Reviewer 1

Pontes and coauthors present a compilation of climate model experiment results from past and future warm states (the mid-Holocene, the Last Interglacial, the mid-Pliocene, SSP5-8.5, and 4xCO_2) to investigate the mechanisms that drive El Niño-Southern Oscillation (ENSO) variability across changing background climate conditions. Taken together, the authors suggest the models support a common underlying mechanism influencing ENSO behavior: the latitudinal position of the Intertropical and South Pacific Convergence Zones (ITCZ and SPCZ, respectively). This response is tied to changes in the surface wind field and its associated impacts on the upper ocean, which can either enhance or weaken the ocean-atmosphere coupling strength that underpins ENSO development. Importantly, the authors find that this response to ITCZ and SPCZ position is non-linear. Peak ENSO suppression occurs when both convection centers are shifted equatorward by ~4 – 5° latitude. Further equatorward migrations, such as in the 4xCO_2 experiment, lead to permanent "El Niño-like" conditions that weaken ocean-atmosphere coupling and ENSO intensity. Likewise, poleward displacements by >8° latitude weaken the convective feedback, which also reduces ENSO intensity. The authors also find that this response is stronger for east Pacific ENSO than central Pacific ENSO. Altogether, the modeling results reveal negative quadratic relationships between convective center displacement and ENSO behavior, variability in easterly wind bursts, and wind-thermocline coupling, supporting a non-linear dynamic between ENSO and background climate.
Overall, I think the analysis presented in this paper is interesting and certainly a worthy contribution to the literature. I do have some major comments regarding the background climate conditions represented in the compilation and whether the authors' proposed mechanism finds support in the paleo record. Otherwise, most of my suggestions are minor/editorial and could be triaged by the authors with ease.

We thank the Reviewer for their constructive comments, which helped improve our manuscript. Below we answer the reviewer's comments and include in purple some excerpts of modified text to be included in the revised manuscript.

Major Remarks

1. What immediately stood out to me was that the modeling experiments selected for the analysis exclusively represent warmer climates. Can the authors explain why they chose not to include model results from colder climate states (e.g., the PMIP LGM experiments)? I think the community's constraints on glacial boundary conditions is particularly strong (perhaps better than, say, the mid-Pliocene) and there is an emerging consensus that ENSO was reduced at this time (e.g., Thirumalai et al., 2024 and references therein). The authors' nonlinearity argument could be substantially bolstered by including the LGM simulation, which I expect would extend the right-hand "poleward displacement" side of the quadratic relationship in Figs. 2 and 3. But currently, without a colder state estimate, it's hard to know if the nonlinearity presented here is a universal ENSO response or if it's true only for warm states.

Unfortunately, only 5 modelling groups have uploaded LGM experiment outputs to the ESGF database (AWI-ESM-1-1-LR, CESM2-FV2, CESM2-WACCM-FV2, INM-CM4-8, MIROC-ES2L and MPI-ESM1-2-LR, last access 31/01/2025). From those, only three models (CESM2-FV2, INM-CM4-8, MIROC-ES2L) had the minimum necessary variables (sea surface temperature and precipitation) available for download. Given that a subset of only three models is likely not representative of the LGM ensemble, we initially opted for not including LGM in our study. Nonetheless, we have now included the available LGM simulations in the analyses presented in Figure 2 and 3.

2. A side note to the comment above: I realized mid-way through this review that I might be mistaking what "equatorward" and "poleward" migrations are in reference to. Are they in reference to the equator, or the mean position of each convection center, or something else? It may be useful to quickly define what cardinal direction the authors are referring to in the discussion (e.g., "equatorward" might be northward for the SPCZ but southward for the ITCZ, according to Fig. 4). This is important because including glacial output might instead improve the left-hand "equatorward displacement" side of the quadratic, which is currently data sparse (as I note below).

The convection-centre index is defined relatively to each model's piControl position. The origin of the graph in Fig. 2 indicates the piControl state of each model. We now included a detailed computation of convection-centres index in the main manuscript and added information in Fig. 2 for clarity (below).

