



Evaluation of the roles of thermal, freshwater, and wind forcing in the Atlantic Meridional Overturning Circulation during the Last Glacial Maximum

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Abstract. We evaluated the relative impacts of thermal, freshwater, and wind forcing on the Atlantic Meridional Overturning Circulation (AMOC) during the Last Glacial Maximum (LGM) by performing ocean general circulation model simulations with surface boundary-condition anomalies obtained from 17 PMIP models. Thermal conditions of the LGM weakened the AMOC, while wind stress changes strengthened it, whereas freshwater flux had a relatively minor effect. The cooling over the Southern Ocean weakened the AMOC by increasing the density of Antarctic Bottom Water (AABW), and differences in Southern Ocean cooling among the PMIP models can contribute to differences in simulated AMOC strength. In contrast, cooling over the North Atlantic had two opposing effects: sea-ice expansion reduced air–sea heat exchange and weakened the AMOC, whereas enhanced heat loss in the open ocean strengthened it. The LGM wind stress anomaly strengthened the AMOC through changes in sea-ice transport and wind-driven ocean circulation, and its effect depended on the thermal background state. These results demonstrate that differences in surface boundary conditions among PMIP models can lead to substantial differences in the simulated AMOC through both thermal and dynamical processes.

1 Introduction

Proxy records suggest that the Atlantic Meridional Overturning Circulation (AMOC) was shallower during the Last Glacial Maximum (LGM), with Antarctic Bottom Water (AABW) from the Southern Ocean dominating the Atlantic below a depth of about 2,000 m (Curry and Oppo, 2005; Duplessy et al., 1988; Howe et al., 2016; Lynch-Stieglitz et al., 2007). Although the strength of the LGM AMOC is less well constrained, several studies suggest that it was weaker than in the modern climate (Böhm et al., 2015; McManus et al., 2004; Pöppelmeier et al., 2023).

Studies of the LGM climate and AMOC have also been conducted using various atmosphere–ocean general circulation models (AOGCMs) as part of the Paleoclimate Modeling Intercomparison Project (PMIP). However, the simulated AMOC under LGM conditions tends to be deeper and stronger than in the present climate, which is inconsistent with proxy reconstructions (Kageyama et al., 2021; Muglia and Schmittner, 2015; Otto-Bliesner et al., 2007; Weber et al., 2007). This discrepancy raises the question of how changes in surface boundary conditions during the glacial period affect the strength of the AMOC.



- 30 Several processes associated with changes in surface boundary conditions have been proposed to affect the AMOC during the glacial period. Cooling over the Southern Ocean has been suggested to weaken the AMOC (Jansen and Nadeau, 2016; Klockmann et al., 2016; Oka et al., 2021; Song et al., 2025), because enhanced brine rejection increases the density of AABW (Jansen, 2017), while the strength of the AMOC is influenced by the density contrast between AABW and North Atlantic Deep Water (NADW) (Sun et al., 2020). In addition, Oka et al. (2012) proposed a thermal threshold of the AMOC, 35 in which cooling over the North Atlantic causes a shift in deep convection accompanied by sea-ice expansion (Zhang et al., 2014), resulting in a shallower glacial AMOC. Changes in wind stress can also affect the AMOC. Westerly winds over the North Atlantic are enhanced during the glacial period due to the presence of continental ice sheets (Sherriff-Tadano et al., 2018; Ullman et al., 2014), potentially increasing northward salinity transport and strengthening the AMOC (Gong et al., 2015; Montoya et al., 2011; Montoya and Levermann, 2008; Muglia and Schmittner, 2015; Sherriff-Tadano et al., 2018).
- 40 Changes in surface wind stress can also alter sea-ice transport and thereby affect the AMOC (Born et al., 2010; Saenko et al., 2002; Zhu et al., 2014; Oka et al., 2012). Westerly winds over the Southern Ocean have also been proposed as a factor affecting the glacial AMOC (Shin et al., 2003; Toggweiler et al., 2006), although their effects may be relatively small (Kohfeld et al., 2013; Sime et al., 2016; Völker and Köhler, 2013).

Despite these efforts to identify the mechanisms controlling the glacial AMOC, many state-of-the-art climate models still fail 45 to reproduce the LGM AMOC consistent with proxy evidence, and the reasons for the discrepancy among models and between models and proxy records remain unclear. Previous studies have identified the importance of Antarctic sea-ice formation (Marzocchi and Jansen, 2017) and Southern Ocean sea surface temperature biases (Sherriff-Tadano et al., 2023) for the simulated LGM AMOC. However, atmospheric and oceanic conditions differ simultaneously among PMIP models, making it difficult to isolate the relative contributions of individual surface boundary conditions to the simulated AMOC. In 50 particular, it remains unclear to what extent differences in thermal conditions, wind stress, and freshwater fluxes among PMIP models can account for the spread in simulated LGM AMOC strength, and how the effects of these boundary conditions depend on each other.

