

Non-linear Climatic Response to the Weakening of the Atlantic Meridional Overturning Circulation During Glacial Times

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Abstract. The climatic response to ~~the~~ 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); ~~with a focus on Southern Hemisphere and Australian hydroclimate.~~ 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~~ ~~the slowdown of the AMOC weakening~~; 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. A shutdown of the AMOC in the simulations leads to an~~ enhanced and expanded, ~~while t~~ ~~northern winter~~ ~~Hadley Cell (HC), with a southward shift of its ascending branch.~~ The southern winter HC is weakened~~r~~ but increased in width due to a northward shift of the ascending branch due to AMOC shutdown. This ~~change in the HC~~ drives seasonal ~~variations~~ ~~climate variability~~ in the ~~tropical and Northern and Southern Hemispheres~~ subtropical ~~regions via changes in the subtropical high pressure systems,~~ ~~and~~ ~~subsequently, changes in the cross-equatorial atmospheric circulation~~ ~~subtropical jet,~~ ~~as well as the Southern Hemisphere~~ ~~Southern Hemisphere~~ mid-latitude westerly winds and other climate features such as the monsoon systems, ~~with significant impacts on Australasian hydroclimates.~~ ~~The simulation results are broadly consistent with available proxy records for Heinrich and D-O stadials as well as previous model simulations.~~ The study demonstrates the potential location of a threshold in the climate system between linear ~~weakening~~ ~~slowdown~~ and nonlinear shutdown of ~~the~~ AMOC, with differing climate impacts ~~that are being broadly consistent with available proxy records for Heinrich and D-O stadials. This,~~ further highlighting ~~ing~~ the importance of not crossing the threshold of AMOC shutdown in the future.

35 1 Introduction

The Last Glacial Period (LGP, ~115,000 to 11,700 years ago) was characterised by repeated millennial-scale climate oscillations, which are commonly referred to as Dansgaard-Oeschger (D-O) ~~variability events~~ (Dansgaard et al., 1993). During each D-O event, Greenland temperature experienced an abrupt ~~warming transition to a relatively warm~~ ~~(a Greenland Interstadial period)~~, ~~after which~~ the temperature ~~then~~ gradually decreased within a few centuries before ~~it ended in~~ an abrupt cooling to near-full glacial ~~(Greenland stadial)~~ conditions (Stadial period), with the latter accompanied by a weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Barker et al., 2009; Corrick et al., 2020; Menviel et al., 2014b). During ~~Greenland cooling events~~ (stadials), reduced northward oceanic heat transport induced by a weaker AMOC resulted in heat accumulation in the South Atlantic, thus leading to Antarctic warming with a lag of ~2400 years (Barker et al., 2009; EPICA Community Members, 2006; Stocker and Johnsen, 2003; WAIS Divide Project Members, 2015). During some of the coldest D-O stadials, massive iceberg discharges into the North Atlantic Ocean led to a substantial weakening or shutdown of the AMOC (Barker et al., 2015; Broecker et al., 1992; Broecker, 1994; Henry et al., 2016; Zhou and McManus, 2024). These episodes are known as Heinrich events (HEs; Bond et al., 1992; Heinrich, 1988), and the cold time periods that contains ~~the HEs~~ ~~such events~~ are named Heinrich stadials (HSs) (Heinrich, 1988). Despite some debates about the usage of different Heinrich terminologies ~~in sedimentary literatures~~ (e.g. Andrews and Voelker, 2018; Hodell et al., 2017), throughout this paper we follow the consistent usage of the term 'these terms Heinrich stadial' as in previous studies (Barker et al., 2015; Sanchez Goñi and Harrison, 2010) ~~throughout the paper~~, as described above.

During D-O stadials, paleoclimate proxy records suggest cooler and drier conditions in the North Atlantic and many regions over Eurasia and North America (Izumi et al., 2023; Martrat et al., 2007). Temperature changes in Greenland ice core records show relatively similar amplitudes between D-O and HSs (Kindler et al., 2014; Svensson et al., 2008). However, sea surface temperature (SST) estimates from marine sediment records from the Iberian Margin display a temperature decrease up to twice as large in HSs compared to D-O stadials (Martrat et al., 2007). The climatic response during HSs is similar in direction but greater in magnitude than D-O stadials due to the large magnitudes of changes in AMOC strength, and thus heat redistribution, via changes in oceanic and atmospheric circulation (Izumi et al., 2023; Menviel et al., 2020; Pedro et al., 2018; Stocker and Johnsen, 2003). Whilst a seasonal southward migration of the Intertropical Convergence Zone (ITCZ) has been inferred during mild stadials ~~conditions~~, year-round displacement of the ITCZ position is suggested during HSs (Deplazes et al., 2013). Nevertheless, it remains ~~less certain~~ unclear whether the climate response to Heinrich and D-O stadials is linearly related to AMOC weakening.

Many D-O and HS ~~were occurred~~ ~~documented~~ 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 ~~the~~ 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 ~~participated~~ 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) ~~occurred at a time~~ (~48.8-47.6 ka; Menviel et al., 2014b; Sanchez Goñi and Harrison, 2010) ~~occurred~~ during Marine Isotope Stage 3 (MIS3, ~~59.4-27.8 ka~~) MIS3, ~~received~~ when both hemispheres were receiving higher summer insolation ~~in both hemispheres~~ relative to pre-industrial (PI) levels due to greater obliquity (Berger, 1978). The atmospheric CO₂ 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. ~~The global temperature is 2.7 °C cooler as a result of changes in all the boundary conditions (orbital, ice sheet albedo, etc.) in model simulations of 49 ka (Saini et al., 2025b). Paleoclimate records at Girraween Lagoon in northern Australia suggest relatively drier background climates during MIS3 relative to PI, with wetter conditions during HSs than interstadials during MIS3 (Bird, 2025). This is consistent with new speleothem records from southern Australia, suggesting wetter conditions during HS5 (Gould-Whaley et al., 2025, in prep.).~~

Many modelling studies have investigated the climatic response to AMOC variability in the past (Cheng et al., 2007; Chiang et al., 2014; Chiang and Friedman, 2012; Du et al., 2025; Kageyama et al., 2013; Lee et al., 2011; Menviel et al., 2014b; Saini et al., 2025a), including during the pre-industrial period (Ben-Yami et al., 2024; Jackson et al., 2015; Orihuela-Pinto et al., 2022; Saini et al., 2025a). A weakened AMOC leads to cooling in the North Atlantic with slow warming over the Southern Ocean and Antarctica ~~in the South Atlantic~~ due to reduced northward oceanic heat transport (Stocker and Johnsen, 2003). The ITCZ shifts southwards towards the warmer hemisphere due to changes in the interhemispheric temperature gradient, leading to an increase in Southern Hemisphere (SH) monsoon precipitation and reduced precipitation in Northern Hemisphere (NH) monsoons (Cheng et al., 2012; Zhang et al., 2023). This is consistent with paleoclimate records, which suggest weakening of the Indian (Deplazes et al. 2014) and East Asian (Wang et al., 2008; Xue et al. 2025), and West African monsoons (Pausata et al., 2011; Xue et al., 2025; Zhao et al., 2010) and increased strengthening of the South American (Campos et al., 2019; Wang et al. 2007) and Indo-Australian monsoons (Ayliffe et al. 2013; Scropton et al. 2022) (Denniston et al., 2013, 2017; Treble et al., 2017) during D-O and HSs. 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.

AMOC variability is linked to large-scale reorganisation of atmospheric and ocean circulation heat transport. Reduced northward oceanic heat transport as a result of AMOC weakening is partially compensated by an increase in the cross-equatorial atmospheric heat transport, via changes in the ITCZ and Hadley Cell (HC) (Bischoff and Schneider, 2014; Frierson et al., 2013; Kang et al., 2008; Lee et al., 2011; Pedro et al., 2018). The ITCZ is the region where low-level trade winds converge and form ascending branches of the Hadley Cell (HC) (Lionello et al., 2024). A southward shift in the ITCZ also

moves the rising branch of the HC southwards, leading to changes in the strength of the northern and southern HCs (Chiang et al., 2014; Chiang and Friedman, 2012; Lee et al., 2011; Saini et al., 2025a; Zhang and Delworth, 2005; Zhang et al., 2023). ~~This anomalous cross-equatorial atmospheric heat transport partially compensates for the reduced northward oceanic heat transport (Lee et al., 2011).~~ Changes in the HC ~~also~~ greatly influence large-scale climate features such as the subtropical high pressure systems (subtropical ridge; STR), located at the surface descending branch of the HC (Nguyen et al., 2013), and atmospheric circulation, including the mid-latitude westerly winds, affecting global hydroclimate accordingly (Chiang et al., 2014; Chiang and Friedman, 2012; Lionello et al., 2024; McGee et al., 2014; Orihuela-Pinto et al., 2022; Zhang and Delworth, 2005). A limited number of proxy and modelling studies suggest a southward shift and intensification of the SH westerlies during austral winter (June–July–August; JJA) during North Atlantic cold events. ~~A southward shift and strengthening of the SH westerly winds during austral winter (June–July–August; JJA) are suggested by limited a few proxy and modelling studies during North Atlantic cold events~~ (Anderson et al., 2009; Lee et al., 2011; Timmermann et al., 2007; Whittaker et al., 2011). The consistency of this response to an AMOC slowdown, however, remains an open question in current modelling studies. ~~A consistent response of the SH westerlies to an AMOC slowdown is still under investigation in different modelling studies~~ (e.g. Lee et al., 2011). ~~Moreover, there is a need to improve our understanding of climatic processes in the Indo-Pacific region from model simulations (Ben-Yami et al., 2024; Izumi et al., 2023; Jackson et al., 2015; Kageyama et al., 2013; Zhang and Delworth, 2005).~~

In this study, we investigate the climatic changes associated with D-O and HSs at 49 ka - coinciding with ~~Heinrich~~ stadial-HS5 - using the Earth System Model ACCESS-ESM1.5. This model has demonstrated high skill in simulating the SH and Australian climates (Grose et al., 2020; Ziehn et al., 2020). We compare the linearity in the climatic responses to changes in AMOC transport, taking an AMOC shutdown as an analogue of HS conditions and an AMOC weakening as an analogue of a D-O stadial. The results expand on previous studies by focusing on the SH climate response beyond the Atlantic Ocean, including exploring the ~~implications~~ mechanisms leading to large-scale climate change in Australasia. ~~e~~ The results aim to provide a detailed description of SH climate response associated with AMOC variability under glacial climates from a modelling perspective and ~~will be~~ are briefly compared with proxy records to assess model-data agreement.

