

Mid-Holocene El Niño Southern Oscillation variability reduced by northern African vegetation changes in climate models

Corresponding Author: Ms Shivangi Tiwari

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Ms Tiwari,

Your manuscript titled "Mid-Holocene ENSO Variability reduced by northern African vegetation changes: a model intercomparison study" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Editorial thresholds include:

- 1) Clearer explanations of how the Green Sahara's induced La Niña-like state is connected to a reduction in ENSO variability.
- 2) Further diagnostic analyses on the role of the Walker Circulation and Atlantic-Pacific teleconnections.
- 3) More discussions on the consistency and inconsistency across models, particularly whether the proposed mechanisms are robust and consistent across models with different Green Sahara boundary condition prescriptions.
- 4) Clarify the novel contributions of this study compared to previous studies, e.g., Pausata et al 2017.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Jiaoyang Ruan
Editorial Board Member
Communications Earth & Environment
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Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript addresses an important topic in paleoclimate research: understanding ENSO variability during the mid-Holocene and how it was remotely influenced by the Green Sahara. The study is well-structured and logically presented, with a clear research question and a comprehensive methodology. The multi-model intercomparison approach is particularly valuable in strengthening the robustness of the conclusions. However, several key areas require clarification and improvement.

Major Comments

1. The study emphasizes the role of the Green Sahara in modifying ENSO variability through teleconnections, yet it lacks direct evidence of key atmospheric circulation changes, such as the change of Walker Circulation. Providing additional figures or analysis on this aspect would strengthen the argument.
2. While the results highlight the teleconnection between the Green Sahara and ENSO, they primarily focus on the impacts on the tropical Atlantic and Pacific separately. However, the manuscript does not clearly show how atmospheric anomalies induced by the Green Sahara propagate from the tropical Atlantic to the Pacific. Further analysis is needed to demonstrate this propagation mechanism.
3. The study states that the Green Sahara significantly warms the tropical Atlantic from February to April more than in other seasons. However, the explanation is unclear. Since the West African Monsoon strengthens in boreal summer, leading to increased precipitation and vegetation over the Sahara, it is not obvious why this would drive the most significant SST warming in boreal spring and winter. Further discussion on the physical process is necessary.

Specific Comments

- Line 45-47: It would be beneficial to add references to support the first two sentences regarding ENSO background.
- Line 57: This paragraph is too long; it would be better to split it into two for improved readability.
- Line 98: "The Green Sahara does not emerge in the PMIP3/4"—is this a result from the study or background information? If it is from a previous study, please cite the relevant reference.
- Line 101: The connection between the motivation and research objective is weak. It would be better to explicitly state the hypothesis that the underestimation of ENSO variability might be due to the absence of Green Sahara conditions in models, rather than simply listing the importance of the Green Sahara and model deficiencies separately.
- Line 124: "Interannual SST variability"—Did you apply any band-pass filtering? Please clarify.
- Line 124: The right column in Figure 1 is not discussed in the manuscript. If it is not crucial, consider removing it. If it presents evidence of weak ENSO variability, please discuss it explicitly.
- Line 134: Why was boreal winter SST specifically chosen?
- Line 137: From Figure 1, the negative SST anomaly is approximately 0.1°C in EC-Earth and about 0.2°C in UoF-CCSM4, while only the GISS model shows a stronger anomaly of -0.4°C. Please be more precise in your description.
- Line 141: "All the Niño index regions"—It would be helpful to add bounding boxes for different ENSO regions in Figure 1 to visually demonstrate the reduction in ENSO variability.
- Line 156: "SPCZ"—This is the first mention of the South Pacific Convergence Zone (SPCZ); please define the acronym upon first use.
- Line 195: "The Green Sahara induces westerly wind anomalies"—Can you provide a physical explanation for this process?
- Line 196: "In the equatorial Atlantic during boreal spring and winter"—Why is the impact of the Green Sahara stronger in boreal spring and winter than in summer? A clearer explanation is needed.
- Line 250: Do you have any figures showing changes in the Walker Circulation? It would be beneficial to include direct evidence supporting this statement.
- Line 254: What is the ESOI? Please define the acronym upon first use.
- Line 332: "Alterations to the Walker Circulation"—Again, there is a lack of direct evidence for Walker Circulation changes. Rather than relying on indirect indicators such as precipitation and wind changes, it would strengthen the manuscript to include direct diagnostics of the Walker Circulation.

Reviewer #2 (Remarks to the Author):

The manuscript presents a comprehensive analysis of the impact of the Green Sahara on ENSO variability. This is the first study of its kind to employ multiple models to demonstrate how vegetation changes over northern Africa during the mid-Holocene altered the tropical Pacific and Atlantic, leading to a La Niña-like mean state and a reduction in ENSO variability. The paper offers important insights into the teleconnections between the Atlantic and Pacific regions and highlights the role of the Green Sahara in modulating ENSO. Overall, the manuscript is well-written. However, I have a few minor comments regarding the mechanisms of the Green Sahara's impact on ENSO, which I believe would benefit from further clarification:

1. The proposed mechanisms in the Discussion section primarily explain the La Niña-like mean state observed in the simulations. However, I would appreciate more clarity on how these mechanisms relate to the decreased variability of ENSO. Specifically, what is the connection between the La Niña-like state and the reduction in ENSO variability? It would be useful to explicitly connect the two and discuss how the La Niña-like mean state influences the interannual variability of ENSO in the mid-Holocene.
2. In lines 237 and 250, the paper mentions a shift in the Walker Circulation. Could you clarify whether this refers to the Walker Circulation over the tropical Pacific? Additionally, what is the connection between the Atlantic Niño and the westward shift of the Walker Circulation? Since the study uses multiple models, it would be helpful to provide direct evidence of this shift by showing vertical circulation plots, rather than speculating on the shift's nature. This would provide more concrete support for the claims made in the discussion.
3. The manuscript indicates that the North Atlantic warms during the mid-Holocene in boreal spring (Line 243). Could you clarify the reasons for this warming? Specifically, what processes in the models lead to this warming, and how is it linked to the Green Sahara's impact on regional climate? More detailed explanations or references to model simulations showing this warming would be helpful.
4. I recommend including a schematic figure illustrating the mechanisms described in the Discussion section, particularly the "first mechanism" mentioned in lines 230-232. This mechanism appears to describe a Gill mode response to the warming in the tropical Atlantic, but a visual representation would greatly aid the reader's understanding. It would be especially useful in illustrating the relationship between the tropical Atlantic warming and the subsequent changes in atmospheric circulation over the Pacific.
5. In line 307, the term "middle Holocene" is used, but based on the context of the discussion, it seems that "early Holocene" would be more appropriate.

Reviewer #3 (Remarks to the Author):

Review of the manuscript "Mid-Holocene ENSO Variability reduced by northern African vegetation changes: a model intercomparison study" by Tiwari et al.

This study uses five global climate models to show that the Green Sahara during the mid-Holocene significantly reduced ENSO variability and drove the tropical Pacific into a La Niña-like state by altering the Walker Circulation and enhancing Atlantic-Pacific teleconnections. Overall, the study is interesting and the manuscript is easy to read. However, the novelty and the illustration of the mechanisms require some clarification or improvement. Below are some comments for the authors to consider.

