Replies to Reviewer #1:

"This manuscript investigates the orbital-scale response of North African (NAF) monsoon rainfall and precipitation water isotopes using an isotope-enabled coupled model, NCAR-iCESM. They conducted a long transient simulation spanning the past 150,000 years forced by orbital parameters (with 100-year orbital acceleration). They also conduct two moisture-tagging fixed-SST iCAM5 experiments for 127 ka (high Northern Hemisphere summer insolation-NHSI) and 116 ka representing a low NHSI, to diagnose the relative roles of moisture source contributions. The authors find that while NAF monsoon rainfall responds uniformly to precessional forcing, $\delta^{18}O_p$ exhibits a pronounced north-south dipole (enrichment in the north vs. depletion in the south). They attribute $\delta^{18}O_p$ depletion in southern NAF primarily to enhanced upstream rainfall and enrichment in northern NAF to shifts toward more local and relatively enriched moisture sources. The topic is timely and relevant, and the use of transient isotope-incorporated simulations combined with moisture tagging has the potential to provide valuable insights into the climatic interpretation of speleothem $\delta^{18}O$ records.

However, while the scientific idea is promising, the manuscript currently has substantial issues in clarity, structure, and methodological description, particularly in the Introduction and Methods sections. Several key concepts and calculations are either insufficiently defined or ambiguously described. Further, I suggest the authors revise the Introduction to focus on background, motivation, and research questions, and move result-oriented statements to the Results/Discussion sections.

Also, I suggest adding more quantifications and graphics, as discussed in detail below in specific comments.

Hence, I recommend major revision before the manuscript can be considered for publication."

Response: Thank you very much for the thoughtful and encouraging comment. We have carefully revised the manuscript and provided the point-by-point response below.

<u>Specific Comments:</u>

1. In Abstract: Please specify the latitude ranges used to define the southern and northern NAF regions, as this spatial distinction is central to the reported $\delta^{18}O_p$ dipole.

Response: Thank you for your suggestions. We specify the latitude ranges used to define the southern and northern NAF regions in the abstract (Line 24): *"…across the NAF region (15°W-35°E, 8°N-25°N) on the orbital timescale. ... In contrast, $\delta^{18}O_p$ presents a spatially dipole pattern, with depletion in the southern NAF (15°W-35°E, 8°N-17°N) and enrichment in the north (15°W-35°E, 17°N-25°N)."*

2. Lines 21, 43: Define $\delta^{18}O_c$ with more clarity, is it the oxygen-18 signal of speleothem calcite?

Response: Thank you very much. We are sorry for the confusion. We have revised this sentence according to your suggestions (Line 64).

3. Line 36: define The North African (NAF) monsoon region's bounds.

Response: Thank you for your suggestion. We have revised this sentence as (Line 36): *"The North African (NAF) monsoon region (15°W-35°E, 8°N-25°N) is one of the most vulnerable hotspots under climate change (Lézine et al., 2011)."*

4. Line 51: Briefly describe what is meant by amount effect.

Response: Thank you for your review. Following your suggestion, we have modified this sentence as (Line 72): *"Therefore, a major feature of the isotopic composition of precipitation in NAF region is the observed anticorrelation at the surface between the amount of precipitation and the proportion of heavier isotopes in the precipitation, called the "amount effect" (Dansgaard, 1964)."*

5. Line 55: Please clarify "isotope composition during convective activity".

Response: Thank you for your suggestion. We have clarified this sentence (Line 78): *"... isotope composition during convective activity such as sub-cloud evaporation and diffusive exchanges between raindrops and the surrounding vapor (Lee and Fung, 2007; Risi et al., 2008; Kurita, 2013; Moore et al., 2014) ..."*

6. Line 60: middle Holocene- Mid-Holocene, also add the approximate time period in BP.

Response: Thank you very much. We have corrected it as (Line 47): *"For example, Kutzbach and Liu (1997) conducted Mid-Holocene (6 ka BP) simulations with a general circulation model that asynchronously couples the atmosphere and the ocean."*

7. Line 90: Please consider rephrasing this sentence to improve clarity (e.g. "is not yet fully understood").

Response: Thank you for your advice. We have revised the sentence (Line 96): *"Therefore, despite growing efforts to simulate $\delta^{18}O_p$, spatial distribution and interpretations remain inconsistent across different modeling studies."*

8. Line 91: Add NCAR to the sentence, also cite Brady et al., 2019 for iCESM.

Response: Thank you for your suggestion. We revise the sentence as (Line 98): *"In this study, we use the isotope-enabled fully coupled Community Earth System Model (iCESM; Brady et al., 2019) developed by the National Center for Atmospheric Research (NCAR) to ..."*

9. Lines 92-: These lines in the Introduction currently contain key results of the study. These should be moved to the Results/Discussion sections, with this part of the introduction revised to emphasize motivation and research questions of this study.

Response: Thank you for your careful consideration. We have removed the content related to the conclusion in this paragraph, and rewrite this paragraph as (Line 98): *"In this study, we use the isotope-enabled fully coupled Community Earth System Model (iCESM; Brady et al., 2019) developed by the National Center for Atmospheric*

Research (NCAR) to perform transient simulations for the past 150,000 years. In addition, we perform moisture tagging experiments to track moisture sources for precipitation and to investigate the corresponding $\delta^{18}O_p$ response. We aim to answer the following central questions: How do monsoon rainfall and $\delta^{18}O_p$ respond to insolation on orbital timescales in NAF region? Do they exhibit spatially coherent patterns? And what is the climatic significance of $\delta^{18}O_p$ in NAF region?"

10. Lines 102-103: Please rephrase to indicate that the stated CAM5 resolution applies to present simulations rather than being a general model property.

Response: Thank you for your suggestion. We have specified the resolution used in the present simulations in the new manuscript (Line 109): *"We use the version 1.3 of iCESM, with a resolution of f19_g16."*

11. Lines 103-107: This sentence could be rewritten for clarity and readability. Consider simplifying the phrasing and splitting it into two sentences.

Response: Thank you for your beneficial comments. We have rephrased this sentence as (Line 115): *"Water isotope ratios, and the associated fluxes and isotopic fractionations, are tracked in all of the components of the hydrologic cycle: atmospheric water vapor and clouds, soil moisture and other land surface water pools, oceans, and sea ice."*

12. Line 111-: The part "albeit with smaller values" is ambiguous. Please clarify what is meant by "smaller values" and relative to which reference.

