Reply to Referee #2

We thank the Anonymous Referee #2 for the thoughtful review and very constructive comments. The comments of Referee #2 are provided in black text below and our replies to each comment are shown in the blue text.

The manuscript explores how changes in the ENSO characteristics and local solar insolation during the mid-Holocene influenced precipitation patterns and oxygen isotope ratios in tropical South America, using a water isotope-enabled atmospheric general circulation model (ECHAM4.6).

The authors use climate simulations to understand the effects of: (1) Reduced ENSO variability, (2) A La Niña-like mean state in the tropical Pacific, (3) Lower Southern Hemisphere summertime insolation (solar input due to orbital changes).

The major finding includes: (1) Reduced ENSO variability had only minor effects on average precipitation and isotope ratios. (2) A La Niña-like mean state and lower insolation both produced an east-west dipole in rainfall changes (drier western Amazon/southern Brazil, wetter northeastern Amazon/Nordeste region), consistent with a number of paleoclimate records. (3) However, changes in isotope ratios did not always mirror precipitation changes due to differences in how precipitation seasonality and mean state changes affected regional isotope records. (4) The model indicates that western Amazon isotope anomalies during the mid-Holocene are more strongly influenced by weaker insolation (seasonality) than by Pacific mean state changes, whereas both factors reinforce strong negative isotope anomalies in the northeast.

I actually really like this "clean" approach but having some concerns about the experiment design. I hope that the following points can be addressed for better understanding and clarity.

Model configuration and experiment design: The study uses the ECHAM4.6 atmospheric general circulation model with prescribed SSTs and runs several experiments manipulating ENSO characteristics and insolation. The decision not to use a fully coupled ocean-atmosphere model in the main analysis may limit the realism of certain feedbacks, especially given the demonstrated importance of global SST feedbacks in shaping isotope patterns (kind of circular). The rationale and limitations of prescribing only tropical Pacific SST anomalies, versus allowing full ocean dynamical feedback, should be explicitly justified.

We thank the reviewer for highlighting this important point regarding the justification for using an AGCM. We used an AGCM with prescribed SSTs because this configuration provides a controlled and computationally efficient way to isolate and cleanly quantify the atmospheric response to specific changes in the tropical Pacific SSTs. We believe this approach is suited for single-forcing sensitivity experiments, where the objective is to examine the direct atmospheric response to a specific boundary condition. Nevertheless, we acknowledge that this approach is closer to an idealised scenario as the lack of a dynamic ocean-atmosphere feedback omits the full range of feedbacks which may influence the long-term variability, and is likely one of the reasons for the mismatch between the LNstate scenario with proxy records. To address this, we will add a clear justification of using an AGCM in the introduction and the implications of how it may differ from a full GCM.

Proxy-Model comparison (Western Amazon): The model fails to replicate positive isotopic anomalies recorded in Western Amazon proxies. More discussion or attempted quantification of the likely causes (missing Atlantic SST feedbacks, proxy uncertainties, limitations of isotope parameterizations or even dynamical reasons) would be valuable for both paleoclimate and modeling audiences.

We agree that the manuscript requires elaboration on the causes for the model-proxy discrepancy in the western Amazon. In the manuscript, we note that the discrepancy is likely attributed to the absence of SST feedbacks, particularly over the Atlantic. We will expand this discussion section (Section 4.3) in the revised manuscript to incorporate more recent literature and to explore these mechanisms in more detail. Specifically, we will show how a comparison between our prescribed-SST experiment and a complementary run using the same model coupled to a slab ocean indicates that the prescribed-SST configuration produces a stronger mid-Holocene Atlantic ITCZ and enhanced precipitation over the tropical Atlantic. The difference likely arises from the missing local ocean feedbacks that would otherwise dampen the convection there. The resulting stronger ITCZ in the prescribed-SST run thus increases the upstream rainout effect, resulting in more depleted d18O in the moisture advected into the western Amazon. This mechanism explains the negative d18O anomalies in the western Amazon despite lower simulated precipitation rates there.

In contrast, a coupled-ocean experiment produces a weaker mid-Holocene ITCZ response and d18O anomalies that are more consistent with proxy records. Although the slab-ocean configuration still lacks the full dynamical feedback of a fully coupled ocean model, even the partial inclusion of surface ocean coupling nevertheless substantially reduces the model-proxy mismatch, highlighting the importance of ocean feedbacks.