In this study, we conducted a suite of ocean general circulation model simulations to evaluate the relative impacts of thermal conditions, wind stress, and freshwater fluxes on the AMOC during the LGM. We obtained LGM anomalies of surface 55 boundary conditions from 17 PMIP models and separately imposed them on a common ocean model, allowing us to examine the effects of differences in these boundary conditions while minimizing differences in ocean model configurations. We further investigated the spatial dependence of the thermal and wind effects and the dependence of wind effects on the background thermal state. Through these experiments, we assessed the extent to which differences in LGM surface boundary conditions among PMIP models can contribute to differences in the simulated AMOC.



2 Methods

2.1 Model and boundary conditions

We used the ocean general circulation model COCO version 4.0 (Hasumi, 2006), which includes a dynamical sea-ice model and constitutes the oceanic component of MIROC (Hasumi and Emori, 2004). The model has a horizontal resolution of 0.56°–1.4° in latitude (192 grids) and approximately 1.4° in longitude (256 grids), with 43 vertical levels. The background vertical diffusion coefficient is formulated following Tsujino et al. (2000), and turbulent mixing is represented using the parameterization of Noh and Kim (1999).

Surface boundary conditions for the preindustrial (PI) climate were obtained from the MIROC3.2.2 (MIROC4m) simulation conducted as part of CMIP4 (Oka et al., 2012). Monthly surface air temperature, surface air specific humidity, net shortwave radiation, downward longwave radiation, wind stress, freshwater flux (evaporation minus precipitation minus runoff; E-P-R), sea level pressure, and surface wind speed were used as boundary conditions. The monthly data were interpolated in time following Killworth (1996). Surface heat fluxes were calculated from these boundary conditions as described in Oka et al. (2012).

To isolate the effects of differences in LGM surface boundary conditions among climate models, we used anomalies between the LGM and PI simulations of PMIP models rather than their absolute LGM boundary conditions. The LGM anomaly for each boundary condition was calculated as the difference between the LGM and PI simulations of each PMIP model and then added to the corresponding PI boundary condition of MIROC3.2.2. Thus, the LGM boundary conditions used in our experiments retain a common ocean model and a common PI background state, while incorporating the LGM anomalies simulated by each PMIP model. Seventeen PMIP models from PMIP2, PMIP3, and PMIP4 were used (Table 1). Zonal-mean distributions of the LGM anomalies are shown in Fig. 1, and the ensemble-mean LGM anomalies are shown in Fig. 2. The preindustrial bathymetry was used in all experiments.



PMIP era	Model	AMOC index (Sv)			
		EXP_H	EXP_T	EXP_W	EXP_HTW
PMIP2	CCSM3	3.9	17.6		
PMIP2	CNRM-CM33	9.4	12.6	3.8	3.0
PMIP2	FGOALS-1.0g	4.1	16.7		
PMIP2	HadCM3M2	7.1	19.2		
PMIP2	IPSL-CM4-V1-MR	11.2	11.0		
PMIP2	MIROC3.2.2	5.3	17.9	14.1	13.7
PMIP3	CCSM4	5.4	19.2	14.1	14.4
PMIP3	CNRM-CM5	2.4	14.7	14.4	16.3
PMIP3	GISS-E2-R	9.3	23.8	14.1	21.7
PMIP3	IPSL-CM5A-LR	6.3	16.6	14.5	16.6
PMIP3	MIROC-ESM	9.4	18.1	13.4	15.2
PMIP3	MPI-ESM-P	4.7	16.8	15.4	14.7
PMIP3	MRI-CGCM3	4.7	18.7	16.0	12.8
PMIP4	AWI-ESM-1-1-LR	7.8	17.1	14.3	13.5
PMIP4	INM-CM4-8	7.7	17.9	14.4	20.3
PMIP4	MIROC-ES2L	6.5	24.0	13.8	17.7
PMIP4	MPI-ESM1-2-LR	6.2	18.9	15.8	12.7

Table 1: List of PMIP models used in this study. AMOC indices (maximum overturning circulation at 25°N) in EXP_H, EXP_T, EXP_W, and EXP_HTW are also shown. EXP_W and EXP_HTW were not conducted for some PMIP2 models because freshwater-flux output was unavailable.