Response: Thank you very much. We have revised it for clarity (Line 119): *"It has been shown to adequately capture key features of $\delta^{18}O_{p}$, albeit with a weaker amplitude compared to observations (Brady et al., 2019; Nusbaumer et al., 2017; Wen et al., 2024)."*

13. Line 115: Citation style-The citation should be inside the main bracket.

Response: Thank you for your careful consideration. We are sorry for this mistake. We have revised it in the new manuscript (Line 121): *"We conduct a 150,000-year transient simulation that is driven solely by variations in Earth's orbital parameters (i.e., precession, obliquity, and eccentricity; Berger, 1978)."*

14. Line 118: Although the dominant signals can be represented with orbital forcing, please mention the caveats of this approach. There are several papers discussing vegetation feedback on the Mid-Holocene climate, for example.

Lines 128-137: My comment above addresses the same caveats discussed here.

The section needs improvements in terms of structure. Please move these lines to the paragraph starting from Line 118 and rephrase/shorten the paragraph without losing the main information.

Response: Thank you for your beneficial comment. We have rewritten this paragraph as (Line 121-128): *"We conduct a 150,000-year transient simulation that is driven solely by variations in Earth's orbital parameters (i.e., precession, obliquity, and eccentricity; Berger, 1978). All other boundary conditions, such as greenhouse gas concentrations, ice sheet extent, and vegetation distribution, are held constant at pre-industrial levels (Wen et al., 2024). Although the ignorance of vegetation and dust feedbacks over the NAF region tends to suppress the magnitude of changes in rainfall and $\delta^{18}O_p$ values (Waldmann et al., 2010; Pausata et al., 2016; Tierney et al., 2017a; Messori et al., 2019; Tabor et al., 2020), the orbital-forcing experiment still captures the dominant precessional signal and the overall phase of regional climate change (Pokras and Mix, 1987; Patricola and Cook, 2007; Weber and Tuenter, 2011; Cheng et al., 2020). This is sufficient for the purpose of this study."*

15. Section 2.2:

This section needs substantial revision for clarity, beginning with the section title, and why annual mean is chosen. It is unclear whether $\delta^{18}Oc$ is explicitly simulated by iCESM or if it's speleothem calcite $\delta^{18}Oc$ as in the introduction. It needs to be clear whether the values discussed (including precipitation, $\delta^{18}Op$) are model outputs or observational cave records, or approximated-$\delta^{18}Oc$ from $\delta^{18}Op$. Please clearly define all isotope-related terms (e.g., $\delta^{18}Oc$, $\delta^{18}Ow$-PDB) and variables such as cave temperature. If cave temperature is approximated using model-simulated surface air temperature, this assumption should be explicitly stated and justified, including whether a single grid point or an average over nearby grid points is used. In its current form, the section lacks sufficient details on the methodology.

Response: Thank you for your comments. We are sorry for the ambiguous sentences. We have rewritten this section as follows:

"2.2 Calculation of water isotopes from iCESM simulation

Since the observed speleothem isotope records reflect the combined influence of moisture from all seasons, the annual $\delta^{18}O_p$ are calculated using the precipitation-weighted $\delta^{18}O$ from 12 months following the previous works (Tabor et al., 2018; He et al., 2021):

$$\delta^{18}O_p = \sum_{m=1}^{12} \delta^{18}O_m \cdot \frac{P_m}{P} \,, \quad (1)$$

where m denotes the calendar month, P_m and $\delta^{18}O_m$ represent the precipitation and $\delta^{18}O$ in precipitation from the m-th month output by the model, respectively. P is the annual total precipitation.

In order to directly compare our simulations with the observed calcite speleothem records of $\delta^{18}O_c$, we need to get simulated-$\delta^{18}O_c$ from the simulated $\delta^{18}O_p$. First, we need to convert the simulated $\delta^{18}O_p$ from the V-SMOW scale (Vienna-Standard Mean Ocean Water; $\delta^{18}O_{p\text{-}SMOW}$) to the PDB scale (Pee Dee Belemnite; $\delta^{18}O_{p\text{-}PDB}$) following Coplen et al. (1983):

$$\delta^{18}O_{p-PDB} = 0.97002 \times \delta^{18}O_{p-SMOW} - 29.98 \quad . \qquad (2)$$

Then, we get the simulated-$\delta^{18}O_c$ following O'Neil et al. (1969):

$$\delta^{18}O_c = \delta^{18}O_{p-PDB} + 2.70 \times 10^6/T^2 - 3.29 \quad , \qquad (3)$$

where T represents the absolute cave temperature. Since this temperature approximately equals the annual mean surface air temperature at the cave site (Fairchild et al., 2012), the model annual mean surface air temperature from the corresponding model grid is used for calculation."

16. Line 150: Replace target region with the name of the monsoon region.

Response: Thank you very much. We have revised it (Line 155).

17. Line 154: "and the climate response between these two periods can infer the climate evolution at the orbital timescale". Please rephrase for clarity.

Response: Thank you for your advice. We have deleted this ambiguous sentence.

18. Line 155: Consider rephrasing, for example: "The boundary conditions are derived from 1000-year climatological mean states corresponding to each period, from the coupled iCESM simulation." Also what about the sea surface isotope ratios? Are they also derived from the 1000-year means?

Response: Thank you very much. We have rewritten it following your advice (Line 159). *"The boundary conditions and sea surface isotope ratios are derived from 1000-year climatological mean states corresponding to each period, from the coupled iCESM simulation."*

19. Line 160: "to study the NAF" -Specify that it is NAF rainfall.

Response: Thank you for your comments. We have revised it.

20. Lines 160-: Please provide a supporting reference for grouping the original 25 source regions into five aggregated regions [Are they the major sources for NAF rainfall from observations/modeling?]. It is unclear how these groupings were determined and why they reflect relative importance for NAF hydroclimate.

Response: Thank you for your suggestion. We have rewritten this paragraph for clarification. *"Here, the original 25 source regions are grouped into five broader regions for simplicity (Appendix Fig. A1): the African continent (AFR), the South Atlantic Ocean (EQA+SSA), the Indian Ocean (EQI+SSI), the North Atlantic Ocean (NNA+SNA), and the rest of the globe. This regrouping is based on their proximity to the NAF region and their relevance as primary contributors to precipitation patterns over NAF region. For the mean climate state, the African continent, the South Atlantic, the Indian Ocean, and the North Atlantic contribute approximately 39.5%,* *22.5%, 16%, and 15% to NAF rainfall, respectively (Appendix Table A1). Collectively, these four regions account for 93% of the total NAF rainfall."*

In this updated manuscript, we also add an *Appendix Table A1* (shown here as Table R1) to quantify the contribution of each subregion to NAF rainfall and δ^{18}O.

