

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

Yanxuan Du^{1,2}, Josephine R. Brown^{1,2}, Laurie Menviel^{3,4}, Himadri Saini^{1,2,3}, Russell N. Drysdale¹, David K. Hutchinson^{3,4,6}, and Calla N. Gould-Whaley^{1,5}

5 ¹School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, Victoria, Australia

²Australian Research Council Centre of Excellence for Weather of the 21st Century, University of Melbourne, Melbourne, Victoria, Australia

³Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia

10 ⁴The Australian Centre for Excellence in Antarctic Science, University of New South Wales, Sydney, New South Wales, Australia

⁵School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales, Australia

⁶Australian Research Council Centre of Excellence for Weather of the 21st Century, University of New South Wales, Sydney, New South Wales, Australia

15 *Correspondence to:* Yanxuan Du (yanxuand@student.unimelb.edu.au)

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). 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
20 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 resulting from the AMOC shutdown. This drives seasonal climate
25 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
30 in the future.

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) events (Dansgaard et al., 1993). During each D-O event, Greenland temperature experienced an abrupt transition to a relatively warm Interstadial period, after which the

35 temperature gradually decreased within a few centuries before an abrupt cooling to near-full glacial 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 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 ~200 years (Barker
et al., 2009; EPICA Community Members, 2006; Stocker and Johnsen, 2003; WAIS Divide Project Members, 2015). During
40 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
contain such events are named Heinrich stadials (HS) (Heinrich, 1988). Despite some debates about the usage of different
Heinrich terminologies (e.g. Andrews and Voelker, 2018; Hodell et al., 2017), throughout this paper we follow the consistent
45 usage of the term ‘Heinrich stadial’ as in previous studies (Barker et al., 2015; Sanchez Goñi and Harrison, 2010), as described
above.

During D-O stadials, paleoclimate proxy records suggest cooler and drier conditions in the North Atlantic and in
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 HS (Kindler et al., 2014; Svensson et al., 2008). However,
50 sea surface temperature (SST) estimates from marine sediment records from the Iberian Margin display a temperature decrease
up to twice as large in HS compared to D-O stadials (Martrat et al., 2007). The climatic response during HS is similar in
direction but greater in magnitude than D-O stadials due to the large magnitude 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
55 inferred during mild stadials, year-round displacement of the ITCZ position is suggested during HS (Deplazes et al., 2013).
Nevertheless, it remains unclear whether the climate response to Heinrich and D-O stadials is linearly related to AMOC
weakening.

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.
60 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
65 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.

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 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), monsoons and strengthening of the South American (Campos et al., 2019; Wang et al. 2007) and Indo-Australian monsoons (Ayliffe et al. 2013; Scroxton et al. 2022) during D-O and HS. 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). Changes in the HC 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 (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 (e.g. Lee et al., 2011).

In this study, we investigate the climatic changes associated with D-O and HS at 49 ka - coinciding with 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 mechanisms leading to large-scale climate change in Australasia. The results aim to provide a detailed description of SH climate response associated with AMOC variability under glacial climates from a modelling perspective and 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 \times 1.25° latitude \times 38 levels (Martin et al., 2010; The HadGEM2 Development Team: G. M. Martin et al., 2011). It is 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 the PI simulation (Table 1, Saini et al., 2025b). The model is forced by 49 ka orbital parameters (Berger, 1978), greenhouse gas concentrations (Köhler et al., 2017); and 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 presence of continental ice sheets, including the conversion of forest to bare soil between the Cordilleran and Laurentide ice sheets. Additionally, C3 (photosynthetic growth form) crops in the PI simulation were replaced by surrounding vegetation types. The land-sea mask and river runoff are also adjusted to reflect the modified topography (see details in Saini et al., 2025b).

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 (ppm)	199	284.3
N ₂ O (ppb)	237	273
CH ₄ (ppb)	432	284.3
Ice-sheet extent and salinity	49 ka	PI
Albedo and vegetation	49 ka	PI
Topography and runoff	49 ka	PI

135 The 49 ka simulation was run with step-wise changes in 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 the 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), which is considered to represent
140 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, and global mean SST is 1.2 °C 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).

2.3 Experimental design for D-O and HS at 49 ka

145 For this study, North Atlantic meltwater hosing experiments (Table 2) are performed from the ~~4~~ quasi-equilibrium state
conditions (49ka_control). Freshwater fluxes are 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).

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
150 though the exact changes in the AMOC transport during D-O and HS are still poorly constrained from proxy records (Henry
et al., 2016; Lynch-Stieglitz, 2017).

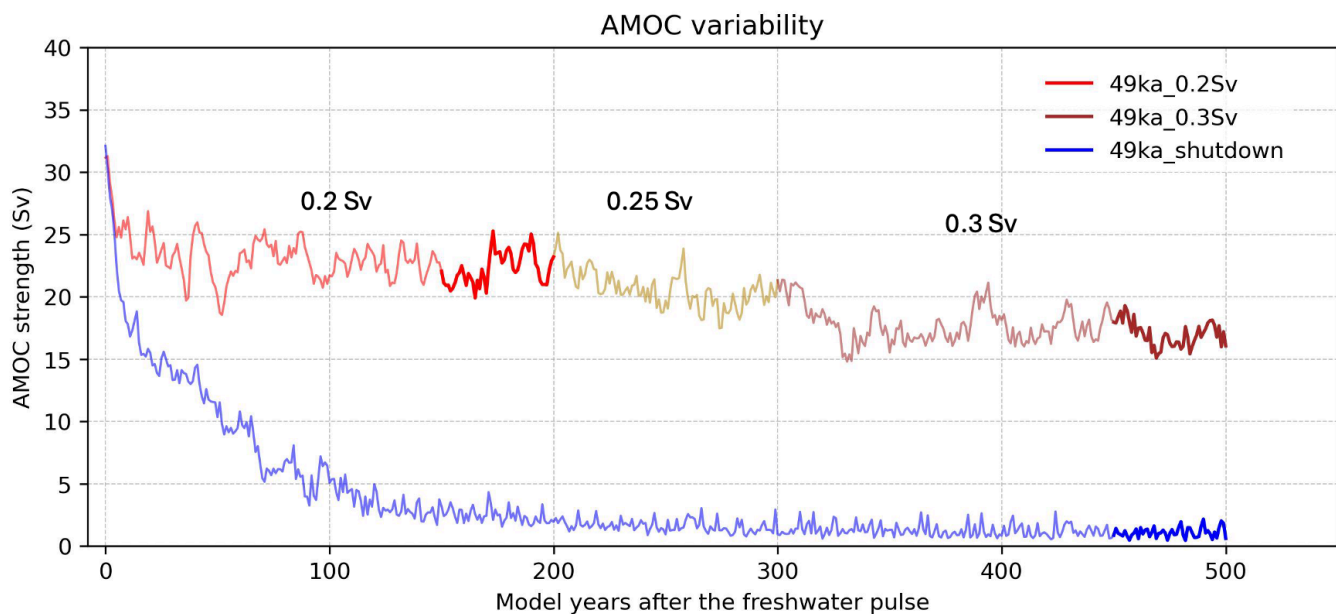
To simulate D-O stadials, we add 0.2 Sv and 0.3 Sv of freshwater in the northern North Atlantic under constant 49ka boundary conditions (49ka_0.2Sv and 49ka_0.3Sv experiments). This leads to ~32 % and ~50 % AMOC reductions relative to the 49ka_control, respectively (see detailed changes in Table 2).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

Table 2: North Atlantic freshwater hosing experiments performed at 49 ka. The forcing strength (Sv), release duration (yr), analysis 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 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 is 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 is 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.