Here, we develop an index that captures their combined displacement during the developing and mature ENSO phases (austral spring-summer; see Appendix). In computing their position, the maximum precipitation regions are used as a proxy of the meridional positions of the ITCZ and SPCZ in both hemispheres (0º-20ºN and 20ºS-0º, respectively). Their positions are thus computed as the average latitudes over which precipitation is greater than 70% of the maximum zonally averaged precipitation over the two hemispheric regions in the Pacific Ocean (160ºE-90ºW). This methodology captures migrations of ITCZ and the SPCZ independently from one another. As our objective is to quantify their overall displacement with respect to the equator, as a proxy for relative equatorial warming, we consider their absolute shift relative to the model's piControl position:

$$D = [|ITCZ_s| - |ITCZ_{PI}|] + [|SPCZ_s| - |SPCZ_{PI}|]$$

where the subscript 'S' indicates the position of the UTCZ and SPCZ in the perturbation scenarios and the subscript 'PI' denotes their position in their respective pre-industrial simulation. Hereafter, the combined meridional displacement of the ITCZ and SPCZ (D) is referred to as the convection-centres index. The index is positive for poleward displacements of the Convergence Zones. It is important noting that in all scenarios the Pacific ITCZ lies in the Northern Hemisphere, therefore a poleward movement reflects a northward shift, whereas for the SPCZ it reflects a southward shift.

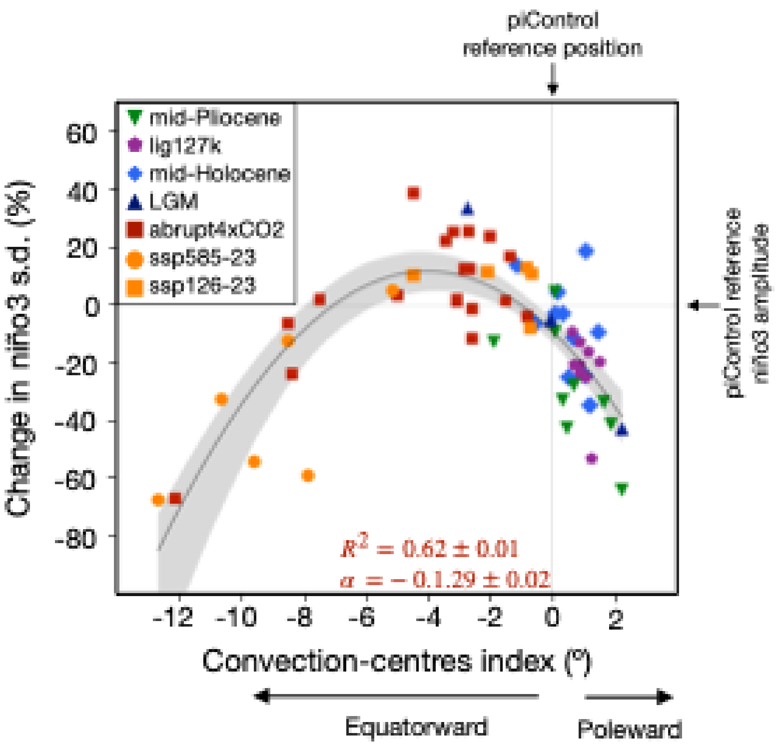

Figure R2.1 – Relationship between the convection-centres index and the change in niño3 amplitude, measured by its standard deviation (s.d). The solid black line indicates the quadratic fit based on the least squares method. Banding indicates 95% confidence interval based on a 1000-sample bootstrap. The mean displacement of the convection centers boreal spring-summer is considered (i.e., encompassing developing and mature ENSO phases). R2 indicates the coefficient of determination and *a* the nonlinear coefficient of the quadratic regression model. Error estimates for R2 and alpha we calculated as one standard deviation of 1000 bootstrap realizations. The convection center index is, by definition, positive for poleward movements of the Convergence Zones referenced at each model's piControl positions.

3. Regarding the experiments included by the authors, the 4xCO_2 simulations does a lot of work in establishing the nonlinearity discussed in the paper. Indeed, three datapoints from this simulation anchor the left-hand "equatorward displacement" side of the quadratic function (Figs. 2b-d and 3b,c). Without these three points, I can see the remaining data forming more of a negative linear relationship, rather than a nonlinear one. Despite its importance, the 4xCO_2 simulation results receive little attention (e.g., it is not mentioned in section 3.1 and not presented in Fig. 1). I think these results should feature at least as prominently as the others, considering their importance for the nonlinearity argument.