Table R1. Regional average of annual mean rainfall (Rainfall; mm/day), precipitation weight (Wgt; proportion of total precipitation) and annual mean δ^{18}O in precipitation (‰) in the NAF monsoon region (15°W-35°E, 8°N-25°N).

Region	Low NHSI			High NHSI			High-Low NHSI		
	Rainfall	Wgt	δ^{18}O	Rainfall	Wgt	δ^{18}O	ΔRainfall	ΔWgt	$\Delta\delta^{18}$O
NAt	0.153	0.14	-9.0	0.333	0.16	-10.0	0.180	0.02	-1.0
SAt	0.196	0.19	-16.1	0.544	0.26	-20.3	0.348	0.07	-4.2
Ind	0.199	0.19	-11.4	0.269	0.13	-14.4	0.070	-0.06	-3.0
AFR	0.443	0.42	-0.0	0.783	0.37	-2.5	0.340	-0.05	-2.5
Others	0.063	0.06	-19.9	0.166	0.08	-22.5	0.103	0.02	-2.6
Total	1.054	1.00	-5.6	2.095	1.00	-7.3	1.041	0.00	-1.7

21. Section 2.3: If appropriate, cite Tabor et al. (2018) for the decomposition framework

Response: Thank you very much. We have cited this paper in Line 180.

22. Section 2: Add a paragraph on the observational data to be compared with the transient simulation

Response: Thank you for your consideration. The first paragraph of section 3 (Line 205-214) discusses the model's ability to simulate North African rainfall and $\delta^{18}O_p$ in comparison with observational data.

23. Line 170: The first term in "Eqn. 6"

Response: Thank you very much. We have added it in Line 180.

24. Figure 1: Suggest to add a scatter plot of annual average GNIP $\delta^{18}O_p$ versus annual average model-simulated $\delta^{18}O_p$ to better quantify model-observation agreement. Also, please specify the model years or simulation period used for this plot. If there was a modern-simulation, please add the description to the methods.

Response: Thank you for your suggestion. We did not use data from modern-simulation in this work.

We have added a scatter plot of observed GNIP $\delta^{18}O_p$ versus model $\delta^{18}O_p$ in Fig. 1 to better quantify model-observation agreement. We add figure caption as *"The simulated data is averaged over the last 1000 years (1 ka-*

0) of the transient simulation". From this figure, we can see that the the model exhibits more negative values compared to the GNIP data. This feature has been stated in the updated manuscript in Line 214. Here, we show this figure as Figure R1 for your convenience.

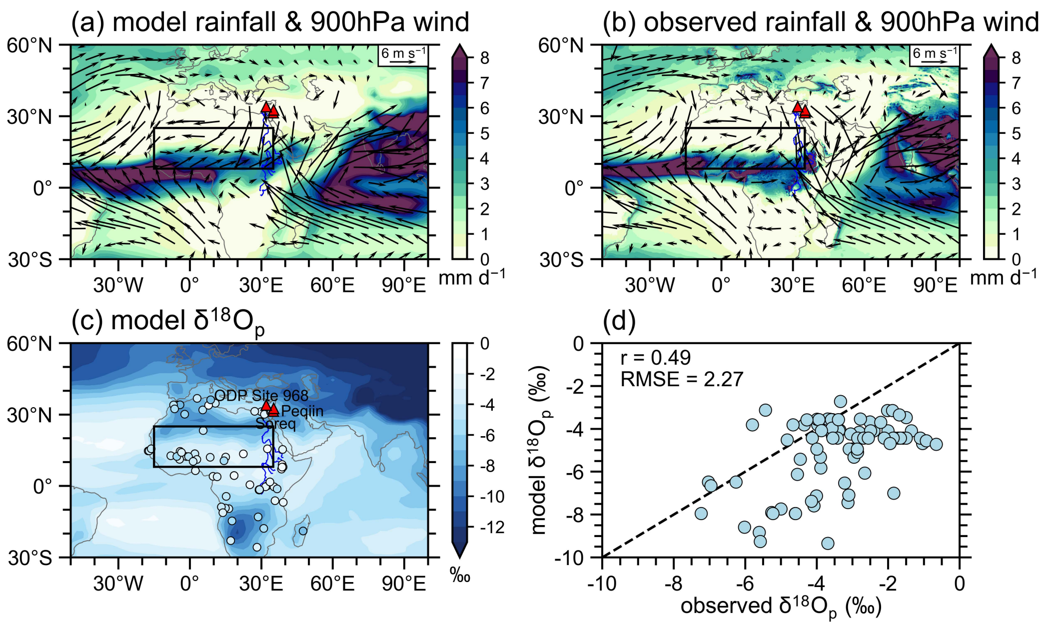

Figure R1: Modern climatology of the North Africa (NAF) summer monsoon and $\delta^{18}O_p$. (a) *Simulated boreal summer (JJA) rainfall (shading; mm d^{-1}) and 900hPa wind (vector; m s^{-1}).* ***(b)*** *Same as (a) but for observation during 1940–2024 from ERA5 (https://cds.climate.copernicus.eu/).* ***(c)*** *Simulated annual precipitation-weighted $\delta^{18}O_p$ (shading; ‰) and observed $\delta^{18}O_p$ from GNIP (https://nucleus.iaea.org/wiser/explore/) (circle; ‰).* ***(d)*** *Point-to-point scatter plot of observed GNIP $\delta^{18}O_p$ versus model-simulated $\delta^{18}O_p$. The simulated data is averaged over the last 1000 years (1 ka-0) of the transient simulation. In (a)-(c), the black rectangle region (15 °W-35 °E, 8 °N-25 °N) is the study area of the NAF monsoon and is used for subsequent regional averaging. The blue curve plots the African Nile River. The red triangles mark the locations of the proxy sites in Fig. 2.*

25. Line 197: Consider citing Sultan&Janicot 2003.

Response: Thank you very much. We have cited this paper in Line 207.

26. Line 221: Please add reference for ODP Site 968 data

Response: Thank you very much. We have added the reference for ODP Site 968 in Line 240.

27. Figure 2 Caption: "(b) Simulated $\delta^{18}O_c$ in the NAF region" As the model does not simulate this value, I suggest rewriting the caption to specify that.

