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

General comments:

The authors describe the impacts of the Northern Hemisphere (NH) ice sheets at 49,000 years ago on the global atmospheric circulation. They shifted the NH westerlies southward, enhancing Eurasian summer rainfall but reducing it in winter. Their influence also extended to the tropics and the Southern Hemisphere (SH), displacing the Intertropical Convergence Zone (ITCZ) southward and intensifying Australian rainfall. The Laurentide and Antarctic ice sheets further modified the SH circulation, pushing the SH Hadley cell and westerlies equatorward. These results highlight the complex, far-reaching impacts of ice sheets on global climate patterns.

The manuscript is well-written, with clear articulation of the main findings and their broader implications. However, the study's conclusions are highly model-dependent, and further validation is needed to assess whether the simulated responses accurately reflect the glacial climate conditions of 49,000 years ago. Geographically extensive observational data for this specific period would be ideal for evaluation. If such data are unavailable, conducting a Last Glacial Maximum (LGM) experiment using the Australian Earth System Model (ACCESS-ESM1.5) could help assess the impacts of continental ice sheets on glacial climate. Given the computational cost and time constraints, referencing prior studies that used the same model for LGM simulations—along with their data-model comparisons—may suffice as an alternative.

Additionally, the authors could consider compiling a global footprint table for the 49,000-year (or MIS3) climate responses, similar to the Dansgaard-Oeschger (DO) event table in Izumi et al. (2023, QSR). While such a table would not provide quantitative metrics, it would facilitate a qualitative assessment of spatial patterns and enhance model evaluation.

If the authors maintain that this study exclusively examines the model's responses, I recommend publication pending the resolution of minor revisions outlined in the specific comments below.

"Please find the Author's response in blue and the modified text in the manuscript in green."

We thank the reviewer for this thoughtful comment and agree to state that the results shown in this study are highly model-dependent. At present, the 49 ka simulation is the only glacial time slice available for ACCESS-ESM1.5. We are currently in the process of simulating the LGM using the same model, following the PMIP4 protocol. This model has previously been used to simulate the last interglacial (lig127k) time slice as part of the Tier 1 PMIP4-CMIP6 experiments (Yeung et al., 2021: https://doi.org/10.5194/cp-17-869-2021, 2021.), MIS9e (~336-321 ka; Duboc et al., 2025, https://cp.copernicus.org/articles/21/1093/2025/), and mid-Holocene (6 ka; Mackallah et al., 2022, https://www.publish.csiro.au/ES/ES21031). This information is now added in section 2.1.

As noted, the computational cost of running this comprehensive Earth system model is considerable, ~16 model years per day.

Nevertheless, we have now included some model–data comparisons for SAT and SST. We compare our simulated results for 49 ka relative to PI with the proxy records, focusing on Greenland Interstadial 13 (GI13; ~49 ka) versus PI (Fig. 2 in the revised manuscript).

