EGUSPHERE-2024-4143

RC2 - Response

1- Reviewer Comment:

"The motivation of the study is unclear. What is the main novelty of this study compared to previous work? Is it that a larger number of interglacials are investigated, going beyond the mid-Holocene and the Eemian, which are also part of recent community efforts (PMIP)? How is this study advancing our understanding of the Earth system response to different orbital configurations?"

Response:

The main novelties of our study are the following:

Inclusion of lesser-studied interglacials:
While the Mid-Holocene (MH) and MIS5e (Eemian) have been extensively investigated especially within the PMIP framework MIS11c and MIS31 remain underexplored, particularly in terms of coupled climate-vegetation feedbacks in the Southern Hemisphere tropics. Our study is, to our knowledge, one of the first to simulate vegetation-climate interactions during MIS31 using a coupled atmosphere-biosphere model (CCM3/IBIS) with SST anomalies derived from fully coupled ocean-atmosphere simulations.

Focus on Southern Hemisphere tropical ecosystems:
A substantial portion of the literature has focused on Northern Hemisphere responses (e.g., Greenland, North Africa, Eurasia). Here, we address a knowledge gap in the Southern Hemisphere, specifically Amazonia, Central and Southern Africa, and Australia regions where vegetation feedbacks are critical but less constrained by paleo-data and modeling studies.

Isolated ocean basin experiments:
We employ a novel set of sensitivity experiments with individualized SST anomalies (Pacific, Atlantic, Indian basins) to diagnose the influence of each oceanic basin on regional precipitation and vegetation dynamics. This allows us to disentangle the contribution of specific ocean–atmosphere interactions, complementing previous studies based on globally prescribed SST anomalies.

Comparison across orbital configurations:
By including interglacials with distinct orbital characteristics (e.g., high eccentricity and precession in MIS31, versus low precession in MIS11c), our study provides new insights into how seasonal insolation patterns interact with SST anomalies to shape tropical vegetation, contributing to a more nuanced understanding of the Earth system's response to long-term orbital forcing.

2- Reviewer Comment:

"The main results need to be better summarized and presented in the abstract and conclusions."

Response:

In the revised manuscript, we'll:

The Abstract was completely modified:

Before:"Climatic feedbacks associated with orbitally driven Sea Surface Temperature (SST) lead to a profound impact on the Southern Hemisphere (SH) vegetation cover during the Mid-Holocene (MH), MIS5e, MIS11c, and MIS31 interglacials. Results are based on a suite of coupled climate simulations conducted with the ICTP-CGCM (Speedy-Nemo), which provides the boundary conditions for the CCM3/IBIS vegetation model. The CCM3/IBIS model was run from the Speed-Nemo output of the global ocean and individualized Atlantic, Pacific and Indian ocean basins forcing, in addition to orbital parameters and greenhouse gas concentrations (GHC). For interglacials, MH, Marine Isotope Stage (MIS) 5e, and 11c, areas have been found to be significantly reduced in tropical evergreen forests, but with more extensive savanna and grasslands, over parts of the southern and central African region and into northern South America (Amazon region). In another important period, the results showed that there have been changes in vegetation cover due to insolation forcing during MIS31 compared to other interglacials, but the impact was greater in Australia and central South America. However, the southern tropical climate became drier due to negative SST anomalies, induced by the Atlantic and Tropical Pacific basins, and thus reduced continental precipitation. This study demonstrates that vegetation responses across tropical regions of the Southern Hemisphere are not solely driven by orbital variations but are also significantly modulated by internal changes in Atlantic and Pacific SST patterns. In the study regions, in particular, during the MH, MIS5e and MIS11c, the seasonality of insolation was reduced in the SH, leading to the cooling of the southern tropical ocean basins, resulting in the migration of the summer precipitation zone to boreal latitudes. Therefore, combined with increased low-latitude summer temperatures and a prolonged dryer period, the forcing led to a slow retraction, but steady in the rainforests of Congo and Amazonia, causing an effect of extreme aridity."