2 Methods

2.1 Model description

In this study, we use the Australian Community Climate and Earth System Simulator (ACCESS) Earth System Model (ESM) version 1.5, which participated in the Coupled Model Intercomparison Project Phase 6 (CMIP6) and includes an interactive carbon cycle (Ziehn et al., 2020). The resolution of the atmospheric model component (UK Met Office Unified Model, UM) is 1.875° longitude × 1.25° latitude × 38 levels (Martin et al., 2010; The HadGEM2 Development Team: G. M. Martin et al., 2011), coupled to the land surface model, which is the Community Atmosphere Biosphere Land Exchange (CABLE) model (Kowalczyk et al., 2013). The ocean component uses the Geophysical Fluid Dynamics Laboratory Modular Ocean Model 5.1

(MOM5.1; Griffies, 2012) and sea ice component uses the Los Alamos Community Ice Code model CICE4.1 (Hunke and Lipscomb, 2010). The ocean and sea-ice components use a common horizontal grid of 360×300 cells at a nominal 1° resolution, with meridional refinement of grid spacing down to 0.33° at the equator and down to $\sim 0.4^\circ$ in the Southern Ocean and a tripolar grid with land-based poles at 65° N over Eurasia and North America (Ziehn et al, 2020). More details of the model description and performance are provided in Ziehn et al. (2020). Previous studies have performed freshwater hosing experiments to alter the AMOC strength in pre-industrial, interglacial boundary conditions, historical and future simulations using this model (Du et al., 2025; Pontes and Menviel, 2024; Saini et al., 2025a), with acceptable AMOC sensitivity to freshwater perturbations within the range of CMIP6 models (Weijer et al., 2020).

2.2 Heinrich 5 climate simulation at 49 ka

The model was first integrated under 49_ka boundary conditions starting from PI simulation (Table 1, Saini et al., 2025b) ~~as described in detail in Saini et al., (2025b). More specifically,~~ 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). ~~V~~ 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 ~~appropriate~~ land-sea mask and river runoff are also adjusted to reflect the modified topography (see details in Saini et al., 2025b) ~~(Table 1).~~

Table 1. Full boundary conditions for the 49_ka ~~control experiment~~ simulation relative to ~~pre-industrial~~ PI simulation (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 ₂ O	237	273
CH ₄	432	284.3
<u>Ice-sheet extent and salinity</u> Albedo and vegetation	49 ka	PI

Salinity <u>Albedo and vegetation</u>	49 ka	PI
Topography and runoff	49 ka	PI

155 The 49_ka simulation was run ~~for a total of 1555 years~~ with step-wise changes in ~~the~~ boundary conditions for a total of 1555 model years, with the last 760 years implemented (Saini et al., 2025b). ~~The 49ka_control simulation~~ with full boundary conditions (49ka-full in Saini et al., 2025b) ~~was run for 760 model years, with~~ the last 100 years in 49ka-full showing relatively stable ~~changes in~~ surface air temperature and sea-surface temperatures ~~changes~~ (Saini et al., 2025b, Fig. A1). Which 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. This 49ka_control displays a stronger AMOC strength than PI (31 Sv compared to 21 Sv for PI), 160 which is considered to represent interstadial conditions at 49 ka. The stronger AMOC at 49 ka is due to changes in the topography and expansion of the ice sheets in the model, which enhances the North Atlantic gyres and cyclonic circulation in the Labrador Sea (Saini et al., 2025b). Simulated globally averaged surface air temperatures are 2.7 °C lower than PI ~~pre-industrial~~, and global mean ~~the~~ SST is 1.2 °C ~~cold~~ lower. Drier conditions are simulated over the NH high latitudes and most land areas of the SH relative to PI (Saini et al., 2025b, Fig. 2c).

165 2.3 Experimental design for D-O and HSs at 49 ka

For this study, North Atlantic meltwater hosing experiments (Table 2) are performed ~~following attainment of~~ from the model quasi-equilibrium state conditions (49ka_control). Freshwater fluxes ~~awere~~ added into the North Atlantic (50° N-70° N, 70° W-0° W) to alter the AMOC strength in the model, similar to previous studies (Du et al., 2025; Pontes and Menviel, 2024; Saini et al., 2025a).

170 Previous modelling studies suggest that D-O stadials are associated with a ~50 % AMOC slowdown, while HSs are more likely to be close to a complete shutdown of the AMOC (e.g. Malmierca-Vallet et al., 2023; Menviel et al., 2020), even though the exact changes in the AMOC transport during D-O and HSs are still poorly constrained from proxy records (Henry et al., 2016; Lynch-Stieglitz, 2017).

175 To simulate D-O stadials, we add 0.2 Sv and 0.3 Sv of freshwater in the northern North Atlantic under constant 49ka boundary conditions (49ka_0.2Sv and 49ka_0.3Sv experiments). This leads to ~32 % and ~50 % AMOC reductions relative to the 49ka_control, respectively (see detailed changes in Table 2). We also perform an AMOC shutdown experiment with a constant 0.4 Sv freshwater forcing to simulate HSs (49ka_shutdown; Table 2). See Fig. S1 for changes in the mixed layer depth in each simulation.

180 **Table 2:** North Atlantic freshwater hosing experiments performed at 49 ka. The forcing strength (Sv), release duration (yr), analysis ~~time~~ period, and the AMOC mean strength (Sv) at analysis period (change relative to 49ka_control) are listed for each experiment.

Experiments	North Atlantic meltwater input (Sv)	Freshwater release duration (yr)	Analysis time period	AMOC strength (change relative to control) (Sv)
49ka_0.2Sv	0.2	200	yr 150-200	21 (-10)
49ka_0.3Sv	0.25	100	yr 450-500	17 (-14)
	0.3	200		
49ka_shutdown	0.4	500	yr 450-500	2 (-29)

The AMOC evolution for each simulation is shown in Fig. 1. In 49ka_shutdown, the AMOC takes ~100 model years to shut down (below 5 Sv ~~i~~was considered shutdown, Saini et al., 2025a). The simulation is then continued for another 400 model years for the model to fully respond to the shutdown, especially at southern high latitudes. The last 50 years of the simulation ~~i~~was used for analysis (dark blue in Fig. 1).

To explore pseudo D-O stadial conditions, we consider both the 49ka_0.2Sv, and 49ka_0.3Sv experiments. For 49ka_0.2Sv, we analyse years 150-200 (dark red in Fig. 1). To further weaken the AMOC, 49ka_0.2Sv is continued first forced with 0.25 Sv meltwater input, then with 0.3 Sv (see Fig. 1). The analysis period for 49ka_0.3Sv is the 50-yr interval ~~from~~ year 450 ~~to~~ -500 (dark brown in Fig. 1), which corresponds to the same integration time as the 49ka_shutdown experiment to allow for better comparisons. 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.

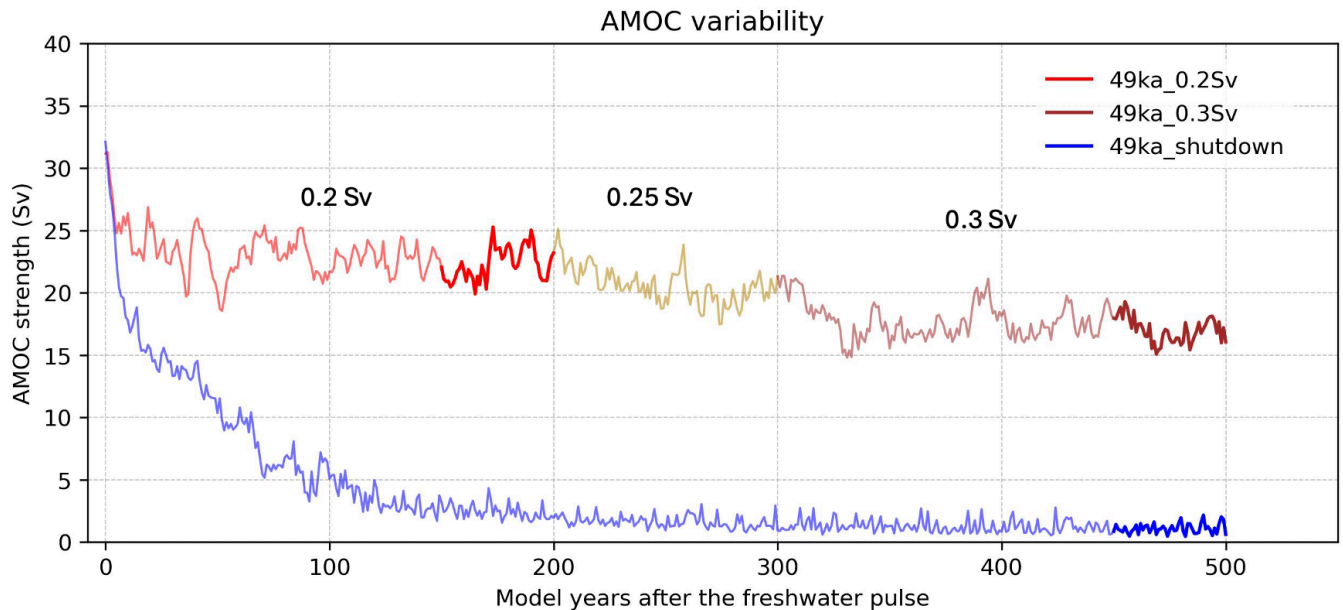


Figure 1: Time series of AMOC strength (Sv) after the freshwater pulse at year 0 for the D-O stadial (red-yellow-brown) and HS (blue) experiments. Darker colours indicate 50-year analysis period shown in Table 2. AMOC strength is calculated as the maximum value of the overturning streamfunction between 30° N and 50° N and below 500 m depth, in the Atlantic basin.

200

2.4 Calculation metrics

The NH and SH HC strength is calculated as the maximum and minimum value of the atmospheric mass streamfunction at 500 hPa in DJF and JJA, respectively. The width of the HC is calculated from the latitudes of zero mass streamfunction at mid-tropospheric level (500 hPa) as edges of the ascending and descending branches (Frierson et al., 2007; Seo et al., 2014).

205 The mass streamfunction is interpolated to 0.5° latitude resolution for the calculations.

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; Bischoff and Schneider, 2014).

210 SH westerlies strength is calculated as the 850 hPa zonal mean maximum wind speed between 40° S to 60° S, whilst the position of the SH westerly winds refers to the latitude of the maximum wind speed interpolated to 0.5° latitude resolution, consistent with previous studies (e.g. Du et al., 2024; Saini et al., 2025b). Changes in the SH westerlies are calculated across different ocean basins, the longitude range for the Atlantic Ocean covers between 70° W and 0°, the Pacific Ocean 130° E-70° W, and the Indian Ocean from 0 to 130° E.

