Response to Reviewer 1, Dr Shih-Yu Lee:

We thank Dr Shih-Yu Lee for her thoughtful and constructive comments to this manuscript.

*Please see our point-by-point responses to each of the comments below in **blue and italic,** and suggested implementations in a revised manuscript in **green**.*

A) Experimental realism & robustness

1. Freshwater forcing magnitude, duration, and geometry: The shutdown uses 0.4 Sv for 500 yr over 50–70° N, 70–0° W (Table 2)—an idealized choice that likely exceeds plausible HE freshwater flux histories. Please (i) discuss physical plausibility versus "shock" idealization; (ii) provide a brief sensitivity or cite prior ACCESS ESM1.5 tests to hosing shape (pulsed vs ramped), duration, and release region (e.g., including/substituting the Nordic Seas or Labrador shelf). Even a short 100 yr/0.4 Sv pulse test or a reduced area hosing would help demonstrate that the non linear atmospheric reorganization at shutdown is not a by product of sustained extreme hosing.

We thank the Reviewer for this comment and understand the concerns associated with the idealized experimental set up. We have added a new Section 4.3 in the Discussion to elaborate this concern.

Line 502-519:

4.3 Robustness of the simulations

Our experimental setup was designed to assess the multi-centennial-scale impact of an AMOC shutdown and an AMOC slowdown on the climate system. The experiments were designed to obtain the AMOC slowdown and shutdown states with the smallest freshwater input. Although the input fluxes are idealized and significantly higher than current estimates (Zhou and McManus, 2024), the experimental design is consistent with the MIS3 protocol (Malmierca-Vallet et al., 2023), and similar to the recent North Atlantic Hosing Model Intercomparison Project (NaHOsMIP), in which 0.3 Sv is added in the North Atlantic for more than 100 model years to simulate the climate response to an AMOC shutdown in CMIP models (Ben-Yami et al., 2024; Diamond et al., 2025; Jackson et al., 2023). The difference in the input fluxes arises from the different sensitivity of AMOC to freshwater perturbations across models. In ACCESS-ESM1.5, the AMOC response to North Atlantic freshwater fluxes depends on both the magnitude and duration of the meltwater input (Du et al., 2025). In our experimental design, a pulse of 0.3 Sv for a few hundred years does not lead to an AMOC shutdown under 49 ka boundary conditions (Fig. 1). This highlights the issue of this model's sensitivity to freshwater forcing.

In this study, the 49ka_0.3Sv experiment is obtained from a two-step increase in freshwater input of 0.25 Sv for 100 model years followed by 0.3 Sv of 200 years after the 49ka_0.2Sv experiment. Nevertheless, this setup should not significantly affect the large-scale climate response given the length of the simulations performed here (500 years), nor should the exact location of the meltwater input in the subpolar North Atlantic, based on previous experiments with different North Atlantic meltwater input location, duration and magnitudes (Pontes & Menviel, 2024, Du et al., 2025, Saini et al., 2025). Future studies should perform a thorough examination of the impact of meltwater input location on the climate response.

2. Internal variability and sampling: Results rely on 50 yr windows. Please consider a simple signal to noise check by resampling 50 yr blocks from the control and from each experiment (or show running 30 yr means across the last 150 yr) to demonstrate that key patterns (DJF ITCZ latitude, HC strengths/widths, STR latitude, SH westerly latitude) exceed internal variability.

Thanks for the suggestion. We have now added a paragraph in the new Discussion Section 4.3 (following the previous response) with a new supplementary Figure S7 to assess the statistical significance of the climate signals.

New Supplementary Figure S7:

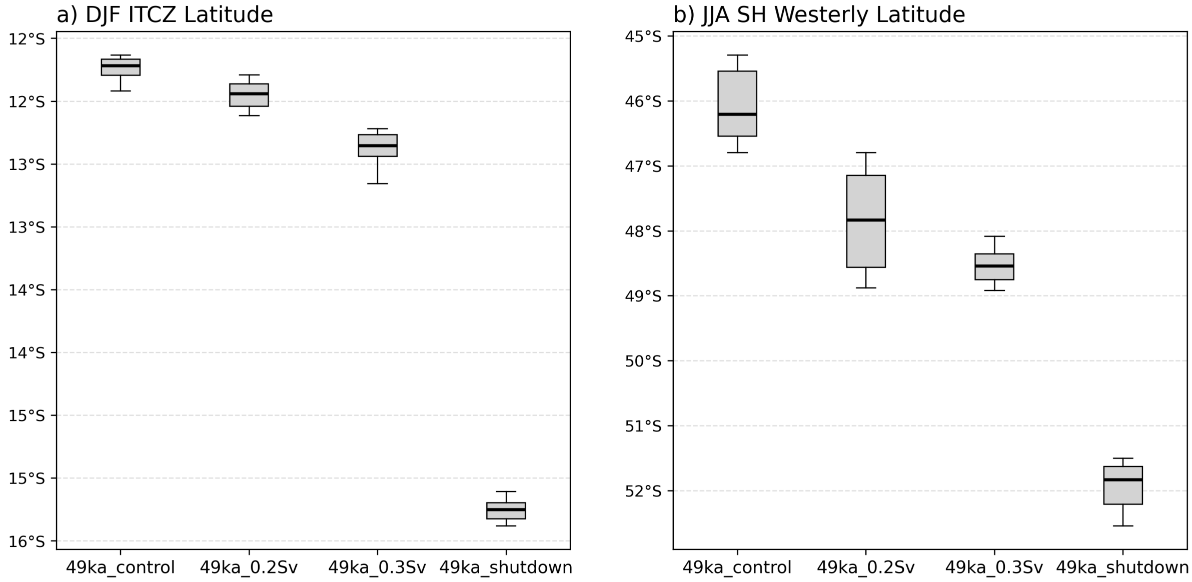

Figure S7: Box plot of 30-year means across the last 150 years for a) DJF ITCZ latitudes, and b) JJA SH westerly wind latitude in each experiment. Within each box, the thick line inside the box represents the median value (50th percentile) of each group; the top and bottom of the box shows the 25th and 75th percentile, respectively; the whiskers show 10th to 90th percentile.

Last paragraph in the Discussion Section 4.3 (Lines 520-522):

Lastly, this study uses the last 50 years of each hosing experiment to assess the climate responses. When using the 30-year running-mean values for the last 150 years in each experiment, the results are consistent with our 50-year average (Fig. S7). We note that only one model was used, and a future study could examine the linearity in multiple models.

B) Mechanistic clarity/suggestion

5. Energetics of the ITCZ shift: Since the story hinges on interhemispheric energy transport compensation, would it be possible to exam TOA energy transport decomposition (DJF/JJA) that connects the ~1 PW reduction in NH ocean heat transport at 30° N to the southward DJF ITCZ jump in shutdown. Even a zonal mean cross equatorial energy flux figure would make the mechanism crisper.

Thanks for the suggestion. We have added a new supplementary Figure S4 to illustrate the zonal-mean atmospheric heat transport to aid the discussion of the energetic mechanism of ITCZ shift in this manuscript.