175 **Figure 1:** Time series of AMOC strength (Sv) after the freshwater pulse at year 0 for the D-O stadal (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.

2.4 Calculation metrics

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

185 The 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 (DJF)/southern (JJA) Hadley Cells. This definition provides a more direct dynamical linkage to HC variability than the conventional precipitation-based metrics (e.g. Braconnot et al., 2007), while yielding consistent ITCZ positions across both approaches (Bian and Räisänen, 2024; Bischoff and Schneider, 2014).

190 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.

The STR position and intensity over Australia is calculated as the maximum mean sea level pressure (MSLP) value
195 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).

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
200 et al., 2021).

3 Results

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

First, we provide an overview of annual temperature and precipitation changes in our D-O and HS simulations relative to the
49ka_control climate and compare the linearity between the climatic responses to each hosing experiment by normalising the
205 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 ~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
210 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
215 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 Labrador Sea (Fig. 2a) due to
the large decrease in the AMOC strength, while the SH displays a significant warming (mean 0.43 °C) from 0 to 55° S.
Simulated SSTs show up to 15.4 °C cooling in the North Atlantic, and up to 6.5 °C warming in the South Atlantic (Fig. S3a).
220 Over Antarctica, significantly colder conditions are simulated in the Ross and Weddell Seas (Fig. 2a), which could be related
to changes in sea ice extent or negative low pressure anomalies over the region (Fig. 6b). The SAT patterns in the 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 reductions in the northward oceanic heat transport in D-O stadial

225 simulations are only sufficient to induce some significant warming beyond the Atlantic Ocean, reaching into the Indian and eastern Pacific Oceans (Fig. 2b, 2c).

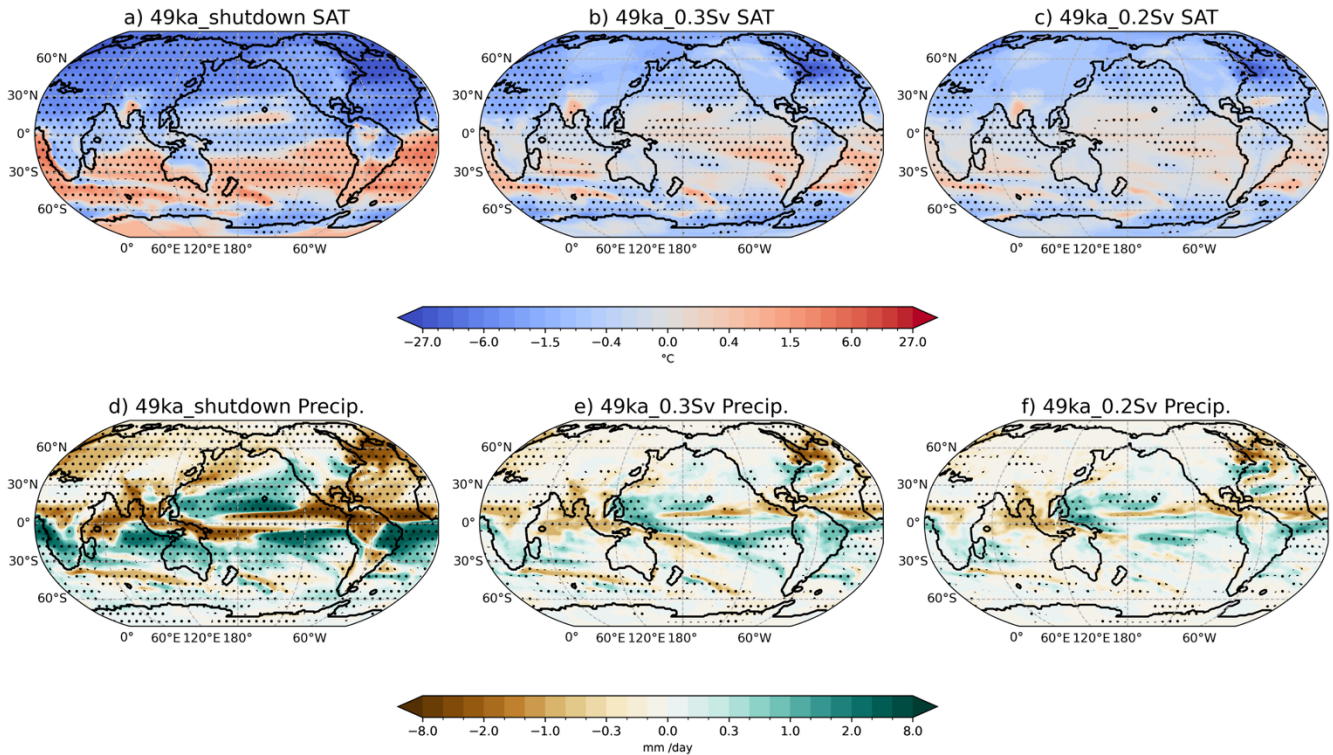
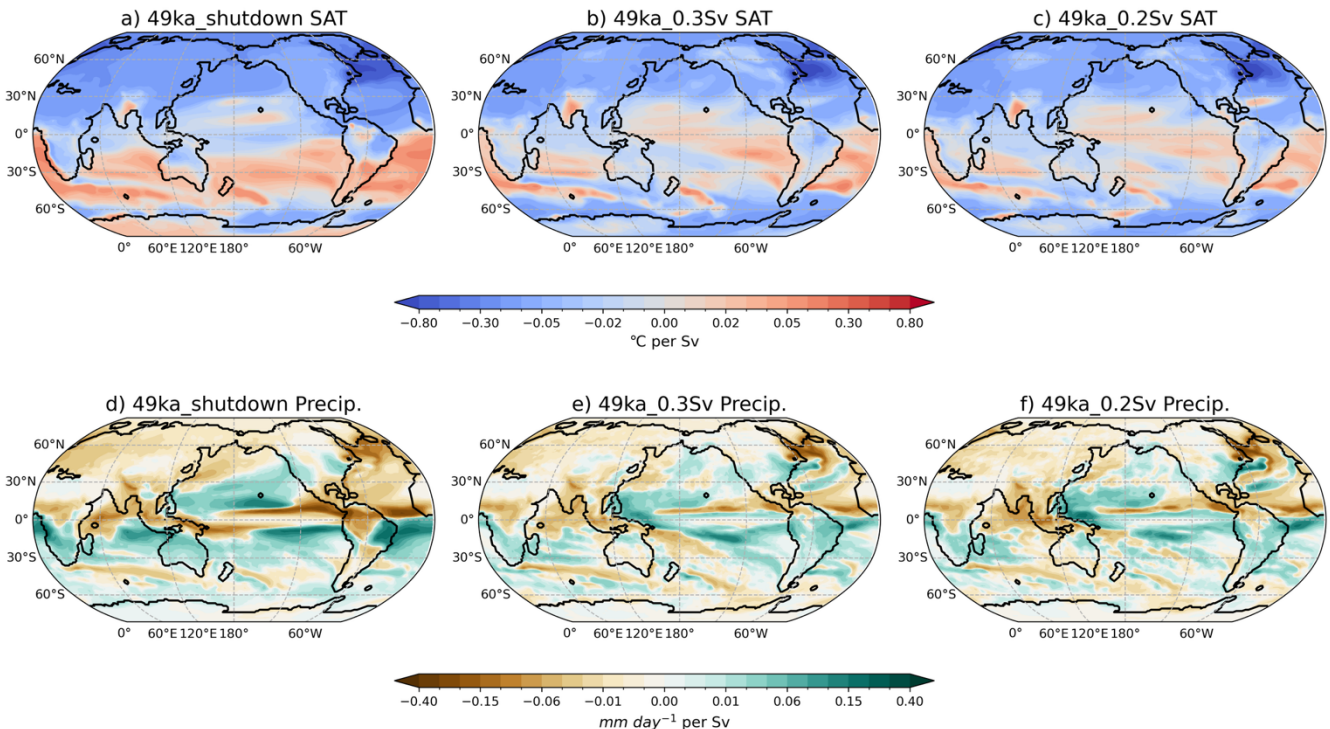