We thank the Reviewer for this suggestion. We have now included the 4xCO2 results in Fig. 1 and are now discussing these results in section 3.1:

In contrast, CO2-driven scenarios (ssp126-23, ssp585-23 and abrupt4xCO2) shows an equatorially amplified warming with weakened trades and upwelling, conditions which resemble an El Niño-like mean state (Figure 1d). It is important noting that the warming pattern intensifies from ssp126-23 to abruptx4CO2 and, finally ssp585-23. Interestingly, however, ENSO variability tends to increase for moderate equatorial warming scenarios and decrease under strong warming (Fig. 1f), thus resulting in a nonlinear ENSO response to the background state.

4. Can the authors speculate on the applicability of their ITCZ response to millennial-scale climate change? I'm familiar with modeling results for the deglaciation (particularly cold stadial events) where a southward displacement of the ITCZ amplifies, rather than dampens, ENSO behavior (e.g., Liu et al., 2014; Timmerman et al., 2007). This is generally attributed to ENSO's "frequency entrainment" to the annual cycle (Chang et al., 1994, 1995; Liu et al., 2002), which is weakened when the winds shift southward. Although this mechanism is still debated, it does find support in the paleo record, where studies have noted an increase in ENSO variability from the LGM to Heinrich Stadial 1 (Leduc et al., 2009; Glaubke et al., 2024; Sadekov et al., 2013) in response to a disruption of AMOC and southward shift of the ITCZ (e.g., Mosblech et al., 2012). Is there something unique about the meltwater-induced ITCZ migrations of the deglaciation that might represent a special case to the universal mechanism proposed here? Could it have something to do with the ITCZ and SPCZ moving in one direction *together* as opposed to moving closer or farther apart, as implied in Fig. 4?

The mechanism we propose in this study should be applicable to all climate states. During North Atlantic meltwater-induced ITCZ migrations, the southward shift of the ITCZ is evident over the Atlantic and Indian basins, however the Pacific response is more complex. In the Pacific, the ITCZ migration will depend on the balance between how much intense the northeasterly trades will become due to a stronger North Atlantic subtropical circulation (Saini et al., 2025, in press), which prevents an ITCZ southward shift, and the change in the interhemispheric temperature gradient, which tends to drive an ITCZ southward shift. It is thus possible that different intensities of meltwater pulses cause different ENSO response, as found by Glaubke et al. (2024). Modelling studies do not necessarily agree on the impact of an AMOC weakening on ENSO variability (e.g. Timmerman 2008, Oriuhuela-Pinto et al., 2022). Furthermore, our results show that the SPCZ migration is also extremely important for ENSO, a feature that has received little attention. As the reviewer mentions if the SPCZ is also moving southward, then the ENSO change will result from a delicate balance of ITCZ vs SPCZ changes.
Finally, our mechanism is in agreement with the 'ENSO's frequency entrainment' to the annual cycle. This is evident from results shown in Fig. 3a: as ENSO activity increases, so does ENSO frequency (i.e. closer to one event per year), until ENSO is fully entrained to the annual cycle (i.e. one event per year - Permanent El Niño-like mean state).
To add insights into ENSO response during climate states not covered by our analyses we have added this discussion:

This mechanism can reconcile divergences in ENSO responses in proxy-data and modelling studies. First, modelling results from the idealized abrupt4xCO2 simulations indicate an inconsistent inter-model ENSO response. We showed that this is related to the sensitivity of ITCZ and SPCZ migration in each model. This argument can be expanded for meltwater-induced AMOC weakening modelling studies and proxy-data covering Heinrich stadials and the Younger Dryas, which often do not agree on the ENSO response (Timmerman2001; Orihuela-Pinto2023; Glaubke et al., 2024) and could be related to the different response of the Pacific Convergence Zones to the intensity and duration of meltwater pulses. Finally, our results provide novel insights into the relationship between ENSO frequency and the annual cycle, as

ENSO is hypothesized to be forced by the annual cycle (Liu, 2002). Our findings suggest that strong equatorward and poleward displacements of the Convergence Zones result in a strong equatorial mean circulation (strong convection and strong trades, respectively) and annual cycle, increasing ENSO's frequency towards the annual cycle and reducing interannual variance. On the other hand, moderate equatorward shift of the Convergence Zones relaxes both mean horizontal and vertical circulations, allowing nonlinear interactions between the annual cycle and ENSO's frequency and increasing interannual variance (termed 'ENSO frequency entrainment').