215 The STR position and intensity over Australia is calculated as the maximum mean sea level pressure (MSLP) value zonally averaged over 140° E-150° E between 10° S and 45° S. The zonal mean MSLP values are then interpolated to 0.5° latitude resolution, followed by a fitted cubic spline to detect the latitude of maximum pressure. The latitude is the STR location, and the pressure value is the STR intensity (Grose et al., 2015).

220 Finally, monsoon domains are defined as regions in which the wet monsoon season precipitation rate exceeds the dry season rate by at least 2.5 mm/day, and is responsible for at least 55 % of the annual precipitation (Wang et al., 2011; Yeung et al., 2021).

3 Results

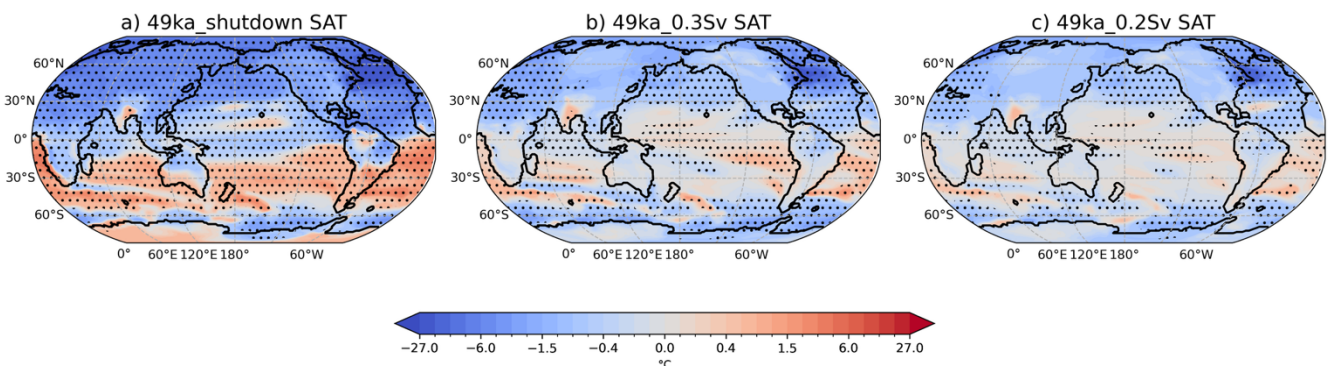
3.1 Overview of the climate response during pseudo D-O and HSs

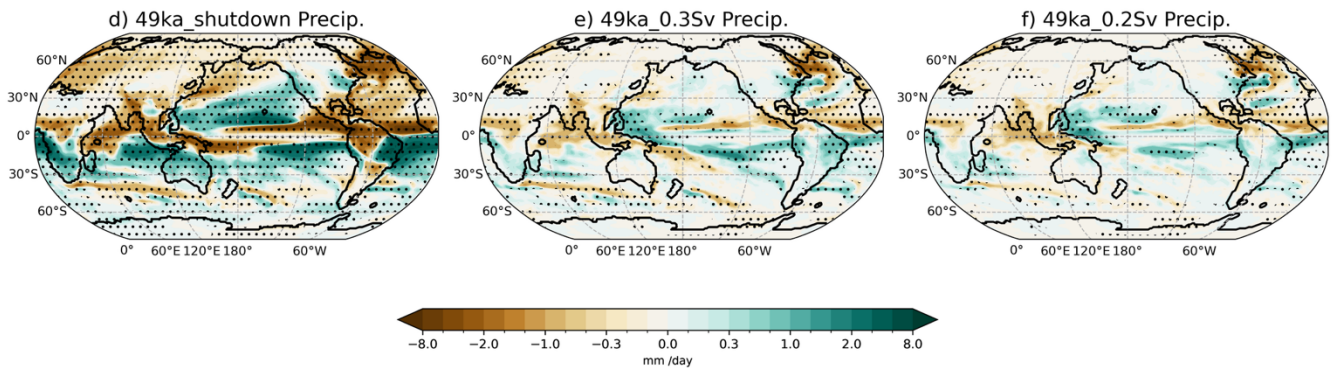
225 First, we provide an overview of annual temperature and precipitation changes in our D-O and HSs simulations relative to the 49ka_control climate and compare the linearity between the climatic responses to each hosing experiment by normalising the temperature and precipitation response to a “per Sv” AMOC decrease. Then, we evaluate the changes in seasonal large-scale

atmospheric circulations by investigating the changes in Hadley Cell, MSLP, and SH westerly winds to AMOC weakening. Finally, we investigate the influence of changes in these climate features on Australasian climates.

The meridional oceanic heat transport to the North Atlantic is reduced by $\sim 77\%$ (~ 1 PW at 30° N) in the HS (49ka_shutdown) experiment associated with AMOC shutdown (see Fig. S2). This change is larger than previous model simulations with of AMOC shutdowns under LGM conditions that found an average $\sim 40\%$ (~ 0.8 PW) reduction in Atlantic meridional heat transport (~ 0.8 PW at 30° N) (Kageyama et al., 2013; (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 $\sim 50\%$ 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.

In the HS simulation, significantly 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 North Atlantic Labrador Sea (Fig. 2a) due to large decrease in the AMOC strength, while the SH displays a significant warming (mean 0.43° C) from 0 to 55° S. Simulated SST show up to 15.4° C cooling in the North Atlantic, and up to 6.5° C warming in the South Atlantic (Fig. S3a). Over Antarctica, significantly cooler conditions are simulated in the Ross and Weddell Seas (Fig. 2a). The SAT temperature patterns in the two AMOC slowdown simulations (representative of D-O stadial simulations) show generally similar responses to the interhemispheric response in HS, with NH cooling and some SH warming anomalies relative to 49ka_control (Fig. 2b, 2c). The small AMOC reduction reductions in the northward oceanic heat transport in D-O stadial simulations seems to be too small are only sufficient enough to only induce some significant warming in the Indian and eastern Pacific that is beyond the Atlantic Ocean (Fig. 2b, 2c), a is with no significant annual mean Antarctic warming is simulated (Fig. 2b, 2c). This is expected, as $\sim 50\%$ of AMOC slowdown in 49ka_0.3Sv experiment only induces 25% reductions in the northward oceanic heat transport at 30° N (see changes in meridional oceanic heat transport in Fig. S2), which is insufficient to lead to the SAT warming over Antarctica observed in the shutdown simulation (Fig. 2a).





255 **Figure 2:** Annual (a)-(c) Surface Air Temperature (SAT; in °C) and (d)-(f) precipitation (in mm/day) anomalies 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.

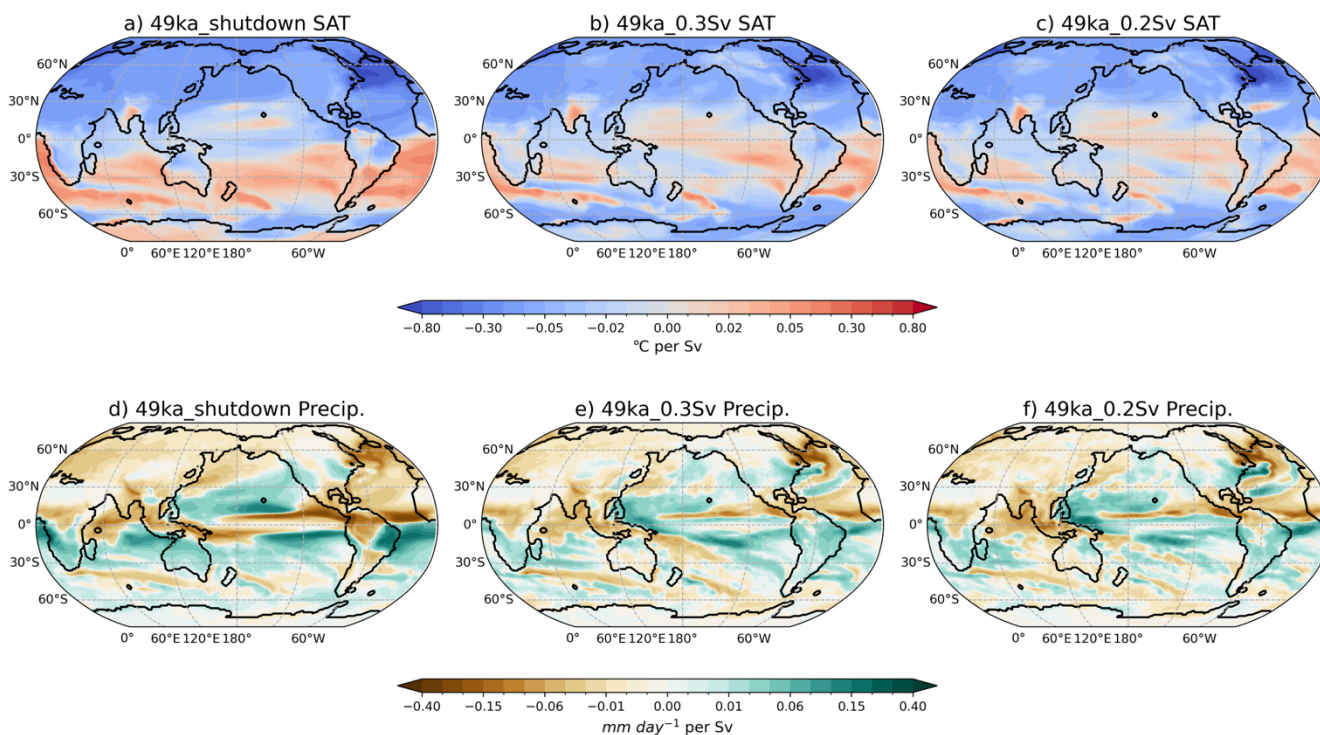
260 To compensate the significantly reduced ocean heat transport in the HS experiment, the ITCZ is pushed southwards towards the warmer hemisphere. Precipitation patterns are more diverse between each simulation (Fig. 2d-2f). In response to an AMOC shutdown (Fig. 2d), The a significant precipitation is significantly reduction reduced by a mean of 2.3 mm/day is simulated to the north of the equator in the Atlantic Ocean while the precipitation is and greatly enhanced to the south in the HS experiment (Fig. 2d). The pattern extends to every ocean basin, -This indicatinges a global-wise southward shift of the annual mean ITCZ position in HS, extending from the Atlantic to every ocean basin. This is due to the large interhemispheric temperature gradient anomalies, which push the ITCZ towards the warmer hemisphere. 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).