Now:"Orbitally driven changes in sea surface temperatures (SSTs) exert a strong influence on vegetation dynamics in the Southern Hemisphere (SH) during past interglacial periods. This study analyzes the vegetation–climate responses during the Mid-Holocene (MH), MIS5e, MIS11c, and MIS31 using coupled simulations with the ICTP-CGCM (SPEEDY–NEMO) and the CCM3/IBIS dynamic vegetation model. Vegetation simulations were forced by global and basin specific SST anomalies (Atlantic, Pacific, Indian), as well as orbital parameters and greenhouse gas concentrations (GHC). Results show that MH, MIS5e, and MIS11c were characterized by significant reductions in tropical evergreen forests and an expansion of savannas and grasslands over central and southern Africa and northern South America (including Amazonia). In contrast, MIS31 presented a distinct vegetation pattern, with more pronounced impacts in Australia and central South America. Across all interglacials, reduced precipitation in the southern tropics was largely driven by negative

SST anomalies in the tropical Atlantic and Pacific, suppressing deep convection and shifting the precipitation zone northward. These findings indicate that vegetation changes in SH tropical regions were not driven solely by orbital forcing, but were also modulated by basin-specific SST anomalies and internal ocean–atmosphere feedbacks. Notably, the reduction in SH summer insolation during MH, MIS5e, and MIS11c cooled the southern tropical oceans and displaced the rainfall belt toward boreal latitudes, promoting persistent drying and contributing to the long-term retreat of tropical rainforests in Amazonia and the Congo Basin."

The following is a revised version of the final paragraph of the Conclusion section.

Our results demonstrate that vegetation responses in the Southern Hemisphere tropics during past interglacials are strongly modulated by the combined effects of orbital forcing and basin-specific SST anomalies. We find that during MH, MIS5e, and MIS11c, negative SST anomalies in the tropical Atlantic and Pacific led to suppressed rainfall and widespread contraction of evergreen forests, particularly in Amazonia and Central Africa. In contrast, MIS31 despite having extreme orbital parameters produced weaker hydrological and vegetation changes, suggesting a more complex interplay of feedbacks under high eccentricity. Individualized ocean basin experiments highlight the central role of Atlantic SSTs in modulating continental precipitation. These findings offer new perspectives on the sensitivity of tropical ecosystems to long-term climate drivers and provide a framework for interpreting future vegetation changes under altered oceanic and radiative forcing.

Last paragraph was deleted from the conclusion section:

Our findings offer valuable insights into how SST variations in distinct ocean basins influence tropical precipitation patterns and dynamic vegetation responses during past interglacial periods. What we want to express is that without forcing these ocean basins it would not be possible to highlight the sensitivity of the CCM3/IBIS model to the response of the vegetation pattern. Despite the absence of these records, the classification of the dynamic vegetation of MH, MIS5e and MIS11c were very similar.

3 - Reviewer Comment:

"Why use an atmosphere-ocean GCM to compute SSTs and then use an atmosphere-vegetation model to investigate the vegetation response? Please justify this non-conventional approach, also because climate–vegetation feedbacks can only partly be represented with this approach. Since two different models are used in the study, which have the same SSTs, could this be used to say something about uncertainties/robustness in the simulated climate change?"

Response:

Indeed, our study uses a two-step modeling strategy: first, computing SST anomalies for different interglacial periods using the fully coupled ICTP-CGCM (SPEEDY-NEMO) system; and second, using those SSTs to force the CCM3/IBIS atmosphere–vegetation model, which simulates vegetation dynamics under specified climate boundary conditions.

This approach was chosen for the following scientific and practical reasons:

Dynamic vegetation capability:
In collaboration with the University of Maryland, the ICTP AGCM has been coupled with the VEGAS (VEgetation-Global-Atmosphere-Soil) model, an interactive vegetation and land surface model. The ICTP-CGCM includes only 5 PFTs (plant function types): broadleaf tree, needleleaftree, cold grass, warm grass, and cropland. The different photosynthetic pathways are distinguished for C3 (the first three PFTs above) and C4 (warm grass) plants. On the other hand, IBIS has a two-layer canopy in which any number of PFTs may exist in each grid cell. PFTs are explicitly allowed to compete for light and water. Coupled to CCM3, is a well established global vegetation model capable of simulating functional vegetation types, phenology, evapotranspiration, and their feedbacks to the atmosphere. To investigate vegetation-climate feedbacks, we thus needed to adopt a model with a dynamic biosphere.

Modular framework for sensitivity experiments:
Using SSTs from ICTP-CGCM as boundary conditions in CCM3/IBIS allowed us to isolate the continental climate and vegetation response to oceanic and orbital forcing while keeping land-surface conditions internally consistent. It also facilitated the design of targeted ocean basin experiments (ATL, PAC, IND), which would have been significantly more complex in a fully coupled tri-component model.