We modified the Results section 3.1 and 3.2.1, as well as the Discussion section 4.1 to emphasize the energetic mechanism that drives the simulated changes, as advised by the editor. Related statements are added at relevant places in the Introduction and Conclusion sections; parts of the Abstract are also rephrased to put more emphasis on the mechanisms.

New supplementary Figure S4:

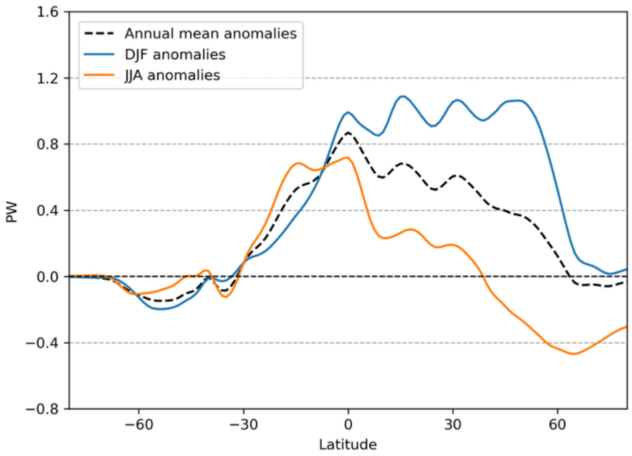

Figure S4: 49ka_shutdown - 49ka_control anomalies for annual mean, DJF, and JJA zonally averaged northward atmospheric heat transport (PW).

Abstract:

The climatic response to weakening of the Atlantic Meridional Overturning Circulation (AMOC) is investigated under glacial conditions representative of Heinrich Stadial 5 using a fully coupled Earth System Model (ACCESS-ESM1.5). We find that the climatic response to an AMOC slowdown or shutdown, respectively representing Dansgaard-Oeschger (D-O) and Heinrich stadials, is non-linear. Global mean temperature and precipitation anomalies increase linearly with an AMOC slowdown; however, crossing the threshold of AMOC shutdown results in non-linear and more complex atmospheric circulation and climate responses. The atmosphere partially compensates for the significantly reduced oceanic energy transport due to AMOC shutdown through alterations in the cross-equatorial Hadley Cell (HC), with pronounced changes in boreal winter season. The northern winter HC is enhanced and expanded, while the southern winter HC is weakened but increased in width due to a northward shift of the ascending branch due to AMOC shutdown. This drives seasonal climate variability in the tropical and subtropical regions via changes in the subtropical high pressure systems, subtropical jet, Southern Hemisphere mid-latitude westerly winds and other climate features such as the monsoon systems, with significant impacts on Australasian hydroclimate. The study demonstrates the potential location of a threshold in the climate system between linear slowdown and nonlinear shutdown of the AMOC, with differing climate impacts being broadly consistent with available proxy records for Heinrich and D-O stadials. This further highlights the importance of not crossing the threshold of AMOC shutdown in the future.

Modifications in the Results Section 3.1:

Lines 206-213:

The meridional oceanic heat transport to the North Atlantic is reduced by ~77 % (~1 PW at 30° N) in the HS experiment (see Fig. S2). This change is larger than previous model simulations of AMOC shutdowns under LGM conditions that found an average ~40 % reduction in Atlantic meridional heat transport (~0.8 PW at 30° N) (Menviel et al., 2008, 2020; Stouffer et al., 2006). The larger reduction in meridional oceanic heat transport can be explained by the large AMOC reduction simulated here (29 Sv reduction compared to an averaged of 15 Sv in previous LGM experiments; Kageyama et al., 2013). In the D-O stadial simulations with ~50 % and 32 % AMOC reductions (Fig. 2e, 2f), the simulated reductions in ocean heat transport at 30° N are limited to 25% and 16%, respectively (Fig. S2), which exert weak constraints on the atmospheric response.

Lines 230-240:

To compensate the significantly reduced ocean heat transport in the HS experiment, the ITCZ is pushed southwards towards the warmer hemisphere. The precipitation is significantly reduced by a mean of 2.3 mm/day to the north of the equator in the Atlantic Ocean and greatly enhanced to the south in the HS experiment (Fig. 2d). The pattern extends to every ocean basin, indicating a global-wise southward shift of the annual mean ITCZ position in HS. This further leads to enhanced precipitation intensity in the South Pacific Convergence Zone (SPCZ) region (10° S-30° S, 155° E-140° W) (Fig. 2d). In the D-O stadial simulations, the southward displacement pattern of the ITCZ is only evident over the Atlantic Ocean, extending into eastern equatorial Pacific. The global precipitation patterns show similar responses between the slowdown simulations (Fig. 2e, 2f); however, greatly different from the HS simulation, particularly in the tropical and subtropical regions. The SPCZ precipitation is reduced in the D-O experiments (Fig. 2e, 2f), which is the opposite of the shutdown experiment. Widespread drying is simulated over much of the NH associated with the cooling in all experiments, which is consistent with previous modelling results with a weaker AMOC (e.g. Jackson et al., 2015).

Section 3.2.1:

Lines 265-271:

In response to AMOC weakening, the annual mean ITCZ position shifts southwards in all simulations (Fig. 2d-2f) to generate the cross-equatorial atmospheric energy transport to partially compensate for the reduced oceanic heat transport. This drives alterations in the strength and width of the HC. Notably, the atmospheric compensation is highly seasonal. In the HS simulation, the TOA energy transport anomaly at 30° N reaches ~1.05 PW in DJF but only ~0.19 PW in JJA (Fig. S4) to compensate for the ~1 PW annual reduction in the North Atlantic ocean heat transport (seasonal variation is minimal). This leads to more pronounced changes in the HC and ITCZ responses during DJF. As a result, the NH HC strengthens in DJF while the SH HC weakens in JJA in all simulations (Fig. 4 & Fig. 5).

Lines 291-304:

In austral winter (JJA) with weaker cross-equatorial heat transport, the ITCZ, as calculated by the location of the 850 hPa zero mass streamfunction (as described in Section 2.3), shifts northwards by 0.97° to around 20.14°, associated with a large expansion of the SH HC width by 11.7 %. The ascending branch at 500 hPa shifts northwards by 3.5° due to AMOC shutdown, attributing to the negative anomalies simulated in 49ka_shutdown experiment along the ascending branch of the SH HC around 18.4° N (Fig. 4b), which are not seen in the slowdown simulations (Fig. 4d & 4f). This northward shift in the JJA ITCZ and ascending branch reduces the cross-equatorial energy transport in JJA, which explains the smaller JJA atmospheric compensation to AMOC shutdown. The SH HC strength in JJA is significantly reduced by 32.5 % in 49ka_shutdown, compared to 4 % and 2.8 % in the 49ka_0.3 Sv and 49ka_0.2 Sv slowdown experiments, respectively (Fig. 5). The ITCZ response at 850 hPa in the D-O simulations is undetectable (thick lines in Fig. 4d, 4f), consistent with negligible JJA energetic constraints on the atmosphere. A 2.9 % reduction in the SH HC meridional extent is simulated in 49ka_0.3Sv due to southward shift in the SH HC ascending branch, while no change is observed in the 49ka_0.2 Sv experiment results (Fig. 5). All these changes suggest a non-linear response of the HC between the slowdown and shutdown simulations, accompanied by a pronounced seasonal asymmetry.