Figure 2: Annual (a)-(c) Surface Air Temperature (SAT; in °C) and (d)-(f) precipitation (in mm/day) anomalies relative to 230 49ka_control in each simulation. Stippling indicates statically significant differences from the control at the 95 % confidence level according to the Student's t-test.

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 stadal simulations, the southward displacement pattern of the ITCZ is mostly evident over the Atlantic Ocean, extending into the 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 slightly reduced in the D-O stadal experiments (Fig. 2e, 2f), which is the opposite of the shutdown experiment. 240

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).

To further quantify the linearity of changes, we normalise the temperature and precipitation response to a “per Sv”
 245 AMOC decrease relative to 49ka_control (Fig. 3). The D-O stadial 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
 250 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 stadial experiments (see Table S1). More specifically, NH temperature displays up to 1.6 times more cooling in 49ka_shutdown, while the SH (from 0 to 55° S) experiences up to 6.8 times warmer temperatures per Sv than in the slowdown experiments (see Fig. 3a-c for normalised spatial patterns). This large difference in SH temperature changes between the D-O and HS simulations are attributed to a simulated SH mean cooling in D-O stadial experiments while
 255 a 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 (Table S1; Fig. 3d-f).



260 **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

265 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

270 In response to the 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 northward 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).

275 In boreal winter (DJF), as the ascending branch of the HC, the ITCZ at 850 hPa shifts southwards by 0.82° and 0.34° ,
respectively in the 49ka_0.2Sv and 49ka_0.3Sv slowdown simulations, compared to a significant southward shift of 3.57° to
 $\sim 15.8^\circ$ S in the 49ka_shutdown simulation (thick lines in Fig. 4a, 4c, 4e). The northern HC strengthens and expands in width
at 500 hPa in all simulations (Fig. 5). The 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
280 (Fig. 4a, 4c, and 4e). The northern HC strength increases by 20 % due to the AMOC shutdown compared to an increase of less
than 2.3 % in the slowdown simulations (Fig. 5). The NH HC width increases slightly between 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 (Fig. 4a, 4c, 4e).