Major Comments:

1. The paper lacks of a detailed model-data comparison of ENSO or SST variability reconstructions, although the supplementary file mentioned that some archives were used (Fig. S1; Table S2). This is primarily important before discussion to increase the credibility of the model result. Please add a model-data comparison and cite related archive/paper.
2. What is the advantage of this work over 27 Pausata et al. (2017) in NC? It should be clearly clarified in the text. To my understanding, the paper used five global climate models, but only one is performed in this study while others are collected from previous work. Different boundary conditions/prescriptions (i.e., lakes, dust) for Green Sahara make it difficult to disentangle the influence of African vegetation changes.
3. Two key mechanisms are proposed to explain the effect of Green Sahara on ENSO variability. I suggest to further discuss whether these mechanisms behave consistently across different models, in particular they differed in Green Sahara prescriptions. For example, do all models support these mechanisms, or are there differences between models? Then what is the most reliable and robust part?
4. The conclusion summarized the effect of Green Sahara on ENSO variability and emphasized the importance of model bias in simulating this phenomenon. What are the implications for future climate simulations and predictions?

Minor:

5. Abstract: Within the last two sentences, I suggest to briefly explain the mechanism how African vegetation changes influenced ENSO.
6. Please add the full name of some abbreviations in the main text, i.e., SPCZ, ESOI, NTA, GSP.
7. Lines 240-267 in discussion part, please cite related figures or papers, so that readers could tell your results or others.
8. Could more statistical significance analysis be provided to enhance the reliability of the results? For example, the mentioned assessed using the Bartlett's test for equal variances.

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Version 1:

Decision Letter:

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Dear Ms Tiwari,

Your revised manuscript titled "Mid-Holocene ENSO Variability reduced by northern African vegetation changes: a model intercomparison study" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Jiaoyang Ruan
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Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I recommend acceptance of this manuscript. It presents a significant and novel contribution to our understanding of Mid-Holocene ENSO Variability.

Reviewer #2 (Remarks to the Author):

I appreciate the authors' effort in revising the manuscript. My previous concerns have been well addressed. I have no further comments.

Reviewer #3 (Remarks to the Author):

The authors have addressed all my comments.

One further: I did not find the Fig. 5 in the main text. I agree that a schematic figure to illustrate the mechanism is essential.

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Reviewer #1 (Remarks to the Author):

The manuscript addresses an important topic in paleoclimate research: understanding ENSO variability during the mid-Holocene and how it was remotely influenced by the Green Sahara. The study is well-structured and logically presented, with a clear research question and a comprehensive methodology. The multi-model intercomparison approach is particularly valuable in strengthening the robustness of the conclusions. However, several key areas require clarification and improvement.

Thank you for the positive comments and the suggestions.

Major Comments

1. The study emphasizes the role of the Green Sahara in modifying ENSO variability through teleconnections, yet it lacks direct evidence of key atmospheric circulation changes, such as the change of Walker Circulation. Providing additional figures or analysis on this aspect would strengthen the argument.

We have added the following figure as Fig. 3 in the revised manuscript, which shows the mean annual zonal mass streamfunction anomalies for the MH_{REF} and MH_{GS} simulations relative to the PI simulation (A-J) and for the MH_{GS} simulation relative to the MH_{REF} simulation (K-O).

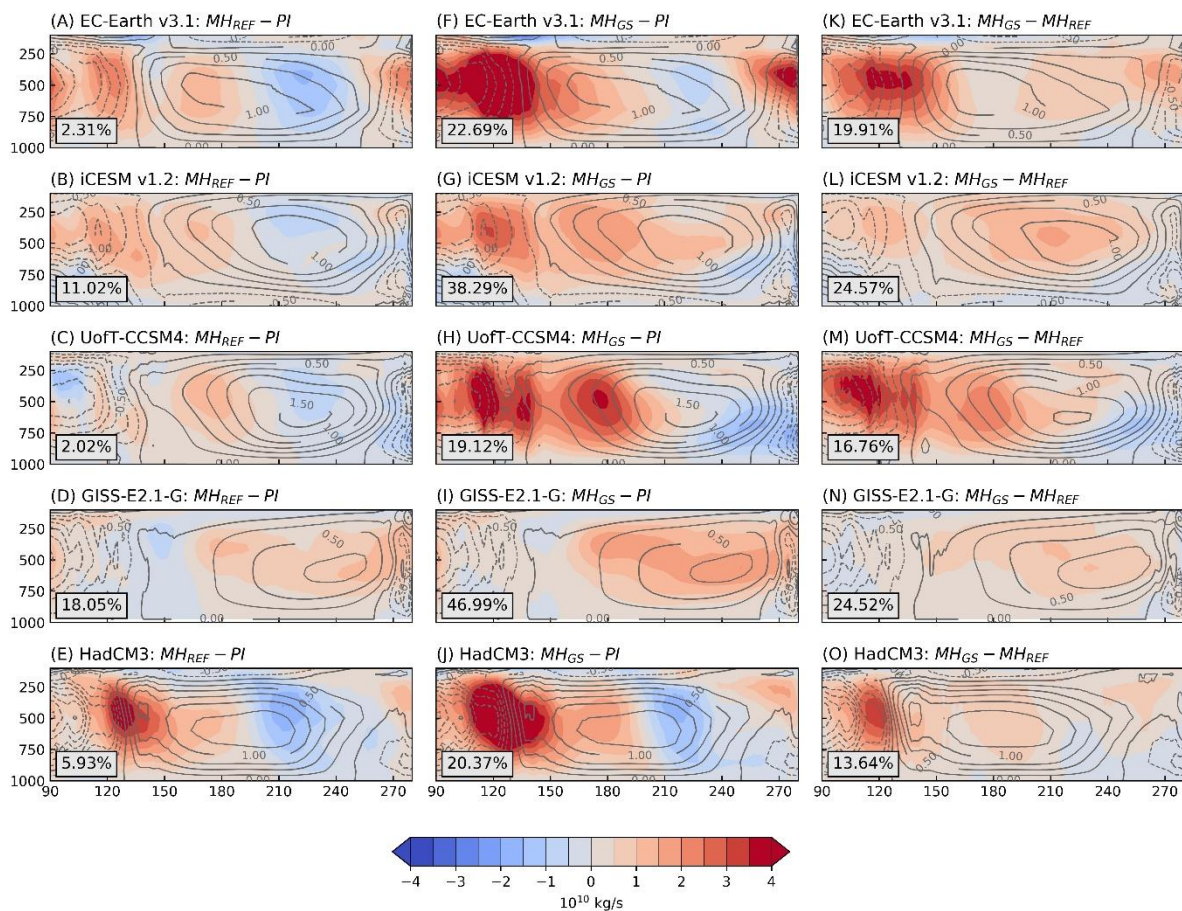


Fig. 3: Changes to the Walker Circulation. Anomalies in mean annual zonal mass streamfunction (in 10^{10} kg/s) for MH_{REF} simulation relative to the PI (A-E), MH_{GS} simulation relative to the PI (F-J), and MH_{GS} simulation relative to the MH_{REF} (K-O). Contours represent values (in 10^{11} kg/s) for the PI simulations (A-J) and MH_{REF} simulations (K-O). Numerical values to the bottom-left represent percentage change in intensity of the Walker Circulation relative to the PI simulation (A-J) and MH_{REF} simulation (K-O).

