Saini et al. "The Influence of Glacial Northern Hemisphere Ice Sheets on Atmospheric Circulation"

General comments:

This manuscript presents a comprehensive modeling study of how atmospheric and oceanic systems responded to boundary conditions during Marine Isotope Stage 3 (MIS 3), with a focus on the 49 ka interval. It is appropriate for Climate of the Past because it examines a less-studied period relative to the Last Glacial Maximum (LGM) and uses the comprehensive Earth System Model (ACCESS-ESM1.5) to identify the primary factors influencing glacial circulation.

By pivoting away from a strictly North Atlantic-centric narrative, this study addresses a significant gap in the paleoclimate literature and establishes a more comprehensive global perspective. Its primary novelty is the examination of the high-obliquity state at 49 ka, characterized by an axial tilt of 24.43°, under the challenging constraints of glacial conditions, including reduced CO_2 levels and expansive ice sheets. This configuration offers a rare opportunity to analyze the complex interplay between orbital forcing and glacial topography. Furthermore, the research elucidates critical interhemispheric teleconnections, demonstrating how Northern Hemisphere ice sheets drive far-reaching climatic responses in the Southern Hemisphere, most notably through the reorganization of the Hadley Circulation (especially the Hadley cells) and the modulation of Australian monsoon patterns.

The stepwise experimental approach is a major strength of this paper. By isolating orbital/GHG effects (49ka-co), albedo (49ka-alb), and topography (49ka-full), the authors clearly identify which boundary conditions influence particular climatic responses.

The study finds that ice sheet topography is the primary driver of a roughly 6° southward shift and a zonal orientation of the North Atlantic jet during winter. While these patterns align with established LGM research, confirming them for smaller MIS 3 ice sheets is a key contribution. The simulated Atlantic Meridional Overturning Circulation (AMOC) also strengthens to 31 Sv, 47% above Pre-Industrial levels, due to topographic shifts that influence North Atlantic wind stress and the transport of warm, saline water into the Labrador Sea. In the Australian climate, the model captures monsoon strengthening and increased northern precipitation consistent with proxy data. However, it predicts drying in southern Australia, contradicting evidence of wetter conditions, highlighting the need for higher-resolution modeling or more detailed discussion to better understand moisture transport.

This manuscript provides a solid understanding of MIS 3 climate dynamics but needs further clarification on key points. 1) Address instances where the combined ice sheet effects differ from their sum to clarify nonlinear interactions, highlighting synergistic or antagonistic responses that elucidate feedback loops. 2) Discuss the Bering Strait closure's role in the 49ka-full experiment, distinguishing its effects on AMOC and salinity from broader topographic influences to identify the primary drivers of the AMOC response. 3) Address equilibrium concerns directly, explaining why the 49ka-alb model state, despite not reaching full equilibrium, captures atmospheric trends, and clarify that minor imbalances do not affect the 49ka-full results from a 760-year run, thereby strengthening the manuscript.

We thank the reviewer for their helpful comments which has led to the improvement of this manuscript and research quality. Please see the point-by-point answers to each of the comments below.

Author comments are provided in "blue" and new added text is provided in green. The line numbers mentioned throughout refer to the revised manuscript.

Specific comments:

[**Abstract**]

The abstract is scientifically sound and aligns with the scope of this journal, though it could be tightened in a few areas for clarity and impact. The main problem is insufficient quantitative detail: although it references "southward shifts" and "minor changes," it fails to include specific magnitudes from the results, like the 6° shift in the westerlies. The shift from focusing on the North Atlantic to findings in the Southern Hemisphere feels abrupt. Although "nonlinear interactions" are highlighted as an important discovery, the abstract does not clearly explain what they are, such as how topography and albedo could oppose or reinforce each other. Additionally, the phrase "all ice sheet-related boundary conditions" is somewhat vague in a summary; clarifying that it encompasses the crucial role of topography would better emphasize the study's mechanistic focus. Finally, clearly tying the "Australian rainfall" link to the ITCZ shift earlier in the text would improve the logical flow of the teleconnections described.

We have now improved the abstract following the Reviewer's suggestions and included the quantifications.

The Laurentide ice-sheet affected the North Atlantic Ocean during the last glacial period, but its impact on the global atmospheric circulation remains unclear. Here, we use the Australian Earth System Model (ACCESS-ESM1.5) to investigate the relative roles of Marine Isotope Stage 3 (MIS 3, 65-25 ka) boundary conditions in shaping global climate ~49,000 years ago (49 ka), a period marked by prominent millennial-scale variability. Our simulations show that Northern Hemisphere (NH) ice sheets were the primary driver of large-scale circulation changes. In particular, NH ice-sheet topography induced a 6° and 4° southward shift of the NH westerlies during boreal winter and summer, respectively, increasing rainfall over Eurasia during summer by 31% but reducing it in winter. In contrast, orbital forcing and greenhouse gas (GHG) changes did not lead to a significant NH westerly shift, while ice-sheet albedo strengthened NH westerlies (10–14%) through enhanced cooling (by 3-4° C) without altering their position in both seasons. NH ice sheets topography also affected the global atmospheric circulation, leading to an additional 0.9° southward shift of the Intertropical Convergence Zone (ITCZ) and 1.5° southward displacement of the NH Hadley cell in austral summer, relative to changes simulated due to orbital forcing plus GHG (0.6° and 2° southward shifts for ITCZ and NH Hadley cell, respectively), and albedo (0.4° and 0.1°, respectively). The full glacial boundary conditions, including changes in Antarctic ice-sheet topography, also lead to a 2° equatorward shift of the SH Hadley cell, and a 2.5° equatorward shift of SH westerlies during austral winter. Orbital forcing plus GHG and albedo primarily modulating the strength of the SH westerlies and tropical atmospheric circulation. These results highlight the roles of ice-sheet topography in controlling shifts in the atmospheric circulation and surface albedo in modulating atmospheric circulation intensity through radiative cooling.