Response: Thank you for your consideration. We have revised it as: *"(b) Simulated-$\delta^{18}O_c$ derived from simulated-$\delta^{18}O_p$ (see section 2.2 for details) in the NAF region (orange; ‰) and ……"*

28. Line 225: Please include a figure to substantiate the reported correlation between $\delta^{18}O_c$ and rainfall.

Response: Thank you very much. In the updated manuscript of Figure 2, we add a sentence to report the correlation between these two variables in the figure caption: *"The correlation coefficient calculated for simulated-$\delta^{18}O_c$ and simulated rainfall is -0.82."*

We also add a sentence in Line 245: *"Therefore, the high NHSI corresponds to regional averaged lower $\delta^{18}O_c$ values and higher rainfall, exhibiting a strong negative correlation between the two variables (r=-0.82; Fig. 2)."*

29. Figure 3: Please specify in the caption that solid contours denote positive values and dashed contours denote negative values.

Response: Thank you for your advice. We have added it in the caption: *"The solid (dashed) contours denote positive (negative) values."*

30. Line 256: "…Sahara, thereby reducing dust emissions." Please clarify with a figure whether there is model-based evidence supporting this.

Response: Thank you for your comment. We are sorry that the model does not directly simulate dust emissions. We have deleted this statement in Line 275: *"A strengthened NAF monsoon also weakens the northeasterly winds over the Sahara. This is consistent with the dust records observed in Atlantic sediment cores located offshore at the NAF continent (Skonieczny et al., 2019; O'Mara et al., 2022; Crocker et al., 2022)."*

31. Line 260: "Furthermore, orbitally forced Northern Hemisphere summer warming amplifies the interhemispheric temperature gradient, shifting the ITCZ northward (Schneider et al., 2014). "You may quantify the simulated ITCZ shift following methodologies from previous studies and provide numerical values or a figure to support this statement.

Response: Thank you for your suggestion. We quantified the movement of the summer ITCZ during high and low NHSI periods following the method of Voigt et al. (2016) (see Figure 4). The Figure 4 in the updated manuscript is plotted here as Figure R2 for your convenience. It shows that the mean position of ITCZ averaged over the NAF region has moved northward by 2.3° from low NHSI periods to high NHSI periods.

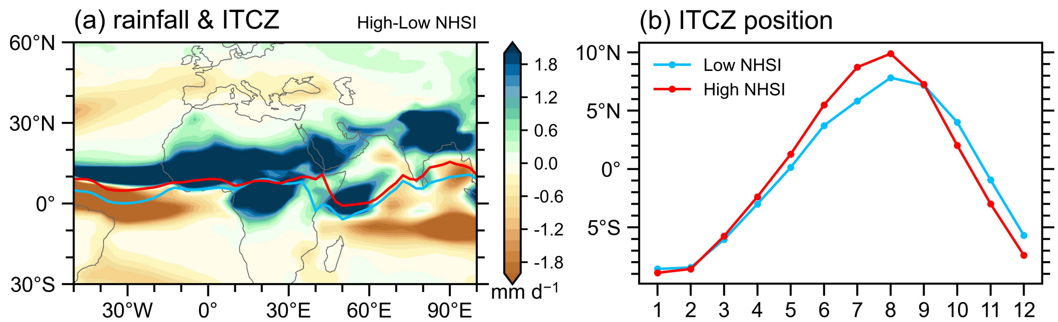

Figure R2: Changes in model rainfall and ITCZ position during boreal summer between high and low NHSI periods. (a) *Changes in summer rainfall (shading; mm d^{-1}). The contours denote the ITCZ position, which is defined as the latitude of the precipitation centroid between 30°N and 30°S following Voigt et al (2016). The red contour is for high NHSI periods, and the blue contour is for low NHSI periods.* ***(b)*** *Seasonal latitudinal shifts of the area-averaged ITCZ position over the longitude range of 15°W-35°E. Compared to the low NHSI periods, the ITCZ shifts northward by an average of 2.3° during the high NHSI periods.*

32. Line 262: ...However, "as discussed" ...

Response: Thank you very much. We have revised it in Line 288.

33. Line 284: The mechanisms are discussed but not shown. Please include figures in the supplementary material to support these results.

Response: Thank you for your suggestion. In this updated version, we plot the components of F_{net} in Figure 6 (shown here as Figure R3 for your convenience). It shows that the enhanced net energy forcing primarily stems from two factors: First, greater shortwave radiation absorption in the atmosphere; and second, increased surface latent heat flux emission to the atmosphere resulting from higher rainfall and evaporation. These sentences are also presented in Line 308.

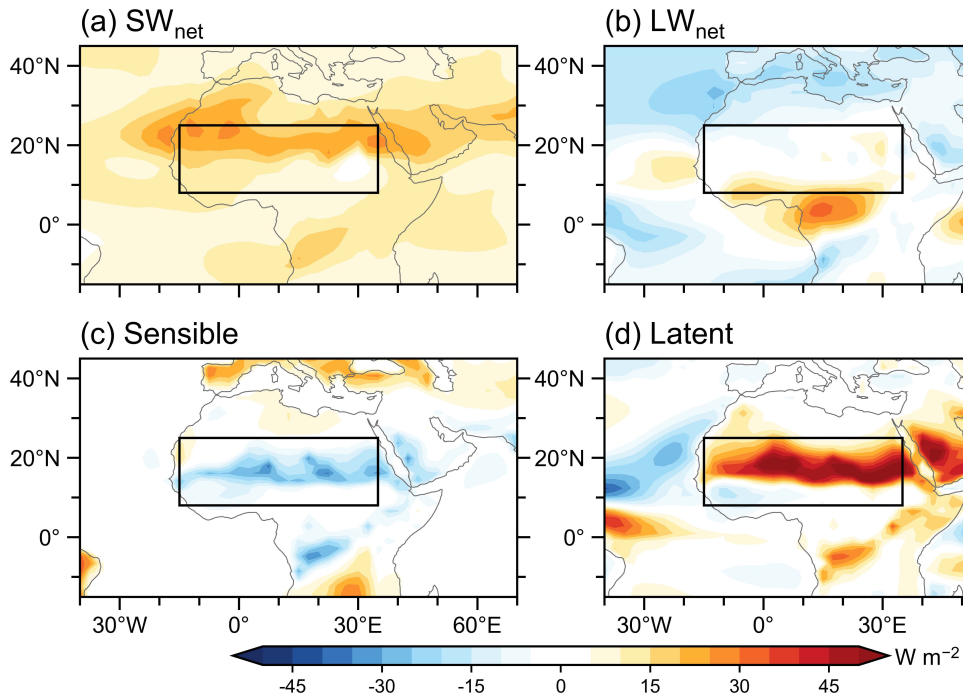

Figure R3: Changes in energy entering the atmosphere during boreal summer between high and low NHSI periods. (a) *Difference in downward shortwave radiation between the top of atmosphere and the surface, denote the net shortwave radiation into atmosphere.* ***(b)*** *Same as (a) but for the net longwave radiation change.* ***(c)*** *Surface sensible heat flux.* ***(d)*** *Surface latent heat flux.*

34. Line 291: Please clarify whether "horizontal moist enthalpy advection" is equivalent to horizontal MSE advection (Fig. 4g), and use consistent terminology throughout the manuscript.