The following figure showing absolute values for the three simulations has been added to the Supplementary Material (Fig. S11):

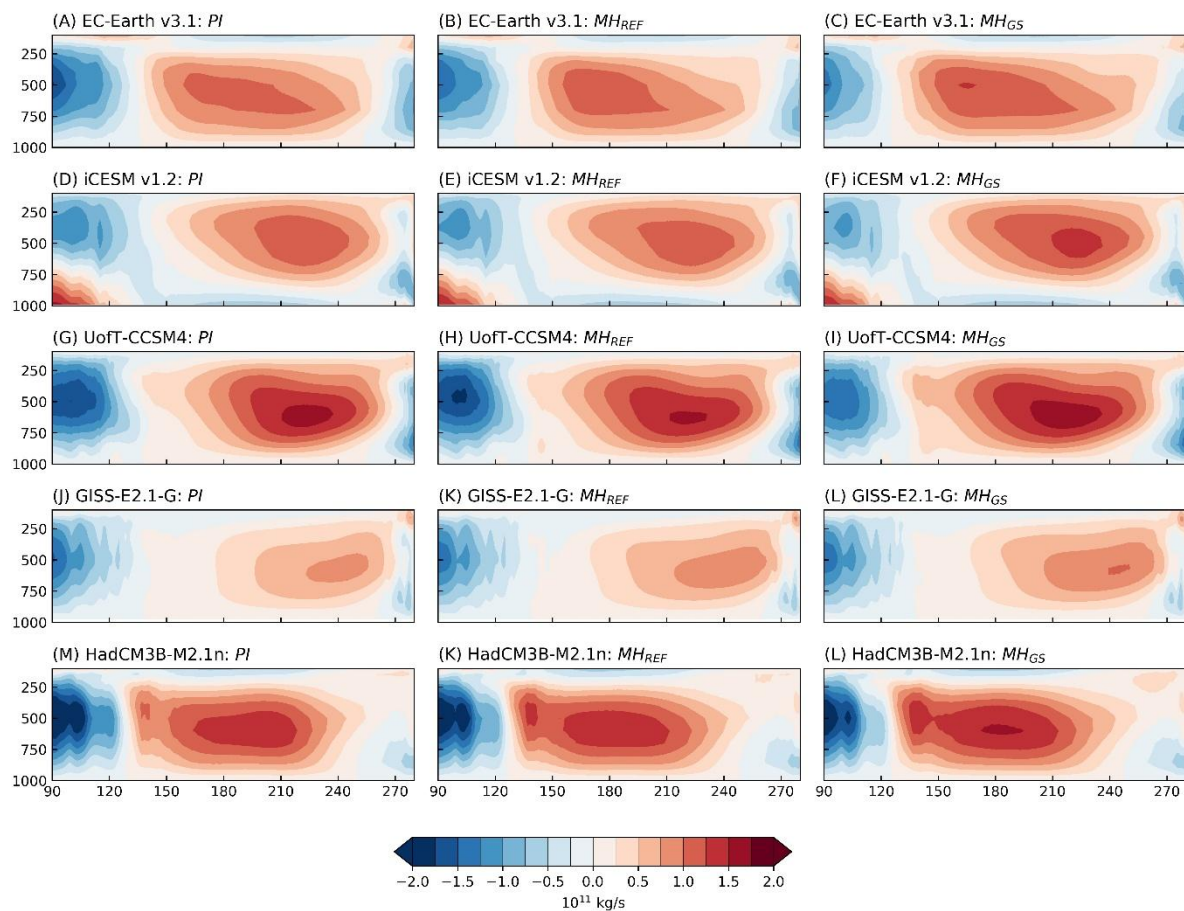


Fig. S11: Mean annual zonal mass streamfunction over the equatorial Pacific ($5^{\circ}\text{S} - 5^{\circ}\text{N}$) in 10^{11} kg/s for all simulations.

The Supplementary Table S2 has been updated with metrics describing the Pacific Walker Cell:

(e) PWC Intensity	EC-Earth	iCESM	UoIT-CCSM4	GISS	HadCM3
PI	1.96	1.21	4.45	0.66	1.59
MH_{REF}	2.01	1.34	4.54	0.79	1.69

MH _{GS}	2.41	1.67	5.29	0.98	1.91
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(f) PWC West bound	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	136	144	137.5	137	126
MH _{REF}	132	144	137.5	138	122
MH _{GS}	126	142	131	137	120

(g) PWC Center	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	170	225	224	245	204
MH _{REF}	170	225	220	245	178
MH _{GS}	166	225	218	245	182

We have added the following text in the Results section describing the changes to the Walker Circulation:

“Lastly, anomalies in the mean annual zonal mass stream function reflect changes to the large-scale atmospheric Pacific Walker Circulation (PWC, Fig. 3). There is a consistent intensification of 2-18% in the PWC intensity in response to the orbital changes from PI to the MH_{REF} (Fig. 3, A-E). In the MH_{GS} simulations, the PWC intensity increases by 19-47% relative to the PI (Fig. 3, F-J). EC-Earth and HadCM3 show a westward expansion of 4° of the PWC in response to the orbital changes, with the other models showing no clear change (Supplementary Table S2). On the other hand, all models show a westward expansion of 1-6° in the MH_{GS} simulations. The models do not show a consistent westward or eastward shift in the position of the PWC centre in response to the orbital changes or the incorporation of the Green Sahara.” (Lines 179-188)

2. While the results highlight the teleconnection between the Green Sahara and ENSO, they primarily focus on the impacts on the tropical Atlantic and Pacific separately. However, the manuscript does not clearly show how atmospheric anomalies induced by the Green Sahara propagate from the tropical Atlantic to the Pacific. Further analysis is needed to demonstrate this propagation mechanism.

We have added the following text to the Discussion:

“However, our results indicate that the key change for transmitting the regional response to the tropical Pacific is in generating westerly wind anomalies in the tropical Atlantic. These westerly wind anomalies were responsible for inhibiting upwelling along the African coast, leading to positive SST anomalies over the tropical Atlantic. These SST anomalies modulate the Pacific Walker Circulation by driving wind anomalies over the equatorial Pacific through a Gill-Matsuno response⁴³.” (Lines 334-339)

We show the westerly wind anomalies over the tropical Atlantic and the Pacific in Figures 4 and 1, respectively. Since Figure 1 shows MH_{GS}-MH_{REF} anomalies (and the only difference in the experimental design of the two simulations is the Green Sahara), we attribute these

anomalies to the Green Sahara.

3. The study states that the Green Sahara significantly warms the tropical Atlantic from February to April more than in other seasons. However, the explanation is unclear. Since the West African Monsoon strengthens in boreal summer, leading to increased precipitation and vegetation over the Sahara, it is not obvious why this would drive the most significant SST warming in boreal spring and winter. Further discussion on the physical process is necessary.

Thank you for raising this important issue. There are two points we'd like to clarify here.

Firstly, the sentence "The Green Sahara induces westerly wind anomalies in the equatorial Atlantic during boreal spring and **winter**.." (Lines 195-196 in previous manuscript) was an unfortunate error. We meant to write "The Green Sahara induces westerly wind anomalies in the equatorial Atlantic during boreal spring and **summer**.." instead.