[**Introduction**]

The introduction has a clear structure and effectively highlights the research gap concerning the less-studied mechanistic effects of Northern Hemisphere ice sheets during MIS 3, compared with the well-studied Last Glacial Maximum. One potential improvement is to make the rationale for selecting the specific 49-ka time slice more explicit, especially by elaborating on how its high obliquity and low greenhouse gas levels are expected to influence global teleconnections. While North Atlantic dynamics are well explained, the transition to Southern Hemisphere impacts, such as Australian rainfall, in the final paragraph feels somewhat disconnected from the earlier regional focus. A more balanced thematic development earlier in the section could better set the stage for the study's broader planetary implications. Furthermore, although the text mentions that millennial-scale variability complicates isolating equilibrium climate responses, it could more clearly explain how the current modeling approach specifically addresses this challenge to provide the "detailed, mechanistic impacts" described.

We have modified the following text in the Introduction to address the above comments.

Lines 51-53: "Some have investigated tropical climate variability, including changes in El Niño–Southern Oscillation (ENSO) behaviour during this period (Brandefelt et al., 2011; Merkel et al., 2010), while others reported a southward-shifted ITCZ and associated changes in tropical precipitation and Southern Hemisphere (SH) circulation (Guo et al., 2019),"

Lines 58-61: "Here, we employ quasi-equilibrium climate simulations with prescribed 49 ka boundary conditions and systematically isolate the effects of orbital parameters and GHGs, ice-sheet albedo, and ice-sheet topography. This framework enables us to quantify the mechanistic contribution of each forcing to atmospheric circulation and hydroclimate changes during MIS 3."

Lines 63-68: Variations in obliquity alter the distribution of incoming solar radiation across latitudes at the top of the atmosphere. High obliquity increases incoming solar insolation at high latitudes in summer, while decreasing it in winter, leading to enhanced seasonal contrast with warmer summers and colder winters in both hemispheres. These changes in radiative forcing influence the large-scale atmospheric circulation and can affect the position and strength of the Hadley circulation and the ITCZ (Mantsis et al., 2022; Liu et al., 2015; Zhang et al., 2022).

Lines 71-74: "This unusual combination of strong seasonal insolation forcing, associated with high obliquity, and low atmospheric CO_2 and extensive ice sheets, provides an opportunity to investigate how competing climate forcings interact to shape atmospheric teleconnections and hydroclimate responses on a planetary scale."

[**Methods**]

Is the following my interpretation correct?

The 49ka-alb experiment's 272-year run was too short for the simulation to fully stabilize. This is especially important given the stepwise changes in boundary conditions, such as salinity shifts and the Bering Strait closure, which could cause model 'memory effects' or incomplete ocean adjustments. Nonetheless, doubts about the reliability of the results are reduced because the main emphasis was on atmospheric circulation responses. Additionally, extending the final experiment by 760 years allowed for better system stabilization.

The interpretation is partly correct. The 272-year segment of the 49ka-alb experiment includes only the introduction of ice-sheet extent and associated vegetation changes. The additional modifications involving increased ocean salinity and closure of the Bering Strait were introduced later, beginning at model year 547 (Fig. A1, magenta line, 49ka-alb+ experiment). The analysis with 49ka-alb experiment focuses on the last 100-year average of the 272 years. 272 years provide enough time for the atmospheric circulation to respond to the changes in albedo and vegetation. However, ocean temperature, and in particular deep-ocean temperature takes a long-time to equilibrate and is thus not in equilibrium in this simulation.

[**Results**]

The Results section highlights several noteworthy findings, beginning with a simulated Atlantic Meridional Overturning Circulation (AMOC) strength of 31 Sv. This value exceeds the pre-industrial control by 47% and is a pronounced outlier among comparable MIS 3 interstadial simulations. The physical plausibility of such vigorous overturning under glacial boundary conditions, and the specific model sensitivities that drive it, require careful scrutiny.

We thank the reviewer for this comment. We agree that the simulated AMOC in 49ka-full (31 Sv) is stronger than in previously published MIS 3 simulations. This issue has been addressed in detail in our response to the corresponding Discussion comment below.

Furthermore, a clear model-data discrepancy emerges over southern Australia, where simulated drying conflicts with proxy evidence for wetter conditions. Addressing this common paleoclimate mismatch requires a deeper discussion of missing processes or resolution-related biases, consistent with the journal's emphasis on model-data integration.

We thank the reviewer for raising this point. We have clarified the relevant mechanisms in the revised Discussion to better explain the mismatch with proxy evidence.

Lines 403-414:

“Our simulations generally show an insignificant response in southern Australian annual rainfall at 49 ka, although austral winter exhibits some drier conditions. These results are consistent with those of Weij et al., (2024), in which speleothem growth rates from southwest and southeast Australia indicate drier-than-modern conditions around 49 ka. In contrast, paleo records from Kemp et al., (2019) suggest increased rainfall in southern Australia. The wetter signal in that study is interpreted as a response to changes in the SH westerlies, involving either strengthening or an equatorward shift. While the wind response is consistent with the equatorward shift simulated in the 49ka-full experiment, the rainfall response is not reproduced, indicating that southern Australian precipitation is not solely controlled by latitudinal shifts of the westerlies in ACCESS-ESM1.5. Instead, rainfall anomalies appear to be more strongly influenced by persistent subtropical high-pressure anomalies and associated subsidence over the Australian continent, which suppress moisture transport convergence despite the shift in westerlies. This may indicate limitations in the simulated coupling between storm-track variability and regional precipitation under glacial boundary conditions. However, the contrasting interpretations from available proxy records also suggest that hydroclimate conditions in southern Australia during MIS 3 remain uncertain."