Liu, Z., 2002: A simple model study of the forced response of ENSO to an external periodic forcing. J. Climate, 15, 1088–1098.

Glaubke, R. H. et al. An Inconsistent ENSO Response to Northern Hemisphere Stadials Over the Last Deglaciation. Res. Lett. 51, (2024).

Saini, et al. Australasian hydroclimate response to the collapse of the Atlantic Meridional Overturning Circulation under pre-industrial and Last Interglacial climates. In press. Paleoceanography and paleoclimatology (2025). https://essopenarchive.org/doi/full/10.22541/essoar.172072238.80662852

Minor/Editorial Comments *(Note: [] represents a deletion; [words] represents added text.)*

Abstract

1. Lines 19-21: The authors may want to consider a stronger and more specific problem statement. Perhaps something like: "However, [a common mechanism that can predict ENSO variability under a range of background conditions remains elusive."]

We thank the Reviewer and have addressed this suggestion.

Introduction

2. Throughout the introduction and later in the paper, the authors switch between using *ka* and *Ma* depending on the time period under discussion. For consistency, it might be worth sticking to one of these.

Given that the only period over 1Ma is the mid-Pliocene, we now use ka throughout the text.

3. Line 62: Change "mid-Holocene" to "MH" here and throughout, as this is how you define it in the sentence prior.

This suggestion has been addressed.

4. Line 63: These are just two of many papers you can cite here. I would either add more for completeness (e.g., for the mid-Holocene, Conroy et al., 2008; Chen et al., 2016; White et al., 2018) or cite a review like Lu et al. (2018) and the references therein.

This suggestion has been addressed.

Data and Methods

5. Line 72: "...key [] periods in Earth's history. Here, we analyze [three past] climate scenarios..."

This suggestion has been addressed.

6. Lines 72-74: You have already introduced and defined these climate periods in the introduction. You do not have to do this again here.

This suggestion has been addressed.

7. Lines 88-89: "... removing the monthly annual cycle." Can you expand on this? What I think you're saying is that you computed the mean annual cycle at a monthly resolution and subtracted that from each monthly value, but it's not immediately clear.

Your interpretation is right. We have modified it to improve clarity:

SST anomalies are computed by removing the mean annual cycle at a monthly resolution.

8. Line 93: "... is projected approximately 45° between..." Is this 45° longitude?

This is 45º in the EOF space (i.e. when plotting the relationship between EOF1 and EOF2). We noted that this sentence is missing a proper reference that has now been added.

Takahashi, K., Montecinos, A., Goubanova, K., & Dewitte, B. (2011). ENSO regimes: Reinterpreting the canonical and Modoki El Niño. *Geophysical Research Letters*, *38*(10). https://doi.org/10.1029/2011GL047364

9. Line 98: "To avoid being [misled]..."

Thank you for noting this mistake.

Results and Discussion

10. Line 105: I would change "Results" to "Results and Discussion"

This suggestion has been addressed.

11. Section 3.1: I would add the 4xCO_2 results here. I would also suggest bringing in LGM simulations (as discussed above) and include them here as well.

We have added the results from the 4xCO2 simulations here, but we could not add results from the LGM simulations as we only have the data for three models (please see comment above). Nonetheless, the results from the LGM have been included in Figures 2 and 3.

12. Line 131: "...ITCZ and SPCZ..." As someone who works on the deglaciation, I think about ITCZ much more and have a better grasp of how it influences ENSO (i.e., changing the position of the trades). It might be helpful for those like me who don't think about the SPCZ much to briefly mention how it relates to ENSO. Perhaps add it to the introduction? As of right now, the SPCZ isn't mentioned until the results, so it would be nice to mention it sooner in the paper.

This suggestion has been addressed. We have moved the first paragraph of section 3.2 to the introduction and made the necessary changes to it.

13. Lines 132-135: "Firstly..." Consider rephrasing. Perhaps "ENSO growth and extreme rainfall events are reduced the farther tropical convection centers are from the equator (Pontes et al., 2022). This occurs since the position of the convection centers determines the equatorial wind field and its associated upper ocean response."