Secondly, we did not mean that the Green Sahara warms the tropical Atlantic during FMA more than in the other seasons. That is, no comparison was made regarding warming among different seasons. We did state that there is a warming during FMA, which is pertinent to invoke the North Tropical Atlantic warming → La Niña mechanism as proposed by Ham et al. (2013) [reference 36 in the manuscript]:

Ham, Y. G., Kug, J. S., Park, J. Y. & Jin, F. F. Sea surface temperature in the north tropical Atlantic as a trigger for El Niño/Southern Oscillation events. *Nat Geosci* **6**, 112–116 (2013).

In the revised manuscript, we explain that the SST warming in boreal spring is associated with inhibited upwelling over the western African coast:

"During the MH, the intensified WAM strengthened southwesterly winds during boreal summer by 2-3 m/s (Fig. S2). The Green Sahara further amplifies the WAM-related southwesterly wind anomalies by 2-3 m/s, leading to substantial westerly wind anomalies over the tropical Atlantic during boreal spring and summer (Figs. 4, S2). The westerly wind anomalies inhibit upwelling along the western coast of Africa and lead to positive SST anomalies of up to 1-1.5 °C over the tropical Atlantic in different models (Fig. 4)." (Lines 230-235)

Specific Comments

Line 45-47: It would be beneficial to add references to support the first two sentences regarding ENSO background.

We have added the following references for ENSO background:

1. Timmermann, A. *et al.* El Niño–Southern Oscillation complexity. *Nature* vol. 559 535–545 Preprint at <https://doi.org/10.1038/s41586-018-0252-6> (2018).
2. McPhaden, M. J., Zebiak, S. E. & Glantz, M. H. *ENSO as an Integrating Concept in Earth Science*. <https://www.science.org> (2006).
3. Cai, W. *et al.* Pan-tropical climate interactions. *Science* (1979) **363**, (2019).

4. Callahan, C. W. & Mankin, J. S. *Persistent Effect of El Niño on Global Economic Growth*. <https://www.science.org> (2023).

Line 57: This paragraph is too long; it would be better to split it into two for improved readability.

This paragraph has been split into two paragraphs – one focusing on the proxy evidence for the Green Sahara and MH ENSO variability reduction, and the other discussing model studies as well as proxy-model discrepancies.

Line 98: "The Green Sahara does not emerge in the PMIP3/4"—is this a result from the study or background information? If it is from a previous study, please cite the relevant reference.

We have added the reference Brierley et al. (2020) which presents large-scale features of the PMIP4 mid-Holocene multi-model ensemble and compares them with the PMIP3 ensemble. Their study shows that both PMIP3 and PMIP4 models under-estimate the increase in precipitation over the Saharan region during the mid-Holocene (best represented in their Fig. 8).

Brierley, C. M. *et al.* Large-scale features and evaluation of the PMIP4-CMIP6 midHolocene simulations. *Climate of the Past* **16**, 1847–1872 (2020).

Line 101: The connection between the motivation and research objective is weak. It would be better to explicitly state the hypothesis that the underestimation of ENSO variability might be due to the absence of Green Sahara conditions in models, rather than simply listing the importance of the Green Sahara and model deficiencies separately.

We have explicitly stated this hypothesis in the Introduction:

"We hypothesize that the under-estimation of the simulated reduction in ENSO variability during the MH is due to an inadequate representation of the Green Sahara in climate models. To test this hypothesis, we study MH ENSO variability in the context of the Green Sahara using simulations from five global climate models. For each model, we analyzed outputs from two MH simulations – with and without prescribed vegetation and land surface changes over northern Africa (MH_{GS} and MH_{REF}, respectively) – to isolate the impact of the Green Sahara on the equatorial Pacific and Atlantic oceans." (Lines 102-108)

Line 124: "Interannual SST variability"—Did you apply any band-pass filtering? Please clarify.

We have specified this in the Methods:

"ENSO variability is estimated through the standard deviation of boreal winter SSTs, and is considered to represent ENSO amplitude⁶³. No band-pass filtering was carried out." (Lines 514-516)

Line 124: The right column in Figure 1 is not discussed in the manuscript. If it is not crucial, consider removing it. If it presents evidence of weak ENSO variability, please discuss it explicitly.

In the revised version, we refer to the right column in Figure 1 in discussing the contribution of the Green Sahara in inducing negative precipitation and easterly anomalies over the equatorial Pacific:

“The Green Sahara alone induced extensive drying of upto 2 mm/day and easterly wind anomalies over the western and central equatorial Pacific (Fig. 1).” (Lines 171-173)

Line 134: Why was boreal winter SST specifically chosen?

We chose to focus on boreal winter SSTs since ENSO events typically manifest most clearly during boreal winter.

Line 137: From Figure 1, the negative SST anomaly is approximately 0.1°C in EC-Earth and about 0.2°C in UofT-CCSM4, while only the GISS model shows a stronger anomaly of -0.4°C. Please be more precise in your description.

This sentence has been rephrased as: “For EC-Earth, UofT-CCSM4 and GISS, the negative anomalies are zonally extensive and up to 0.1 °C, 0.2 °C and 0.4 °C in magnitude, respectively.” (Lines 143-144)

Line 141: "All the Niño index regions"—It would be helpful to add bounding boxes for different ENSO regions in Figure 1 to visually demonstrate the reduction in ENSO variability.

The bounding boxes have been added to Figure 1.

Line 156: "SPCZ"—This is the first mention of the South Pacific Convergence Zone (SPCZ); please define the acronym upon first use.

This has been corrected.

Line 195: "The Green Sahara induces westerly wind anomalies"—Can you provide a physical explanation for this process?

This sentence builds on the previous sentence regarding the intensification of the WAM-related southwesterly winds. We have rephrased this sentence to connect better to the previous one, so the physical explanation is clearer:

“During the MH, the intensified WAM was associated with intensified southwesterly winds during boreal summer that brought moisture into the Saharan region (Fig. S2). The Green Sahara further amplifies the orbitally-driven WAM intensification due to land surface feedbacks, and contributes to inducing westerly wind anomalies in the equatorial Atlantic during boreal spring and summer (Figs. 4, S2). The westerly wind anomalies inhibit

upwelling in the eastern equatorial Atlantic and lead to positive SST anomalies of up to 1-1.5 °C over the tropical Atlantic in different models (Fig. 4).” (Lines 230-235)

Line 196: "In the equatorial Atlantic during boreal spring and winter"—Why is the impact of the Green Sahara stronger in boreal spring and winter than in summer? A clearer explanation is needed.

Addressed above under “Major comments”.

Line 250: Do you have any figures showing changes in the Walker Circulation? It would be beneficial to include direct evidence supporting this statement.

Addressed above under “Major comments”.

Line 254: What is the ESOI? Please define the acronym upon first use.

Since the acronym is used only once, we have removed it altogether and used the full phrase “Equatorial Southern Oscillation Index” in its place.

Line 332: "Alterations to the Walker Circulation"—Again, there is a lack of direct evidence for Walker Circulation changes. Rather than relying on indirect indicators such as precipitation and wind changes, it would strengthen the manuscript to include direct diagnostics of the Walker Circulation.

Based on the new results for the zonal mass streamfunction discussed above, the phrase “alterations to the Walker Circulation” has been changed to “a westward expansion and intensification of the Walker Circulation”.