Two methodological aspects also merit clarification: first, the intermediate "albedo-only" experiment is not in equilibrium, complicating the quantitative isolation of albedo versus topography effects; and second, if possible, the combined forcings in the "full" ice sheet experiment (topography and Bering Strait closure) call for a clearer separation of the oceanic responses to wind stress from those to the altered land-sea mask, the latter being a known driver of Atlantic salinity and AMOC intensification.

As clarified above, the 272 years of 49ka-alb (the albedo only experiment) provide enough time for the atmospheric circulation to respond to the changes in albedo and vegetation.

We acknowledge that the 49ka-alb experiment had not reached complete equilibrium after 272 years. However, the primary focus is on atmospheric circulation responses to imposed ice-sheet albedo and vegetation changes, which adjusts on shorter timescales than the deep ocean. The large-scale atmospheric circulation patterns analysed here are stable over the analysed period. We therefore interpret these results as representative of the atmospheric response, while noting that incomplete equilibration may limit quantitative comparison of forcing magnitudes between experiments.

We have added the text below in section 2.2 (Lines 136-139).

"Although the deep ocean has not fully equilibrated in the 49ka-co and 49ka-alb simulations, our comparison with the 49ka-full simulation focuses primarily on atmospheric circulation responses, which adjust to changes in boundary conditions much more rapidly than the ocean. Surface and atmospheric variables exhibit no systematic drift over the analysis period, supporting the robustness of the diagnostics presented here."

While both wind-driven circulation changes and ocean adjustments contribute to AMOC strengthening in 49ka-full, the stepwise nature of the experiments and their lack of full equilibration prevent a robust decomposition of the relative roles of salinity changes, land–sea mask adjustments, and topography including Bering Strait closure.

[**Discussion**]

Significant issues include the regional mismatch in Southern Australian hydroclimate, where the model predicts drying while paleo-archives suggest increased wetness. The manuscript acknowledges this discrepancy and attributes it to a lack of a northward shift in the westerlies in the model, but (as a reviewer) I would like to require a more thorough investigation of why ACCESS-ESM1.5 specifically fails to capture this signal.

We thank the reviewer for raising this point. While our simulations do show a northward shift of the Southern Hemisphere westerlies during JJA, this does not translate into enhanced precipitation over southern Australia. Instead, the regional rainfall response is primarily controlled by persistent subtropical high-pressure anomalies and associated large-scale subsidence over the Australian continent, which suppresses moisture convergence despite the poleward displacement of the jet. This indicates that Southern Australian rainfall in ACCESS-ESM1.5 is not solely governed by westerly jet position, but also by regional pressure systems and storm-track dynamics.

As noted in the response above, we have clarified this mechanism in the revised Discussion (Lines 403-414).

It is probably worth noting that the simulated increase in precipitation over northern Australia is consistent with proxy reconstructions for austral summer and annual mean conditions highlighting that the model captures large-scale tropical–subtropical hydroclimate shifts, even though regional southern Australian rainfall remains biased.

Another major point of contention is the simulated AMOC strength, which at 31 Sv represents a 47% increase over pre-industrial levels and stands as an outlier compared to several other MIS 3 modeling studies that report significant AMOC weakening. While the authors connect this to ice-sheet topography and wind-stress changes, we expect a more detailed mechanistic comparison that explains why this specific model configuration deviates so significantly from previous results in the literature.

We thank the reviewer for this comment. We agree that the simulated AMOC in 49ka-full (31 Sv) is stronger than in previously published MIS 3 simulations. However, the MIS 3 modelling literature does not show a consistent response relative to pre-industrial conditions, with AMOC changes ranging from substantial weakening (−40% to −50% in CCSM3 stadial configurations; Merkel et al., 2010; Brandefelt et al., 2011) to modest strengthening (+7% to +13%; Zhang and Prange, 2014; Guo et al., 2019), along with changes in some intermediate-complexity models (van Meerbeeck et al., 2009; Saini et al., 2024).

Previous work on LGM climate modelling has shown that ice-sheet–induced changes in North Atlantic wind stress can contribute to AMOC strengthening (Muglia and Schmittner, 2015). In our simulations, NH ice-sheet topography induces significant changes in atmospheric circulation (lines 322-331), including enhanced westerlies over the North Atlantic, consistent with this mechanism. Furthermore, previous studies have demonstrated that AMOC strength is highly sensitive to Laurentide Ice Sheet configuration and can undergo substantial changes in response to relatively small differences in ice-sheet height (Zhang et al., 2014). Given that MIS 3 Laurentide Ice Sheet reconstructions remain uncertain, the strong AMOC simulated here likely reflects the specific ice-sheet configuration prescribed in the 49 ka experiment rather than a robust feature of all MIS 3 climates.