Thank you for your suggestion. It has been addressed.

14. Line 141: "...[which underpins] ENSO development."

This suggestion has been addressed.

15. Line 151: I would delete "preliminary".

This suggestion has been addressed.

16. Line 152: Add (Fig. 2) to the end of the sentence.

This suggestion has been addressed.

17. Lines 155-158: Could the authors clarify what the equatorward and poleward shifts are with respect to? Is it the physical equator (0°)? The mean position of each convective center?

We use each model's piControl position as reference. We have now included a detailed description of the calculation of the convection-centres index in main manuscript, as described in the major comment #2.

18. Line 163, 165, 173, etc: Consider italicizing parameters of an equation: "... (*a* = 0.XX)..."

This suggestion has been addressed.

19. Lines 182-183: Consider simplifying. "To investigate the [rainfall response to convection center migration], we..."

This suggestion has been addressed.

Conclusions

20. Line 229-230: Eliminate redundancy. "...linking meridional shifts of the [atmospheric] convection centers, [] ocean stratification, and zonal thermocline oscillations."

This suggestion has been addressed.

21. Line 236: "...(<9°)..." Did the authors mean <8°, as mentioned in line 157?

Thank you for noticing this typo. Yes, it should read '<8º'.

22. Line 247-252: Is there room in an appendix of supplementary material to elaborate on these model biases and how they might influence the results? This could be helpful for non-modelers (such as myself) reading the paper. For example, I imagine the double-ITCZ problem is a relevant bias to dig into. If the SPCZ is defined as the region where precipitation is >50% the zonal average between 0° and 20°S (Line 530-531), then how might the excess precipitation south of the equator from the artificial southern ITCZ (mentioned in Line 540-541) influence that estimation?

Thank you for this suggestion. When computing our convection-centres index, an artificial ITCZ south of the equator would tend to artificially displace the position of the SPCZ equatorwards. However, we note that although it is a model deficiency, it dynamically affects the simulated ENSO response, through producing additional biases in the intensity of the trade winds and zonal SST gradient. To make the implications of this bias to ENSO clearer, we have added this discussion:

It is important noting that double-ITCZ biases may affect the calculated SPCZ position. The double-ITCZ bias is an artificial feature produced by most climate models that overestimates the tropical precipitation south of the equator in the central-eastern Pacific. This biased precipitation artificially induces the index (D) to capture an apparent SPCZ displaced northwards. Nevertheless, although being an artificial feature, the double-ITCZ dynamically influences the tropical Pacific climate through simulating weaker trade winds and warmer SSTs than in observations, therefore affecting the model's ENSO response, and are thus considered in our evaluation.

Figures

23. Figure 1: Excellent figure. Of course, I think adding the 4xCO_2 results and some data from a glacial simulation would make it perfect.

This suggestion has been addressed.

24. Figure 2: Be sure to add what "equatorward" and "poleward" are in reference to. Consider also adding cardinal directions, if that helps.

We have added the definition of the convection centres index to the figure caption. Unfortunately, adding cardinal directions is not possible in this case because an equatorward shift would mean a southward shift for ITCZ and northward shift for SPCZ.

As our objective is to quantify their overall displacement with respect to the equator, as a proxy for relative equatorial warming, we consider their absolute shift relative to the model's piControl position.

and

Therefore, a poleward movement reflects a northward shift, whereas for the SPCZ it reflects a southward shift.

25. Figure 3a: Consider using unique markers for each climate simulation like in Figs. 2b-d and 3b,c. It would be useful to see, for example, what proportion of the "strong equatorial shift" category of model results is from the $4xCO_2$ experiment.

Results presented in Fig. 3a are produced by a bootstrap analysis, in which we consider all simulations that lie in each group of convection-centres shift (i.e. defined by poleward, moderate equatorward and strong equatorward shifts). When applying the bootstrap analysis, a first assumption is that all these simulations are part of the same sample (i.e. same group). It is thus not possible to distinguish them after bootstrapping.

26. Figure 4: I like this figure! I was initially confused by how it was arranged, but once I was oriented, it clicked. Maybe make the X and Y arrows a bit larger to draw the eye?

Thank you! We have made the arrows longer and wider and increased the font of the X and Y labels.

References

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