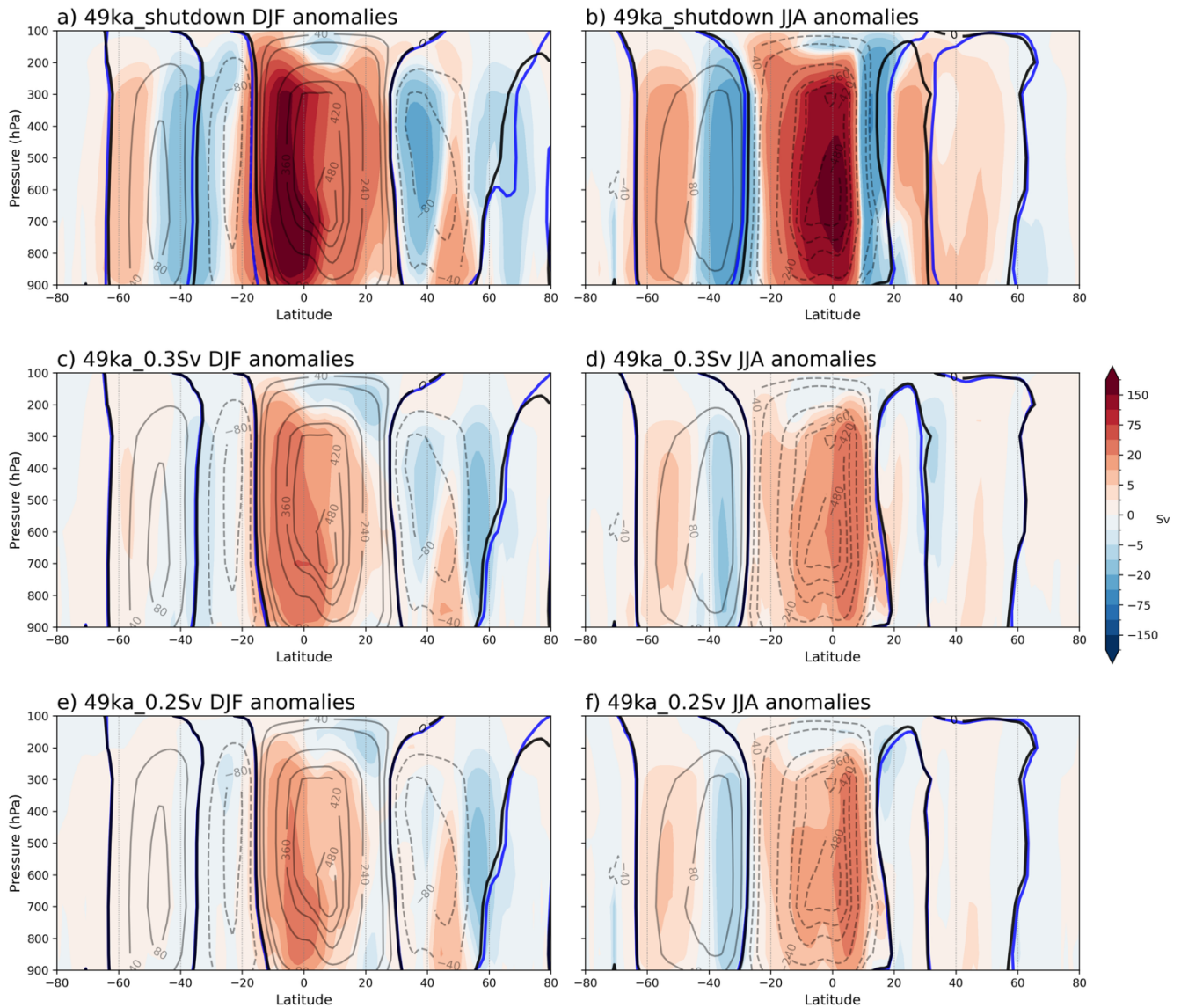


Figure 4: DJF and JJA 49ka_shutdown (a, b), 49ka_0.3Sv (c, d), and 49ka_0.2Sv (e, f) minus 49ka_control atmospheric mass streamfunction anomalies (Sv, shading). Black contours (solid=positive; dashed=negative) are 49ka_control absolute streamfunction values. The thick black and blue lines represent the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

In austral winter (JJA)₂, with a weaker northwards atmospheric heat transport of ~ 0.19 PW at 30° N (Fig. S4), 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° N, associated with a large expansion of the SH HC width by 11.7 % in the 49ka_shutdown

experiment (Fig. 5). Due to the AMOC shutdown, the ascending branch of the SH HC shifts northward by 3.5° at 500 hPa, contributing to the negative anomalies around 18.4° N simulated in the 49ka_shutdown experiment (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 the 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 stadial 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.

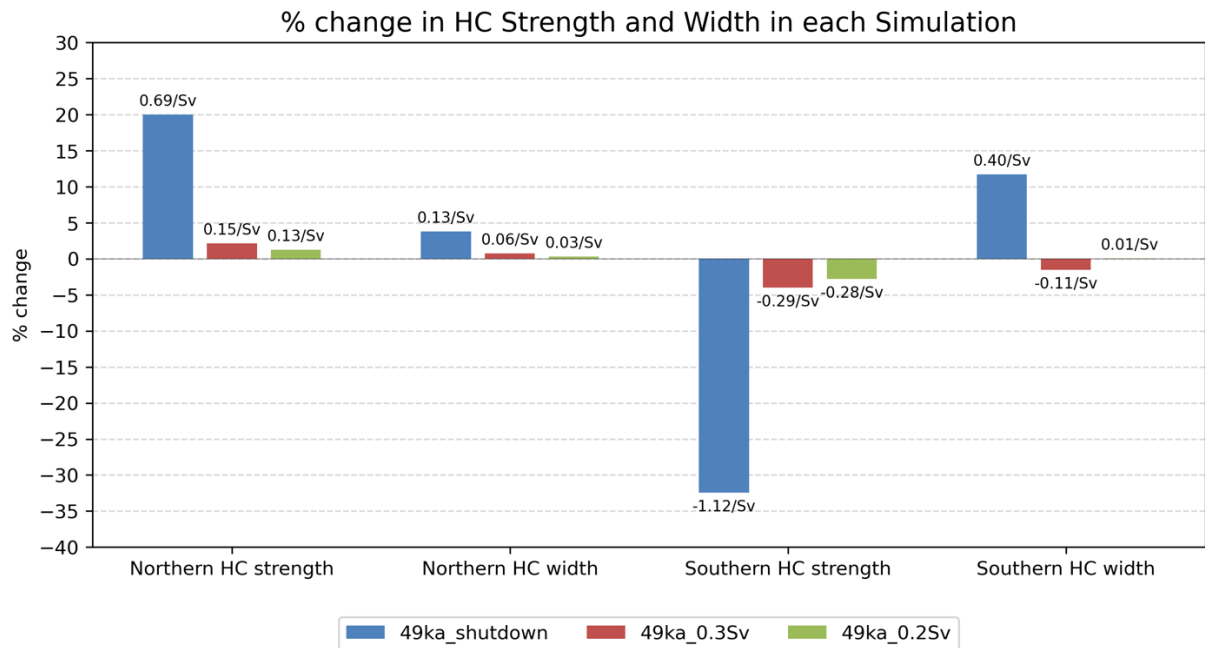


Figure 5: Percentage of absolute changes in the NH wintertime (DJF) HC and SH winter (JJA) HC strength and width at 500 hPa in the 49ka_shutdown, 49ka_0.3Sv and 49ka_0.2Sv simulations (values in Table S2). Normalised changes in percentage per Sv AMOC decrease are shown on top of each bar. [The method](#) for the calculations is described in Section 2.4.