ITCZ calculation definition added in the Method section to aid the discussion:

Lines 183-186:

ITCZ position in this study is defined as the latitude of zero zonal-mean meridional mass streamfunction at 850 hPa, corresponding to the cross-equatorial ascending branch of the northern/southern Hadley Cells. This definition provides a better dynamical perspective linkage to HC changes than the conventional precipitation-based ITCZ location (e.g. Braconnot et al., 2007), with similar results as the precipitation definition (Bian and Räisänen, 2024).

Discussion Section 4 (Lines 435-150):

4.1 Climatic response to AMOC shutdown in HS simulation

In this section, we present a diagnostic of the role of energetic constraints in shaping the atmospheric response to AMOC weakening through simulations of HSs at 49 ka, as well as how that leads to the SH mid-latitude changes and hydroclimate response around Australasia through changes in the cross-equatorial Hadley Cells.

The northward oceanic heat transport is reduced by ~ 77% at 30° N in the HS simulation (Fig. S2), which generates a significant interhemispheric energy imbalance that is primarily compensated by the atmospheric response, particularly in DJF (Fig. S4) - through a southward shift of the annual ITCZ, and reorganization of the HC strength and width. The winter (DJF) northern HC strengthens and increases in width, with a southward shift in its ascending branch (ITCZ position), while the southern wintertime (JJA) HC weakens but increases in width due to a small northward shift in JJA ITCZ position at 850 hPa. The northward shift in the JJA ITCZ reduces the cross-equatorial heat transport, which explains the smaller contributions to atmospheric compensation in JJA. Note that the simulated change in the southern JJA width is different from responses under the Last Interglacial and PI boundary conditions using the same model (Saini et al., 2025a). This difference may be due to the different background states between warm interglacial and cold glacial climates, with more investigation needed in the future. Nevertheless, our findings of an enhanced northern HC and weaker southern HC in response to AMOC weakening are consistent with previous modelling studies (Chiang et al., 2014; Chiang and Friedman, 2012; Lee et al., 2011; Saini et al., 2025a).

Discussions in Section 4.2 have been rearranged to add the energy influence:

Lines 478-500:

4.2 Non-linear climatic response between D-O and HSs

In this study, we use normalised temperature and precipitation response to the AMOC decrease to quantify the linearity of climatic changes. The global area-averaged precipitation and temperature anomalies show linear changes per Sv of AMOC decrease in AMOC slowdown simulations at 49 ka, with roughly -0.003 mm/day and -0.05 °C per Sv change for both the 0.2 Sv and 0.3 Sv experiments, respectively (see more details in Table S1). However, crossing the threshold of AMOC shutdown between 0.3 Sv and 0.4 Sv triggers a different response in precipitation and temperature patterns which do not continue this linear response either globally or regionally (Fig. 3). The Australian temperature field between the slowdown and shutdown experiments shows relatively linear changes (Fig. 8), but this is not the case for hydroclimates, particularly during the DJF monsoon season (Fig. 9). The magnitude of global annual changes in precipitation and temperature in the shutdown experiment are 1.3 times as large per Sv relative to the slowdown simulations (Fig. 3 for spatial patterns), with larger changes in the SH (Table S1). This appears to be due to the non-linear responses in the large-scale atmospheric circulations such as the Hadley Cell, leading to different responses in the climatic processes (e.g. pressure system, westerly winds, etc.) between AMOC slowdown and AMOC shutdown.

We attribute this non-linearity between D-O and HS climate responses primarily to a threshold in the ocean heat transport response between the modest reductions associated with AMOC slowdown and the much larger reductions due to AMOC shutdown. The northward ocean heat transport in D-O simulations is reduced by less than 25% at 30 °N (Fig. S2), which imposes a weak energetic constraint on the atmosphere. This results in minimal compensation by the atmosphere and consequently insignificant anomalies in the Hadley circulation and regional atmospheric responses. This study provides a possible location of the threshold between linear weakening and nonlinear shutdown, but it is important to note that the location is likely to differ between models and climate states both in the real world and in simulations. Comparison of simulations from different climate models would also provide evidence of the robustness of model responses to AMOC weakening under glacial conditions. Future studies performing longer simulations would be useful to explore slower responses, such as changes in sea ice extent and Southern Ocean temperatures

6. Southern Ocean/sea-ice feedbacks: You note notable SAT cooling near the Ross/Weddell sectors and stronger SH westerlies in shutdown (Fig. 2a; Fig. 7). The argument will be more comprehensive to show how wind/ice/ocean coupling amplifies the SH response.

Thanks for the suggestion. We added a statement in Section 3.2.3 to demonstrate the impact of the high southern latitude cooling on the westerlies.

Lines 353-355:

The strengthening of the westerlies is driven by enhanced meridional sea surface temperature gradient in the Southern Ocean due to high latitude cooling near the Ross/Weddell sectors (Fig. S3), associated with weakened SH subtropical jet (Fig. S5).

7. Basin contrasts in SH westerlies: The Atlantic sector behaves differently from the Pacific/Indian in slowdowns; shutdown realigns them (Fig. 7). Would be good to clarify why the Atlantic deviates.

Thanks for the suggestion. This is due to the stronger and clearer temperature response in the Atlantic basin that leads to changes in the SH westerlies. Since the AMOC reductions in the slowdown experiments are small, the temperature response is limited to the Atlantic basin, which leads to larger changes in the SH westerlies in the Atlantic basin compared to the others where there is little change in the interhemispheric temperature gradient.

We realized the discussion here is a bit confusing, we have now made it clearer and included a possible explanation.

Lines 359-366:

Over the Atlantic basin, there is no change in the westerly strength in the shutdown experiment in JJA and DJF (Fig. 7b, 7f). The strength in the slowdown simulations is slightly reduced relative to 49ka_control in both seasons. This is different from other ocean basins, which experience enhanced westerly strength in the slowdown simulations relative to 49ka_control. This may be due to the stronger temperature response to AMOC slowdown in the Atlantic Ocean than other basins, which drives the distinct Atlantic response. In addition, the different alterations of the SH HC in HS relative to D-O simulations (Fig. 5) may contribute to the difference in Atlantic response between the HS and D-O experiments, where the climate is most sensitive to AMOC weakening. Future studies will examine the basin-dependent changes in the westerlies in more detail.

8. Carbon cycle configuration and outputs: ACCESS ESM1.5 includes an interactive carbon cycle, and the author discuss potential CO_2 links via SH westerlies (p. 22). Please state whether carbon was prognostic or prescribed here and, if active, showing simulated air–sea CO_2 flux (Southern Ocean sectors), DIC/alkalinity, and atmospheric CO_2 response will be of great interest.