Based on these points, we have expanded the Discussion section as below:

Lines 313-321: "Model simulations of MIS 3 climates show a range of AMOC responses depending on the prescribed boundary conditions, particularly the configuration of Northern Hemisphere ice sheets. For example, CCSM3 simulations at 35 ka and 44 ka show AMOC reductions of approximately 40% (Merkel et al., 2010) and 50% (Brandefelt et al., 2011), respectively, while a University of Victoria (UVic)-ESM simulation at ~40 ka produces a ~33% reduction relative to PI (Saini et al., 2024). In contrast, other simulations show little change or a modest strengthening of the AMOC. For example, Zhang et al., (2014) simulated a ~7% strengthening at 38 ka using CCSM3, while Guo et al. (2019) reported a ~13% strengthening at 38 ka using NorESM. Similarly, van Meerbeeck et al. (2009) simulated a 22% increase in AMOC strength during MIS 3 compared to PI (estimated from Menviel et al., 2008) using the LOVECLIM model."

Lines 332-344:

The simulated AMOC in 49ka-full is stronger than that reported in most previous MIS 3 simulations. However, the spread among MIS 3 simulations highlights the sensitivity of AMOC strength to the prescribed LIS configuration. Previous studies focusing on LGM climate have shown that changes in North Atlantic westerlies induced by the presence of the LIS can strengthen the AMOC through enhanced wind-driven circulation and deep-water formation (Muglia and Schmittner, 2015). Consistent with this mechanism, the stronger AMOC in our 49ka-full simulation is associated with LIS-driven changes in atmospheric circulation and enhanced westerlies over the North Atlantic. Conversely, changes in LIS height have also been shown to strongly affect AMOC stability and can trigger transitions between different overturning states (Zhang et al., 2014), indicating that different ice-sheet reconstructions can produce markedly different AMOC responses. Since the LIS evolved substantially throughout MIS 3 and remains poorly constrained (Malmierca-Vallet and Sime, 2023), alternative but equally plausible ice-sheet configurations may yield weaker AMOC states than simulated here. This sensitivity is consistent with evidence for large AMOC variability during MIS 3, including rapid transitions and possible overshoots following Heinrich stadials. We therefore interpret the strong AMOC in 49ka-full as a response to the specific ice-sheet configuration prescribed in our experiments rather than as a robust feature of all MIS 3 climates.

Furthermore, the explicit mention that the 49ka-alb simulation did not reach complete equilibrium may limit quantitative comparisons of the separate influences of albedo and topography.

We have addressed this in the Results section above.

Finally, although the manuscript's title highlights the role of Northern Hemisphere ice sheets, the Discussion confirms that the experiments did not isolate the individual roles of the Laurentide and Antarctic ice sheets, which may be seen as a missed opportunity to refine the understanding of hemispheric-scale climate forcing during this period.

We acknowledge that the experimental design does not fully isolate the individual contributions of the Laurentide and Antarctic ice sheets. However, the sensitivity experiments provide robust indications of their relative roles. In particular, Northern Hemisphere ice sheet topography exerts the primary control on midlatitude circulation changes through its strong influence on stationary waves and storm-track shifts, whereas Antarctic topography primarily affects Southern Hemisphere circulation via meridional temperature gradients and associated Hadley–eddy interactions. We have clarified this in the revised Discussion.

(Lines 295-299):

"Although the present experimental design does not fully isolate the individual contributions of the Laurentide and Antarctic ice sheets, sensitivity experiments and previous studies indicate that the NH ice sheet topography, dominated by the LIS, provides the primary control on midlatitude circulation changes. SH circulation changes arise from the combined influence of both ice sheets, with Antarctic topography acting primarily through modulation of inter-hemispheric temperature gradients."

[**Conclusions**]

The primary scientific limitation of this study lies in its inability to isolate the individual contributions of the Laurentide and Antarctic ice sheets within the 49ka-full experiment. Consequently, while the research aims to elucidate MIS 3 mechanisms, we cannot definitively attribute Southern Hemisphere climatic shifts to specific ice masses. The conclusions also adopt an overly optimistic tone regarding Australian rainfall, overlooking a key model-proxy discrepancy noted in the discussion: the simulated drying of southern Australia directly contradicts paleo-records suggesting wetter conditions. Explicitly highlighting such tensions in the final synthesis would strengthen the paper by pinpointing where glacial boundary conditions or model physics may require refinement, thereby offering greater value to the journal's audience.

We have modified our conclusion as below.

Our results, based on a stepwise set of MIS 3 boundary condition experiments, underscore the impacts of orbital forcing, greenhouse gases, surface albedo, and ice-sheet topography on global atmospheric circulation and regional hydroclimate. Orbital parameters and greenhouse gases alone produce limited dynamical shifts, while the addition of ice-sheet albedo primarily enhances high-latitude cooling without substantially altering circulation patterns. In contrast, the presence of NH ice sheets during MIS 3 strengthens and shifts the North Atlantic westerlies equatorward by 6° in DJF and 4° in JJA, leading to increased precipitation over the North Atlantic in both seasons, while over the Eurasian landmass precipitation increases in boreal summer but decreases in winter due to colder conditions. These ice sheet-induced changes affect the global atmospheric circulation, with a southward shift of the NH Hadley cell and ITCZ during DJF, resulting in enhanced monsoonal rainfall over northern Australia, while producing a comparatively weak hydroclimatic response in southern Australia. Regional differences, particularly between northern and southern Australia, reflect contrasting dynamical controls, with northern Australia dominated by monsoon and ITCZ-related moisture convergence, and southern Australia more strongly influenced by subtropical high-pressure anomalies and associated subsidence. These patterns are broadly consistent with proxy evidence indicating spatially heterogeneous hydroclimate conditions during MIS 3, with records suggesting both wetter and drier conditions across different regions and archives.

Although our experiments do not isolate the individual roles of the Laurentide and AISs, they show that the combined ice sheet configuration contributes to an equatorward shift of the SH westerlies and SH Hadley cell. Overall, our findings highlight the importance of the LIS in modulating atmospheric circulation and climate dynamics, noting that its geometry and extent varied substantially during MIS 3 and the deglaciation, likely contributing to diverse AMOC responses and associated climate changes.