265 Widespread drying is simulated over much of the NH associated with the cooling, which is consistent with previous modelling results with a weaker AMOC (e.g. Jackson et al., 2015). In the D-O stadal simulations with -50% and 32% AMOC reductions (Fig. 2e, 2f), 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. with slightly reduced precipitation in the South Pacific Convergence Zone (The SPCZ) precipitation is reduced in the D-O experiments (Fig. 2e, 2f) region (10° S-30° S, 155° E-140° W) in the slowdown simulations (Fig. 2e, 2f), which is not evident the opposite of in the shutdown experiment (Fig. 2d). 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). The precipitation rate is significantly increased in the tropical western Pacific in the slowdown simulations (Fig. 2e, 2f),

275 corresponding to the warming anomalies (Fig. 2b, 2c).

To further quantify the linearity of changes, we normalise the temperature and precipitation response to a “per Sv” AMOC decrease relative to 49ka_control (Fig. 3). The D-O stadal simulations with 10 Sv and 14 Sv decrease in AMOC

strength show the same degree of annual mean temperature and precipitation changes per Sv change (details in Table S1), which indicate linear relationships. This can be seen from the regions of significant changes in the 49ka_0.2Sv experiment (Fig. 2c, 2f) being enhanced in magnitude and expanded in areal extent in the 49ka_0.3Sv simulation (Fig. 2b, 2e), and similar normalised spatial patterns between the two experiments (Fig. 3b, 3c, and 3e, 3f). Nevertheless, crossing the tipping point of a full shutdown of the AMOC under glacial conditions leads to around 1.3 times the global annual average temperature cooling per Sv AMOC decrease compared to D-O experiments (see Table S1). More specifically, NH temperature ~~displays is simulated to show~~ up to 1.6 times more cooling in 49ka_shutdown, while SH (from 0 to 55° S) experiences up to 6.8 times warmer temperatures per Sv than the slowdown experiments (see Fig. 3a-c for normalised spatial patterns). This large difference in SH temperature changes between the D-O and HSs simulations are attributed ~~by~~ to a simulated SH mean cooling in D-O experiments while ~~aa~~ SH warming ~~is simulated~~ in the HS (Table S1; Fig. 3a-c). Globally averaged precipitation changes under AMOC shutdown are also ~1.3 times larger per Sv of AMOC reduction than in the AMOC slowdown simulations, with the NH becoming ~2 times drier and the SH ~3 times wetter per Sv compared to the D-O slowdown simulations. The globally averaged precipitation in AMOC shutdown is also ~1.3 times the reductions in AMOC slowdown simulation per Sv of AMOC decrease, with ~2 times drier NH while 3 times wetter SH per Sv compared to the D-O slowdown simulations (Table S1; Fig. 3d-f).



295 **Figure 3:** Normalised annual surface air temperature anomalies (SAT; °C per Sv), and precipitation anomalies per Sv AMOC decrease (mm day^{-1} per Sv) relative to 49ka_control in each simulation.

3.2 Non-linear response in large-scale seasonal atmospheric circulations and mechanisms

300 In this section, we investigate the drivers of the diverse hydroclimate response in the simulations by examining the changes in the HC, and the associated changes in the MSLP, 850 hPa wind circulations, including the SH mid-latitude westerly winds, and the STR using the metrics described in Section 2.3.

3.2.1 Alterations in the Hadley Cell

305 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~~winter (DJF)~~ HC strengthens in DJF while the SH~~winter JJA~~ HC weakens in JJA in all simulations (Fig. 4 & Fig. 5).

310 ~~The shift in the ITCZ is only evident in the Atlantic basin, extending into the eastern equatorial Pacific in the slowdown simulations from the annual mean precipitation spatial patterns (Fig. 2d-2f).~~ As the ascending branch of the HC, the ITCZ at 850 hPa in DJF season shifts southwards by 0.82° and 0.34°, respectively in the 49ka_0.2Sv and 49ka_0.3Sv slowdown simulations, compared to a significant 3.57° southward shift of 3.57° to ~15.8° S in the 49ka_shutdown simulation (thick lines in Fig. 4a, 4c, 4e). ~~On the other hand, the global mean position of the JJA ITCZ shifts northwards by 0.97° to around 20.14° N in 49ka_shutdown experiment while a slight southward displacement of 0.38° is simulated in 49ka_0.3Sv and 0.05° northward shift in 49ka_0.2Sv simulation at 850 hPa (thick lines in Fig. 4b, 4d, 4f).~~

315 In ~~the~~ boreal winter (DJF), ~~season,~~ the northern HC strengthens and expands in width at 500 hPa ~~due to AMOC weakening~~ in all simulations (Fig. 5). The DJF northern HC central position with maximum HC strength shifts southwards by 10° to 1.88° S in the 49ka_shutdown simulation, however, remains unchanged at around 8.13° N in the slowdown simulations (Fig. 4a, 4c, and 4e). The northern HC strength increases by 20 % due to AMOC shutdown compared to an increase of less than 2.3 % in the slowdown simulations (Fig. 5). The NH HC width increases slightly between ~~the two slowdown~~ 49ka_0.2Sv and 49k_0.3Sv simulations but is more than doubled in the shutdown simulation (Fig. 5), and is dominated by the southward shift in the ascending branch of the NH HC at 500 hPa, albeit with little change in location of the descending branch (~~details in Table S2~~ Fig. 4a, 4c, 4e).

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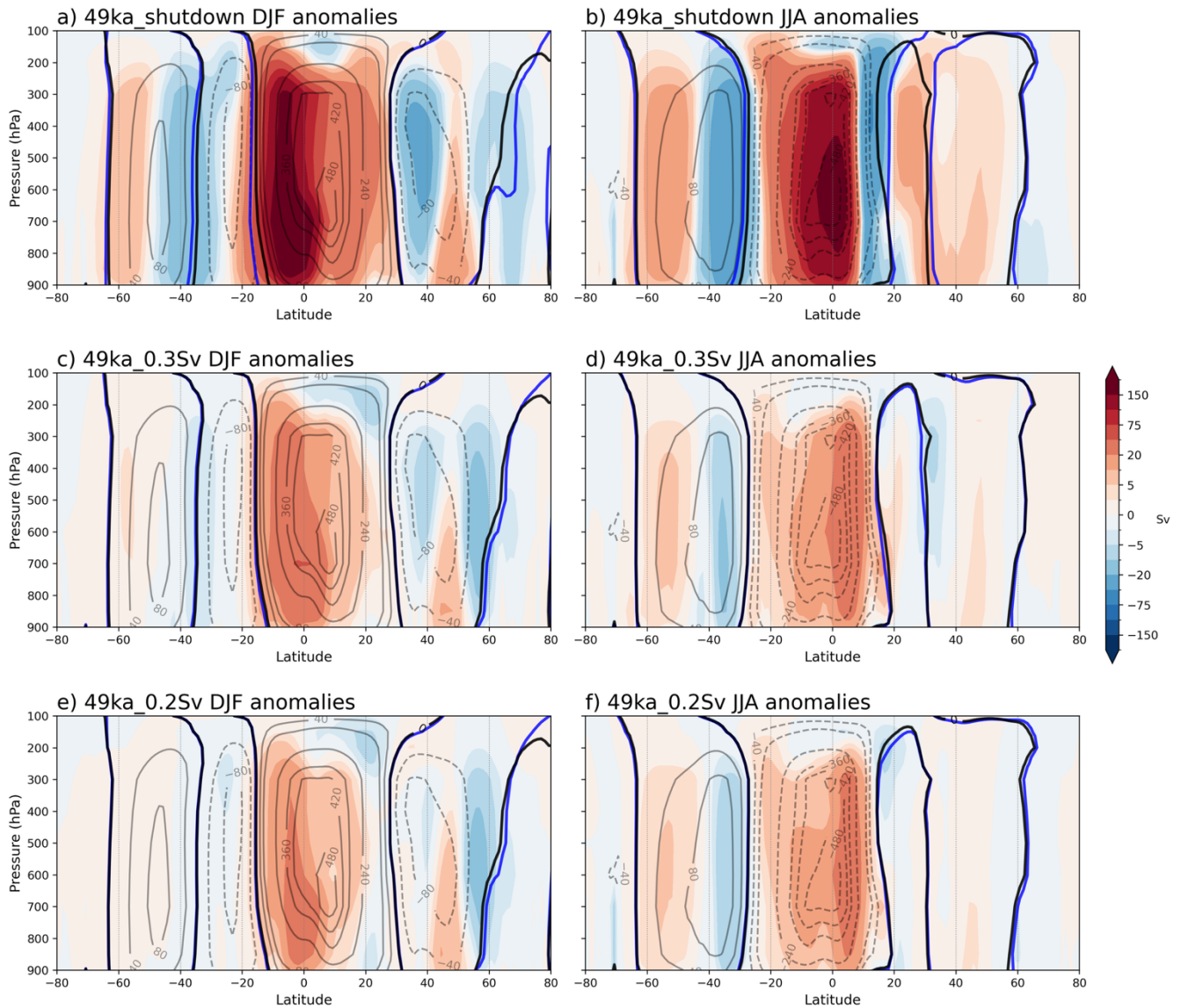


Figure 4: DJF and JJA 49ka_shutdown (a, b), 49ka_0.3Sv (c, d), and 49ka_0.2Sv (e, f) minus 49ka_control atmospheric mass streamfunction anomalies (Sv, shading). Black contours (solid=positive; dashed=negative) are 49ka_control absolute streamfunction values. The thick black and blue lines represent the zero contour in 49ka_control and each freshwater hosing experiments, respectively.

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 SH HC strength is 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 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. This may be attributed by a 3.5° northward shift of the ascending branch of the SH HC due to AMOC shutdown, leading to an expansion of the SH HC width by 11.7%. 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.