While for the radiative forcing, atmospheric CO_2 *is kept constant at 284.3 ppm, the model also includes a prognostic atmospheric* CO_2 *tracer. However, this research question is the focus of other studies (e.g. Willeit et al., 2025), and it is out of scope of the topic of the manuscript. This question is explored by another PhD student in our group.*

Reference:

Willeit, M., Ganopolski, A., Kaufhold, C., Dalmonech, D., Liu, B., and Ilyina, T.: Earth system response to Heinrich events explained by a bipolar convection seesaw, Nat. Geosci., 18, 1159–1166, https://doi.org/10.1038/s41561-025-01814-0, 2025.

Response to Reviewer 2, Dr Marlene Klockmann:

Review of Du et al - Non-linear Climatic Response to the weakening of the Atlantic Meridional Overturning Circulation During Glacial Times

Du and colleagues compare the response of the climate system to weakened AMOC versus a collapsed AMOC, representative of Greenland Stadials (in relation to Dansgaard-Oeschger events) and Heinrich Stadials. They find that both temperature and precipitation change approximately linearly, as long as AMOC is decreasing linearly. As soon as the AMOC weakening crosses a threshold such that the AMOC collapses, also the climate system response becomes non-linear. The study initially analyses global fields, with a second focus on the Southern hemisphere/Australasia. In response to AMOC shutdown, both the Northern and Southern hemisphere winter Hadley cells (HC) increase in width, while the northern winter HC strengthens and the southern winter HC weakens. This leads to an expansion of the Indo-Australian summer monsoon and increased precipitation over most of the Australian continent.

The study is mostly well written and the figures well designed. Studies on the impact of AMOC weakening are of great general interest and relevance. I have a few major and a list of minor issues that should be addressed before publication of the study.

We thank Dr Marlene Klockmann for all her thoughtful comments and valuable suggestions, which would greatly improve the quality of the manuscript.

*Please see our point-by-point responses to each of the comments below in **blue and italic,** and suggested implementations in a revised manuscript in **green**.*

Major comments

1. Framing

In the abstract and the conclusions, the study is framed in the context of a potential future AMOC shutdown/threshold. How transferable are the results of this study to future climate, given that the background climate (glacial vs global warming) are fundamentally different? This is briefly mentioned in l.424-429, but deserves a some more discussion.

Thanks for the suggestion. We have added discussion in Section 4.1 and Conclusions in the revised manuscript.

Lines 469-471:

The results of this study can be an example of the climate response to a strong AMOC reduction that can be compared with available proxy records to better understand the processes at play.

Lines 560-564:

This study provides a modelled climate response to AMOC shutdown under glacial conditions. Although the background state is fundamentally different from future warming, the relatively good agreement between the model response and the proxy records provides better understanding of the climatic processes arising from a strong AMOC weakening, providing a basis for future comparisons under alternative background climate states, and more detailed model-data investigations.

2. Mechanistic link between AMOC weakening and Hadley cell changes

In parts, the manuscript remains very descriptive. I am missing some discussion of the mechanism how the AMOC changes lead to the described ITCZ and HC changes. Is it only the change in heat transport and the resulting change in temperature gradients?

Thanks for the question. Yes, it is the changes in the cross-equatorial energy transport due to AMOC weakening that leads to changes in the ITCZ and HC in the atmospheric energy balance (Bischoff and Schneider, 2014; Kang et al., 2008; Lee et al., 2011; Pedro et al., 2018).

In response to AMOC weakening, we would expect an increase in the northward cross-equatorial atmospheric heat transport to compensate for the reduction in the northward ocean heat transport. This shifts the ITCZ southwards and alters the strength and width of the HC.

We have added more discussion about the energetic mechanism in the Results section 3.1 and 3.2.1, and the Discussion section 4.1 with a new supplementary Figure S4 which shows the atmospheric heat transport. Related statements are also added at relevant places in the Introduction and Conclusion sections. Parts of the Abstract are rephrased to put more emphasis on the energetic mechanism that drive the simulated changes, as advised by the editor.

New supplementary Figure S4:

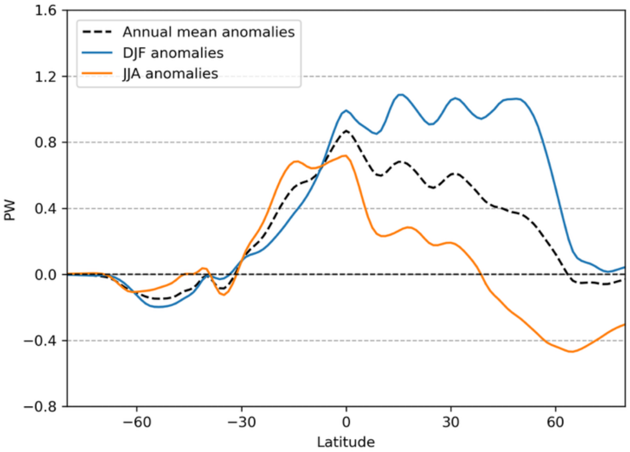

Figure S4: 49ka_shutdown - 49ka_control anomalies for annual mean, DJF, and JJA zonally averaged northward atmospheric heat transport (PW).

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Modifications in the Results Section 3.1:

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ITCZ calculation definition added in the Method section to aid the discussion:

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Lines 478-500:

4.2 Non-linear climatic response between D-O and HSs

In this study, we use normalised temperature and precipitation response to the AMOC decrease to quantify the linearity of climatic changes. The global area-averaged precipitation and temperature anomalies show linear changes per Sv of AMOC decrease in AMOC slowdown simulations at 49 ka, with roughly -0.003 mm/day and -0.05 °C per Sv change for both the 0.2 Sv and 0.3 Sv experiments, respectively (see more details in Table S1). However, crossing the threshold of AMOC shutdown between 0.3 Sv and 0.4 Sv triggers a different response in precipitation and temperature patterns which do not continue this linear response either globally or regionally (Fig. 3). The Australian temperature field between the slowdown and shutdown experiments shows relatively linear changes (Fig. 8), but this is not the case for hydroclimates, particularly during the DJF monsoon season (Fig. 9). The magnitude of global annual changes in precipitation and temperature in the shutdown experiment are 1.3 times as large per Sv relative to the slowdown simulations (Fig. 3 for spatial patterns), with larger changes in the SH (Table S1). This appears to be due to the non-linear responses in the large-scale atmospheric circulations such as the Hadley Cell, leading to different responses in the climatic processes (e.g. pressure system, westerly winds, etc.) between AMOC slowdown and AMOC shutdown.