The below line by line comments are now addressed in the manuscript.

Line-by-line comments:

L.229: “Tabel A1” to “Table A1”

L.240: “Figures 3, 9a,” to “Figures 3 and 9a,”

L.264: “on Australian climate” to “on the Australian climate”

L.277: “in 49ka-full experiment” to “in the 49ka-full experiment”

L.282: “different..” to “different.”

L.283: “for 38 ka time slice” to “over a 38 ka time slice”

L.283: “the Norwegian Earth System Model (NorESM) model” to “the Norwegian Earth System Model (NorESM)”

L.288-289: “The processes … is” to “The processes … are”

L.358: “occur” to “occurs”

L.365: “with Weij et al. (2024)” to “with those of Weij et al. (2024)”

2nd Review of Saini et al. (egusphere-2025-1990)

The authors Saini et al. have provided an updated version of the manuscript based on the referees' remarks.

Many of those have been nicely taken into account which led to a clear improvement of the manuscript. However, since the manuscript is quite comprehensive and presents a lot of details, the large number of minor issues still needs to be clarified/corrected before final publication. This should help to avoid that the reader will get lost in the details and will help that the key messages of the manuscript on the climate response to MIS3 boundary conditions and their relative role can be clearly conveyed.

Please note that the referee's comments (page/line numbers) refer to the revised manuscript version. Where reference to the first submission (FS) version is necessary, it will be referred to accordingly.

We thank the reviewer for providing their second feedback, which has improved the manuscript further. Please see the point-by-point answers to each of the comments below. Author comments are provided in "blue" and new added text is provided in green. The line numbers mentioned throughout refer to the revised manuscript.

Remarks with respect to the previous revision

1. The authors modified the abstract by adding more details on the simulated responses, which I appreciate. However, you should include one sentence making the main approach explicitly clear, e.g. near l. 4: "...around 49,000 years ago and study the relative role of the MIS3 boundary conditions…. Sentence 2 in the Abstract is a bit misleading by explicitly mentioning the ice sheets only.

The abstract is now modified as below.

"Here, we use the Australian Earth System Model (ACCESS-ESM1.5) to investigate the relative roles of Marine Isotope Stage 3 (MIS 3, 65-25 ka) boundary conditions in shaping global climate ~49,000 years ago (49 ka), a period marked by prominent millennial-scale variability."

2. Thank you for providing figure R1 in "Reply to Referee 2" on global ocean temperature and AMOC. The trends you mention in your reply only refer to the final 100 years of 49ka-full, but caution is required with the trends in 49ka-co and 49ka-alb.

We thank the reviewer for this comment. The trends shown for 49ka-full were presented to address the reviewer's original request regarding the fully equilibrated end-state analysed in Section 3.1. For 49ka-co and 49ka-alb, we acknowledge that the deep ocean has not reached full equilibrium, and therefore long-term trends in subsurface variables should be interpreted with caution. However, these experiments are primarily used to analyse atmospheric circulation responses, which exhibit minimal drift over the analysed periods, supporting their suitability for the diagnostics presented.

We have added the below text in section 2.2 (lines 136-139):

"Although the deep ocean has not fully equilibrated in the 49ka-co and 49ka-alb simulations, our comparison with the 49ka-full simulation focuses primarily on atmospheric circulation responses, which adjust to changes in boundary conditions much more rapidly than the ocean. Surface and atmospheric variables exhibit no systematic drift over the analysis period, supporting the robustness of the diagnostics presented here."

3. I appreciate Figs. R2 and R3, although I find it still a bit puzzling to center everything at 49 ka and then use 52 ka forcings for vegetation and ice sheets. R2 and R3 figures are not part of the manuscript, therefore you should at least mention 52 ka in Tab. 2 where required. In the current version of Tab. 2, one gets the impression that everything is set to 49 ka boundary conditions. I would also adjust the caption and titles in your new Fig. 1 to something like
"49 ka" ice sheet
"49 ka" vegetation and ice mask
Many people only look at figures and captions nowadays, so some hint to your special "52 instead of 49" forcings should be there. Please be precise whether the height values in ll. 105-106 are from Gowan et al. for 49 or 52 ka? Please be precise also in l. 119/120: "topography at 49 ka" is confusing.
Please also adjust the caption of Fig. 1 into "represented by the ice sheet at 52.5 ka".

We had previously kept 49 ka in the text to avoid confusion. However, we realize it could be misleading to use 52.5 ka instead of 49 ka. So, in addition to clearly stating in the text that we use 52.5 ka ice sheets, we have changed the labels in Fig. 1 and Table 2 to "52.5 ka ice sheet". Also, all values in the text correspond to 52.5 ka.

4. In my previous remarks, I was asking about the link between insolation / high obliquity and the Hadley cell strength (FS p. 8 l. 184). I don't see a big change in the revised manuscript (l. 215). Some more details about how high obliquity affects the ITCZ would be helpful (or a reference to a previous study that investigated this).

The sentence was revised from *"This shift is driven by peak summer insolation in the SH due to higher obliquity at 49 ka"* to *"The shift in the ITCZ is driven by peak summer insolation in the SH due to higher obliquity at 49 ka"* . This sentence was intended to specifically refer to the ITCZ shift rather than changes in Hadley cell strength. We acknowledge that this was not sufficiently clear in the previous version. To clarify the physical mechanism, we have now added additional context in the Introduction.