Response: Thank you for your comment. We have changed *"horizontal moist enthalpy advection"* to *"horizontal MSE advection"*.

35. Line 294: Like the comparisons with modern precipitation and water isotope ratios in Figure 1, it'd be appropriate to discuss how the simulated percentage contributions of moisture sources compare with present-day observations, and identify the dominant moisture sources for the region.

Response: Thank you for your advice. Unfortunately, present-day observations do not allow us to quantify the relative contributions from individual moisture sources, as no tagging experiment is available for the present-day. We therefore treat the final 1,000 years of our transient simulation as representative of present-day conditions, which also correspond to a period of low NHSI. Here, we present the percentage contributions of different moisture sources under both low and high NHSI regimes. The results show that during low NHSI periods (representative of present-day conditions), the moisture sources from these four regions (the African continent, the South Atlantic, the Indian Ocean, and the North Atlantic) accounts for 42%, 19%, 19%, and 14% of rainfall in NAF region. In comparison, under high NHSI conditions, contributions from these four regions amount to 37%, 26%, 13%, and 16% respectively (Table R1).

36. Line 295: "While the mean state rainfall in the NAF region is primarily supplied by the African continent" - Please quantify the contribution.

Response: Thank you for your suggestion. We have added it in Line 321: *"Although the mean state rainfall in the NAF region is primarily supplied by the African continent (about 46%), ... "*

37. Conclusions Section:

The study's limitations related to orbital-only forcing, and implications if any, should be briefly discussed in the Conclusions, along with any comparisons with other transient climate model studies. Furthermore, in both results and conclusions, please consider adding quantifications (percentage contribution of source effects vs. upstream rainout) to strengthen the main conclusions.

Response: Thank you for your careful consideration. We have rewritten this section. In the updated version, of Discussion section, the summary of this work is presented in paragraph 1. The comparison between our results and other reconstructions and climate model studies are shown in paragraph 2-6. The caveats of this work are demonstrated in paragraph 7. Please see Line 389-461 in the updated manuscript.

38. Line 384: "Our results indicate that the "amount effect" does not work in the southern NAF region"

I suggest the authors add comparisons with a few more studies, such as Risi et al. (2008), and also contrast their results with these existing literature. Also I suggest rephrasing "does not work".

Response: Thank you for your comment. We have rewritten this paragraph in Line 441-452: *"Our results reveal that the forcing mechanisms governing $\delta^{18}O_p$ across North Africa are complex. While the "amount effect" is widely invoked to interpret $\delta^{18}O_p$ in tropical monsoon regions, its applicability varies across different subregions of North Africa. In the southern NAF, although $\delta^{18}O_p$ and rainfall are negatively correlated, that is consistent with the "amount effect" in a statistical sense, the primary control on $\delta^{18}O_p$ is en route depletion processes rather than local precipitation amount. The interpretation of $\delta^{18}O_p$ on orbital timescales also differs from that on seasonal timescales. At the seasonal scale, Risi et al. (2008) demonstrated that convective activity is the main control on the isotopic composition of precipitation in North Africa, supporting the "amount effect." This contrast highlights* *the complex, scale-dependent relationship between $\delta^{18}O_p$ and rainfall. On orbital timescales, it is essential to consider changes in rainfall along upstream vapor transport trajectories when interpreting isotopic proxies of past climate change. Although $\delta^{18}O_p$ cannot be used to directly infer past monsoon rainfall intensity, it remains a robust indicator of monsoon strength. Overall, depleted $\delta^{18}O_p$ values across North Africa are associated with an intensified NAF monsoon, characterized by enhanced southwesterly winds and increased monsoon rainfall."*

39. Further, please discuss in detail how your findings related to the amount effect would affect the usage of speleothem archives as a proxy for African rainfall.

Response: Thank you for your review. Please see our reply to your previous comments.

40. Comment on technical difficulty in locating line numbers: Line numbers are shown only every five lines in the file, making referencing difficult.

Response: Thank you for your suggestion. We are sorry for the inconvenience. The line numbers have been displayed consecutively in the new manuscript.

Replies to Reviewer #2:

"For the most part, the manuscript is interesting, it is easy to read, and it provides a thorough description of the mechanisms underlying the simulated spatial distribution of water isotope ratios in precipitation over the North African (NAF) monsoon region during different states of orbital precession. The choice to use paleoclimate simulations with both water isotopic tracers and water tag diagnostics is well supported. Tying the simulations more closely to observations would strengthen the paper."

Response: Thank you very much for the encouraging comment. We have carefully revised the manuscript and provided the point-by-point response below.

Major comments:

1. I found the order in which material was presented in Figures 5-7 confusing. Each figure duplicates material from another figure, but this is not stated explicitly in the captions. Figure 5 (b-row) shows the changes in absolute precipitation contribution from distinct moisture source regions, while Figure 7 (b-row) shows the changes in relative contribution. Why not put these side-by-side? Both Figure 6 (b-row) and Figure 7 (a-row), which are identical, show changes in relative precipitation contributions scaled by the average isotope ratio from the source region. Therefore, four of the rows across three of the figures show essentially the same type of information: the contribution of changing moisture source regions to precipitation isotope ratios. I recommend re-organizing and consolidating this information.