We attribute this non-linearity between D-O and HS climate responses primarily to a threshold in the ocean heat transport response between the modest reductions associated with AMOC slowdown and the much larger reductions due to AMOC shutdown. The northward ocean heat transport in D-O simulations is reduced by less than 25% at 30 °N (Fig. S2), which imposes a weak energetic constraint on the atmosphere. This results in minimal compensation by the atmosphere and consequently insignificant anomalies in the Hadley circulation and regional atmospheric responses. This study provides a possible location of the threshold between linear weakening and nonlinear shutdown, but it is important to note that the location is likely to differ between models and climate states both in the real world and in simulations. Comparison of simulations from different climate models would also provide evidence of the robustness of model responses to AMOC weakening under glacial conditions. Future studies performing longer simulations would be useful to explore slower responses, such as changes in sea ice extent and Southern Ocean temperatures

3. The results of this study in the broader context of previous literature

In the introduction (l.68-73), the authors summarise the findings of previous studies on the atmospheric response to glacial AMOC weakening/shutdown. It would help in highlighting the relevance of this study, to emphasise more strongly the open questions that this study addresses and in the conclusions also to emphasise the new knowledge gained by this study. I understood that the results or this study are broadly consistent with previous literature based on both climate models and proxies. But what is the key new insight from this study?

Thanks for the suggestion. We are now better explaining in the Introduction the gaps of previous studies, namely the lack of study of the impact of an AMOC weakening on the SH atmospheric circulation, and particularly the Hadley cells.

Lines 83-84:

Nevertheless, few studies have investigated the large-scale processes through which the impacts of AMOC variations on tropical atmospheric circulation are transmitted to the SH mid-latitudes and Australasian regions

The linearity of the climate response to an AMOC decrease is another key new insight from this study. Moreover, the simulation results provide a plausible mechanism of the hydroclimate response around Australasia due to AMOC weakening through changes in atmospheric circulation, which can be used to compare with high-resolution proxy records *around Australia in future studies. We have now added discussion in the introduction, as well as emphasised the new insights from this study in the Conclusion.*

Lines 69-72:

In this study, we further perform freshwater forcing experiments at 49 ka to explore and provide an analysis of the dynamics of climate changes in D-O and HS simulations, with implications on Australasian climates. While there are limited proxy reconstructions of HS5 climate over Australasia, the results of this study will provide a suite of outputs that can be used in future paleo model-data comparisons.

Lines 545-547 (Conclusions section):

The simulation results are relatively consistent with proxy records for global temperature and precipitation changes, presenting a plausible insight into the SH and Australasian hydroclimate responses to AMOC weakening via changes in the seasonal HC and atmospheric circulation.

4. Setup of the hosing simulations

The setup seems not 100% consistent. Does it affect the results that the hosing is increased successively in the weaker hosing experiments? Would the 49ka_0.3Sv have the same state if it was started from 49ka_control? Or vice versa, would the response to 0.4Sv hosing be the same if you had continued to successively increase the hosing?

Thanks for the questions. We have added a new Discussion Section 4.3 to address them.

And yes, 49ka_0.3Sv and 49ka_shutdown have the same total integration time, but 49ka_0.2Sv does not. And also the integration time under the same hosing strength is different for the two DO-analogues vs the shutdown experiment. It probably does not have a big effect on the results, but it would be good to have this at least discussed.

Thanks for the suggestion, this is also included in the new Discussion section.

Line 502-519:

4.3 Robustness of the simulations

Our experimental setup was designed to assess the multi-centennial-scale impact of an AMOC shutdown and an AMOC slowdown on the climate system. The experiments were designed to obtain the AMOC slowdown and shutdown states with the smallest freshwater input. Although the input fluxes are idealized and significantly higher than current estimates (Zhou and McManus, 2024), the experimental design is consistent with the MIS3 protocol (Malmierca-Vallet et al., 2023), and similar to the recent North Atlantic Hosing Model Intercomparison Project (NaHOsMIP), in which 0.3 Sv is added in the North Atlantic for more than 100 model years to simulate the climate response to an AMOC shutdown in CMIP models (Ben-Yami et al., 2024; Diamond et al., 2025; Jackson et al., 2023). The difference in the input fluxes arises from the different sensitivity of AMOC to freshwater perturbations across models. In ACCESS-ESM1.5, the AMOC response to North Atlantic freshwater fluxes depends on both the magnitude and duration of the meltwater input (Du et al., 2025). In our experimental design, a pulse of 0.3 Sv for a few hundred years does not lead to an AMOC shutdown under 49 ka boundary conditions (Fig. 1). This highlights the issue of this model's sensitivity to freshwater forcing.

In this study, the 49ka_0.3Sv experiment is obtained from a two-step increase in freshwater input of 0.25 Sv for 100 model years followed by 0.3 Sv of 200 years after the 49ka_0.2Sv experiment. Nevertheless, this setup should not significantly affect the large-scale climate response given the length of the simulations performed here (500 years), nor should the exact location of the meltwater input in the subpolar North Atlantic, based on previous experiments with different North Atlantic meltwater input location, duration and magnitudes (Pontes & Menviel, 2024, Du et al., 2025, Saini et al., 2025). Future studies should perform a thorough examination of the impact of meltwater input location on the climate response.

5. Significance/Robustness of very small changes in latitude

In many occasions, very small changes in latitude are reported (0.1° or even smaller). Given that the latitudes are interpolated to 0.5°, are changes smaller than 0.5° even significant/robust/detectable? Is not any change <0.5° below the accuracy of the spatial resolution?

Thanks for the questions. We agree that changes below 0.5° can be interpreted as non-significant changes, and they are mainly coming from the 0.2Sv and 0.3Sv experiments. The reason why we included the values in the text is to compare with the larger shift due to AMOC shutdown to evaluate linearity of changes.

We have now removed values of very small changes (≤ 0.1°) and instead indicated them as not statistically significant in the text. An additional paragraph in a new Discussion Section 4.3 is also added to assess the statistical significance of some of the climate signals with relatively stronger response with a new supplementary Figure S7.

New Supplementary Figure S7:

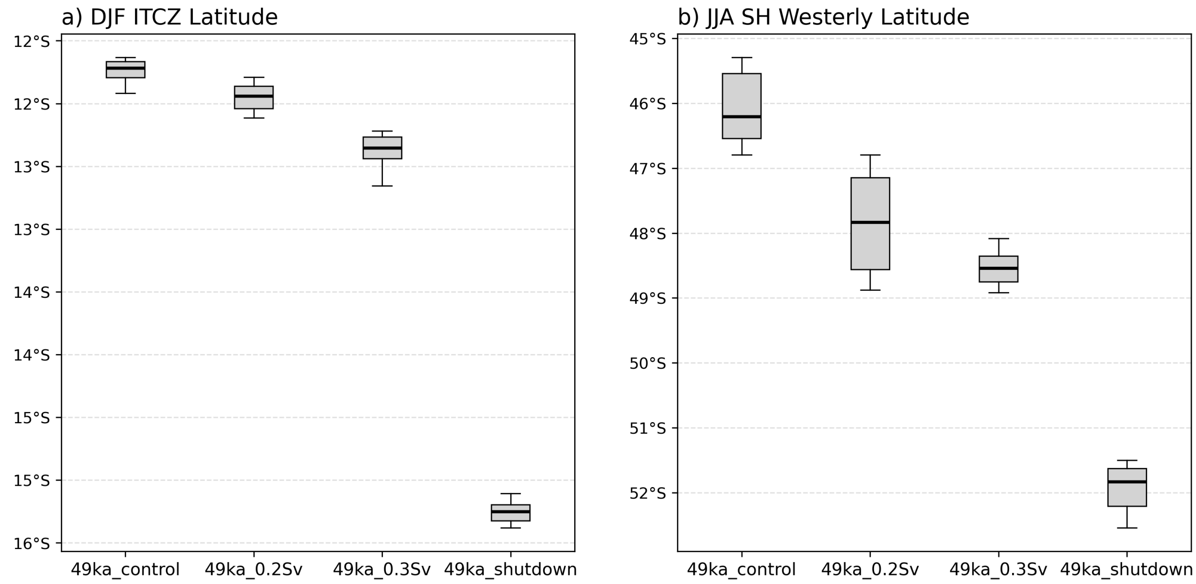

Figure S7: Box plot of 30-year means across the last 150 years for a) DJF ITCZ latitudes, and b) JJA SH westerly wind latitude in each experiment. Within each box, the thick line inside the box represents the median value (50th percentile) of each group; the top and bottom of the box shows the 25th and 75th percentile, respectively; the whiskers show 10th to 90th percentile.