3.2.2 Changes in the subtropical pressure systems and circulation

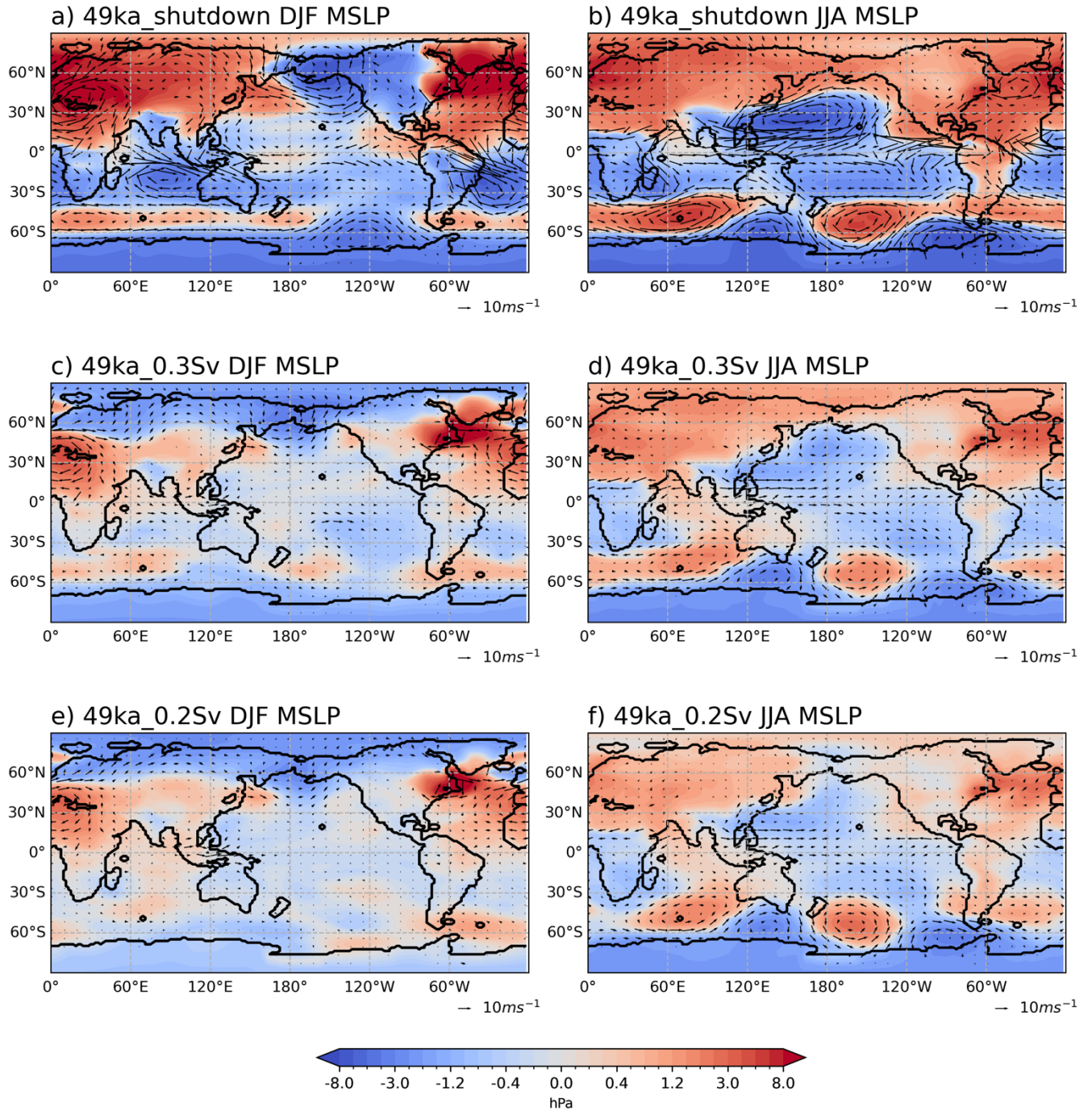
Changes in the HC strength and width influence the STR and surface wind stress associated with the subtropical descending branch of the HC. In the shutdown simulation, the position of the southern JJA HC descending branch is shifted southwards

315 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 DJF, 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. 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 shown in the shutdown simulation (Fig. 6a) due to weakened DJF southern HC strength (Fig. 4a). The slowdown simulations show different patterns compared to the 49ka_shutdown experiment (Fig. 6c, 6e). This difference in the spatial pattern is most likely driven by the small changes in the DJF southern HC strength in the slowdown simulations. 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 easterly anomalies to the south. This change in the winds generates anomalous cyclonic circulation over the Indian and south Atlantic Oceans, associated with weakened surface pressure due to the AMOC shutdown (Fig. 6a).

In austral winter (JJA), 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. S5b, 5d, 5f). In the shutdown simulation, the subpolar low pressure belt shows negative surface pressure anomalies, while positive surface pressure anomalies of up to 5.7 hPa are found between 45° S and 67° S in the Indian and Pacific basins (Fig. 6b). This increase in the positive anomalies is primarily due to a southward expansion of the southern HC, with its descending branch shifting to ~ 27° S, which then drives a southward shift of the high pressure systems in the HS simulation. The subpolar low-pressure belt is enhanced and pushed southward, particularly in the South Pacific and Indian basins. The 200 hPa subtropical jet around 30° S weakens due to a decrease of the southern HC (Fig. S5b). The mid-latitude jet is enhanced around 50° S to 70° S, with a weakened South Pacific split jet (Fig. S5b). This further leads to increased SH westerlies and Rossby wave propagation pattern anomalies around 40° S and 60° S (Fig. 6b). These responses are consistent with Lee et al. (2011) proposed SH circulation responses to North Atlantic cooling. The slowdown simulations display a broadly similar spatial pattern in the mid-high southern latitudes, ~~albeit with reduced magnitudes~~ (Figs. 6d and 6f), resulting from a strengthening of the ascending branch and weakening of the descending branch of the southern Ferrell cell (Figs. 4b, 4d, 4f). These differences in pressure response anomalies between the shutdown and slowdown simulations are likely attributable to the large shift in the southern HC descending branch ~~of the southern HC~~ in the shutdown simulation, ~~despite a weakened HC strength being simulated in all simulations~~ while no shift is simulated in the D-O stadial simulations (Figs. 4b, 4d, 4f). 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. 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 cyclonic

circulation over the North Pacific subtropical regions in the shutdown experiment (Fig. 6b), which is less evident in the
350 slowdown simulations due to smaller changes in the southern HC (Fig. 6d, 6f).



355 **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.

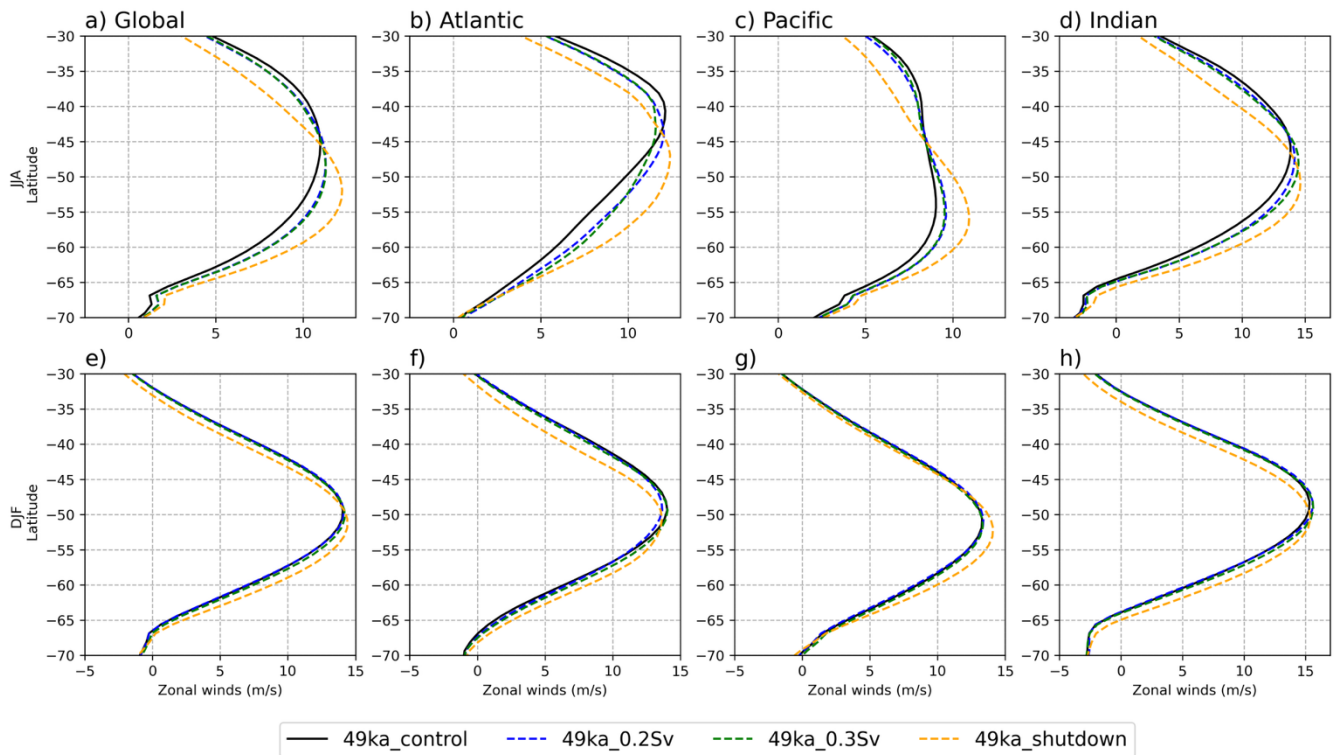
3.2.3 Changes in the SH mid-latitude westerly winds