Response: Thank you for your suggestion. In this updated version, we have re-organized the previous Figures 5-7. The new Figure 7 illustrates the changes in rainfall and $\delta^{18}O_p$ contributed by 5 source regions. The new Figure 8 presents the decomposition of $\Delta\delta^{18}O_p$ according to Eq. (5)-(6). Specifically, Figure 8a shows the $\Delta\delta^{18}O_p$ induced by changes in precipitation weight ($\delta^{18}O_{pi} \cdot \Delta\left(\frac{P_i}{P}\right)$), with its component, that is, $\Delta\left(\frac{P_i}{P}\right)$ and $\delta^{18}O_{pi}$ displayed in Figure 8b and 8c, respectively. Figure 8d depicts the $\Delta\delta^{18}O_p$ induced by changes in the isotope ratio, with the source term, en route term and condensation term are shown in Figures 8e-g, respectively. Here, we show this figure as Fig. R4 and R5 for your convenience.

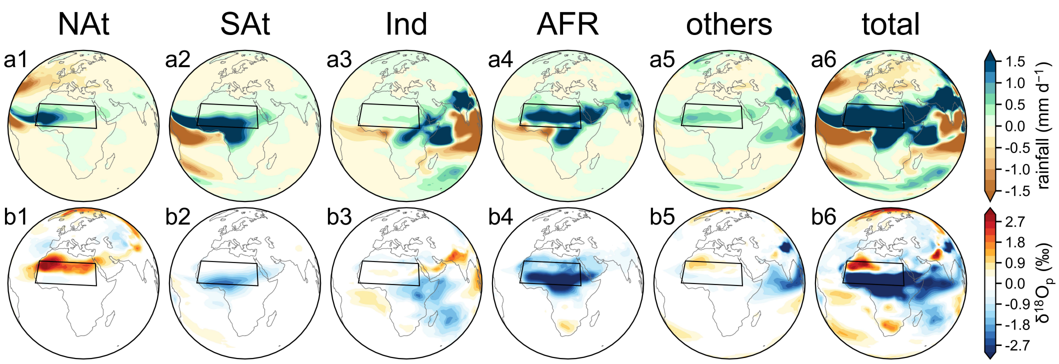

Figure R4: Tracking moisture and $\delta^{18}O_p$ from source regions (high-low NHSI in tagging experiments). *Summer rainfall (mm d^{-1}) difference between high and low NHSI periods originating from moisture source regions* ***(a1)*** *North Atlantic Ocean (NAt),* ***(a2)*** *South Atlantic Ocean (SAt),* ***(a3)*** *Indian Ocean (Ind),* ***(a4)*** *African continent (AFR),* ***(a5)*** *other regions and* ***(a6)*** *the global total of 25 sub regions.* ***(b1)****-*__*(b6)*__ *Same as (a1)-(a6) but for the difference of $\delta^{18}O_p$ between high and low NHSI periods. The black rectangles mark the NAF monsoon region.*