Reviewer #2 (Remarks to the Author):

The manuscript presents a comprehensive analysis of the impact of the Green Sahara on ENSO variability. This is the first study of its kind to employ multiple models to demonstrate how vegetation changes over northern Africa during the mid-Holocene altered the tropical Pacific and Atlantic, leading to a La Niña-like mean state and a reduction in ENSO variability. The paper offers important insights into the teleconnections between the Atlantic and Pacific regions and highlights the role of the Green Sahara in modulating ENSO. Overall, the manuscript is well-written. However, I have a few minor comments regarding the mechanisms of the Green Sahara's impact on ENSO, which I believe would benefit from further clarification:

Thank you for the positive comments and the suggestions.

1. The proposed mechanisms in the Discussion section primarily explain the La Niña-like mean state observed in the simulations. However, I would appreciate more clarity on how these mechanisms relate to the decreased variability of ENSO. Specifically, what is the connection between the La Niña-like state and the reduction in ENSO variability? It would be useful to explicitly connect the two and discuss how the La Niña-like mean state influences the interannual variability of ENSO in the mid-Holocene.

We have clarified this in the Discussion and it now reads:

“The relationship between ENSO mean state and variability may not be a stationary feature of the ENSO system, as paleoclimatic evidence reveals inconsistent linkages between zonal SST gradient and ENSO variability across different climate periods. For example, reduced ENSO variability coincides with stronger zonal gradients during the Last Millennium⁴⁰ and the MH¹⁸ in agreement with our findings. In contrast, lower ENSO variability is associated with weaker zonal gradients during the Last Glacial Maximum⁴¹ and Pliocene⁴², underscoring the non-uniform nature of this relationship. These contrasts are partly sensitive to the approaches used in different studies of the same climate periods. While some proxy records imply stronger MH gradients paired with suppressed ENSO activity, the PMIP3/4 model ensemble fails to replicate this connection, highlighting sensitivities to data sources and metrics. Our results indicate that the reduction in ENSO variability was associated with a La Niña-like mean state which emerges more distinctly through basin-wide oceanic and atmospheric circulation shifts than via zonal SST gradients alone. Previous results³¹ with the model EC-Earth suggested that persistent thermocline deepening in the eastern Pacific, driven by boreal summer westerly wind anomalies and winter eastward Kelvin waves, weakens the thermocline feedback. This process dampens the Bjerknes positive feedback, which is essential for El Niño development. Intriguingly, thermocline-driven ENSO suppression also explains variability reductions during the Last Glacial Maximum⁴¹, even under weaker zonal SST gradients, bridging apparent contradictions between climate states. Future work is planned to explore inter-model consistency focusing on thermocline adjustments and the Bjerknes feedback's sensitivity to mean-state changes.” (Lines 298-318)

2. In lines 237 and 250, the paper mentions a shift in the Walker Circulation. Could you clarify whether this refers to the Walker Circulation over the tropical Pacific? Additionally, what is the connection between the Atlantic Niño and the westward shift of the Walker Circulation? Since the study uses multiple models, it would be helpful to provide direct evidence of this shift by showing vertical circulation plots, rather than speculating on the shift's nature. This would provide more concrete support for the claims made in the discussion.

We have added the following figure as Fig. 3 in the revised manuscript, which shows the mean annual zonal mass streamfunction anomalies for the MH_{REF} and MH_{GS} simulations relative to the PI simulation (A-J) and for the MH_{GS} simulation relative to the MH_{REF} simulation (K-O).

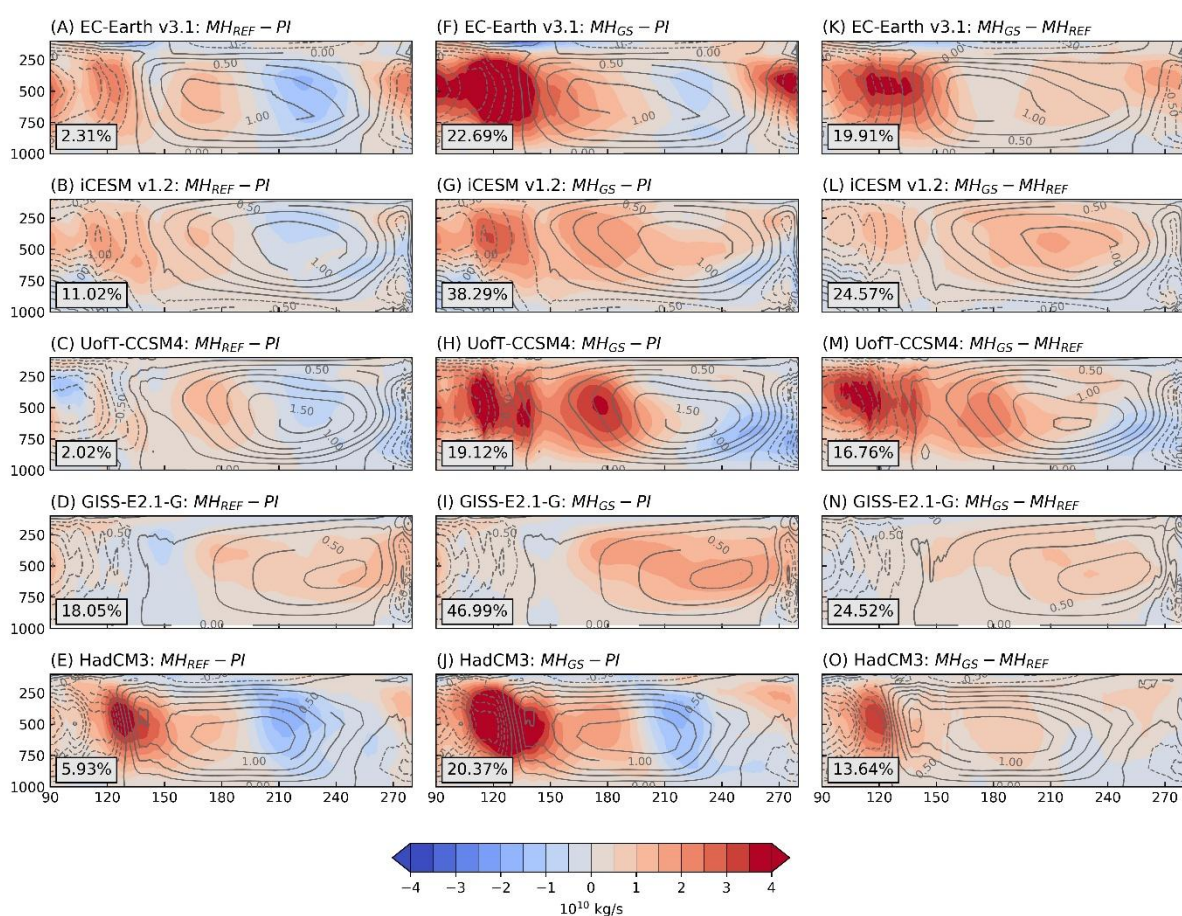


Fig. 3: Changes to the Walker Circulation. Anomalies in mean annual zonal mass streamfunction (in 10^{10} kg/s) for MH_{REF} simulation relative to the PI (A-E), MH_{GS} simulation relative to the PI (F-J), and MH_{GS} simulation relative to the MH_{REF} (K-O). Contours represent values (in 10^{11} kg/s) for the PI simulations (A-J) and MH_{REF} simulations (K-O). Numerical values to the bottom-left represent percentage change in intensity of the Walker Circulation relative to the PI simulation (A-J) and MH_{REF} simulation (K-O).