In this section, we explore the impacts of the altered HC on SH mid-latitude westerly winds. Changes in the position and
360 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 in JJA, due to the weakening of the southern winter HC and southward displacement of its descending branch
365 (Fig. 7a). Similarly, global mean strengthening and southward displacement of the SH westerlies are simulated in DJF (Fig.
7e), but the changes are smaller than those simulated during 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. S6c), associated with the weakened SH subtropical jet (Fig. S5).

The westerlies show the strongest intensification over the South Pacific Ocean in both seasons, with more than 21 %
370 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
375 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 stadial simulations (Fig. 5) may contribute to the difference in Atlantic response between the HS and D-O stadial
experiments, where the climate is most sensitive to AMOC weakening. Future studies will examine the basin-dependent
changes in the westerlies in more detail.

380 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 increases 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 simulated over the Atlantic (Fig. 7b). Relatively little change
385 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), while more
complex responses are simulated in the other ocean basins.



390 **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).

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.
395

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 insignificant (Fig. 8c). In JJA, an overall cooling pattern is simulated across Australia in the slowdown experiments (Fig. 400 Fig. 8e, 8f), while significant warming anomalies are simulated over southern Australia due to AMOC shutdown (Fig. 8d).

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).

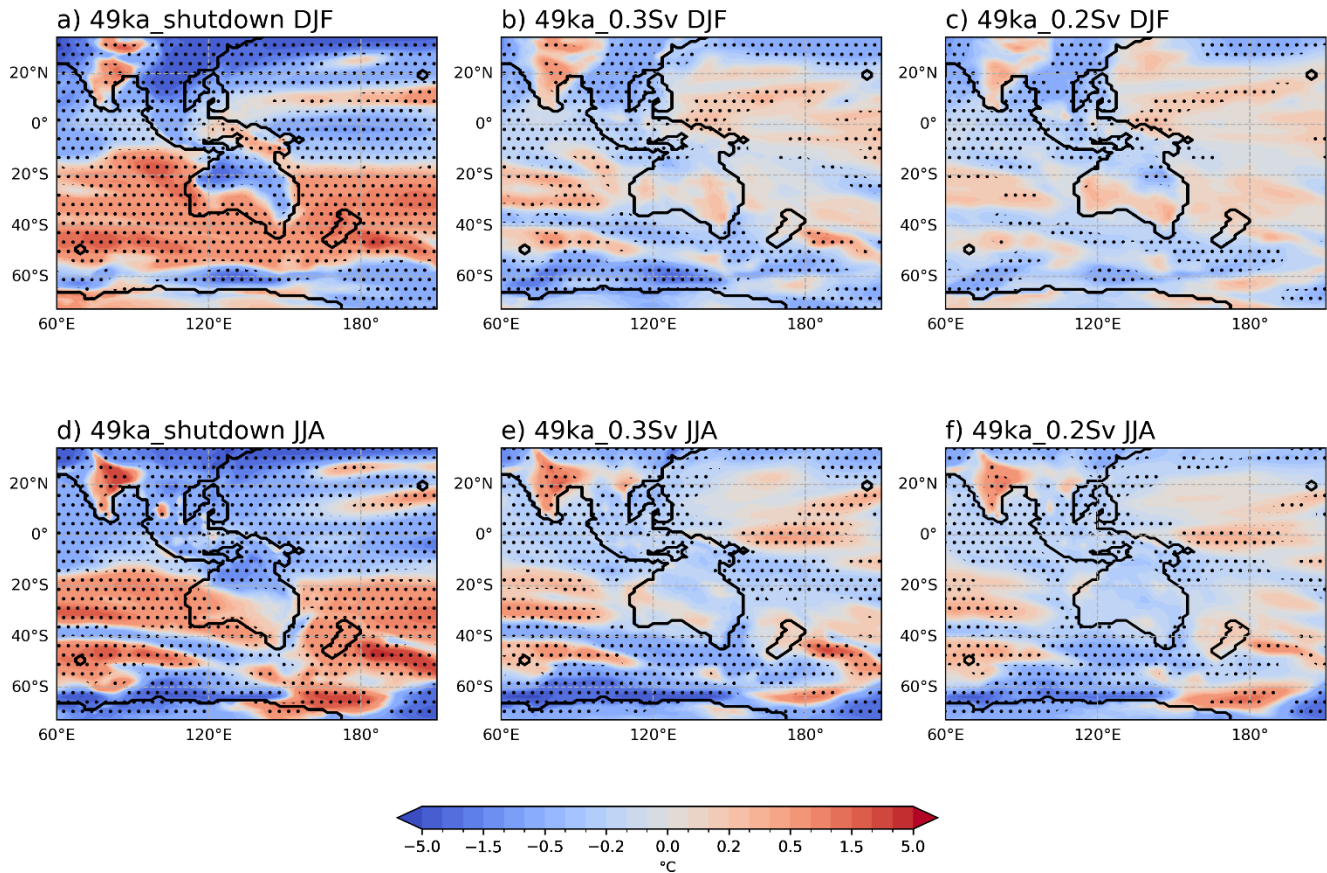
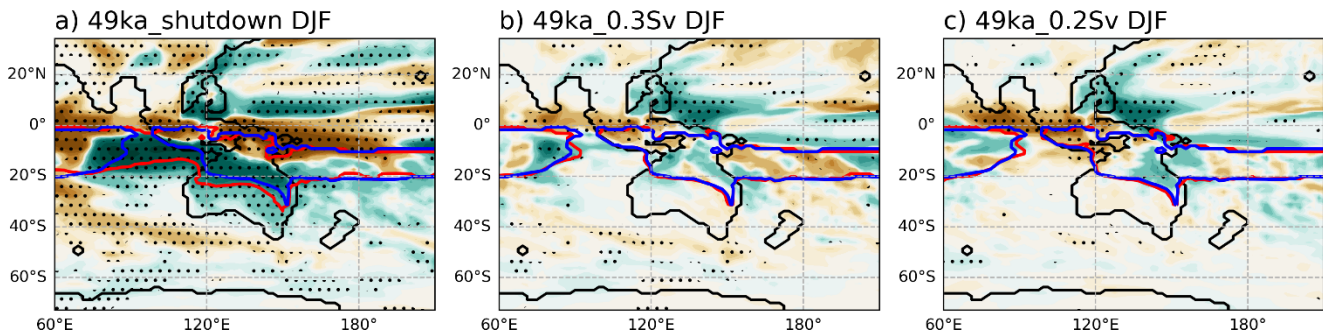