Lines 63-68: Variations in obliquity alter the distribution of incoming solar radiation across latitudes at the top of the atmosphere. High obliquity increases incoming solar insolation at high latitudes in summer, while decreasing it in winter, leading to enhanced seasonal contrast with warmer summers and colder winters in both hemispheres. These changes in radiative forcing influence the large-scale atmospheric circulation and can affect the position and strength of the Hadley circulation and the ITCZ (Mantsis et al., 2022; Liu et al., 2015; Zhang et al., 2022).

5. Table A1 is very helpful. Please double-check the headings in Tab. A1 with "49ka-ice" and "49kaalb", while you stated earlier that you have renamed 49ka-ice into 49ka-alb. Please be precise with the sign of the anomalies in brackets. Shouldn't the anomalies from PI show a cooling (negative numbers)?

The headings and the signs of the anomalies are now fixed.

6. The authors replied to my previous comment on the temperature gradient between hemispheres (FS p. 10, l. 190) that they quantified this and added the information to Table A1. But in the revised manuscript, I don't see numbers for the meridional contrast which would help the reader.

The meridional temperature contrast is represented by the difference between the NH and SH mean temperature values for respective seasons in Table A1 (Line 247). In the revised manuscript, we have now explicitly reported the temperature anomalies for all experiments in Table A1, to make this comparison clearer.

7. Fig. 2: Even with the adjustment of the sea ice isolines, it is very hard to see and distinguish the isolines. I understand the authors' argument of sticking with the projection, but you should at least increase the size of the figures a bit, e.g. by having 2 global plots next to each other and moving the third one (Fig. 2c) to a 2nd row.

We have modified Fig. 2 as per the suggestion.

8. Fig. A3 caption still does not mention the barotropic streamfunction in contrast to the authors' reply. Why did you choose a different lat-lon coverage for the three rows of the Figure? The reader should at least be pointed to this in the caption.

We have modified the caption and also fixed the projection.

Some new remarks (referring to the revised manuscript)

9. Overall, I would recommend a detailed double-checking of the text. For instance, "the" is missing here and there (l. 57, 73, Fig. 2 caption "at the 95% confidence level"…), l. 163 ("in"=> "over"),...

We have fixed this. Thank you for noticing.

10. A modified title of the manuscript such as "The Influence of Marine Isotope Stage 3 boundary conditions on Atmospheric Circulation" would better reflect the content of the manuscript, since the study is not only investigating the ice sheets' impact (also relevant for l. 2, 65 and 69 where only the ice sheet forcing is emphasized).

We thank the reviewer for this comment. Yes, we are investigating the impact of MIS 3 boundary conditions; however, given that the NH ice sheets have the major impact and are the component that has changed the most (compared to the Antarctic Ice Sheet) during MIS 3, we feel that the current title could still be suitable.

11. Abstract l. 2: “North Atlantic” => “North Atlantic region” : Fixed.

12. Abstract l. 14/15: This sentence mixes forcing and responses. => “… non-linear effects of Marine Isotope Stage 3 forcings on large-scale atmospheric circulation and precipitation patterns.”

We have modified the abstract and the last sentence is now modified to : “These results highlight the roles of ice-sheet topography in controlling shifts in the atmospheric circulation and surface albedo in modulating atmospheric circulation intensity through radiative cooling.”

13. The authors specify the paleo timeslices e.g. by 49 ka. I would suggest to include “before present (BP)” at some early point in the manuscript. :

We already define this in our abstract: 49,000 years ago (49 ka).

14. l. 35: “on understanding the impact” => “on the impact”: Modified.

15. l. 40: Suggestion for shortening: “An exception from this list is the work of Löfverström et al. (2014), who investigated… Their study found...” => Löfverström et al. (2014) investigated both the LGM as well as … and found that the…”: Applied.

16. l. 46: “of varying LIS height on the atmospheric-oceanic system” => “of different LIS heights on both the atmosphere and the ocean.”: Modified.

17. l. 49/50: Please double-check the journal’s guidelines on lists of references (alphabetically, by publication year…?). Modified to publication year.

18. l. 64: “how ice sheets influenced” => “how Marine Isotope Stage 3 boundary conditions influenced”: Modified.

19. l. 83/84: I am not a WOMBAT expert, but would rearranging the sentence be more appropriate? => “The ocean carbon cycle is modeled using the World Ocean…. (WOMBAT) model for ocean biogeochemistry which also includes a nutrient… (NPZD) scheme…” Modified.

20. l. 86-88: please double-check for typos in the brackets :Checked.

21. Tab. 1: There are no units given for the GHG concentrations.: Units provided.

22. The numbering of subsections needs correction. 2.1.1 => 2.2 : Corrected

In order to also take into account the ITCZ part at the end of section 2, the title of section 2.2 could be “Experimental setup and diagnostics”. : Modified.

23. l. 90: I would rephrase into “As a reference for our paloeclimate simulations, we use the 1000-year preindustrial control simulation (piControl) based on the year 1850 CE by Ziehn….” Since the control simulation is the less prominent part of your study, you could move this sentence towards l.d start section 2.2 directly with “To investigate the climate around 49 ka…”

We have rephrased this part. However, for simplicity, I would leave the description of the PI control simulation at the beginning of Section 2.2 and then proceed with the description of the 49ka setup.

24. l. 97: “For instance…” is not clearly connecting these sentences. I would rephrase into “Therefore, in a second step (49ka-alb), we modify the land surface properties by incorporating only the ice-sheet extent (no topography yet)….” : Modified.

25. l. 113+114: => “broadleaf deciduous type” (2x): Applied.

26. l. 124: => “averages”: Applied.

27. l. 129/130: I would move the psi symbol to the next line, since according to the formula, psi denotes the streamfunction, not the strength based on the max. Modified.