We also note that while factors including the proxy uncertainties and model biases could influence the magnitude of the simulated-proxy differences, they are unlikely to fully account for the directional mismatch in the western Amazon. For instance, systematic model biases are expected to remain similar across experiments, and therefore they would influence the amplitude of d18O rather than the directional sign of the isotopic response. Moreover, they do not account for counterintuitive pattern in the western Amazon of lower precipitation accompanied by more negative d18O anomalies, which is more plausibly explained by the Atlantic ITCZ mechanism above (i.e., a change in the d18O of the upstream moisture source).

Separation of ENSO magnitude and mean state: The experimental design cleanly separates mean state and ENSO amplitude effects, but real-world ENSO regimes often exhibit co-variation and nonlinearities. Please elaborate on how robust these attributions are, and discuss any residual uncertainty in interpreting main findings as the result of independent factors.

Our experimental design treats ENSO amplitude and mean state as separate boundary conditions to isolate the first-order atmospheric and isotopic responses to each component. We acknowledge, however, that in the real climate system these components are coupled and can covary. For example, changes in ENSO variability over the recent decades have been linked to shifts in the background state of the tropical Pacific (e.g., Chung and Li, 2013; Lübbecke et al., 2014). Therefore, in a fully coupled system, non-linear interactions between the ENSO amplitude and mean state may modify the full magnitude of the isotopic responses simulated here.

Therefore, our experiments can be view as sensitivity test that examine the direction and relative strengths of atmospheric and isotopic responses, rather than equilibrium outcomes of a fully coupled climate system. We will include this caveat in the introduction section to better contextualise the scope and interpretive limits of our findings, and emphasize that our results illustrate the mechanistic pathways linking each forcing to isotopic responses, while recognizing that the absolute magnitude and spatial patterns of these responses may differ in a fully coupled system.

Isotope dynamics and proxy interpretation: The manuscript acknowledges that the $\delta^{18}O$ rainfall signal is complicated by competing effects of precipitation amount, seasonality, and source moisture. This section would benefit from a more dynamical explanation to show how the induced circulation plays a role. Also The ECHAM4.6 runs at a relatively coarse resolution, which may dampen key gradients and convective responses. The implications for hydroclimate signal fidelity should be discussed more explicitly.

We agree that a more explicit discussion of how modified circulation plays a role in shaping the d18O signal will strengthen this section. We will provide more detail in Section 4.2 to relate the interpretation of the d18O anomalies more directly to the underlying changes in the circulation dynamics, in order to extend the discussion beyond the local precipitation amount effect.

Specifically, we will better detail how the changes in both precipitation and precipitation d18O in the eastern and western Amazon (shown in Figure 6) are tied to changes in the zonal circulations (such as the changes in Walker Circulation discussed in section 4.1) and how this modulates d18O thorough both the amount effect as well as the source moisture. In the LNstate experiment, for instance, the enhanced ascending motion over during DJF-MAM over the eastern Amazon, associated with a shifted Walker Circulation, intensifies convective rainout, producing more depleted d18O in precipitation upstream. The concurrent simulated strengthening of the Atlantic ITCZ further increases upstream rainout over the tropical Atlantic, which depletes the d18O of the moisture advected westward into the Amazon Basin. Conversely, in the ΔMHinsol experiment, weaker continental convection (during DJF) reduces local rainout in the northeast and enhance the contribution of isotopically heavier Atlantic-sourced moisture, resulting in comparatively enriched d18O anomalies.

Regarding the model resolution, the coarser resolution used in the model leads to a reduced continental gradient of d18O towards the west, likely due to the underestimation of topographic influence near the Andes. This limitation has been evaluated and explicitly noted in the validation section. While the coarse resolution may dampen the local hydroclimate and isotopic variability, we emphasize that our analysis focuses on relative anomalies between experiments, which minimizes the influence of systematic biases. We will make these caveats and implications clearer in the revised discussion.

References cited in the response

Chung, P., and T. Li, 2013: Interdecadal Relationship between the Mean State and El Niño Types. J. Climate, 26, 361–379, https://doi.org/10.1175/JCLI-D-12-00106.1.

Lübbecke, J. F., and M. J. McPhaden, 2014: Assessing the Twenty-First-Century Shift in ENSO Variability in Terms of the Bjerknes Stability Index. J. Climate, 27, 2577–2587, https://doi.org/10.1175/JCLI-D-13-00438.1.