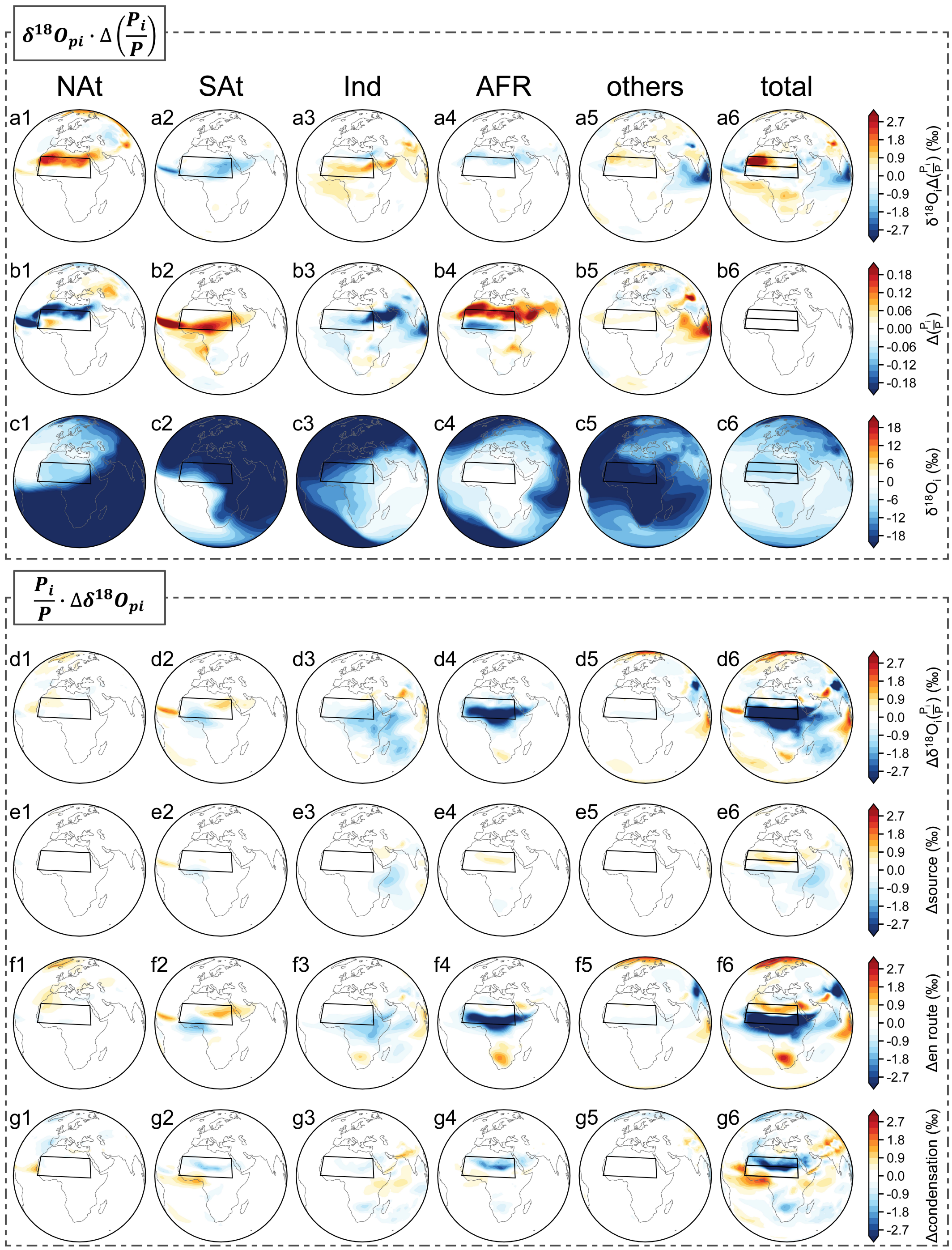

Figure R5: Decomposition of $\delta^{18}O_p$ response. (a1)-(a6) *$\delta^{18}O_p$ response due to changes in precipitation weight $\delta^{18}O_{pi} \cdot \Delta\left(\frac{P_i}{P}\right)$.* ***(b1)-(b6)*** *Changes in precipitation weight $\Delta\left(\frac{P_i}{P}\right)$ from each source region.* ***(c1)-(c6)*** *Climatological $\delta^{18}O$ value from each source region.* ***(d1)-(d6)*** *$\delta^{18}O_p$ response due to changes in $\delta^{18}O_p$ value $\frac{P_i}{P} \cdot \Delta\delta^{18}O_{pi}$, which are further decomposed into the change due to* ***(e1)-(e6)*** *source $\delta^{18}O_v$,* ***(f1)-(f6)*** *en route* *depletion and **(g1)-(g6)** condensation enrichment. In addition to marking the NAF monsoon region with a black rectangle, a north-south division of the NAF region is also marked in the sixth column of subplots.*

2. Figure 8 and related text argue that much of the isotopic depletion in the southern part of the NAF monsoon region results from distillation (rainout) as air masses "travel" from their source on the African continent to their sink within the NAF monsoon region (boxed on the figures). While this mathematical construct (term 2 on the RHS of Equation 6) makes sense for source regions that do not overlap with the sink region, I'm not sure it works for the African (continental) source. It implies that the isotope ratio of vapor within the NAF monsoon box is lower than the average isotope ratio over the continent. It does not give us any information about whether distillation occurs as air masses "travel" across the continent, as the term "en route" suggests.

Response: Thank you for your valuable advice. You are correct that the en route depletion framework is conceptually more appropriate for source regions that do not overlap with the sink region. Mathematically, Eq. (6) provides a closed-form decomposition, allowing changes in isotope composition to be decomposed into changes in the source region, the en route depletion, and condensation enrichment. The decomposition results presented in Fig. R5 indicate that the observed changes in isotopic composition are predominantly governed by en route depletion processes, while contributions from the source term and condensation enrichment are negligible. Accordingly, the depletion in $\delta^{18}O_p$ observed in the southern NAF region can be primarily attributed to en route depletion of moisture originating from the African continent.

Physically, the African continent is large, so en route depletion processes can still occur within it. From the low to high NHSI period, strong southwesterly winds prevail over the NAF region (Fig. 3c), driving a northward migration of the mean ITCZ location by approximately 2.3° (Fig. 4), and extending rainfall eastward into the Horn of Africa (Fig. 3c). This notable expansion of the monsoon system is certainly accompanied by the transport of air parcels away from their source locations, during which they experience rainout processes, leading to progressive isotopic depletion. These sentences are also demonstrated in Line 377-380.

3. The paper begins by discussing the importance of interpreting isotope ratios in paleoproxies correctly. However, the paper gives no indication whether the dipole pattern simulated in iCESM is representative of isotopic spatial patterns inferred from paleo records. Furthermore, the Introduction suggests that other models simulate a spatially uniform isotopic response to precession forcing. Why should we trust the iCESM results? How well do they inform our ability to interpret paleo records? The Discussion should compare and contrast the simulation *results with other models and contextualize the research findings by describing their relevance for paleoclimate interpretation.*

Response: Thank you for your careful review. In this updated version, we have rewritten the abstract beginning with *"On orbital timescales, the North African (NAF) monsoon variability is featured by dramatic fluctuations between wet and dry periods, which have played a significant role in early human migration and the development of agricultural civilizations. However, the spatial patterns of hydroclimate response, particularly changes in rainfall and precipitation oxygen isotopes ($\delta^{18}O_p$) remain poorly constrained due to the scarcity of proxy records. Here, we use the isotope-enabled Community Earth System Model (iCESM) to investigate the spatial-temporal variations of both rainfall and $\delta^{18}O_p$ across the NAF region……"*. We believe this version is more appropriate for our model-based study, rather than attempting solely to explain the observed speleothem δ^{18}Oc records.

In addition, we have rewritten the Discussion section in Line 389-461. In this new version, we have discussed the consistency and inconsistency between our results with previous studies, confidence of our iCESM simulation, as well as caveats in this work.

Minor comments:

1. Line 71: Despite "these advances…" what does this refer to? The previous sentences discuss simulation output, not necessarily advances.

Response: Thank you for your suggestion. We have deleted these words. We summarize this paragraph in Line 58: *"Overall, the NAF monsoon rainfall has been extensively studied."*

2. L 83: "This coherent depletion pattern appears inconsistent with…" I recommend emphasizing the apparent contradiction sooner to help motivate the work.

Response: Thank you for your comment. We have restructured the paragraph and emphasized this apparent contradiction at the beginning of the paragraph in Line 82-97: *"Over the past few decades, isotope-enabled models have evolved as valuable and well-established tools for improving our understanding of the relationship between water isotopes and climate variables. However, there are still controversies regarding the spatial patterns of $\delta^{18}O_p$ and its forcing mechanisms over the NAF region. Herold and Lohmann (2009), using an isotope-enabled General Circulation Model (ECHAM4), identified a dipole pattern in $\delta^{18}O_p$ across NAF, characterized by enrichment in* *the west and depletion in the east. They attributed western enrichment to reduced upstream rainfall depletion from Atlantic, and eastern depletion to increased local rainfall and enhanced moisture transport from the Atlantic. A similar dipole structure was later reported by Battisti et al. (2014) using the same model. Nonetheless, this west-east dipole structure has been challenged by subsequent studies showing a spatially coherent depletion pattern across the NAF region. For example, Cauquoin et al. (2019) have demonstrated a clear "amount effect" across the NAF monsoon region, with significant* $\delta^{18}O_p$ *……"*

3. L 90: Suggest replacing "among different models" with "based on different simulation results."

Response: Thank you very much. We have rewritten it in Line 96: *"Therefore, despite growing efforts to simulate* $\delta^{18}O_p$*, spatial distribution and interpretations remain inconsistent across different modeling studies."*

4. L 130: "other factors…do not fundamentally change the perception". Perception is the wrong word here. Consider rephrasing this paragraph to say that effects from these factors are expected to be negligible because of results from Roe and other papers.