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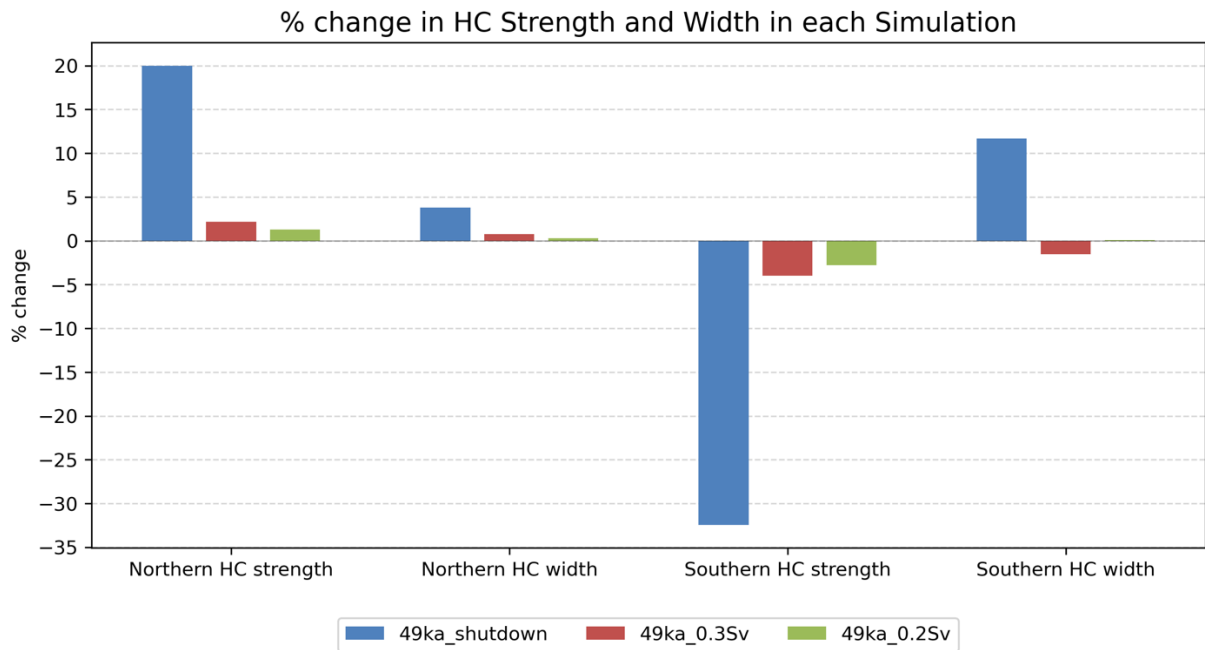


Figure 5: Percentage of changes in NH wintertime (DJF) HC and SH winter (JJA) HC strength and width in 49ka_shutdown, 49ka_0.3Sv and 49ka_0.2Sv simulations at 500 hPa (detailed values are in Table S2). Method for the calculations is described in Section 2.4.

355

3.2.2 Changes in the subtropical pressure systems and circulation

Changes in the HC strength and width influence ~~changes in~~ the STR and surface wind stress associated with the subtropical descending branch of the HC. In the shutdown simulation, the position of the southern JJA HC descending branch is shifted southwards by 1.5° from 27.2° S with reduced strength while the northern DJF HC strength is enhanced with a small northward shift (0.1°) in the position of the subtropical descending branch (Fig. 5 and Table S2). The position of the descending branches in the slowdown simulations changes by less than 0.3° (Table S2).

In ~~the~~ austral winter (JJA), ~~season,~~ the SH MSLP at ~27° S weakens in all simulations in response to a weaker southern HC (Fig. 6b, 6d, 6f), with some slight strengthening over the Indian Ocean in the slowdown simulations (Fig. 6d, 6f). The upper-level subtropical jet at 200 hPa weakens as a response of weakened southern HC (Fig. ~~S4b~~S5b, ~~4d~~5d, ~~4f~~5f). The subpolar low pressure belt shows negative surface pressure anomalies, while positive surface pressure anomalies of up to 5.7 hPa are found between 50° S and 70° S in the Indian and Pacific basins (Fig. 6b). In the NH, a region of low surface pressure with negative MSLP anomalies of up to 7.2 hPa in the North Pacific subtropics is simulated in the 49ka_shutdown experiment in JJA (Fig. 6b), associated with significantly increased precipitation (Fig. ~~S5f~~S6f), which corresponds to a northward displacement of JJA ITCZ position to ~20.1° N. The surface winds adjust to changes in the surface pressure and ITCZ shifts, generating an anomalous subtropical anticyclonic circulation over the North Pacific subtropical regions in the shutdown experiment (Fig. 6b), which is less evident in the slowdown simulations due to smaller changes in the southern HC (Fig. 6d, 6f).

In DJF ~~season,~~ there is an increase in pressure ~~in the~~ northern subtropical regions over Africa, the Atlantic and the eastern Pacific in response to an enhancement of the descending branch of the northern HC in all simulations (Fig. 6a, 6c, 6e). The upper-level subtropical jet strengthens in the NH across all experiments (Fig. ~~S4a~~S5a, ~~5c~~, ~~5e~~), associated with stronger subtropical cyclonic circulation and positive surface pressure anomalies over Europe and the North Atlantic (Fig. 6a, 6c, 6e). A decrease in surface pressure in the SH subtropical regions is simulated in all simulations, with less clear changes over the Indian Ocean in the 49ka_0.2Sv experiment due to smaller southward shifts in DJF ITCZ positions at ~13° S. In the 49ka_shutdown experiment (Fig. 6a), it is evident that the surface wind changes are consistent with the southward shift in the ITCZ to ~15.8° S, particularly over the Indian and South Atlantic Oceans, with westerly anomalies to the north and while easterly anomalies to the south, ~~which~~ This change in the winds generates anomalous cyclonic circulation over the Indian and south Atlantic Oceans ~~in 49ka_shutdown experiment,~~ associated with ~~the~~ weakened surface pressure due to AMOC shutdown (Fig. 6a). In comparison to 49ka_shutdown, the changes in MSLP patterns and circulation between the 49ka_0.2Sv and 49ka_0.3Sv simulations show relatively linear relationships to AMOC weakening (Fig. 6c, 6e and 6d, 6f).

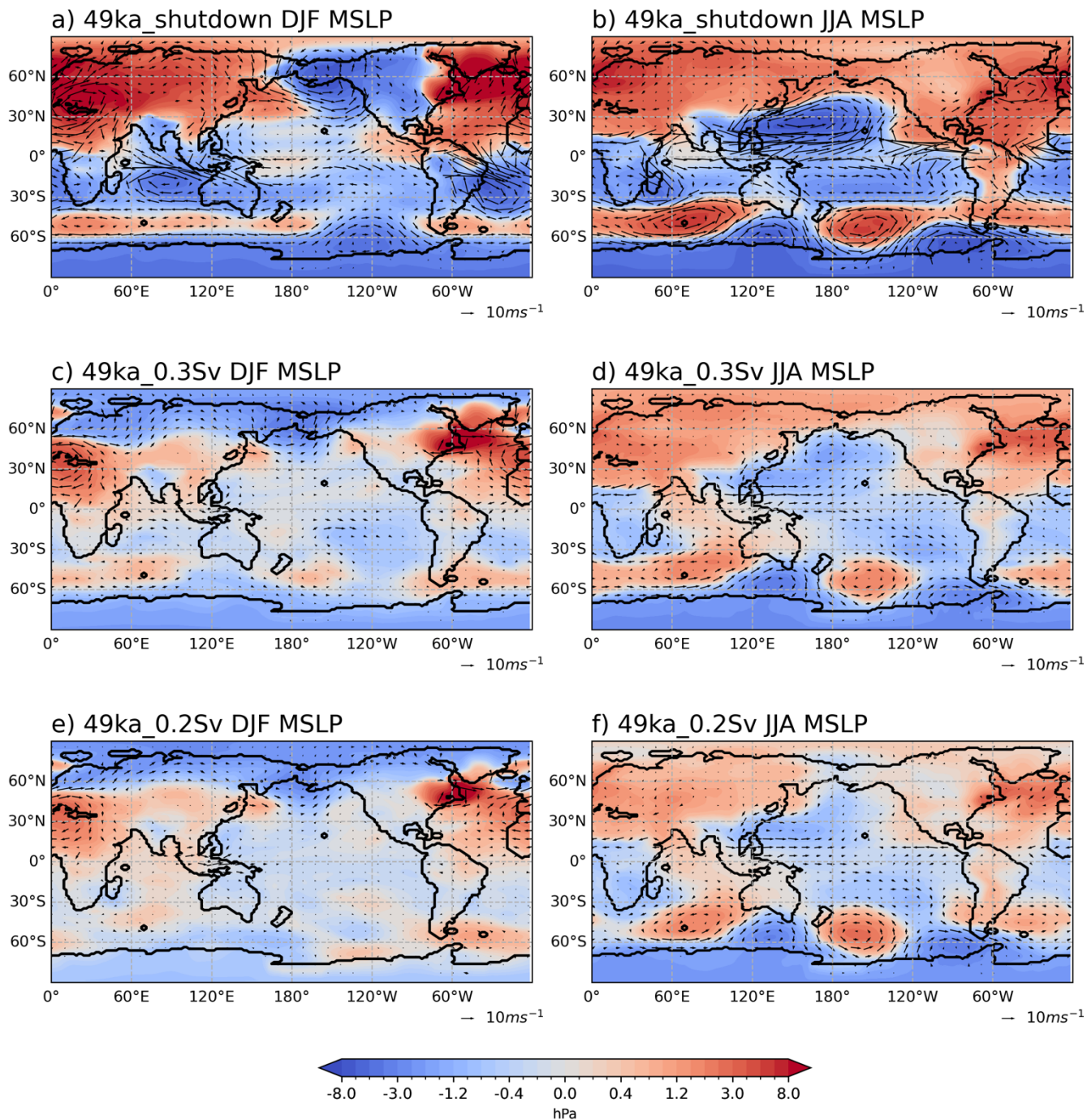


Figure 6: DJF (left column) and JJA (right column) MSLP anomalies (hPa) in each simulation relative to 49ka_control, with 850 hPa wind vector anomalies.

3.2.3 Changes in the SH mid-latitude westerly winds

In this section, we explore the impacts of the altered HC on SH mid-latitude westerly winds. Changes in the position and intensity of the SH westerly winds are evaluated, defining the SH westerlies strength as the zonal mean maximum wind speed between 40° S to 60° S at 850 hPa and the position of the SH westerly winds as the latitude of the maximum wind speed, interpolated to 0.5° latitude resolution.

The globally averaged SH westerlies strength increases by 11.4 % and shifts southwards by 6.5° to ~52° S in 49ka_shutdown simulation in JJA season, due to the weakening of the southern winter HC and southward displacement of its descending branch (Fig. 7a). Similarly, global mean strengthening and southward displacement of the SH westerlies are simulated in DJF season (Fig. 7e), but the changes are smaller than those simulated during JJA ~~but with smaller responses to AMOC weakening compared to JJA.~~ 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).

The westerlies ~~strengths~~ shows the strongest intensification over the South Pacific Ocean in both seasons, with more than 21 % at around 55° S in JJA (Fig. 7c) and 6 % at ~51° S in DJF (Fig. 7g). There is little change in the meridional position over the Pacific basin (Fig. 7c, g), while the SH westerlies in JJA shift southwards by 6° and 5° over the Atlantic and Indian Oceans, respectively (Fig. 7b & 7d). 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 ~~the westerlies strength reduces~~ ~~weaken in the slowdown simulations in both seasons relative to 49ka_control~~ ~~but seems to only increase back to 49ka_control levels when the AMOC is shut down in JJA season (Fig. 7b), with relatively unchanged strength in response to AMOC shutdown in DJF (Fig. 7f).~~ 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.