Please also double check the units of the streamfunction (Fig. 8). For instance, in a paper by Pikovnik et al. (https://wcd.copernicus.org/articles/3/625/2022/), the absolute values are at about 10^{11} kg/s (their Fig. 1) which would correspond to about 10^5 Sv when assuming a representative air density, wouldn't it?

We thank the reviewer for pointing this out. The atmospheric mass streamfunction in our study is expressed in Sverdrups (Sv), where 1 Sv = 10^9 kg s^{-1}. Therefore, the range shown in Fig. 8 (approximately ±150 Sv) corresponds to $\pm 1.5 \times 10^{11}$ kg s^{-1}, which is comparable to the magnitudes reported in Pikovnik et al. (2022). The reported strengthening of the NH Hadley cell by 20 Sv corresponds to an anomaly of 2×10^{10} kg s^{-1} relative to PI.

To avoid confusion, we have clarified the streamfunction units in Section 2.2 (lines 147) and explicitly state that the Hadley cell strength is diagnosed from the maximum (or minimum for SH) streamfunction value between 400 and 600 hPa.

28. l. 140: The annual mean numbers of 4.9°C and 2°C are not given/visible in Tab. A1 nor in Fig. 2a.

We have modified this sentence as below.

"Global annual mean surface air temperatures (SATs) at 49 ka are 2.7°C lower than PI (Table A1 and Figure 2a), with the NH cooling by 4.9°C and the SH by 2°C (not listed)."

29. l. 149+151: Please refer to the individual panels of Fig. A3. Modified.

30. l. 146: Wouldn't higher SST lead to a stabilization of the water column and weaken deep-water formation?

There are also substantial salinity changes in this region that contribute to maintaining the AMOC.

31. Section 3.2 title: I would delete "changes". Deleted.

32. l. 170-171: Since 850 hPa is not the jetstream level, I would just write "tilt of the wind field" and "...both at the surface and at the jetstream level in the upper troposphere": Modified.

33. l. 174: "southward shift and zonal jet"=> "southward shift and more zonal orientation of the jet" Modified.

34. 33. l. 175: "more zonal configuration". How about "more southerly pathway"?: Modified.

35. 34. l. 178: I would delete "the persistence of". Deleted.

36. l. 179: "remaining more zonal than during PI" – I don't clearly see this.

I have modified this sentence to clearly refer to the correct figures. The zonal orientation is visible in the arrows in the red region of the North Atlantic.

37. l. 181: I guess you mean "moisture transport convergence". Modified.

38. l. 182: "the westerly band" => What do you mean by this? Changed to "westerlies".

39. l. 183: "mild temperature conditions". But this still shows cooling. Do you mean "minor cooling" then? Yes, modified to minor cooling.

40. l. 188: Please delete "the influx of". Deleted.

41. l. 190: I would make the structure of the section even more clear by inserting a sentence here, e.g. such as “The role of individual boundary conditions (only orbit and GHG forcing) becomes evident from the 49ka-co experiment.” Added.

42. l. 191: I wonder whether this shift is really significant. How about just writing “enhanced and hardly shift southward (Fig. 4a, 9a)”. Modified.

43. l. 196: => “by 8°C”: Modified.

44. l. 198/199: I am not so sure about this being consistent and directly coupled since GH and precipitation responses seem to be on different spatial scales here. Changed to “some increased precipitation (line 215)”.

45. l. 201: => “temperature and hardly any significant precipitation changes”: Modified.

46. l. 205: Instead of starting the paragraph with a list of Figures, you could write “In summary, only the full implementation….” and move the list of Figure refs. towards the end of the paragraph in brackets. Modified.

47. l. 206: “southward-shifted” => “southward-shifted and intensified”: Modified.

48. l. 216: shift by 0.6° - Maybe you could mention that regionally shifts may be larger (if this is the case). Since, we are only discussing global shifts here, we would like to keep the original sentence.

49. l. 213: I find it still hard to see the 20 Sv. Maybe you could at least refer back to your diagnostics part in section 2 and make clear that the 20 Sv are the anomaly between the two experiments’ max values between 400 and 600 hPa. Added (Line 230).

50. l. 224: Fig. 3h does not really show the globally averaged ITCZ. Changed to “global ITCZ”.

51. l. 228/229: Which numbers in Tab. A1 do you refer to here? The annual or seasonal means? Please try to help readers find the information directly.

Added in Line 247: “(Table A1, comparison of JJA NH minus SH SAT differences between 49ka-full, 49ka-alb and 49ka-co)”

52. l. 233: “in 49ka-co but weaken further in 49ka-alb” => “in 49ka-co and 49ka-alb”: Modified.

53. l. 236: “strongest weakening” => “most pronounced weakening”: Modified.

54. l. 240/241: I would move the reference to the figures to the end of the sentence in brackets and start the sentence with “The implementation of 49 ka…” : Modified.

55. l. 242/243: “broader” is very unspecific. Furthermore, you investigate all boundary conditions in your study. Modified.

56. l. 247: “the NH ice sheet forces”, but then you refer to Fig. 8a which points to the response to all boundary conditions in 49ka-full. Changed to “full boundary conditions in 49ka-full”

57. l. 257: moisture transported from ? into the region

Changed to “from the Southern Ocean into the Australian region”

58. l. 259: “part off Australia” or “part of Australia”? This is correct in the revised version.

59. l. 279: “consistent with PMIP4” => “similar to PMIP4”: Modified.

60. l. 282-285: For the sake of completeness, you should specify whether the given numbers denote global and annual (seasonal?) means.