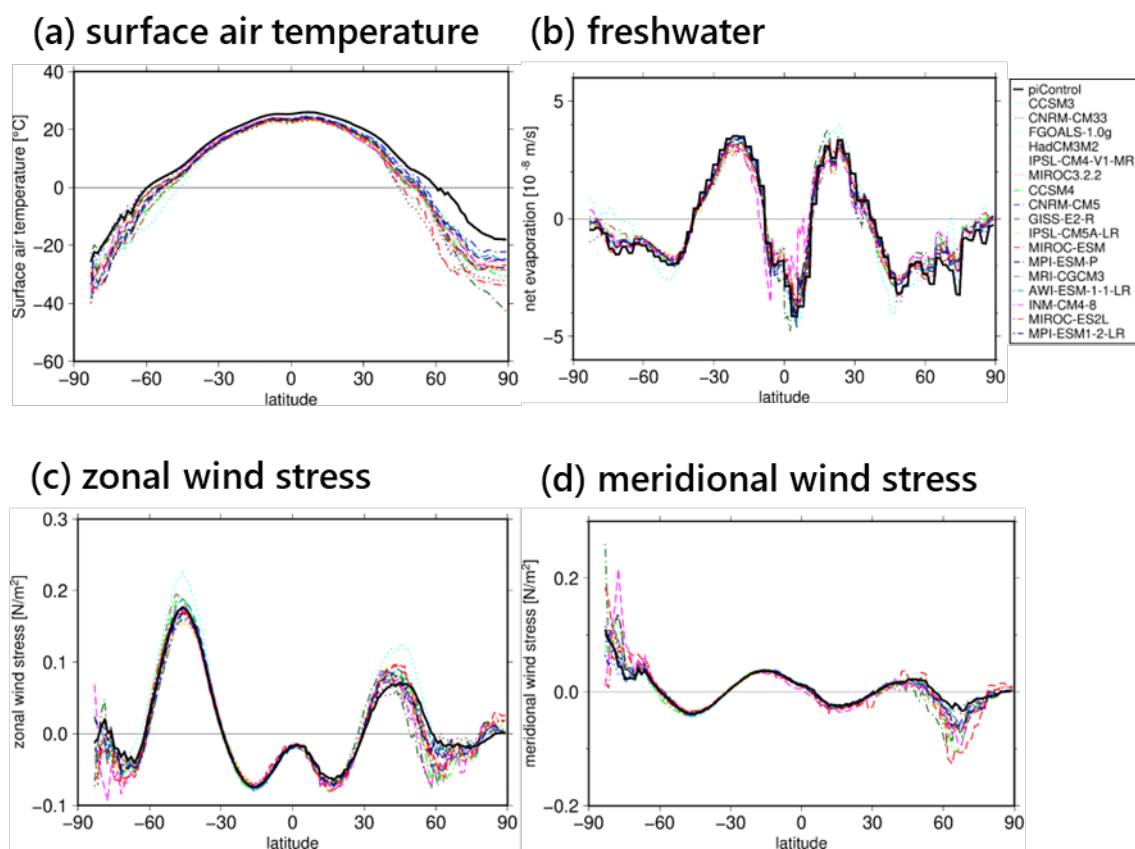


Figure 1: Zonal-mean profiles of surface boundary conditions with LGM anomalies from each PMIP model. (a) Surface air temperature, (b) freshwater flux (E-P-R), (c) zonal wind stress, and (d) meridional wind stress over the global ocean. The black line indicates the CTL value from the MIROC3.2.2 preindustrial simulation.

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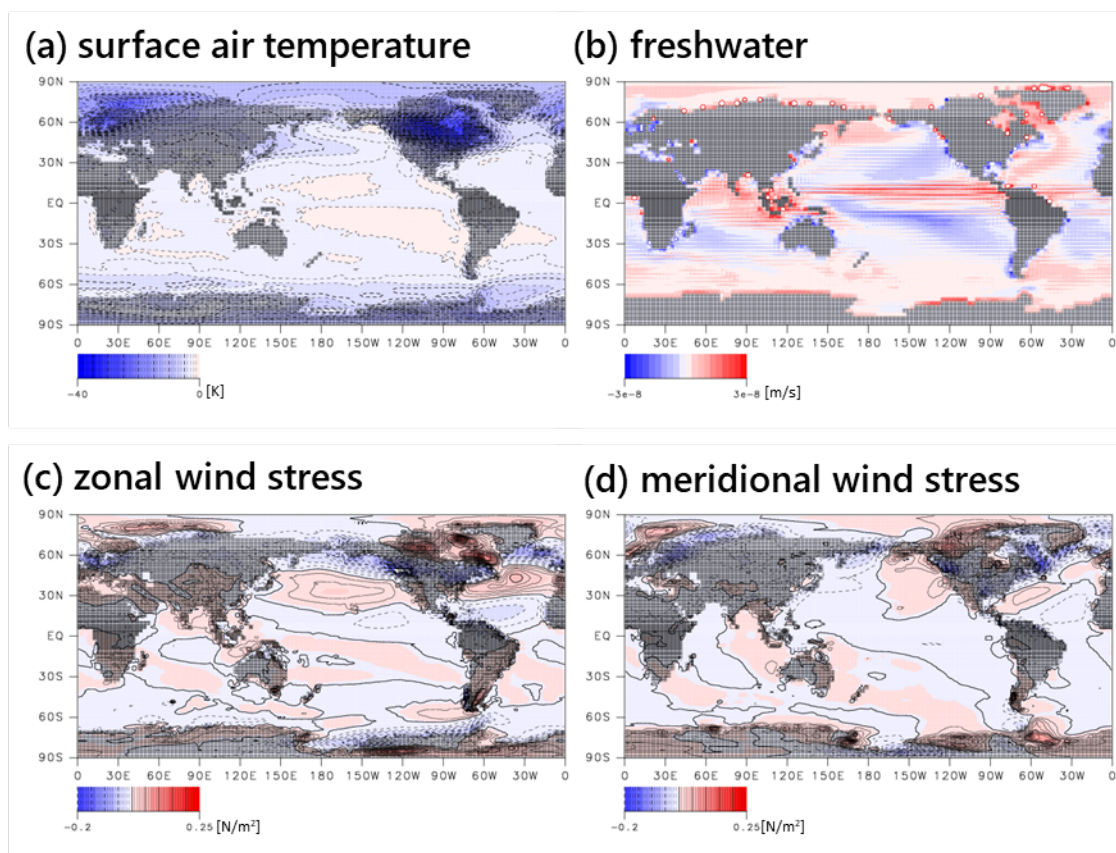