In summary, the SH westerlies strength and meridional position in the AMOC slowdown experiments (49ka_0.2Sv and 49ka_0.3Sv) show little differences in their response to AMOC weakening (Fig. 7), despite some variations over the Atlantic and Indian Oceans in JJA due to slightly different changes in the southern winter HC. The strength ~~is slightly strengthened~~ ~~increases~~ ~~by less than 6 %~~ ~~slightly~~ over the Pacific and Indian basins with no meridional displacement in the slowdown experiments relative to 49ka_control in JJA (Fig. 7c, d), while weaker and southward SH westerlies ~~are~~ ~~is~~ simulated over the Atlantic (Fig. 7b). Relatively ~~no~~ ~~little~~ change is simulated in the slowdown simulations in DJF (Fig. 7e-h). However, when the AMOC is shut down, the SH westerlies response seems to follow the tendency over the Pacific Ocean with increased strength in both seasons (Fig. 7c, g), ~~however,~~ while more complex responses are simulated in the other ocean basins.

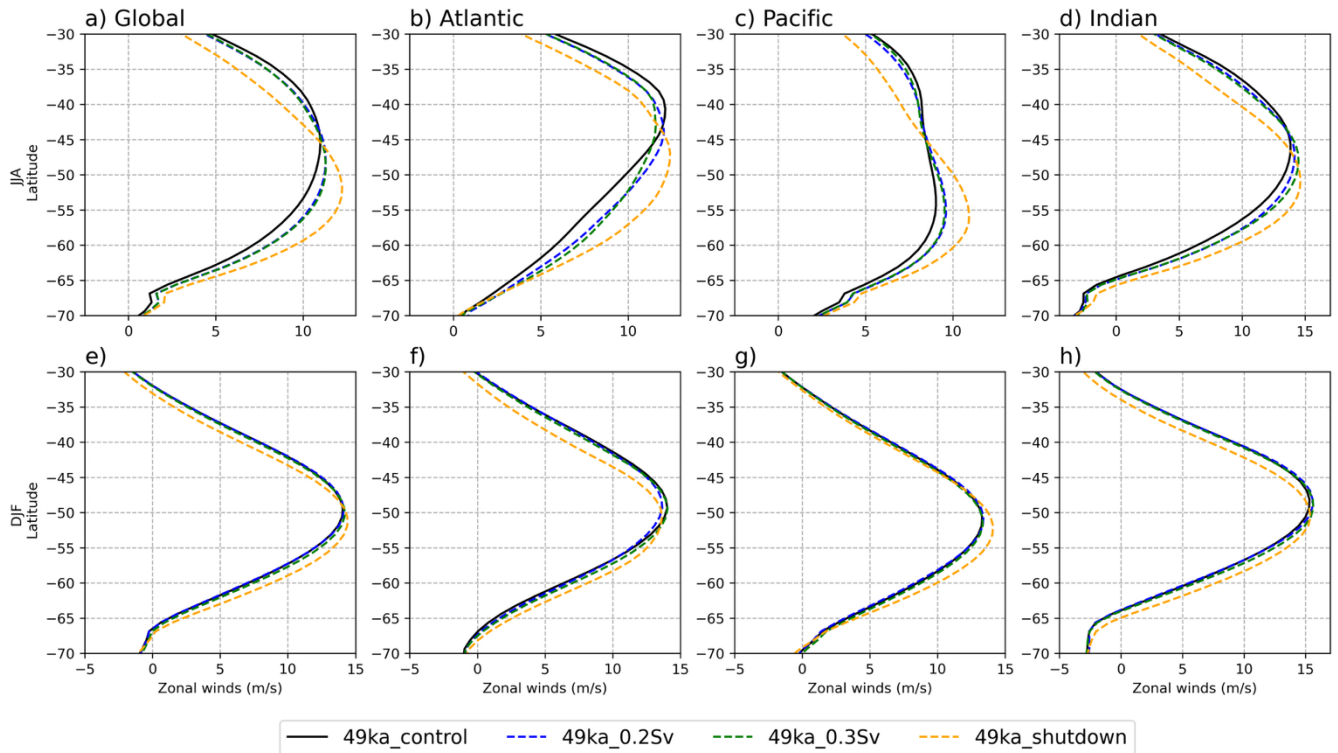


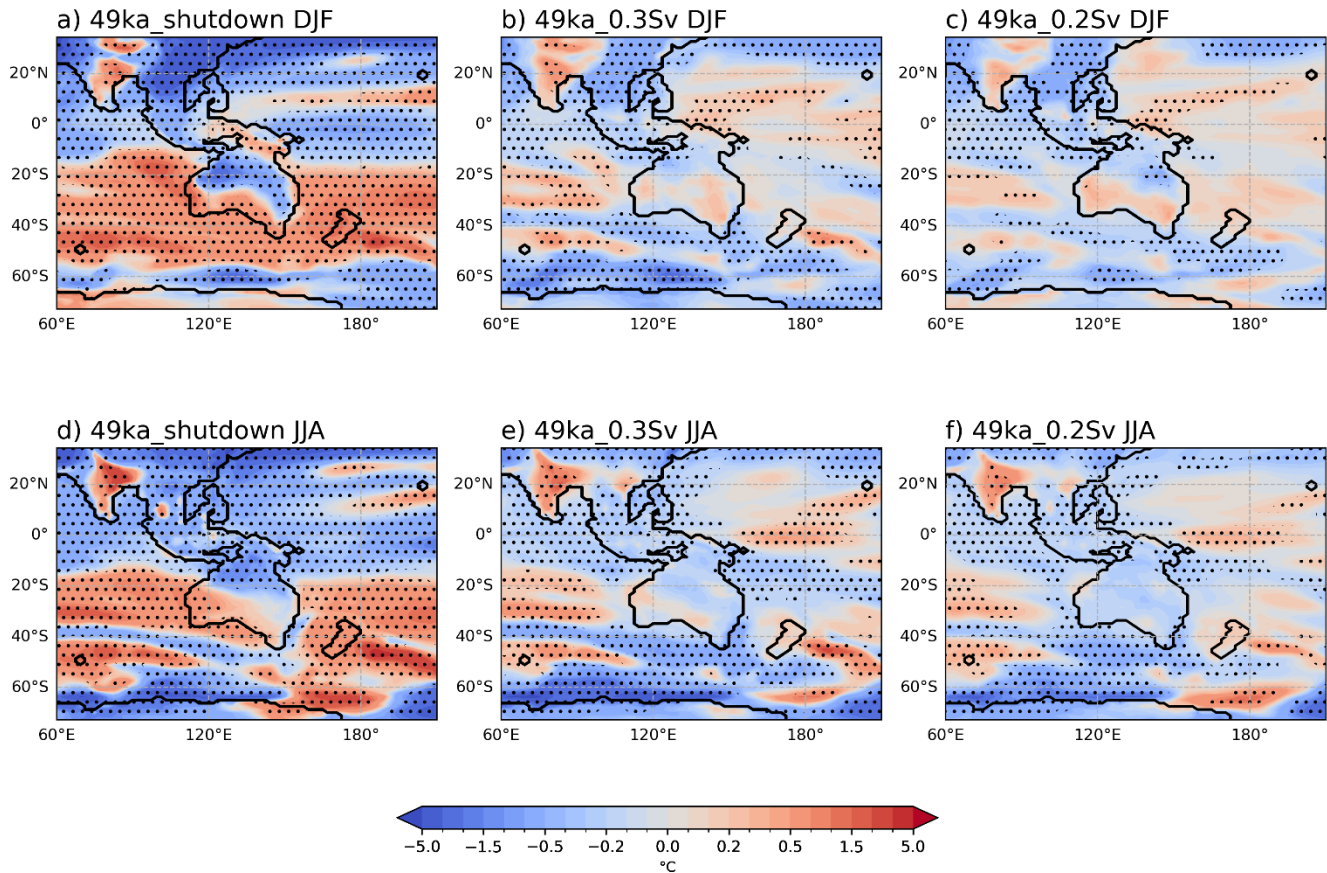
Figure 7: Southern Hemisphere JJA (a-d) and DJF (e-h) 850 hPa average westerly wind speed (m/s) in each simulation relative to 49ka_control (in black) globally, and across each ocean basin (longitude range defined in Section 2.4).

430 3.3 Impacts on seasonal Australasian climate

In this section, we investigate the climatic changes over Australia and the surrounding region in response to AMOC slowdown and shutdown at 49 ka and propagated by large-scale changes in atmospheric circulation discussed above.

The northern half of the Australian continent, as well as parts of New Guinea, are simulated to be colder while the southern part of Australia is warmer in the shutdown simulation in both DJF and JJA seasons (Fig. 8a, 8d). This is consistent with previous AMOC weakening experiments performed with the same model under interglacial background climates (Du et al., 2025; Saini et al., 2025a). However, the amplitude of this temperature gradient is smaller in the slowdown experiments (Fig. 8b-c, 8e-f). The 49ka_0.2Sv experiment displays a similar pattern as 49ka_shutdown in DJF, even though the changes are in-significant (Fig. 8c). In JJA, an overall cooling pattern is simulated across Australia in the slowdown experiments (Fig. 8e, 8f), compared to while significant warming anomalies are simulated over southern Australia due to AMOC shutdown (Fig. 8d-f).

Over New Zealand, significant warming is triggered by AMOC shutdown (Fig. 8a, 8d), while small temperature changes are suggested in the slowdown experiments, with significant cooling to the south and warming to the east of New Zealand (Fig. 8b-c, 8e-f).



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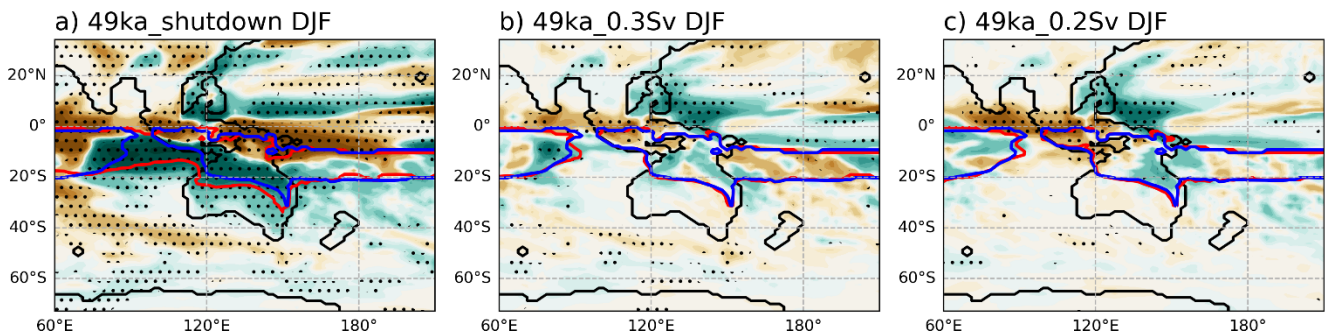
Figure 8: Australian annual (left column), DJF (middle top row) and JJA (right column bottom) surface air temperature (SAT; in °C) anomalies in each simulation relative to 49ka_control. Stippling indicates areas with significant changes at the 95 % confidence level according to a Student's t-test.