Computational efficiency:
A fully coupled ocean-atmosphere-vegetation system with long integrations across four interglacials, including multi-decadal spin-ups, would exceed our computational resources. The stepwise approach offered a computationally viable compromise, maintaining physical realism in SST forcing while allowing for vegetation dynamics.

We agree with the reviewer that this framework does not fully capture two-way feedbacks between vegetation and SSTs such as surface albedo or roughness changes influencing ocean-atmosphere exchange which remain a limitation. We will explicitly acknowledge this in the revised Discussion section.

Regarding the second point, we appreciate the suggestion to explore model consistency as an indirect proxy for uncertainty. Since both ICTP-CGCM and CCM3/IBIS simulate atmospheric variables (e.g., temperature, precipitation) under the same SST forcing, we can indeed compare their respective climatologies. In fact, as noted in a previous comment, we are now including a new Supplementary Figure comparing CTRL precipitation and temperature fields between the two models.

This comparison provides a useful although indirect insight into inter model variability and structural uncertainty, especially in how atmospheric components respond to SST boundary conditions. We'll reference this point explicitly in the discussion as a way to strengthen the robustness of our conclusions.

4 - Reviewer Comment:

"Experiments need to be better explained: boundary conditions and initial conditions (for ocean, atmosphere and vegetation models) have to be clearly specified. How close to equilibrium are the models (particularly surface ocean and vegetation), considering the

relatively short simulations of ~100 years? It is not clear what the CTRL simulation represents, which is important to know in order to properly interpret the simulated anomalies during the interglacials. Is it derived from a realistic transient historical simulation?"

Response:

The CTRL simulation represents a climatological mean of the modern pre-industrial climate, consistent with the year 2000 conditions in terms of orbital parameters, GHG levels, SSTs, and land configuration. It is not derived from a fully transient historical simulation, but from a long integration (500 years) of the ICTP-CGCM under fixed modern boundary conditions (GHG, orbital, topography, land ice, aerosols). This run is used to spin up the coupled ocean-atmosphere system and establish a stable reference state.

The first 400 years were discarded to allow for oceanic and atmospheric adjustment; the last 100 years were analyzed, assuming a quasi-equilibrium state of the upper ocean and surface climate. Given the intermediate complexity of the SPEEDY-NEMO model and the absence of evolving sea ice or carbon cycle, the upper ocean reaches thermal equilibrium within this timescale, particularly for the tropical SSTs that are used in the subsequent step.

5 - Reviewer Comment:

"Results of the simulations for the mid-Holocene and 127 ka should be compared with results from PMIP models (Brierley et al., 2020; Otto-Bliesner et al., 2021). It seems that the results presented in this paper deviate quite substantially from the results of most PMIP models, particularly regarding temperature and precipitation changes over tropical land. For example, the enhanced West-African monsoon is one of the most prominent features of the mid-Holocene and Eemian in PMIP models, but is not seen in the ICTP-CGCM (or in the CCM3-IBIS?). Why?"

"It is not clear if the differences in simulated climate between the interglacials and the control shown in the paper are from the ICTP-CGCM of from the CCM3-IBIS simulations."

Response:

PMIP4 and earlier PMIP phases have robustly documented the strengthening of the West African monsoon during both the mid-Holocene (6 ka) and the Eemian (127 ka), based on an ensemble of fully coupled GCMs (e.g., Brierley et al., 2020; Otto-Bliesner et al., 2021). In our study, however, such monsoon enhancement is not captured to the same extent, particularly in the ICTP-CGCM results.

The ICTP-CGCM employs the SPEEDY atmospheric component, which is an intermediate-complexity model with simplified physics and lower horizontal resolution (~2.0° × 2.0°) compared to PMIP models. This configuration likely limits the representation of important regional processes such as the Saharan heat low and land–atmosphere coupling over northern Africa key drivers of monsoon amplification in the PMIP ensemble.
PMIP studies have shown that enhanced vegetation cover and reduced dust load during the mid-Holocene contribute significantly to the monsoon intensification (e.g., Braconnot et al.,

2012). In our ocean-atmosphere simulations (ICTP-CGCM), vegetation and dust are prescribed as modern, which likely dampens feedbacks that would otherwise reinforce the West African monsoon.

Since our atmospheric–vegetation simulations (CCM3/IBIS) are forced by SSTs from ICTP-CGCM, any underestimation of monsoonal SST patterns especially in the tropical Atlantic translates into a weaker atmospheric response in CCM3/IBIS as well. Thus, part of the vegetation and precipitation signal reflects the limitations of the SST forcing.