Last paragraph in the Discussion Section 4.3 (Lines 520-522):

Lastly, this study uses the last 50 years of each hosing experiment to assess the climate responses. When using the 30-year running-mean values for the last 150 years in each experiment, the results are consistent with our 50-year average (Fig. S7). We note that only one model was used, and a future study could examine the linearity in multiple models.

6. Consistent way of referring to the simulations

Sometimes "AMOC weakening" refers to only the 0.2SV and 0.3Sv simulation, sometimes it seems to refer to all three simulations, including the shutdown. This makes it sometimes hard to clearly follow the argument. You could e.g. consistently refer to the 0.2SV and 0.3Sv simulations as "the DO simulations" and to the shutdown simulation as "the HS simulation" and then be very clear, whether your current result applies only to the DO or HS simulations or to both. Other clear nomenclatures are of course possible as well.

Sorry about the confusion, we have now made the naming consistent throughout the paper and added a statement in the Method section to define the terminology in the manuscript.

Lines 169-171:

The 49ka_0.2Sv and 49ka_0.3Sv experiments are hereafter referred to as D-O stadial or slowdown experiment, and the 49ka_shutdown experiments are also referred to as HS or shutdown experiment. AMOC weakening refers to all three experiments.

7. Absolute changes vs changes normalised by AMOC change

This is more a question that I had while reading: would it make sense to express changes in other variables (HC strength, width, etc) also as a function of AMOC change?

Thanks for the suggestion. The reason why we only show the normalised changes for temperature and precipitation is that we aim to focus more on the teleconnection between HC and other elements of atmospheric circulation in this study.

Moreover, as seen in Fig. 5 and 7, and the ITCZ changes in the 0.2 and 0.3 Sv are too small to be detected. The normalised changes would thus be even less robust. Therefore, we only included the normalised changes for temperature and precipitation.

Minor

l.17: "global mean temperature and precipitation anomalies increase linearly" This is not reflected in the main text, where you emphasise non-linearity also for the global mean fields (factor of 1.3 for both variables).

Sorry for the confusion, in this sentence we meant to express that the anomalies increase linearly in the slowdown simulations; however, crossing the threshold of AMOC shutdown leads to non-linear changes.

We have now rephrased the sentence and added a definition in the Method to define the AMOC weakening simulations (as for comment 6).

Lines 19-21:

Global mean temperature and precipitation anomalies increase linearly with an AMOC slowdown; however, crossing the threshold of AMOC shutdown results in non-linear and more complex atmospheric circulation and climate responses.

l.55: HS5 is introduced quite abruptly. Any particular reason why you focus on HS5?

Thanks for the comment. One main reason we focus on HS5 is that HS5 occurred in a time with many D-O and HSs documented, however, most previous modelling simulations of D-O events are performed under the LGM boundary conditions. Even fewer applied the MIS3 conditions. Saini et al. (2025) presented a satisfactory quasi-equilibrium 'interstadial' state at 49 ka– coinciding with the time of HS5 in ACCESS-ESM1.5 model. We aim to further explore the D-O and HS-type climate response in the same model.

We have now modified this paragraph.

Lines 58-72:

Many D-O and HS occurred during Marine Isotope Stage 3 (MIS3, ~59.4-27.8 ka; Sanchez Goñi and Harrison, 2010); however, most simulations of D-O events are performed under Last Glacial Maximum (LGM, 21 ka) boundary conditions. Few studies have performed simulations under MIS3-like conditions (e.g. Armstrong et al., 2023; Guo et al., 2019; Niu et al., 2025; Saini et al., 2024, 2025b; Zhang et al., 2021; Zhang and Prange, 2020), with only three PMIP4/CMIP6 models utilised (Guo et al., 2019; Niu et al., 2025; Saini et al., 2025b), including ACCESS-ESM1.5 (Saini et al., 2025b). Heinrich stadial 5 (HS5; ~48.8-47.6 ka; Menviel et al., 2014b; Sanchez Goñi and Harrison, 2010) occurred during MIS3, when both hemispheres were receiving higher summer insolation relative to pre-industrial (PI) levels due to greater obliquity (Berger, 1978). The atmospheric CO_2 concentration was lower than PI (Köhler et al., 2017). Global sea level was ~60-65 m lower than PI (Shakun et al., 2015), with extensive Laurentide and Scandinavian ice sheets (Gowan et al., 2021). Model simulations under 49 ka boundary conditions (orbital, ice sheet, albedo, etc.) representing a satisfactory quasi-equilibrium 'interstadial' climate - indicate drying across the Maritime continent and enhanced precipitation across Northern Australia during austral summer (Saini et al., 2025b). In this study, we further perform freshwater forcing experiments at 49 ka to explore and provide an analysis of the dynamics of climate changes in D-O and HS simulations, with implications on Australasian climates. While there are limited proxy reconstructions of HS5 climate over Australasia, the results of this study will provide a suite of outputs that can be used in future paleo model-data comparisons.

l.84-85: what do you mean by "consistent response here" what are the open questions?

The sentence is rephrased to: "A consistent response in the strength and meridional shift of the SH westerlies to […]".

Tab1: how are albedo, vegetation, topography and runoff obtained for 49ka? what are they based on?

Sorry for the incompleteness, this section is now modified to clarify the 49 ka boundary condition changes. Table 1 is also modified with respect to changes in the texts.

Modified Table 1:

Table 1. Full boundary conditions for the 49 ka simulation relative to PI (reproduced from Saini et al., 2025b).