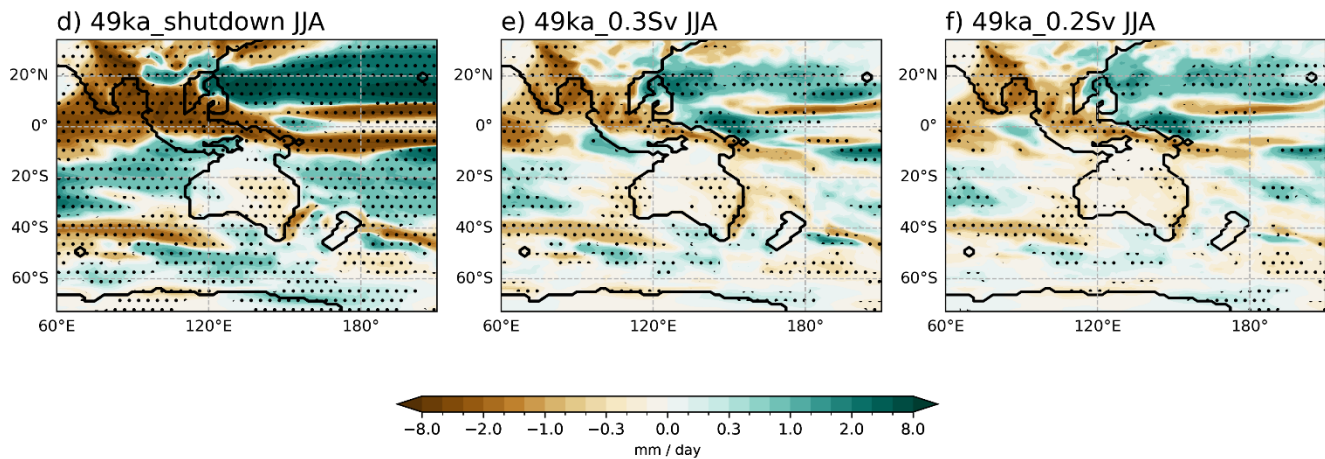
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The current hydroclimate of northern Australia and nearby Maritime Continent and New Guinea are influenced by the Indo-Australian summer monsoon in the austral summer (DJF), while southern Australian and New Zealand hydroclimate is more affected by a northward shift of the SH westerly winds in austral winter (JJA) season. Moreover, the STR, as the surface descending branch of the Hadley Cell, undergoes meridional displacement with the seasons, greatly influencing the timing of moisture delivery over Australia (Große et al., 2015; Pepler et al., 2018).

455 In the shutdown experiment, significantly increased precipitation in DJF is simulated across the Australian continent south of 10°S, with an up to 6 mm/day increase in northern Australia due to AMOC shutdown (Fig. 9a). The increase is likely driven by stronger north-westerly winds associated with an enhanced and expanded Indo-Australian summer monsoon (see Fig. 9a, where blue contours represent 49ka_control monsoon domain, and red contours represent the monsoon domains in the shutdown and slowdown experiments). The STR shifts southwards by 1° to around 41° S, allowing more tropical moisture to reach central Australia while drier conditions prevail around the high-pressure regions (Fig. 9a). The STR shift is associated with significantly ~~lower~~ lower summer (DJF) temperatures of more than 2 °C over northern Australia and New Guinea due to increased precipitation and cloud, whereas most of the SH mid-latitudes are warmer (Fig. 8a). 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 ~~the monsoon spatial domains show little change~~ relative to the 49ka_control. 460 Reduced DJF SPCZ precipitation is simulated ~~No significant ITCZ shift is simulated over the western Pacific, thus no significant changes in precipitation are simulated~~ corresponding to the warming anomalies over the area (Fig. 8b, 8c) ~~over New Guinea.~~ 465

During the austral winter (JJA), significant drying is simulated along the east coast of Australia, extending to central Australia ~~for in~~ all simulations (Fig. 9d-f). This drying trend is due to slightly increased pressure across Australia and New Zealand (Fig. 6b, 6d, 6f). In HS simulation, -and a 1° southward displacement of the JJA STR is shifted southward by 1° to ~30° S, associated with a displaced descending branch of the southern HC in JJA. The southward shift of the STR suppresses the mid-latitude frontal systems associated with low pressure that brings the cold south-westerly winds and precipitation into southern Australia in winter, as occurs under ~~the modern climate, which then -~~ These changes in the STR also leads to drying conditions in southeastern Australia in ~~the shutdown-HS simulation-~~ (Fig. 9d). There is a ~~The consistent~~ drying pattern over southern Australia in JJA is consistent across all experiments, which may be due to the southward shift of the SH westerlies in all simulations (Fig. 7a). The STR position and intensity remains unchanged in the slowdown simulations in both seasons. 470 475





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Figure 9: Australian (~~left column~~), DJF (~~middle top row~~) and JJA (~~right column bottom~~) precipitation anomalies in each simulation relative to 49ka_control (mm/day). The blue contours in DJF (a-c) represent the 49ka_control monsoon domains while the red contours indicate monsoon domains in each hosing experiments Stippling indicates areas with significant changes at the 95 % confidence level according to a Student's t-test.

485 4 Discussion

In this study, we performed freshwater hosing experiments to slow down and shut down the AMOC under glacial conditions at 49 ka to represent D-O and HSs, respectively. We explored how the large-scale climate features, such as the atmospheric circulation and precipitation respond to different magnitudes of AMOC weakening and their impacts on ~~how it leads to changes~~ ~~in~~ SH regional climates.

490 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 HS 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.

495 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. ~~In response to an AMOC shutdown at 49 ka, the annual mean position of the ITCZ moves southwards due to a strong interhemispheric temperature gradient, with cooler NH and warmer SH.~~ 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-

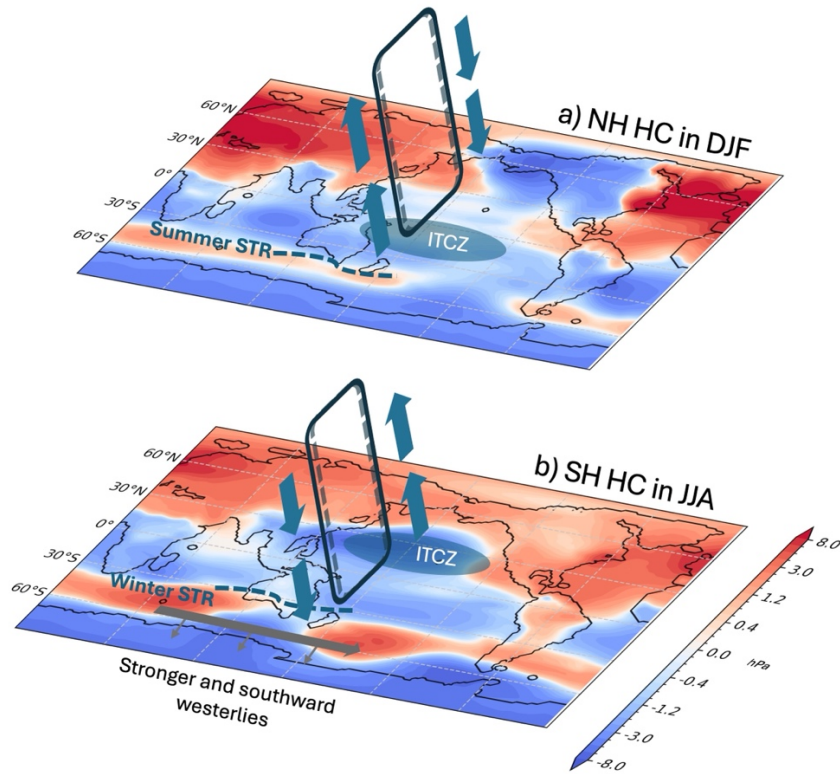
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equatorial heat transport, which explains the smaller contributions to atmospheric compensation in JJA. Note that the simulated change in the southern JJA width is different from responses under the Last Interglacial and PI boundary conditions using 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).

Changes in the subtropical high surface pressure (STR) are associated with variations in the descending branch of the HC. An increase in DJF MSLP is simulated in the NH subtropics due to enhanced descending branch of the northern HC, while the opposite weakening of the STR is seen in the SH (Fig. 10). A strong decrease in surface pressure accompanied by anomalous anti-cyclonic circulation is simulated over North Pacific in JJA, associated with significantly increased precipitation over the region (Fig. S5f-S6f). The upper-level SH subtropical jet weakens in JJA as a result of weakened southern winter HC. Global mean SH mid-latitude westerly winds at 850 hPa strengthens and migrating southwards in both JJA and DJF seasons, which further leads to strengthened upwelling of the cold deep waters across the Antarctic circumpolar latitudes and drives surface Southern Ocean cooling (Anderson et al., 2009). The strengthening of the SH westerly winds may also explain the increase in atmospheric CO₂ concentration during Heinrich 5 inferred from proxy records via the Southern Ocean (Menviel et al., 2014a; Wendt et al., 2024).

The STR over the Australian region is weaker and moves southwards in both seasons. The austral summer (DJF) STR sits south of the Australian continent during the HS (Fig. 10a), which allows tropical moisture from the expanded Indo-Australian monsoon domain to reach southern Australia, leading to significantly enhanced precipitation across the Australian continent south of ~10° S. A southward shift in the winter (JJA) STR reduces the fronts that pass over southern Australia, leading to drier conditions over southern Australia along with the enhanced and southwards displacement of the SH westerlies (Fig. 10b).

~~Our findings of 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); however, the simulated width of the southern HC due to an AMOC shutdown is expanded under 49 ka rather than reduced under Last Interglacial and PI boundary conditions in 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, the simulated atmospheric circulation response to AMOC shutdown agrees with previous modelling studies, suggesting weaker South Pacific jet, stronger SH westerlies (Bard and Rickaby, 2009; Chiang et al., 2014; Lee et al., 2011), and increased SH monsoon precipitation (Cheng et al., 2012; Zhang et al., 2023) due to AMOC weakening. The results of this study can provide 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.



535 **Figure 10:** Schematic of changes in (a) NH HC in DJF, and (b) SH HC in JJA in the 49ka_shutdown simulation, plotted over MSLP (hPa) anomalies relative to 49ka_control. Dashed lines represent 49ka_control, solid lines represent 49ka_shutdown HC.