While our experiments use appropriate orbital and GHG levels for 6 ka and 127 ka, we maintain modern ice sheets and topography across all simulations. Some PMIP models incorporate slight differences in orography and land ice, which could influence atmospheric circulation.

Figures showing ocean and atmospheric circulation patterns (e.g., SST, sea-level pressure): these are derived from ICTP-CGCM simulations.

Figures showing temperature, precipitation, and vegetation changes over land: these are based on CCM3-IBIS simulations, which are forced by the SSTs from ICTP-CGCM.

6 - Reviewer Comment:

"The results section should be structured in a clearer way, by e.g. first discussing the results of the CTRL experiment and how well the different model results compare with present-day observations, and then: 1) discussing the results of the ICTP-CGCM model, particularly in terms of SST changes, which are then used to force the CCM3/IBIS model, 2) discussing the simulated climate change in CCM3/IBIS, 3) describing changes in the vegetation distribution and 4) separating the effects of SST changes in the different ocean basins."

Response:

We agree that the current organization of the Results section does not fully reflect the stepwise logic of the modeling approach, which could lead to confusion regarding the source and sequencing of each result.

We thank the reviewer again for this suggestion and believe this reorganization will improve the clarity and impact of the manuscript.

Minor comments

L. 3: here and elsewhere: 'Speed' -> 'Speedy'

Response:

Done.

L. 13: MH not defined

Response:
Mid-Holocene (MH) has been defined in the new text, now being on line 2.

L. 24: ‘interglacial’ -> ‘interglacials’

Response:
Done.

L. 24: MH not defined

Response:
Line 25: Mid-Holocene (MH).

L. 24-25: make it clearer that MH is ~6000 and MIS 5e ~ 12000 years ago

Response:
Done. Thanks.

Before:“such as during the MIS 5e and MH, which occurred about 6000, 120000 years before the present. However, the MIS 11c and 31 stages, which took place 411000 years ago, and 1.08M have not been investigated in detail on a global perspective based on global climate simulations”

Now:”such as during Marine Isotope Stage (MIS) 5e and the Mid-Holocene (MH), which occurred at approximately 120 ka and 6 ka, respectively (Prentice et al., 2000; Harrison et al., 2014; Kageyama et al., 2017; Minckley et al., 2023). However, the MIS11c and MIS31 stages, which took place around 411 ka and 1.08 Ma, respectively, have not been investigated in detail from a global perspective using comprehensive climate simulations (Shugart and Woodward, 2011).”

L. 28-31: This sentence is generally unclear. And what does ‘geological time scales’ mean here?

Response:
Done. Thanks.

Before:”In fact, oceanic changes on a geological time scale, mediated by interglacial periods, favor ecosystem changes worldwide, and because of modifications in climate feedbacks (Vázquez-Rivera and Currie, 2015) can shed light on Earth’s climate, which is currently experiencing remarkable changes in its thermal structure.”

Now:”Oceanic changes occurring over multiple interglacial periods in the late Quaternary have influenced global ecosystems through modifications in climate feedbacks (Vázquez-Rivera and Currie, 2015), offering insights into Earth climate system, which is currently undergoing rapid thermal changes.”

L. 38: Do you really mean ‘landscape dynamics’ here?

Response:
The sentence "...investigating the responses of vegetation dynamics to climate change associated with the past offers us the opportunity to understand the distribution of landscape dynamics (Jamieson et al., 2012)." was deleted.

L. 71: check sentence

Response:

Modified.

Before: 800 years

Now: 800 ka

L. 78: What is a ‘smoothed release of CO2’? From where?

Response:
The word "smoothed" has been changed to "gradual".

L. 106: Please specify what components are part of the CCM3-IBIS model.

Response:
CCM3/IBIS operates with a 20-minute time step for atmospheric integration and hourly coupling with the IBIS land surface and vegetation components. These configurations are standard for the resolution used and have been validated in prior studies (e.g., Foley et al., 2000; Justino et al., 2019).

L. 117: I think that here you should already refer to Table 2 with the boundary conditions for the different simulations.

Response:
Done. Thanks.

Before:”The experiments include a control simulation (CTRL), representative of the twentieth century climate (Figure 1), performed with the ICTP-CGCM model.”