The following figure showing absolute values for the three simulations has been added to the Supplementary Material (Fig. S11):

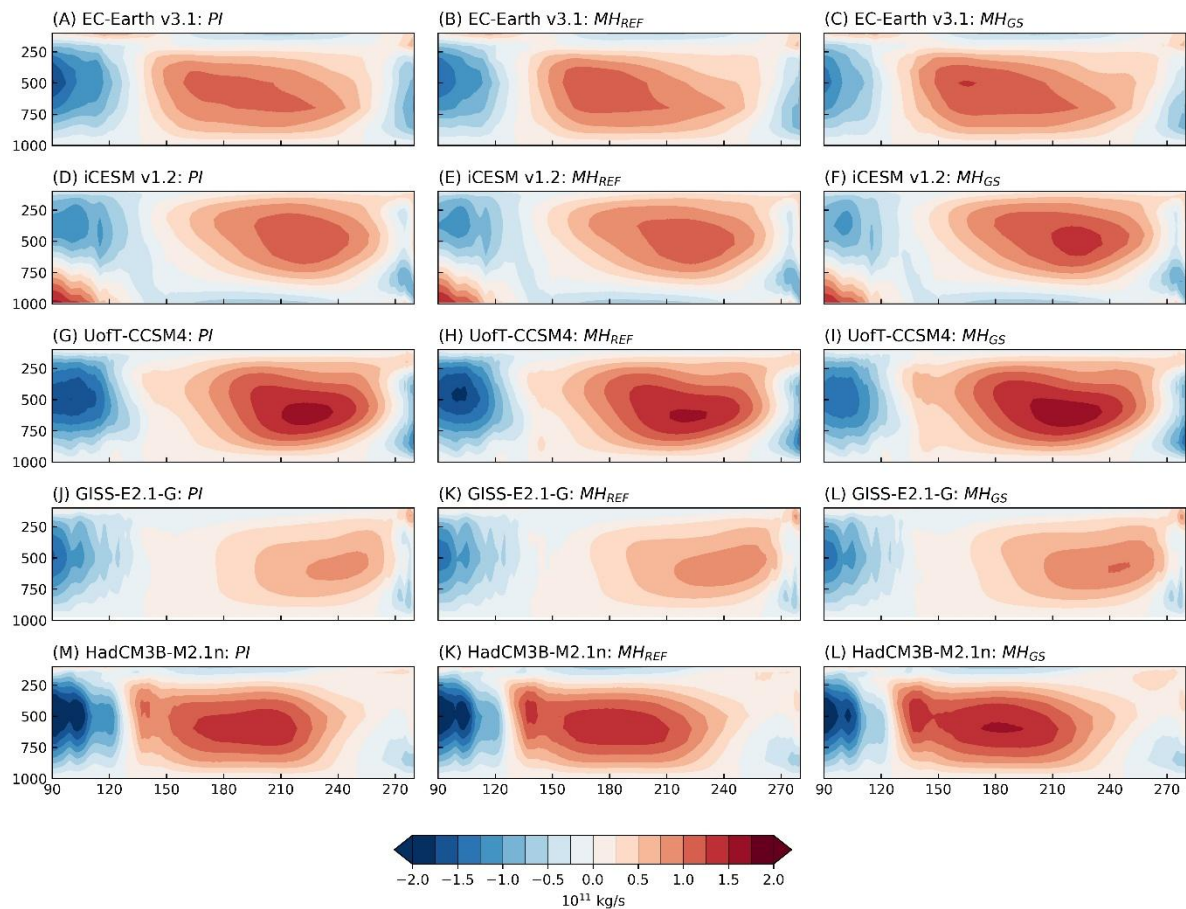


Fig. S11: Mean annual zonal mass streamfunction over the equatorial Pacific (5°S – 5°N) in 10^{11} kg/s for all simulations.

The Supplementary Table S2 has been updated with metrics describing the Pacific Walker Cell:

(e) PWC Intensity	EC-Earth	iCESM	UoFt-CCSM4	GISS	HadCM3
PI	1.96	1.21	4.45	0.66	1.59
MH _{REF}	2.01	1.34	4.54	0.79	1.69
MH _{GS}	2.41	1.67	5.29	0.98	1.91

(f) PWC West bound	EC-Earth	iCESM	UoFt-CCSM4	GISS	HadCM3
PI	136	144	137.5	137	126
MH _{REF}	132	144	137.5	138	122
MH _{GS}	126	142	131	137	120

(g) PWC Center	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	170	225	224	245	204
MH _{REF}	170	225	220	245	178
MH _{GS}	166	225	218	245	182

We have added the following text in the Results section describing the changes to the Walker Circulation:

“Lastly, anomalies in the mean annual zonal mass stream function reflect changes to the large-scale atmospheric Pacific Walker Circulation (PWC, Fig. 3). There is a consistent intensification of 2-18% in the PWC intensity in response to the orbital changes from PI to the MH_{REF} (Fig. 3, A-E). In the MH_{GS} simulations, the PWC intensity increases by 19-47% relative to the PI (Fig. 3, F-J). EC-Earth and HadCM3 show a westward expansion of 4° of the PWC in response to the orbital changes, with the other models showing no clear change (Supplementary Table S2). On the other hand, all models show a westward expansion of 1-6° in the MH_{GS} simulations. The models do not show a consistent westward or eastward shift in the position of the PWC centre in response to the orbital changes or the incorporation of the Green Sahara.” (Lines 179-188)

3. The manuscript indicates that the North Atlantic warms during the mid-Holocene in boreal spring (Line 243). Could you clarify the reasons for this warming? Specifically, what processes in the models lead to this warming, and how is it linked to the Green Sahara’s impact on regional climate? More detailed explanations or references to model simulations showing this warming would be helpful.

In the revised manuscript, we explain that the SST warming in boreal spring is associated with inhibited upwelling over the western African coast:

“During the MH, the intensified WAM strengthened southwesterly winds during boreal summer by 2-3 m/s (Fig. S2). The Green Sahara further amplifies the WAM-related southwesterly wind anomalies by 2-3 m/s, leading to substantial westerly wind anomalies over the tropical Atlantic during boreal spring and summer (Figs. 4, S2). The westerly wind anomalies inhibit upwelling along the western coast of Africa and lead to positive SST anomalies of up to 1-1.5 °C over the tropical Atlantic in different models (Fig. 4).” (Lines 230-235)

4. I recommend including a schematic figure illustrating the mechanisms described in the Discussion section, particularly the "first mechanism" mentioned in lines 230-232. This mechanism appears to describe a Gill mode response to the warming in the tropical Atlantic, but a visual representation would greatly aid the reader’s understanding. It would be especially useful in illustrating the relationship between the tropical Atlantic warming and the subsequent changes in atmospheric circulation over the Pacific.