4.2 Non-linear climatic response between D-O and HS*

540 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

545 linear response either globally or regionally (Fig. 32a, 2d). 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

550 Hadley Cell, leading to different responses in the climatic processes (e.g. pressure system, westerly winds, etc.) between AMOC slowdown and AMOC shutdown. It is important to note that the location of the threshold between linear weakening and nonlinear shutdown is likely to differ between models and climate states both in the real world and in simulations.

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.~~Global temperature and precipitation anomalies display non-linear patterns between D-O and HSs (as seen in 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). This may be associated with a different response of regional atmospheric systems to AMOC changes, such as altered Hadley circulation strength and differing interhemispheric temperature gradients and energy transport between the shutdown and slowdown simulations. Future studies performing longer simulations would be useful to explore slower responses, such as sea ice extent and Southern Ocean temperatures.~~ 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.

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. 2a, 2d). 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. It is important to note that the location of the threshold between linear weakening and nonlinear shutdown is likely to differ between models and climate states both in the real world and in simulations.

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., 2025a). Future studies should perform a thorough examination of the impact of meltwater input location on the climate response.

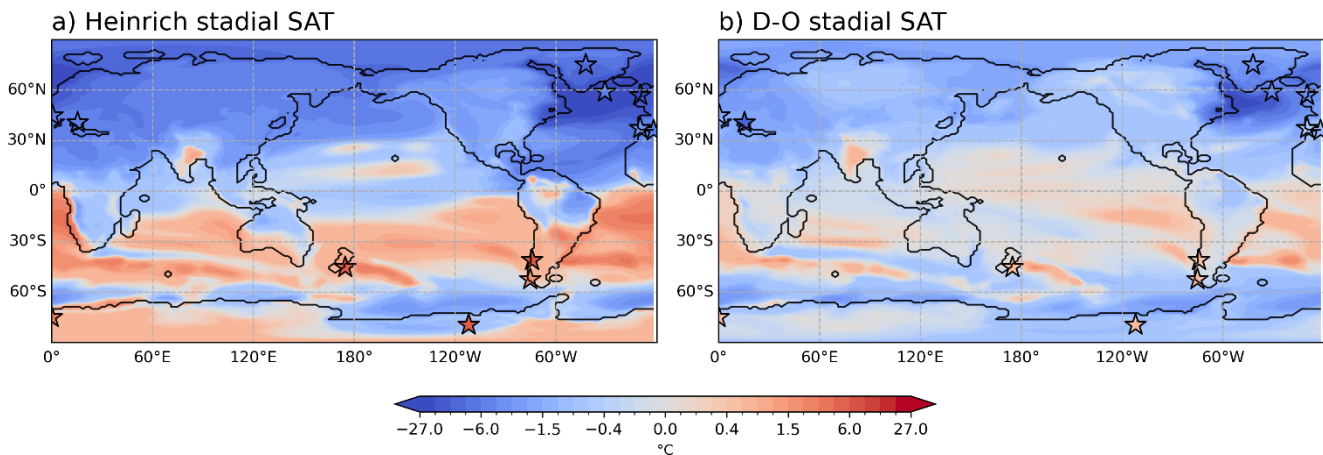
Lastly, this study uses the last 50 years of each hosing experiment to assess the climate responses. When using the 30-year running-mean values for the last 150 years in each experiment, the results are consistent with our 50-year average (Fig. S7). We note that only one model was used, and a future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

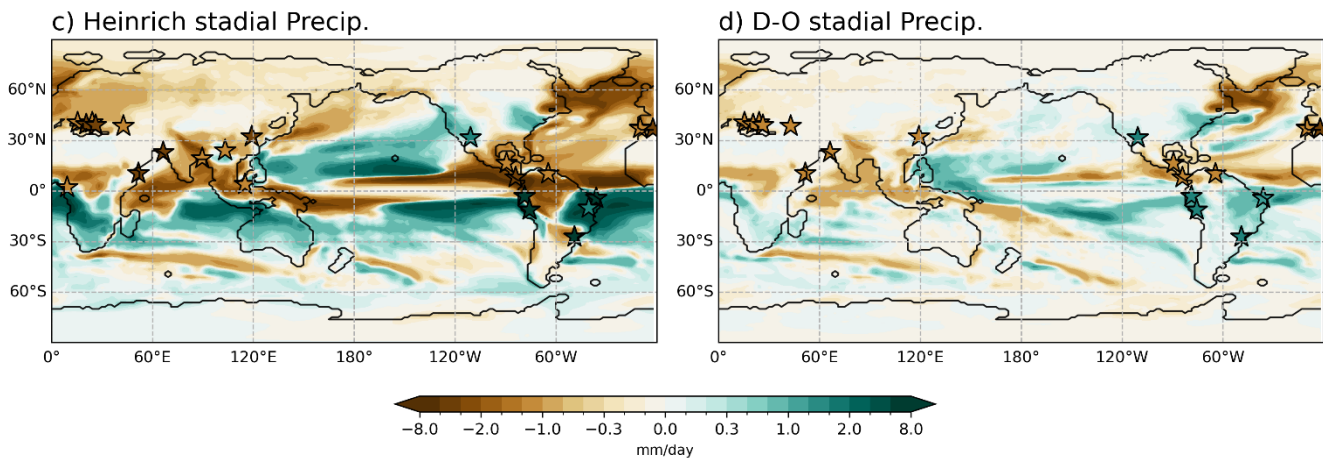
4.4.3 Model-data comparison for D-O and HSs

We now compare our model simulations with available proxy records for D-O and HSs during MIS3 (Menviel et al., 2020), focusing on temperature and precipitation anomalies in 49ka_shutdown versus the 49ka_0.3Sv experiment (as representative of HS and D-O stadial respectively in Fig. 1011). Our model simulation is overall generally consistent with these proxy records, as well as with the proxy benchmarks as summarized by Izumi et al. (2023) in their Table 1 and Table 3, with colder and drier conditions over the NH, a weakened NH summer monsoon, and stronger South American and South African monsoons. However, the monsoon responses from our simulations in the South American and South African monsoons domains show are more complex response (Fig. S6S8). Both D-O and HS simulations (Fig. 11c, 11d) are consistent with high resolution proxies of surface moisture from northern Queensland, Australia, suggesting wetter conditions during D-O and HSs (Denniston et al., 2013, 2017; Treble et al., 2017). Moreover, our simulated monsoon changes for HS5 (Fig. S8a) are consistent with

615 proxy records indicating weaker [Indian \(Deplazes et al. 2013\)](#) and [East Asian summer monsoons \(Zhang et al. 2024\)](#). The
simulated Indo-Australian summer monsoon is significantly enhanced in HS experiment (Fig. S6b), which is consistent with
a new speleothem record from southern Australia suggesting increased monsoon rainfall during HS5 (Gould-Whaley et al.,
2025, in prep.), and appears consistent with lacustrine record from Girraween Lagoon in northern Australia (Bird et al., 2025)
as well as southward displacement and strengthening of the IASM (Carolin et al. 2013; Ayliffe et al. 2013; Scroxton et al.
2022). Both D-O and HS simulations appear to be consistent with [high-resolution proxy records](#) of surface moisture
~~aerossfrom Australasia~~ Australia in HS1, suggesting wetter conditions during North Atlantic cooling events (Denniston et al.,
620 [2013, 2017; Treble et al., 2017](#)).

Changes in the position and intensity of SH westerly winds are broadly consistent with results from previous studies, with
intensification of the SH westerlies in austral winter, being strongest over the South Pacific sector (Fig. 7c), which is associated
with a reduction in angular momentum transport from the tropics to the subtropics (Chiang and Friedman, 2012). This
strengthening of the SH westerly winds may explain the increase in atmospheric CO₂ concentration during Heinrich 5 inferred
625 from proxy records via the Southern Ocean (Menviel et al., 2014a; Wendt et al., 2024). In future work, we plan to compare
our simulation of Heinrich and D-O stadials with HS5 records in more detail.





630 **Figure 11:** Model simulations of annual surface air temperature (a, b; °C) and precipitation (c, d; mm/day) anomalies in 49ka_shutdown (Heinrich stadial; left column) and 49ka_0.3Sv (D-O stadial; right column) simulations relative to 49ka_control with [MIS3](#) proxy records indicated by stars taken from Menviel et al. (2020).

5 Conclusions

635 This study investigates the climate response to AMOC slowdown and AMOC shutdown under 49 ka glacial conditions, corresponding to the time of HS5. [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, through changes in the seasonal HC and atmospheric circulation.](#) The linearity of the temperature and precipitation responses to the magnitude of AMOC decrease is explored. [The NH is cooled by an average 3.8 °C in HS while most of the SH shows significant warming](#) ~~There is a strong bipolar seesaw response due to AMOC shutdown with an average 3.8 °C cooling over the NH in HS.~~ [In the AMOC shutdown experiment, a pronounced southward shift of the annual-mean DJF ITCZ position](#) is simulated, [associated with stronger DJF atmospheric compensation for the reduced NH ocean heat transport than in JJA.](#) ~~which~~ [This asymmetric atmospheric response](#) leads to a ~~stronger-strengthened~~ northern [winter \(DJF\) HC](#) and weakened southern [wintertime \(JJA\) HC](#), influencing the [seasonal](#) climate response in the tropical and subtropical regions. Significantly increased precipitation is simulated over the entire Australian continent in summer (DJF) due to enhancement and southward expansion of the Indo-Australian summer monsoon and a southward shift of the STR, which allows tropical moisture to reach southern Australia in HS. However, this is not seen in the AMOC slowdown simulations representing D-O stadials, with [an insignificant increase in precipitation in northern Australia and drier conditions to the south.](#) This is due to the subdued response of HC strength and width. The JJA period is much drier over Australia in the HS simulation, possibly due to an intensification and southward migration of the SH westerly winds. This drying pattern is also observed in the D-O stadial simulations. ~~The simulations are generally consistent with proxy records.~~

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Our results suggest that the climate system responds linearly to an ~~weakening-slowdown~~ of the AMOC, but once the threshold of AMOC shutdown is crossed, a more complex atmospheric circulation and climate response is simulated. 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, enabling providing a basis for future comparisons under alternative background climate states, and more detailed model-data investigations. Additional simulations of AMOC weakening ~~and shutdown~~ under glacial conditions with other climate models would also provide a valuable comparison with our results.

Data availability

660 All the model outputs used in this manuscript will be published on the DRYAD repository under the corresponding author's account (<https://datadryad.org/search?utf8=%E2%9C%93&q=Yanxuan+Du>) and made publicly available upon acceptance of the manuscript.

Author contribution

YD, JRB, LM, and RND designed the study. YD performed the modelling simulations (model configuration from HS and 665 DKH), conducted the analysis and wrote the manuscript with the input from JRB, LM, RND, DKH, and CNG provided comments on the manuscript.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Climate of the Past.

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