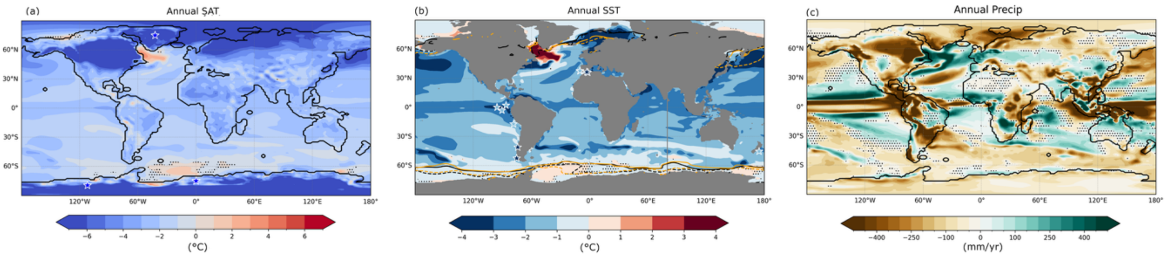

Fig. R1: Annual mean anomalies of surface air temperature (SAT), sea surface temperature (SST), and precipitation for 49 ka climate (exp 49ka-full) compared to PI. Contours show seasonal mean 15% sea ice concentration for (orange) 49 ka and (black) PI during DJF (dashed) and JJA (solid). Stippling indicates non-significant changes based on a Student's t-test at 95% confidence level. Stars in subpanels (a) and (b) indicate qualitative estimates of the changes between Greenland Interstadial (GI 13) and PI climate, as inferred from the proxy records (MDO1-2444,ODP-977A,MD95-2043,MD01-2443,MD95-2042 [Martrat et al., 2007]; ODP-1233 [Kaiser et al., 2005]; TR163-19 [Lea et al., 2000]; RC13-110 [Feldber and Mix, 2003]; ODP846B [Martinez et al., 2003]; TG-7 [Calvo et al., 2001]; MD97-2120 [Pahnke et al., 2003]; MD07-3128 [Caniupan et al., 2011]; EPICA Dronning Maud Land [EPICA community members]; WAIS [WAIS community members]; NGRIP [Huber et al., 2006, Kindler et al., 2014]; SO188-17286-1 [Lauterbach et al., 2020]. Dark (light) blue colors represent much colder (slightly colder) climate).

The following text is also added in the manuscript.

Lines 146-147:

"The simulated SATs and SSTs anomalies show a good agreement with proxy records indicating that the simulation presents a qualitatively appropriate estimate of the changes between Greenland Interstadial (GI 13; ~49ka-50ka) and PI climate (Fig. 2a,b)."

Our focus on 49 ka at this stage, rather than the LGM, is motivated by a broader project investigating millennial-scale variability in Australian hydroclimate. Specifically, we aim to simulate Heinrich Event 5 (H5), which occurred around 49 ka. This paper represents the first in a series of studies and provides a baseline description of the glacial climate at 49 ka prior to H5. In forthcoming work, we will present H5 model simulations and compare them with new speleothem records from Australia that span this interval. This will allow us to directly evaluate the modelled hydroclimate response against proxy data.

Specific comments:

• The rationale for focusing on continental ice sheets at 49 ka rather than the Last Glacial Maximum (LGM) remains unclear. Given the greater availability of paleoclimate records for the LGM, as well as the more extensive ice sheet coverage and its pronounced influence on atmospheric circulation, the choice of 49 ka warrants further justification. The authors should explicitly address why the LGM was deemed unsuitable for this study or why the 49 ka timeframe provides critical insights that the LGM cannot.

We thank the reviewer for this comment. We agree that the LGM is an interesting time period with greater availability of paleoclimate records, however, MIS3 is a period of high interest because of the occurrence of millennial-scale variability. Some of this millennial-scale variability could have arisen from the interaction between ice-sheets and climate, thus motivating studies on that time period. This time period also provides information on the impact of a mid-size Northern Hemispheric ice-sheet on climate.

Currently, Lines 29-29 describe previous studies that focus on LGM to understand the impact of ice sheets. Lines 40-52 further elaborate on the motivation to investigate MIS3. While significant progress has been made in understanding LGM climate, the influence of ice sheets during the MIS3 period—when millennial-scale climate variability was pronounced—remains less well understood.

In the revision, we have now included a few modelling studies which have assessed the impact of MIS3 boundary conditions.

Lines 47-57:

"In contrast, the climate of MIS 3 (65–25 ka) has received comparatively less attention in the context of ice sheet–atmosphere interactions. Existing studies of MIS 3 have largely concentrated on large-scale oceanic responses, such as AMOC variability, surface temperature patterns, and sea ice changes (Malmierca-Vallet and Sime, 2023; Brandefelt et al., 2011; Merkel et al., 2010; Guo et al., 2019). Some have investigated tropical climate variability, including changes in ENSO behaviour during this period (Brandefelt et al., 2011; Merkel et al., 2010), while others briefly mention reduced global precipitation, a southward-shifted ITCZ, intensified Southern Hemisphere (SH) westerly wind stress, and strengthened NH trade winds alongside weakened SH trade winds (Guo et al., 2019). However, the detailed, mechanistic impacts of NH ice sheets on atmospheric circulation during MIS 3—particularly beyond the North Atlantic—remain underexplored. This gap may be partly due to the significant millennial-scale climate variability that characterizes MIS 3—including abrupt temperature fluctuations in Greenland of 8–10°C (Huber et al., 2006) and multiple episodes of AMOC weakening (Menviel et al. (2020) and references therein)—which make it challenging to isolate equilibrium climate response to boundary conditions."