We have added the following schematic figure as Figure 5:

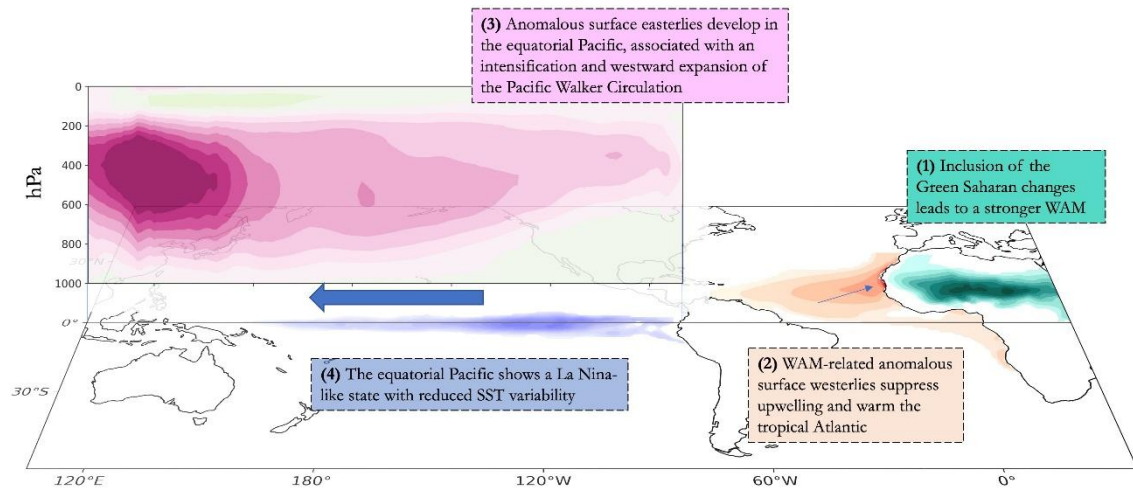


Fig. 5: Effect of the Green Sahara. Colors are based on multi-model mean MH_{GS} anomalies relative to the MH_{REF} simulation for mean annual precipitation (green), SST (orange), zonal mass streamfunction (pink) and boreal winter SST variability (blue).

5. In line 307, the term "middle Holocene" is used, but based on the context of the discussion, it seems that "early Holocene" would be more appropriate.

Thank you for raising an interesting point. Borrowing from the idea of Shanahan et al. (2015), the peak of the GSP was likely time-transgressive, with different reconstructions showing greatest precipitation anomalies at different times. For eg. different cores in the study by Tierney et al. (2017) show latitude-dependent peak precipitation anomalies. Since "peak of the GSP" is not a well-defined phrase, we choose to replace "middle Holocene" with "early and middle Holocene (9-6 ka)" here.

Reviewer #3 (Remarks to the Author):

Review of the manuscript “Mid-Holocene ENSO Variability reduced by northern African vegetation changes: a model intercomparison study” by Tiwari et al.

This study uses five global climate models to show that the Green Sahara during the mid-Holocene significantly reduced ENSO variability and drove the tropical Pacific into a La Niña-like state by altering the Walker Circulation and enhancing Atlantic-Pacific teleconnections. Overall, the study is interesting and the manuscript is easy to read. However, the novelty and the illustration of the mechanisms require some clarification or improvement. Below are some comments for the authors to consider.

Thank you for the positive comments and the suggestions.

Major Comments:

1. The paper lacks of a detailed model-data comparison of ENSO or SST variability reconstructions, although the supplementary file mentioned that some archives were used (Fig. S1; Table S2). This is primarily important before discussion to increase the credibility of the model result. Please add a model-data comparison and cite related archive/paper.

We have updated the text in the Discussion to provide a more detailed model-data comparison:

“Several proxy reconstructions from the tropical Pacific have indicated a La Nina-like mean state and reduced ENSO variability during the early and middle Holocene relative to the present day. For instance, SST and SST variability reconstructions based on lake sediments^{13,51} from Galapagos Islands and planktonic foraminifera in marine sediments^{14,52} near the Galapagos Islands reflect cool and dry conditions, reduced variability and an enhanced zonal SST gradient. The planktonic foraminiferal $\delta^{18}\text{O}$ record from core V21-30¹⁴ suggested that ENSO variance may have been reduced by up to 50% relative to the present day. These conclusions align with reduced SST⁵³ and precipitation variance (48% reduction before 4.4 ka)⁵⁴ shown by marine records from the northeastern tropical Pacific. Similarly, a fossil mollusk record from seven sites along the Peruvian coast indicated reductions of up to 55% (around 4.7 ka)⁵⁵. Records are relatively sparse in the central and western equatorial Pacific compared to the eastern equatorial Pacific. Coral¹¹ and marine sediment¹² records from or near the Line Islands in the central equatorial Pacific indicated a reduction in ENSO variance (up to 77% around 4.2 ka¹¹). In the western tropical Pacific, a coral record from Papua New Guinea¹⁶ suggests a reduction in ENSO variance of up to 85% during 7.6 – 7.1ka and speleothem¹⁷ and lake sediment¹⁸ records from teleconnected regions of Malaysian Borneo and eastern Australia respectively also suggest reduced ENSO variance during the middle Holocene. Proxy-model comparisons have shown that climate models tend to underestimate the ENSO variability reduction during the early and middle Holocene^{20,24,25}. Since the evolution of the orbital forcing through the Holocene is widely considered to be the primary driver of ENSO variance reductions, the model under-estimations are viewed as under-estimations of ENSO sensitivity to orbital forcing in the climate models²⁵. In our

study, the maximum reduction observed in the MH_{GS} simulations relative to the PI simulations is around 35% and 30% in the case of UoFT-CCSM4 and EC-Earth, respectively (Fig. S3). While this remains less than the proxy estimates, the estimates from MH_{GS} simulations show consistent decreases over the estimates from MH_{REF} simulations, suggesting that the inclusion of northern African vegetation changes during the Holocene may partly reconcile proxy-model differences.

Another aspect of proxy-model discrepancy pertains to the timing of the maximum variance reduction. While some records indicate lease ENSO variability during the early Holocene^{12,52}, most indicate that the lowest variability occurred during the transition from the middle to late Holocene, with variability increasing during the late Holocene^{11,13,14,17,54,55}. On the other hand, climate models tend to show a monotonic intensification of ENSO variability from the early to the late Holocene, as seen through transient simulations² or snapshots of equilibrium simulations^{3,16}. The observation that proxy reconstructions do not widely show such a monotonic increase in accordance with the evolution of the orbital forcing also indicates the relevance of another factor.” (Lines 395-431)

2. What is the advantage of this work over 27 Pausata et al. (2017) in NC? It should be clearly clarified in the text. To my understanding, the paper used five global climate models, but only one is performed in this study while others are collected from previous work. Different boundary conditions/prescriptions (i.e., lakes, dust) for Green Sahara make it difficult to disentangle the influence of African vegetation changes.

Pausata et al. (2017) used one climate model: EC-Earth v3.1. We have added results from ENSO analyses for the other four climate models for the first time. The simulations with HadCM3 were performed specifically for this study. The outputs from the other three climate models have been previously used in unrelated studies which did not include any ENSO analyses.

We agree that a coordinated experiment with the same boundary conditions/prescriptions for the Green Sahara would be preferable. However, despite the differences in regional northern African climate, the large-scale mechanisms are evident due to consistent warming shown over the North Tropical Atlantic and the equatorial Atlantic.