	49 ka	**PI**
Orbital parameters		
Eccentricity	0.01292	0.01674
Obliquity (°)	24.435	23.459
Perihelion – 180 (°)	62.451	100.33
Greenhouse gases		
CO_2	199	284.3
N_2O	237	273

CH_4	432	284.3
Ice-sheet extent and salinity	49 ka	PI
Albedo and vegetation	49 ka	PI
Topography and runoff	49 ka	PI

Lines 125-130:

The model was first integrated under 49 ka boundary conditions starting from PI simulation (Table 1, Saini et al., 2025b). The model is forced by 49 ka orbital parameters (Berger, 1978), greenhouse gases concentrations (Köhler et al., 2017); ice-sheet extent and topography corresponding to 52.5 ka (Gowan et al., 2021) with closest match to ~ 48-52 ka sea level estimates (Shakun et al., 2015). Vegetation was modified to reflect the associated continental ice cover and converting forest to bare soil between the Cordilleran and Laurentide ice-sheet and C3 crops were replaced by surrounding vegetation. The land-sea mask and river runoff are also adjusted to reflect the modified topography (see details in Saini et al., 2025b).

l.119-120: this sentence is not fully clear. The 1555 years are the spinup of the 49ka_control simulation? Or are the 760 years of 49ka_control part of the 1555 years? why were boundary conditions changed stepwise and how?

Sorry about the confusion. We have changed the discussion here to clarify it. The reason why the boundary conditions were implemented step-wise is that in the previous study by Saini et al. (2025b), the authors compare the influence from different boundary conditions (e.g. NH ice sheets) on model's response in atmospheric circulation.

Lines 134-137:

The 49 ka simulation was run with step-wise changes in the boundary conditions for a total of 1555 model years, with the last 760 years implemented with full boundary conditions (49ka-full in Saini et al., 2025b). The last 100 years in 49ka-full show relatively stable surface air temperature and sea-surface temperatures (Saini et al., 2025b, Fig. A1). We therefore consider this as a quasi-equilibrium state for 49 ka climate, and define this period as the 49ka_control experiment in this study.

l.113-122: This section relies heavily on information from Saini et al 2025b. While you of course don't need to go as much into the details as Saini et al, it shoud still be possible to understand the relevant aspects of the setup without having to read Saini et al in addition.

Thanks for the suggestion, we have now modified this section as detailed in the previous two comments.

l.140/Fig.S1: include 49ka_control in Figure S1 for comparison

We have added it now.

Updated Figure S1:

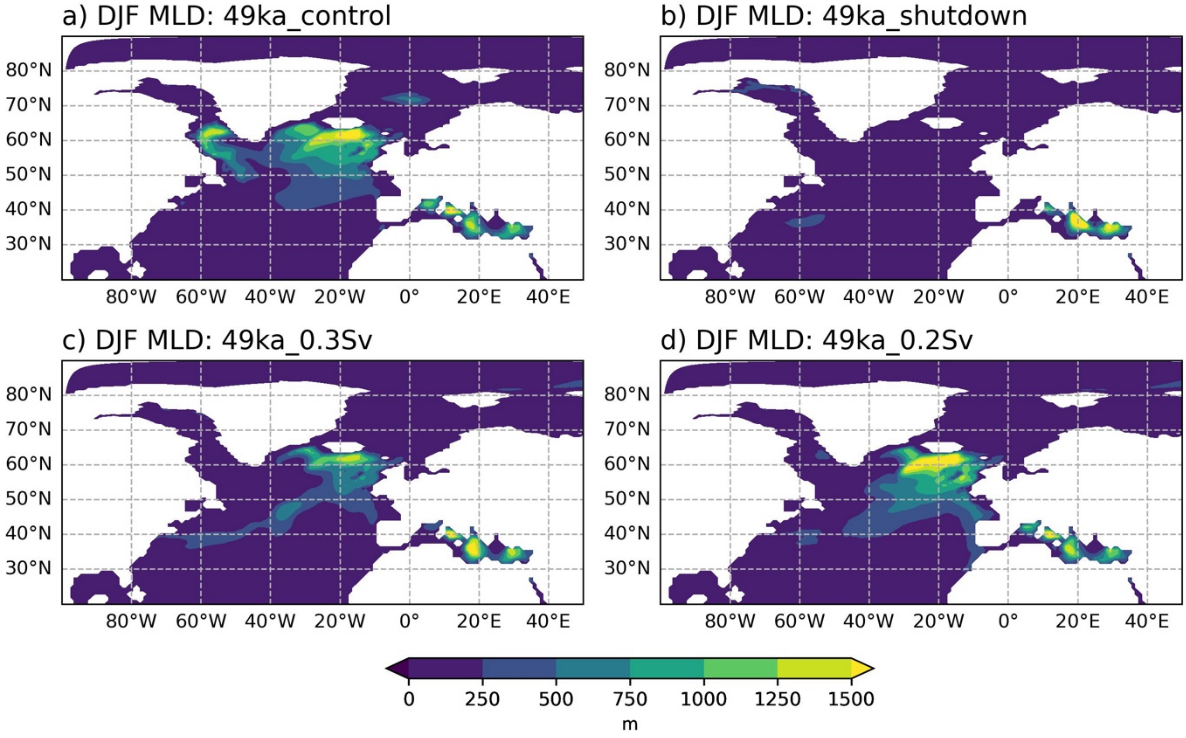

Figure S1: DJF mixed-layer depth (MLD; in m) in the North Atlantic for (a) 49ka_control, (b) the Heinrich stadial simulation (49ka_shutdown), and D-O stadial simulations (c) 49ka_0.3Sv, (d) 49ka_0.2Sv.

l.175: what is the additional benefit of the cubic spline? are the results very sensitive to the fitting parameters?

This method is adopted from Grose et al. (2015), with the use of a fitted cubic spine, we would be able to be detect the location and pressure of maximum MSLP more precisely. We have checked the codes for computing the cubic spline, our results are not sensitive to the parameters chosen.

l.188-189: was the AMOC reduction in the simulations with the 40% heat transport weakening of a similar magnitude as in 49ka_shutdown? If the residual AMOC strength after the "shutdown" was stronger than in 49ka_shutdown, this could be an explanation for the difference in heat transport reduction. Also, these numbers are probably very model dependent to begin with.

Thanks for the suggestion, we have modified the discussion here.

Lines 206-210:

The meridional oceanic heat transport to the North Atlantic is reduced by ~77 % (~1 PW at 30° N) in the HS experiment (see Fig. S2). This change is larger than previous model simulations of AMOC shutdowns under LGM conditions that found an average ~40 % reduction in Atlantic meridional heat transport (~0.8 PW at 30° N) (Menviel et al., 2008, 2020; Stouffer et al., 2006). The larger reduction in meridional oceanic heat transport can be explained by the large AMOC reduction simulated here (29 Sv reduction compared to an averaged of 15 Sv in previous LGM experiments; Kageyama et al., 2013).

l.191: How is this huge change in the subpolar North Atlantic possible? is that sea-ice related? I can see that air temperatures over sea ice may change dramatically, but a similar cooling seems to be happening in the SST as well. This implies that the subpolar North Atlantic must have temperatures of around 25° or higher, is it really that warm? But perhaps the SST changes are not as large and only the non-linear spacing of the colourbar in Fig. S3 makes it hard to read the actual magnitude of the SST change.

Sorry about the colorbar in Fig. S3, the maximum cooling in SST (-15.4 °C, Line 192) is indeed not as large as SAT. We have now changed it in Fig. S3.