Added the information that these are “globally averaged annual means.”

61. l. 293: => “in our 49ka-full simulation”: Modified.

62. l. 295/296: Where does the model have its deep-water formation regions in the North Atlantic? So the transport of saline waters may be more important than the warm waters (see my comment #30)?

Yes, as mentioned above, saline waters play a more dominant role than warm waters in maintaining the AMOC in this case.

63. l. 321: => “fully”: Modified

64. l. 343: “westerly intensification” => “westerly intensification in 49ka-full”: Added.

65. l. 348: => “under different combinations of boundary conditions”: Modified.

66. l. 355-357: Are you always referring to annual values here? It seems that the 2nd sentence would rather be valid for the seasonal response, wouldn’t it?

The second sentence is modified to “The increase in monsoonal rainfall during austral summer”….

67. l. 357: “during high obliquity” => “in response to high obliquity”: Modified

68. l. 361: I am wondering whether you should discuss an insignificant response. “somewhat consistent” (l. 365) does not sound very scientific.

We have modified the text to “Our simulations generally show an insignificant response in southern Australian annual rainfall at 49 ka, although austral winter exhibits some drier conditions. These results are consistent with….” while expanding this paragraph (lines 403-405)

69. l. 362: remove “seen in”. Removed

70. l. 364: => “a response that is not reproduced in our simulation”: Modified

71. Section 3.4: Why do many changes around/over Australia happen in the coastal areas and less over the continent (Figs. 3h, 7i)?

We slightly disagree with this observation. The DJF response extends over a large portion of the Australian continent, and the annual mean also shows widespread changes in northern region. During JJA, the response is weaker over the continental interior, while more pronounced signals remain along the northern and southeastern margins.

72. Section 5 does not fully capture the main message of your study. There should be an explicit mentioning that your study used a stepwise approach to investigate the role of individual MIS3 boundary conditions and what is your main conclusion from their relative importance. The manuscript title and the Conclusions section give the impression that you only investigated the response to ice sheets. You might want to use something from the first paragraph of Section 4 for Section 5.

We thank the reviewer for this comment. Here is the improved conclusion description.

Our results, based on a stepwise set of MIS 3 boundary condition experiments, underscore the impacts of orbital forcing, greenhouse gases, surface albedo, and ice-sheet topography on global atmospheric circulation and regional hydroclimate. Orbital parameters and greenhouse gases alone produce limited dynamical shifts, while the addition of ice-sheet albedo primarily enhances high-latitude cooling without substantially altering circulation patterns. In contrast, the presence of NH ice sheets during MIS 3 strengthens and shifts the North Atlantic westerlies equatorward by 6° in DJF and 4° in JJA, leading to increased precipitation over the North Atlantic in both seasons, while over the Eurasian landmass precipitation increases in boreal summer but decreases in winter due to colder conditions. These ice sheet-induced changes affect the global atmospheric circulation, with a southward shift of the NH Hadley cell and ITCZ during DJF, resulting in enhanced monsoonal rainfall over northern Australia, while producing a comparatively weak hydroclimatic response in southern Australia. Regional differences, particularly between northern and southern Australia, reflect contrasting dynamical controls, with northern Australia dominated by monsoon and ITCZ-related moisture convergence, and southern Australia more strongly influenced by subtropical high-pressure anomalies and associated subsidence. These patterns are broadly consistent with proxy evidence indicating spatially heterogeneous hydroclimate conditions during MIS 3, with records suggesting both wetter and drier conditions across different regions and archives.

Although our experiments do not isolate the individual roles of the Laurentide and AISs, they show that the combined ice sheet configuration contributes to an equatorward shift of the SH westerlies and SH Hadley cell. Overall, our findings highlight the importance of the LIS in modulating atmospheric circulation and climate dynamics, noting that its geometry and extent varied substantially during MIS 3 and the deglaciation, likely contributing to diverse AMOC responses and associated climate changes.

73. Fig. 2 caption: I guess the last sentence refers to the proxy asterisks. Please make this more clear. Modified.

74. Fig. 3: I cannot see any significance stippling in Figs. 3a and b. Also, the white areas in Fig 3c-f should be described in the caption. Is it the ice mask at the surface level or at the 850 hPa level? This also holds for other Figs, e.g. Fig. 5 where the white areas seem to be the same for PI and 49ka-full.

The stippling indicates the non-significance and is now provided for subpanels (a, b) and (g, h) for this figure. We have now described the white space in the relevant figure captions. *"The white space indicates the ice mask at the 850 hPa level."*

75. Fig. 4: I guess this is based on 850 hPa as well. Please include into the caption. Modified.

76. Please double-check in all wind vector plots captions whether it should read "overlaid with 850 hPa wind vectors" or "overlaid with 850 hPa wind vector anomalies" (or 200 hPa in Figs. A4 and A5). Modified.

77. Fig. 8 caption still contains 49ka-ice. Please correct. Modified.

78. Fig. 9: I don't fully understand how you determine the latitudinal shift in westerlies over the North Atlantic when averaging also over the latitudes (both in a and b)? Regarding the last sentence in the caption about the latitudinal shift, wouldn't this only hold for the northern hemisphere?

It is the latitude of the max wind speed averaged in that region. We clearly mention this now.

79. Fig. A1 caption: Modified.

"These experiments" => "The 49ka-alb+ experiment is not analysed"

"based on the prescribed ice sheet" => to account for the increase of continental ice mass"

"the time-averaged periods" => "the periods used for the analysis of time averages from each exp."- "...the zero line" => "the zero line for each diagnostic shown"

80. Fig. A2: => "Shortwave downward radiation" Modified.