We have clarified this in the Discussion:

“In particular, the first study to compare the MH ENSO with and without prescribed vegetation and dust changes over northern Africa showed that the Green Sahara was critical in modulating the Atlantic mean state and variability and driving a reduction in ENSO variability³¹. This study was based on a single model EC-Earth v3.1 (also included in this study). Here, we show that the reduction in ENSO variability due to the Green Sahara is a consistent result across five climate models, and is thus a robust conclusion, which does not dependent on model physics and parameterizations³¹. We further demonstrate that while the specific vegetation and land surface changes incorporated to simulate the Green Sahara play modulate regional climate, it is the large-scale atmospheric changes that govern the Atlantic-Pacific teleconnection. In addition to the Atlantic Niño-mechanism shown in the previous study³¹, we identify the warming over the North Tropical Atlantic as an additional

mechanism for triggering La Niña conditions and identify the accompanying south-westward shift in the SPCZ. Our results do not discount the role of the orbitally-driven changes to seasonality or the Walker Circulation but instead suggest that they were amplified by the Green Saharan changes. Further, our findings may have implications for explaining changes in ENSO diversity, since the two mechanisms identified here favour different impacts on different regions of the equatorial Pacific. Further work is necessary to identify the varying importance of the different mechanisms during different phases of the Green Sahara Period and to understand the coherence between simulated and reconstructed changes to ENSO diversity.” (Lines 375-393)

3. Two key mechanisms are proposed to explain the effect of Green Sahara on ENSO variability. I suggest to further discuss whether these mechanisms behave consistently across different models, in particular they differed in Green Sahara prescriptions. For example, do all models support these mechanisms, or are there differences between models? Then what is the most reliable and robust part?

We have added the following paragraph in the Discussion regarding an inter-model comparison:

“While all models exhibit a reduction in ENSO variability upon the incorporation of Green Saharan changes, the magnitudes and spatial extents differ in the models. Differences among model responses arise from three causes: simulation protocols, climate response in models and model biases. Firstly, the MH_{GS} simulations analyzed here were not a part of a coordinated modelling experiment. Thus, they employ slightly different schemes for prescribing vegetation changes, though each scheme is qualitatively consistent with proxy reconstructions (see Methods and Supplementary Table S1 for further details). The vegetation changes are further treated differently within each model. For instance, albedo over northern Africa reduces from 0.3 (typical of desert regions, similar in all models) to 0.19 in GISS whereas it reduces to 0.15 in EC-Earth, leading to differences in the surface radiative balance and simulated surface temperatures. In addition to vegetation changes, simulations from different models further incorporate different changes like dust reduction (EC-Earth, iCESM) and soil and lake cover changes (UofT-CCSM4). Secondly, the climatic response to the Green Saharan changes differs over northern Africa (in terms of WAM strength; Fig. S2) as well as over the tropical Atlantic (Fig. 3). However, our results indicate that the key change for transmitting the regional response to the tropical Pacific is in generating westerly wind anomalies in the tropical Atlantic. These westerly wind anomalies were responsible for inhibiting upwelling along the African coast, leading to positive SST anomalies over the tropical Atlantic. These SST anomalies modulate the Pacific Walker Circulation by driving wind anomalies over the equatorial Pacific through a Gill-Matsuno response⁴³. EC-Earth, iCESM and UofT-CCSM4 simulate a stronger intensification of the WAM (Fig. S2) and show greater tropical Atlantic SST anomalies (Fig. 4), along with a more reasonable simulation of equatorial Atlantic variability (Fig. S7). This may explain why they simulate a greater reduction in ENSO variability compared to HadCM3. On the other hand, the strong reduction shown by GISS is most likely linked to its unusually high variability in

the MH_{REF} simulations. Further, these reductions are manifested in different parts of the equatorial Pacific in different models. For EC-Earth, the Green Sahara leads to the greatest reduction in SST variability in the western-central equatorial Pacific with a 31% decrease relative to the PI over the Niño4 region. For the other models, the greatest reductions in SST variability occur in the central-eastern equatorial Pacific with decreases of up to 17% relative to the PI over the Niño3 region (Fig. S3). Thirdly, a consistent reduction in SST variability is not observed over the tropical Atlantic with respect to the Atlantic Niño changes (Fig. S7), due to large model biases in SST and SST variability (Figs. S4, S5, S7). We conclude that the ability of a climate model to simulate changes to ENSO variability depends not only on an adequate representation of the Green Sahara (particularly the representation of changes to low-level winds over the tropical Atlantic), but also on model SST biases in the tropical Atlantic. This conclusion is supported by studies which show that ENSO forecasts are improved by improving model skill in the Atlantic ^{44,45}." (Lines 320-356)

4. The conclusion summarized the effect of Green Sahara on ENSO variability and emphasized the importance of model bias in simulating this phenomenon. What are the implications for future climate simulations and predictions?

We have added a line to mention this in the Conclusions:

"Thus, reducing model biases in the tropical Atlantic may be key to simulating the Green Sahara – ENSO teleconnection, as well as in ensuring a reasonable representation of the Atlantic-Pacific teleconnection in future climate model projections and ENSO predictions." (Lines 464 – 467)

Minor:

5. Abstract: Within the last two sentences, I suggest to briefly explain the mechanism how African vegetation changes influenced ENSO.

We have rephrased the Abstract to briefly mention the mechanisms:

"Several paleoclimatic reconstructions have indicated that the mid-Holocene (6,000 years before present) was characterized by stronger east-west temperature contrast and lower ENSO variability relative to the present day. While climate models show a reduction in ENSO variability, they underestimate this reduction compared to paleoclimate reconstructions. Further, the drivers behind these changes remain unclear. In this work, we use five global climate models to show that incorporating vegetation changes over northern Africa during the mid-Holocene amplifies the orbitally-driven strengthening of the West African Monsoon, warms the tropical north Atlantic and nudges it to an Atlantic Niño-like mean state. Changes over the Atlantic lead to a La Niña-like mean state over the tropical Pacific, with reductions in interannual variability amplified by up to 18% in the Niño3.4 region due

to the Green Sahara alone. Our work highlights the importance of the Atlantic influence on ENSO and provides paleoclimatic evidence for this synergistic teleconnection.” (Lines 27-38)

6. Please add the full name of some abbreviations in the main text, i.e., SPCZ, ESOI, NTA, GSP.

This has been corrected.

7. Lines 240-267 in discussion part, please cite related figures or papers, so that readers could tell your results or others.

We have cited the related figures (the previous papers were already cited).

8. Could more statistical significance analysis be provided to enhance the reliability of the results? For example, the mentioned assessed using the Bartlett’s test for equal variances.

Since our results are focused on two types of anomalies – anomalies reflecting mean state changes and changes to variance – we have employed the Welch’s t test and the Bartlett’s test respectively, which are the most widely used tests for statistical significance in such cases.

We have also provided details in the Methods regarding the same:

“Statistical significance: Statistical significance for mean state changes was tested using the two-sided Welch’s t test for independent samples that does not assume equal variances. For variance changes, we used the Bartlett’s test for equal variances. Only results significant at the 90% confidence level are shown.”

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I recommend acceptance of this manuscript. It presents a significant and novel contribution to our understanding of Mid-Holocene ENSO Variability.

Thank you for your positive recommendation and your helpful review.

Reviewer #2 (Remarks to the Author):

I appreciate the authors' effort in revising the manuscript. My previous concerns have been well addressed. I have no further comments.

Thank you for your positive comment and your helpful review.

Reviewer #3 (Remarks to the Author):

The authors have addressed all my comments.

One further: I did not find the Fig. 5 in the main text. I agree that a schematic figure to illustrate the mechanism is essential.

Thank you for pointing this out. Apologies for the omission – the figure was previously added to the Response to Reviewers, but not to the main text. We have added the schematic figure as Figure 5 in the main text too now.