC edge during the mid-Holocene. This further results in a contracted and weakened northern HC, while the southern HC expands and intensifies. Meanwhile, the changes between ITCZ and Hadley cell are closely linked but their dependency is non-linear and complex (Watt-Meyer and Frierson, 2019), which highlights the intricate nature of the cause-and-effect dynamics between them.

- To better clarify this connection and the complicated cause-effect relationship, we have revised the title to: **Mid-Holocene ITCZ migration: connection with Hadley cell dynamics and impacts on terrestrial hydroclimate**. Furthermore, we have greatly extended the discussion of the ITCZ-Hadley cell dynamics in the **Introduction**, **Section 3.3**, and **Section 4**.
- We have rewritten the Introduction to explain the dynamic connection between ITCZ and Hadley cell and its possible limitations. **L47-61**: Kang et al. (2008) demonstrated an anti-correlation between the annual ITCZ position and the cross-equatorial energy flux (EFE): the northward (southward) migration of the annual ITCZ position corresponds to an anomalous southward (northward) EFE. Further studies indicate that, in the annual mean, the global ITCZ position, the EFE, and the inner edge of global Hadley cell are nearly co-located (Donohoe et al., 2013; Donohoe and Voigt, 2017; Hill, 2019; Kang, 2020; Geen et al., 2020). This co-location implies that the ITCZ and the shared rising branch of the Hadley cell rely on atmospheric energy transport from the hemisphere in which the ITCZ is situated, with the energy export proportional to the ITCZ displacement away from the equator. Consequently, the ITCZ remains aligned with the ascending branch of the Hadley cell, meaning that changes in tropical precipitation with the ITCZ necessitate concurrent changes in Hadley cell (Donohoe and Voigt, 2017; Hill, 2019). Therefore, the ITCZ shift has a correlation with changes

in the edges, width, and intensity of the Hadley cell in the mid-Holocene (Diaz and Bradley, 2004; Lau and Kim, 2015; Donohoe et al., 2013; Donohoe and Voigt, 2017; Byrne et al., 2018; Hill, 2019; Kang, 2020).

- **L73-80**: The energetic constraint theory offers a quantitative framework linking the annual ITCZ position and the Hadley cell, predicting that the annual ITCZ location is near the latitude (ϕ_{EFE}) at which the vertically integrated meridional MSE flux within the Hadley cell approaches zero (Kang et al., 2008; Adam et al., 2016; Wei and Bordoni, 2018; Kang, 2020; Geen et al., 2020; Lionello et al., 2024). However, this theory also has limitations on shorter time scales and regional ITCZ variations (Roberts et al., 2017; Kang, 2020), suggesting a potential gap between the seasonal evolution of ϕ_{EFE} and the ITCZ seasonal and regional migrations (Donohoe and Voigt, 2017; Wei and Bordoni, 2018; Kang et al., 2018; Kang, 2020; Geen et al., 2020). For this study, we primarily focus on annual changes in the global ITCZ position and its possible connection to Hadley cell changes from the PI to the mid-Holocene.
- **L272-280:** It is worth noting that while the changes between the ITCZ and the Hadley cell were closely linked during the mid-Holocene as discussed above, their relationship is inherently nonlinear and complex (Watt-Meyer and Frierson, 2019). Although they share the ascending branch near the Equator and are correlated via the cross-equatorial atmospheric energy flux under annual-mean state (Watt-Meyer and Frierson, 2019; Hill, 2019), a complete understanding of the factors driving their changes may be difficult to achieve when considering the influence from the extratropics and multiple climate drivers (Byrne et al., 2018; Kang et al., 2018; Kang, 2020; Geen et al., 2020; Lionello et al., 2024). To simplify this complexity, the classical energetic theory for the ITCZ position assumes that cross-equatorial atmospheric energy flux arises entirely from the Hadley cell, with negligible contributions from transient and stationary eddies (Byrne et al., 2018; Kang, 2020).
- **L541-557:** The core of energetic theory assumes that the atmospheric cross-equatorial energy flux transport is primarily driven by the zonal mean meridional circulation (i.e. Hadley cell), with contributions from stationary and transient eddy fluxes and changes in gross moist stability (GMS) considered negligible (Adam et al., 2016; Donohoe and Voigt, 2017; Wei and Bordoni, 2018; Hill, 2019; Kang, 2020). However, both observations and climate simulations reveal that eddy fluxes play a non-negligible role in energy and moisture budgets in the tropical atmosphere (Roberts et al., 2017; Byrne et al., 2018; Geen et al., 2020; Kang, 2020). This means energetic constraint theories