We selected 49 ka in particular due to its unique combination of boundary conditions: it features relatively high obliquity—higher than both the PI and the Last Interglacial—alongside low atmospheric CO_2 concentrations (~200 ppm), similar to the LGM.

• Do the ice sheets of the Last Glacial Maximum (LGM) and Marine Isotope Stage 3 (MIS3 or 49 ka) produce similar large-scale atmospheric and oceanic circulation responses—such as shifts in the Hadley Cell, Intertropical Convergence Zone (ITCZ), and the Atlantic Meridional Overturning Circulation (AMOC) —even if their magnitudes differ? For instance, do they induce the same direction of change (e.g., positive or negative anomalies) despite amplitude variations?

As far as we know, the atmospheric circulation response to LGM and MIS3 ice-sheets has not been studied in detail within a similar modelling framework. Our results thus present important information related to the impact of MIS3 ice-sheets on atmospheric circulation. Further studies should assess the impact of growing glacial ice-sheets on large-scale atmospheric circulation.

In contrast, AMOC changes have been more widely studied. Our results show that the influence of ice sheet topography on AMOC strength is indeed similar between the LGM and 49 ka ice sheet configurations in some studies (see Lines 248–254). However, we have also noted large variations among different MIS3 time slices and models, as mentioned in the new text below.

Lines 290-294:

Model simulations also show considerable spread in AMOC strength across different MIS 3 timeslices and model setups. For instance, a Community Climate System Model version 3 (CCSM3) simulation at 35 ka, initialized from the LGM, showed a ~40% reduction in AMOC strength (Merkel et la., 2010), while the same model produced a ~50% reduction at 44 ka, also initialised from the LGM state (Brandefelt et al., 2011). In contrast, the Norwegian Earth System Model (NorESM) simulations indicate a ~13% strengthening of the AMOC at 38 ka (Guo et al., 2019). The simulated AMOC in our model is strong at 49 ka (31 Sv) with a ~47\% increase relative to PI.

Additionally, the response of the North Atlantic westerlies to ice sheets is also consistent between the two climates (see Lines 264–267). Thus, while the magnitude of the climate response may differ, some of the directional changes are comparable across the two glacial periods. Nevertheless, previous studies (Zhang et al., and Armstrong et al., 2022) have shown that even relatively small changes in NH ice-sheets can have significant impacts. Therefore, while our study provides an estimate of MIS3 ice-sheet impacts on climate, additional work is required to fully understand how glacial ice-sheets influenced large scale circulation.

• L43-45: Is it possible to take into account millennial-scale fluctuations in this study design?

Yes, a companion study is currently in preparation that will explore millennial-scale fluctuations in AMOC during Heinrich Stadial 5 (H5). This follow-up study builds upon the 49 ka control experiment presented here and will specifically address the transient response of the climate system to millennial-scale perturbations.

Do the author's results indicate stadial or interstadial climates?

Our results resemble an interstadial climate as the AMOC is stronger than PI. We have now clearly mentioned this in the manuscript.

Line 278

"Here, the simulated state in 49ka-full experiment represents an interstadial climate."

Isn't the concentration of research in the northern hemisphere due to the distribution of data for comparison?

Yes, the concentration of research in the North Atlantic region is likely influenced by the greater availability of paleoclimate data from that area, as well as the presence of extensive ice sheets over North America, which had a strong impact on regional and global climate. This makes our results particularly interesting, as they highlight that the influence of glacial ice sheets extends well beyond the North Atlantic, with significant impacts in other regions, including the Southern Hemisphere

We have now added this to our discussion.

Lines 273-277

"Additionally, much of the existing research has focused primarily on the North Atlantic region, driven by the greater availability of paleoclimate data from this area and the presence of extensive North American ice sheets that strongly influenced both regional and global climate. Our results add to this literature by demonstrating that the influence of glacial ice sheets extends well beyond the North Atlantic, with significant climatic impacts also occurring in other regions, including the SH."