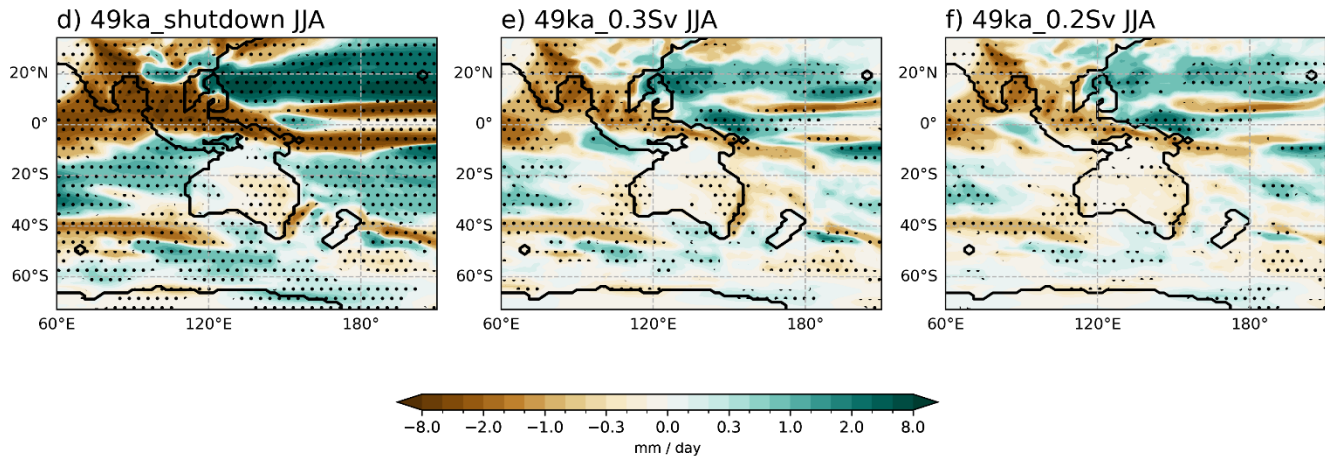
Figure 8: Australian annual DJF (top row) and JJA (bottom) surface air temperature (SAT; in °C) anomalies in each simulation relative to 49ka_control. Stippling indicates areas with significant changes at the 95 % confidence level according to a Student's t-test.

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).

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 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 relative to 49ka_control. Reduced DJF SPCZ precipitation is simulated, corresponding to the warming anomalies over the area (Fig. 8b, 8c).

During the austral winter (JJA), significant drying is simulated along the east coast of Australia, extending to central Australia 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, the JJA STR is shifted southward by 1° to ~30° S, associated with a displaced descending branch of the southern HC. 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 modern climate, which then leads to drying conditions in southeastern Australia in HS (Fig. 9d). The 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.





440 **Figure 9:** Australian DJF (top row) and JJA (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.

4 Discussion

445 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 HS, 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 SH regional climates.

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
 450 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.

The northward oceanic heat transport is reduced by $\sim 77\%$ 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 a reorganization of the HC strength and width. The winter
 455 (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 the 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

460 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
465 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 cyclonic circulation is simulated over North Pacific in JJA, associated with significantly increased precipitation
over the region (Fig. 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 strengthen and migrate southwards in both JJA and DJF, which further
470 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
475 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).

480 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.

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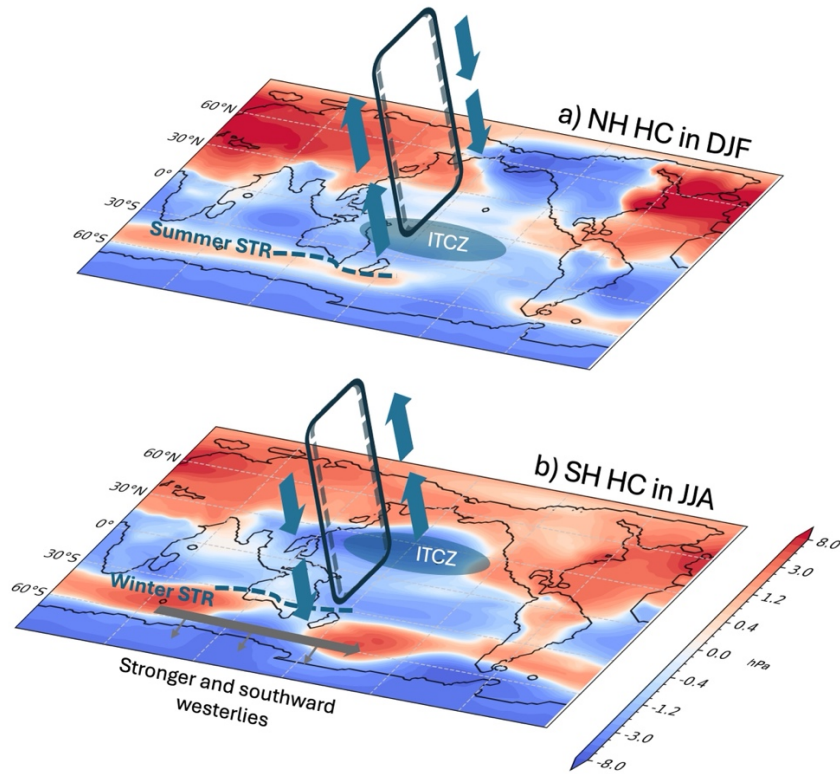


Figure 10: Schematic of changes in (a) NH HC in DJF, and (b) SH HC in JJA in the 49ka_shutdown simulation, plotted over MSLP (hPa) anomalies relative to 49ka_control. Dashed lines represent 49ka_control, solid lines represent 49ka_shutdown HC.

490

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

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

500

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 stadial 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 in hosing strength 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.

515 **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.