Now:”The experiments include a control simulation (CTRL) (Figure 1 and Table 2), representative of the twentieth century climate, performed with the ICTP-CGCM model.”

L. 117-118: The sentence is not clear. Is the CTRL simulation a transient simulation of the historical period with realistic forcings? Or for some constant boundary conditions? And if yes, what are these conditions? What does ‘after the creation’ mean? Does this refer to some initial model state?

Response:
The verb “creation” was checked and the sentence was modified.

Before:”The experiments consist of the control simulation (CTRL) conducted for the climate of the twentieth century (Figure 1), integrated 500 years after the creation of the ICTP-CGCM model, taking as the reference climate state.”

Now:“The experiments include a control simulation (CTRL), representative of the twentieth-century climate (Figure 1), performed with the ICTP-CGCM model. The model was integrated for 500 years, starting from a standard initial condition, in order to obtain a stable reference climate state.”

L. 120: 100 years are probably not enough to reach an equilibrium of the atmosphere-ocean system. How relevant is that for the presented results?

Response:
This question was answered previously:
“The CTRL simulation represents a climatological mean of the modern pre-industrial climate, consistent with the year 2000 conditions in terms of orbital parameters, GHG levels, SSTs, and land configuration. It is not derived from a fully transient historical simulation, but from a long integration (500 years) of the ICTP-CGCM under fixed modern boundary conditions (GHG, orbital, topography, land ice, aerosols). This run is used to spin up the coupled ocean-atmosphere system and establish a stable reference state.

The first 400 years were discarded to allow for oceanic and atmospheric adjustment; the last 100 years were analyzed, assuming a quasi-equilibrium state of the upper ocean and surface climate. Given the intermediate complexity of the SPEEDY-NEMO model and the absence of evolving sea ice or carbon cycle, the upper ocean reaches thermal equilibrium within this timescale, particularly for the tropical SSTs that are used in the subsequent step.”

L. 125: unclear sentence

Response:
Before: glacials
Now: glacial

L. 142: What are SAM, CAF and SAF?

Response:
South America (SAM), Central Africa (CAF) and South Africa (SAF).

L. 148: ‘feedback’ or ‘response’?

Response:
Thanks. The word “feedback was deleted; the correct is ”response”.

L. 158: ‘cover land’ -> ‘land cover’?

Response:
Thanks. Land cover!

L. 158: The section ‘3.2 Changes in cover land’ doesn’t describe land cover changes at all.

L. 169: CTR -> CTRL

Response:
Done. CTR -> CTRL

Fig. 1: It is not just orbital parameters that are different, as shown also in Table 2.

Response:
Thank you for bringing this to our attention.
Greenhouse gas concentrations (GHC) have been included in Figure 1 and its caption.

Fig. 2: What is shown in the left column is not SSTs, but near-surface air temperatures, I guess. Not clear if the results shown here are from the ICTP-CGCM of from the CCM3-IBIS simulations.

Response:
Dear reviewer, I agree that you are absolutely right. Please make it clear that the results are from CCM3/IBIS and that the first panel refers to the near-surface temperature. Thank you. The caption has been corrected.

Before: “Spatial distribution of annual mean surface temperature difference and annual mean precipitation difference between interglacials experiments compared to SST and precipitation from CTRL; MH minus CTRL (a,e), MIS5e minus CTRL (b,f), MIS11c minus CTRL (c,g) and MIS31 minus CTRL (d,h). Black dots represent correspond to statistically significant anomalies at the 95% confidence interval.”

Now: “Spatial distribution of annual mean differences in surface temperature and precipitation between each interglacial experiment and the control simulation (CTRL), based on CCM3/IBIS outputs. MH minus CTRL (a,e), MIS5e minus CTRL (b,f), MIS11c minus CTRL (c,g) and MIS31 minus CTRL (d,h). Black dots represent correspond to statistically significant anomalies at the 95% confidence interval.”

Fig. 3: Not clear if the results shown here are from the ICTP-CGCM of from the CCM3-IBIS simulations.

Response:
The caption has been corrected.

Before:”Aridiy index to CTRL (a), MH minus CTRL (b), MIS5e minus CTRL (c), MIS11c minus CTRL (d) and MIS31 minus CTRL (e).”

Now:”Aridity index calculated from CCM3/IBIS simulations. Panel (a) shows the CTRL reference simulation, and panels (b), (c), (d), and (e) display the differences for MH, MIS5e, MIS11c, and MIS31, respectively, compared to CTRL.”