Response: Thank you for your review. We have rewritten this paragraph following your suggestions in Line 121-128: *"We conduct a 150,000-year transient simulation that is driven solely by variations in Earth's orbital parameters (i.e., precession, obliquity, and eccentricity; Berger, 1978). All other boundary conditions, such as greenhouse gas concentrations, ice sheet extent, and vegetation distribution, are held constant at pre-industrial levels (Wen et al., 2024). Although the ignorance of vegetation and dust feedbacks over the NAF region tends to suppress the magnitude of changes in rainfall and* $\delta^{18}O_p$ *values (Waldmann et al., 2010; Pausata et al., 2016; Tierney et al., 2017; Messori et al., 2019; Tabor et al., 2020), the orbital-forcing experiment still captures the dominant precessional signal and the overall phase of regional climate change (Pokras and Mix, 1987; Patricola and Cook, 2007; Weber and Tuenter, 2011; Roe et al., 2016; Cheng et al., 2020). This is sufficient for the purpose of this study."*

5. Eqn 2 and 3: w-PDB and p-SMOW should be spelled out in the text and explained for greater accessibility.

Response: Thank you for your advice. We have rewritten section 2.2. Please see our reply to the question 15 from reviewer #1.

6. L 159: by "integrated" do you mean "run for 40 years?"

Response: Thank you for your question. You are right, it means "*the experiment is run for 40 years*". In the new manuscript, we have used this more understandable expression in Line 164.

7. L 166: I might suggest "terms" instead of "parts" when discussing the equations.

Response: Thank you for your careful review. The word "*part*" has been replaced with "*term*" in the article.

8. L 180: Please explain what vertical advection means within a vertically integrated atmospheric column. Why doesn't Fnet capture MSE gain/loss through the top/bottom?

Response: Thank you for your advice. The MSE budget equation is:

$$\left\{\bar{\omega}\frac{\partial\bar{h}}{\partial p}\right\} \approx \bar{F}_{net} - \{\bar{v}\cdot\nabla_p\bar{h}\} - \{\nabla_p\cdot\overline{(v'h')}\} - \{\partial_t\bar{h}\}$$

The $\left\{\bar{\omega}\frac{\partial\bar{h}}{\partial p}\right\}$ denotes the total vertical advection of MSE in the atmospheric column. Based on the equation, this term can be inferred from the sum of the net energy flux into the atmosphere column (F_{net}), horizontal advection ($\{\bar{v}\cdot\nabla_p\bar{h}\}$), and transient eddy activity ($\{\nabla_p\cdot\overline{(v'h')}\}$). Note that the $\{\partial_t\bar{h}\}$ is very small in the equilibrium state, so we neglect it in the following analysis. The vertical integral of MSE stratification in the troposphere ($\partial_p\bar{h}$) is mostly negative in pressure coordinate. Therefore, the inferred positive vertical MSE advection ($\{\bar{\omega}\partial_p\bar{h}\} > 0$) corresponds to ascending vertical motion ($\bar{\omega} < 0$) and thus the intense precipitation, and vice versa (Chen and Bordoni, 2014).

The *Fnet* is the net energy flux into the atmosphere column, which is calculated as the net radiation flux at the top of atmosphere (TOA) minus the net radiation flux at the surface. The net radiation flux at TOA = net shortwave - net longwave. The net radiation flux at the surface = net shortwave - net longwave - sensible heat - latent heat.

We have rewritten the section 2.5 for clarity.

9. L 227: Suggest replacing "satisfies" with "is consistent with"

Response: Thank you for your suggestion. We have revised it in Line 246.

10. L 261: "Since the $\delta^{18}O_c$ record evolves coherently…" This statement suggests the $\delta^{18}O$ should decrease everywhere (since precipitation amount increases over the whole box). But there's a dipole in the spatial isotopic pattern. So, this sentence should be clarified or rephrased.

Response: Thank you for your comment. We are sorry for the misunderstanding. We have revised this sentence in Line 286-290: *"Since the observed $\delta^{18}O_c$ records evolves coherently with the NAF monsoon rainfall as in "amount effect" (Fig. 2b-c), one may expect a spatially uniformly distributed $\delta^{18}O_p$ response to insolation* *forcing similar to rainfall response (Fig. 3c). However, the simulated $\delta^{18}O_p$ exhibits a dipole response with increasing in the northern NAF but decreasing in the southern part (Fig. 3e). This pattern shows a positive correlation with rainfall in the north but a negative correlation in the south. This implies the complex regional response of $\delta^{18}O_p$ to external forcing."*

11. L 272: I suggest using "MSE" consistently between text, caption, and methods, rather than introducing the term "enthalpy" here.

Response: Thank you for your suggestion. We have revised the term "*horizontal moist enthalpy advection*" to "*horizontal MSE advection*" in the new manuscript.

12. L 273: Refers to Fig 1 but I think Fig 4 is intended.

Response: Thank you for your careful review. We are sorry for the mistake and we have revised it in the new manuscript.

13. L 283: "Moving from low to high" is confusing here. I would suggest replacing with "Comparing high minus low NHSI periods."

Response: Thank you for your comment. We have revised it in Line 307.

14. L 285: Please explain why greater shortwave radiation absorption occurs with increased cloud cover. In many regions, the dominant role of more cloudiness is to increase SW reflected.

Response: Thank you for your suggestion. We have deleted this sentence and rewritten it in Line 308-310: *"This enhanced net energy forcing primarily stems from two factors (Fig. 6): First, greater shortwave radiation absorption in the atmosphere; and second, increased surface latent heat flux emission to the atmosphere resulting from higher rainfall and evaporation."*

15. L 290: Fig 4h is not discussed anywhere.

Response: Thank you for your suggestion. We briefly discuss it in Line 314: *"The transient eddy term exhibits a north-south dipole pattern (Fig. 5h), but it contributes little to the area-averaged vertical MSE advection."*

16. L 303: Fig 5 caption and axes labels suggest the plotted quantity is 16O. Is this actually the mass flux of 16O? Or H216O? I would strongly recommend using bulk precipitation rate or H216O precipitation rate rather than the flux of light atomic oxygen.

Response: Thank you for your advice. The ^{16}O here refers to the mass flux of $H_2{}^{16}O$, which denotes the precipitation rate. We have rewritten it as the precipitation rate in the new manuscript.

17. L 316: "To address this, we next employ…tagging…" However, tags are already introduced in the previous section and discussed near L 295. I would skip this sentence.

Response: Thank you for your suggestion. We have revised this sentence in Line 336: *"To explore the mechanisms behind this pattern, we analyze the results from the aforementioned moisture tagging experiments."*