• What were the thicknesses of the continental ice sheets—particularly the Laurentide and Antarctic ice sheets—at 49 ka (thousand years ago)?

The ice thickness of the Laurentide Ice sheet was more than 3km, while the Antarctic ice sheet reached an altitude of more than 3.6km. The height as well as the extent at this time period were less than LGM. We have now included this information in the manuscript and the below plot of ice sheet thickness in Fig. 1.

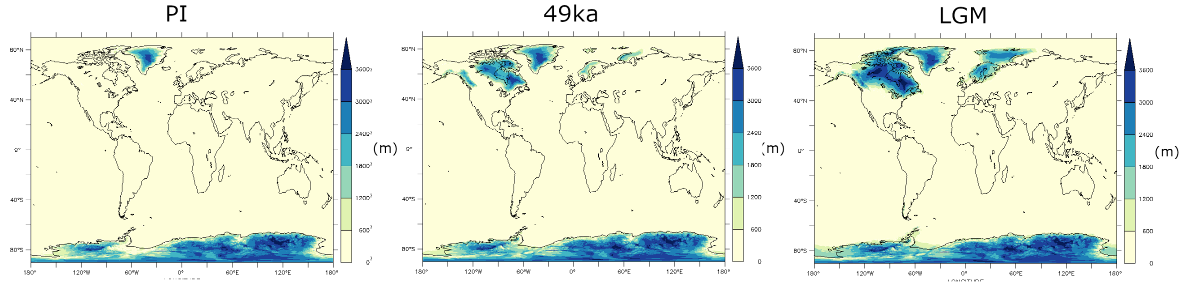

Fig.R2: Ice sheet thickness and extent from Gowan et al., (2021) for PI, 49 ka (represented by 52.5 ka as described in the manuscript), and LGM climates.

Lines 101-108:

“The NH ice sheets at 49 ka include two separate ice sheets over the North American continent—Laurentide in the east and Cordilleran in the west—as well as the Greenland Ice Sheet and Fennoscandian and Eurasian ice sheets (Figure 1b). Their extent and height are smaller than during the LGM, which featured a single, extensive LIS over North America and continuous ice sheet coverage from Eurasia to Scandinavia, fully covering the Barents Sea. The Antarctic Ice Sheet (AIS) at 49 ka also has a smaller extent compared to that of the LGM, especially over the Ross and Weddell Seas. At 49 ka, the LIS was up to 3 km thick, while the AIS was up to 3.6 km thick. In the present day, permanent ice cover in the Northern Hemisphere is restricted to Greenland (Figure 1a).”

• L97-98: “The final experiment... 49ka-full...was run for 292 years.” Is it true? It does not match the contents of Table 2, if I understand correctly.

Apologies for this confusion. We have corrected it to 760 years now.

• L100: The authors should start a new paragraph here.

Done.

• L116: The study suggests that higher sea surface temperatures (SSTs) in the Labrador region are associated with a stronger AMOC in the 49ka-full experiment. Is this AMOC response mechanistically plausible?

Yes, this response is mechanistically plausible as the AMOC strengthening enhances the oceanic heat transport towards the Labrador Sea. However, due to the strong heat loss to the atmosphere, surface waters become cold enough to form deep waters.

• Precision in AMOC Comparisons (L245–246): “AMOC strength at the onset of interstadials versus the pre-industrial (PI) control”, or “AMOC strength during stadial versus interstadial periods?”

Rephrased to the suggested change.

• In section 3.3, I don't quite understand the relationship between the strength of the Hadley cell and the migration of the ITCZ through the texts and figures. Does the strength of the Hadley cells affect their width?

In general, changes in the strength of the Hadley circulation can be associated with changes in its width and the latitude of the ITCZ, but these relationships are not always linear or straightforward. In our study, we observe that an intensification of the NH Hadley cell during DJF is accompanied by an equatorward shift of its ascending branch (i.e., the ITCZ). This suggests that the Hadley cell is not only strengthening but also narrowing.