We still prefer to use the non-linear spacing for the colorbar as it is easier to see the pattern of smaller temperature changes outside the high latitudes which may be important for precipitation and circulation changes in the tropics, e.g. ITCZ and monsoons.

Modified Figure S3:

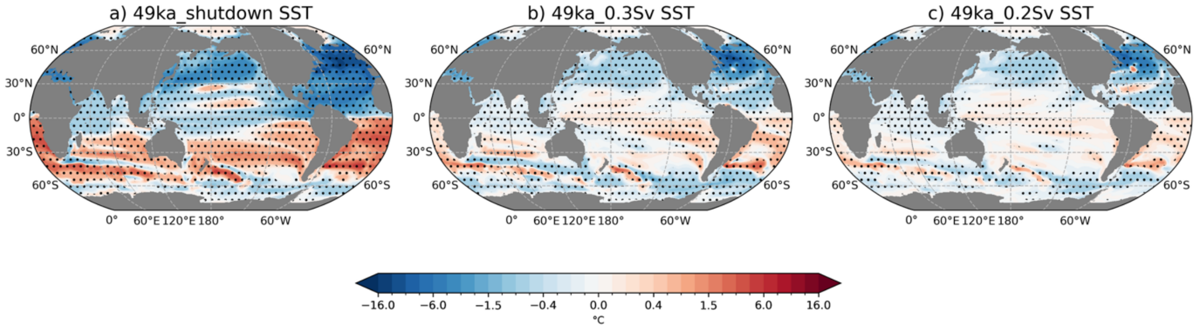

Figure S3: Annual mean sea surface temperature anomalies (SST; °C) relative to 49ka_control in each simulation. Stippling indicates statically significant differences from the control at the 95 % confidence level according to the Student's t-test

We have checked the location with the maximum SAT cooling of -26.3 °C in the 49ka_shutdown, at 55° N and 55° E. The absolute 49ka_control SAT at this location is simulated at 2.3 °C, while -24 °C at 49ka_shutdown. This can be seen in the warming anomalies at 49ka_control relative to PI (Figure 2 from Saini et al., 2025b) due to the higher AMOC strength. The sentences are rephrased to reflect this.

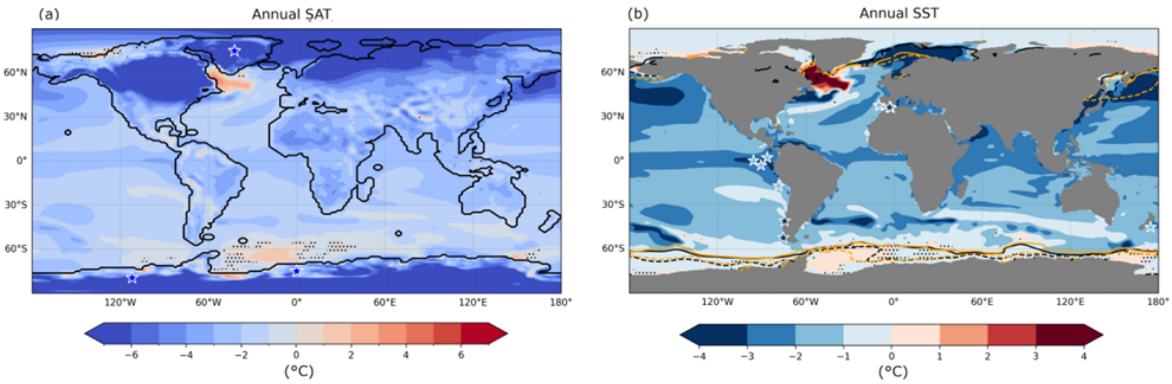

*Figure 2 in Saini et al. (2025b)***:** *Annual mean (a) SAT and (b) SST anomalies (°C) in 49ka_control relative to PI.*

Lines 214-216:

Reduced heat transport leads to a widespread significant NH mean cooling of 3.8 °C, with maximum annual mean surface air temperature (SAT) decrease of up to 26.3 °C in the Labrador Sea (Fig. 2a) due to large decrease in the AMOC strength, while the SH display a significant warming (mean 0.43°C) from 0 to 55°S.

l.198: warming over Antarctica is also non-significant in 49ka_shutdown (no stippling over Antarctica).

Thanks, we have removed the statement and rephrased it as below:

Lines 220-222:

The small reductions in the northward oceanic heat transport in D-O stadial simulations are only sufficient to induce some significant warming in the Indian and eastern Pacific that is beyond the Atlantic Ocean (Fig. 2b, 2c).

l.209: To me, the precipitation patterns do not seem more diverse than the temperature patterns. At least not on the global scale. Which is probably also reflected by the fact that the global mean temperature and precipitation both change by a factor of 1.3 between DO and HS simulations.

Thanks, we have deleted the sentence.

l.257-259: this sentence should refer to the change in HC width, not the absolute HS width

Thanks, this is modified.

l.300: this seems to be true mostly over Africa/the subtropical Atlantic/eastern pacific.

Thanks, we added the regions into the sentence.

l.380-382: These two sentences seem to contradict each other "[...] Australia and New

Guinea receive increased monsoon precipitation [...]. [...] thus no significant changes in precipitation are simulated over New Guinea."

Thanks for pointing it out, we have changed the discussion here.

Lines 411-414:

In the slowdown simulations, parts of northern Australia and New Guinea receive a small increase in monsoon precipitation (Fig. 9b, 9c), but little change in the spatial extent of the monsoon is simulated relative to 49ka_control. Reduced DJF SPCZ precipitation is simulated, corresponding to the warming anomalies over the area (Fig. 8b, 8c).

l.474-475: What were the previous studies based on?

Thanks for pointing out, the previous studies are based on modelling studies. We have now removed this paragraph from this section and moved parts of the discussion to Section 4.1 for consistency and fluency.

Editorial

Thanks for the editorial suggestions, the below editorial comments are all implemented in the revised manuscript.

l.31-32 nomenclature: the sentence in its current form seems to imply that the warming/cooling transitions are the Greenland Interstadials/Stadials. But Interstadial/Stadial refers to the more or less stable periods between the transitions. Please reformulate

l.34 same as above. Also, stadial was already introduced in the sentence before.

l.40 "contain" instead of "contains"

l.40-43: please shortly explain what is debated and which usage you follow.

l.48: Add "The" before "climatic response" at the beginning of the sentence.

l.59: "global temperature was" instead of "is"

l.121-122: should this not be "relative stable surface air and sea surface temperatures" rather than "stable changes in SAT and SST changes"?

l.134: "more likely to close to a complete shutdown", something is missing in the sentence, please reformulate

l.197-199: sentence does not work. please reformulate

l.305-309: super long sentence. please break it down to smaller, easier sentences.

l.356-357: sentence does not work. please reformulate

l.383-391: difficult to follow which part applies to all or only the DO or HS simulations. Please reformulate for clarity

Fig.9 (caption): the identifiers "left column", "middle" and "right column" do not fit the structure of the figure. It should probably be only "top" and "bottom" behind DJF and JJA, respectively.

l.415: "strengthen and migrate" instead of "strengthens and migrating"