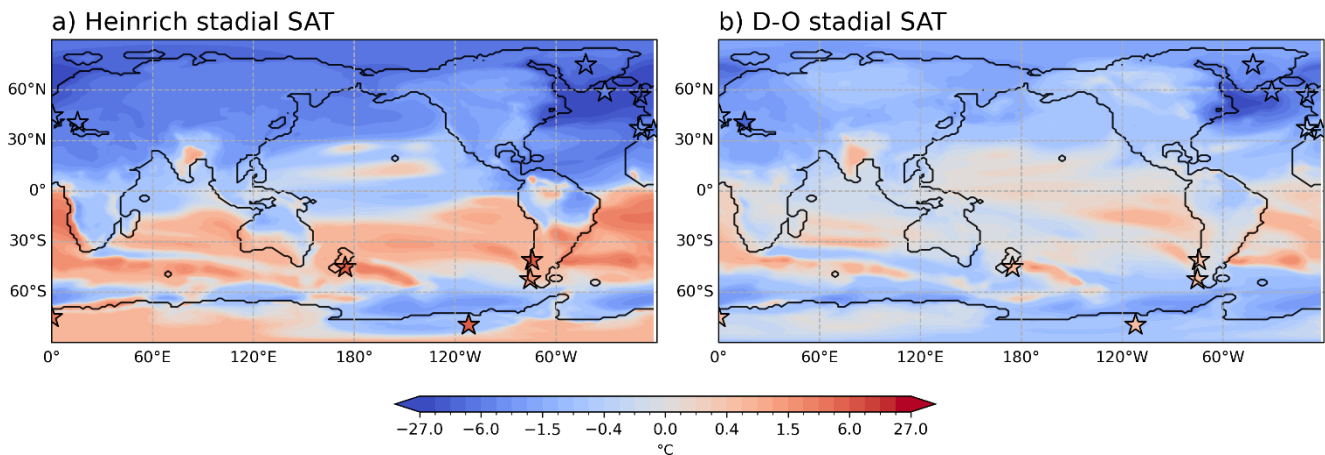
In this study, the 49ka_0.3Sv experiment is obtained from a two-step increase in freshwater input of 0.25 Sv for 100 model years followed by 0.3 Sv of 200 years after the 49ka_0.2Sv experiment. Nevertheless, this setup should not significantly affect the large-scale climate response given the length 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 Model-data comparison for D-O and HS

We now compare our model simulations with available proxy records for D-O and HS 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. 11). Our model simulation is generally consistent with these proxy records, as well as with the proxy benchmarks 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 domains are more complex (Fig. S8). Moreover, our simulated monsoon changes for HS5 (Fig. S8a) are consistent with proxy records indicating weaker Indian (Deplazes et al. 2013) and East Asian summer monsoons (Zhang et al. 2024), as well as southward displacement and strengthening of the IASM (Carolin et al. 2013; Ayliffe et al. 2013; Scroton et al. 2022). Both D-O and HS simulations appear to be consistent with high-resolution proxy records of surface moisture from Australia in HS1, suggesting wetter conditions during North Atlantic cooling events (Denniston et al., 2013, 2017; Treble et al., 2017). In future work, we plan to compare our simulation of Heinrich and D-O stadials with HS5 records in more detail.

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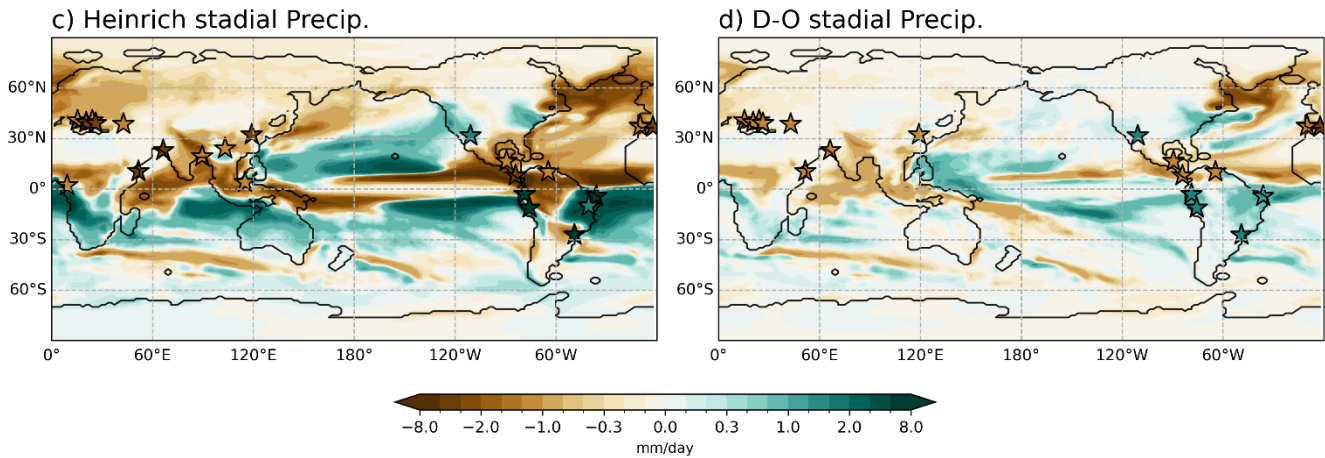


Figure 11: Model simulations of annual surface air temperature (a, b; °C) and precipitation (c, d; mm/day) anomalies in 49ka_shutdown (Heinrich stadial; left column) and 49ka_0.3Sv (D-O stadial; right column) simulations relative to 49ka_control with MIS3 proxy records indicated by stars taken from Menviel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

5 Conclusions

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. In the AMOC shutdown experiment, a pronounced southward shift of the DJF ITCZ is simulated, associated with stronger DJF atmospheric compensation for the reduced NH ocean heat transport than in JJA. This asymmetric atmospheric response leads to a 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.

Our results suggest that the climate system responds linearly to a slowdown of the AMOC; but once the threshold of AMOC shutdown is crossed, a more complex atmospheric circulation and climate response emerges. We identify a possible threshold in the hosing strength between 0.3 Sv and 0.4 Sv for triggering an AMOC shutdown in the ACCESS-ESM1.5

575 model, ultimately leading to the non-linear response of the climate system under glacial conditions. Although the background
state is fundamentally different from present or future warming conditions, the amount of freshwater input required to trigger
the non-linear response may be comparable, given that a freshwater input of 0.4 Sv is necessary to shut down the AMOC under
both PI and Last Interglacial (127 ka) background conditions (Saini et al., 2025a). Nevertheless, given the variability and
unprecedented nature of future climates, additional simulations across different background climate conditions, as well as
580 multi-model comparisons under glacial conditions, are needed to provide more comprehensive insights.

Data availability

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.

585 **Author contribution**

YD, JRB, LM, and RND designed the study. YD performed the modelling simulations (model configuration from HS and
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

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

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