linking the ITCZ and Hadley cell have limitations in explaining ITCZ changes and their nonlinear dependency on the Hadley cell changes. For instance, the Hadley cell did not exert a dominant influence on changes in atmospheric heat transport across the Equator during glacial periods when tropical rainfall and meridional heat transport underwent substantial changes (Donohoe et al., 2013, 2014; McGee et al., 2014; Roberts et al., 2017). Roberts et al. (2017) highlights that there is insufficient evidence to support the Hadley cell as the primary driver of tropical rainfall and energy transport, particularly when considering the effect of stationary and transient energy fluxes. Moreover, energetic theory for the zonal-mean framework cannot fully account for the relationship between regional rainfall changes and meridional migrations of the ITCZ, as the direction and magnitude of regional rainfall band migration vary significantly by longitude (Roberts et al., 2017; Atwood et al., 2020). Additionally, even when Hadley cell meridional circulation dominates cross-equatorial atmospheric energy transport, the energetic framework may still be insufficient, as changes in GMS can also make a contribution (Wei and Bordoni, 2018; Kang, 2020).

The asymmetry responses of Hadley Cells in the Northern Hemisphere and Southern Hemisphere are interesting. It would be great if the authors could show a more dynamic understanding of the asymmetry responses, especially more focus on the moisture static energy budget in the revision.

--Reply. We agree that the asymmetric response of Hadley cells is a very interesting and important question.

- **Figures 4c, 4d, and 4f** illustrate that the increased terrestrial rainfall is closely linked to positive anomalies in atmospheric energy divergence ($\nabla\cdot Fa > 0$) over the Northern Hemisphere. This is primarily driven by enhanced vertical moist static energy (MSE) advection over land (Terms III and IV), while changes in horizontal MSE advection (Terms I and II) and eddy MSE flux (Term V) have a compensating influence, as illustrated in **Figure 4f**.
- For the $\delta\nabla\cdot Fa > 0$ and associated changes in MSE vertical advection over land in the Northern Hemisphere: Changes in radiative forcing due to orbital parameters result in increased net radiation ($\delta Ra > 0$) in the Northern Hemisphere during spring and summer (Brierley et al., 2020). This alters the net energy flux divergence ($\delta\nabla\cdot Fa$), which further

influences the temperature and moisture distributions and affects the MSE gradient and advection over land during the mid-Holocene (**Figures 4b, 4d**), altering the energy balance of the atmosphere ($\delta\nabla\cdot Fa$). This further influences the temperature and moisture distributions and affects the MSE gradient and advection over land. See also **L359-364** in the manuscript.

- However, 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. See also **L364-367** in the manuscript.
- Analysis of the separate contributions of the SW and LW flux components to the atmospheric radiation balance shows reduced NH surface shortwave radiation alongside increased atmospheric shortwave absorption, indicating that enhanced cloudiness and water vapor play key roles (**Figure A1**).
- Changes in the annual net surface energy budget ($\delta(Rs - SH0 - LE)$) over the ocean are slightly positive in the Southern Hemisphere tropics but negative in the Northern Hemisphere tropics (**Figure A2**). This 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. See also **L378-383** in the manuscript.

In most of the analysis, this study uses multiple model ensemble mean, I am wondering whether there are any models and realizations that could better capture the reconstructed precipitation patterns, or how different the simulated precipitation patterns change among different models. For example, does a model with a larger Hadley Cell northward shifting and intensifying show more precipitation increases in the Northern Hemisphere extra-tropical monsoon regions? I think some more discussions on the model uncertainties might further help to understand the dynamic links between the large-scale circulation change and precipitation patterns.

--Reply. We agree with the comment and acknowledge that although all nine simulations show a northward migration and zonal precipitation belt during the mid-Holocene (not shown; Bian and Räisänen, 2024), intermodel differences in precipitation changes may introduce uncertainties when these results are compared with paleoclimate reconstructions (McGee et al., 2014; Byrne et al., 2018; Bian and Räisänen, 2024). The metrics used to quantify Hadley cell width and strength can significantly affect the patterns and magnitude of mid-Holocene changes.

Among the nine models evaluated, MRI-ESM2-0, MPI-ESM1-2-LR, and EC-EARTH3-LR exhibit larger shifts in Hadley cell edges and width, alongside greater precipitation increases in the Northern Hemisphere extra-tropics (**Table 1, Figure 3**). These three models also demonstrate relatively better performance in capturing ITCZ changes, based on multiple metrics noted by Bian and Räisänen (2024). However, we chose to not discuss the behaviour of the individual models in more detail, to avoid a further lengthening of the manuscript.

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