Figure 2: Average LGM anomalies of surface boundary conditions among the PMIP models. (a) Surface air temperature, (b) freshwater flux (E-P-R), (c) zonal wind stress, and (d) meridional wind stress.

2.2 Experimental design

A control experiment (CTL) was conducted using the PI surface boundary conditions from MIROC3.2.2. The CTL experiment was integrated for 3000 years, starting from the temperature and salinity fields of the MIROC3.2.2 PI simulation.

All other experiments were initialized from the final state of the CTL experiment and integrated for 3000 years.

We first conducted a set of anomaly experiments to separately evaluate the effects of thermal conditions, wind stress, and freshwater flux on the AMOC under LGM conditions (Table 2). In EXP_H, the LGM anomalies of the thermal boundary conditions—surface air temperature, surface air specific humidity, net shortwave radiation, and downward longwave radiation—were added to the corresponding PI boundary conditions. EXP_H was conducted using the LGM anomalies obtained from each of the 17 PMIP models. Thus, EXP_H isolates the effect of the thermal boundary conditions while keeping the wind stress and freshwater flux at their PI values. Similarly, EXP_T was conducted by adding the LGM wind stress anomaly while retaining the PI thermal and freshwater boundary conditions, and EXP_W was conducted by adding the



LGM freshwater-flux anomaly while retaining the PI thermal and wind boundary conditions. EXP_HT included both the LGM thermal and wind stress anomalies, whereas EXP_HTW included the LGM anomalies of all three types of surface boundary conditions.

Name	Thermal conditions	Wind stress	Freshwater flux	AMOC (Sv)	index
CTL	CTL	CTL	CTL	14.1	
EXP_H	LGM	CTL	CTL	6.7	
EXP_T	CTL	LGM	CTL	17.7	
EXP_W	CTL	CTL	LGM	13.7	
EXP_HT	LGM	LGM	CTL	14.5	
EXP_HTW	LGM	LGM	LGM	14.8	

Table 2: Summary of anomaly experiments in this study.

We further conducted sensitivity experiments to investigate the spatial dependence of the thermal and wind effects and the dependence of wind effects on the background thermal state (Table 3).

First, EXP_Hn and EXP_Hs were conducted to separately examine the effects of thermal anomalies in the Northern and Southern hemispheres, respectively. The LGM thermal anomalies were applied only between 0° and 90°N in EXP_Hn and between 0° and 90°S in EXP_Hs. The magnitude of the applied anomaly was gradually increased by multiplying the full LGM anomaly by a factor, f_c , ranging from 0.2 to 1.0.

Second, the spatial dependence of the wind stress effect was examined using EXP_Tnl, EXP_Tnh, and EXP_Ts. In EXP_Tnl, the LGM wind stress anomaly was applied only between 0° and 60°N; in EXP_Tnh, it was applied only between 60° and 90°N; and in EXP_Ts, it was applied only between 0° and 90°S. We also conducted EXP_Ti and EXP_To to distinguish the effects of wind stress acting on sea ice from those acting over the open ocean. When the ocean surface is covered by sea ice, the momentum flux between the atmosphere and sea ice (τ_{ai}) is prescribed, whereas the momentum flux between sea ice and the ocean (τ_{io}) is calculated from the velocities of the sea ice and ocean. To separate the effects of wind stress on sea ice and the open ocean, EXP_Ti and EXP_To were performed. In EXP_Ti, the LGM anomaly was added to τ_{ai} , while τ_{io} and the wind stress over the open ocean (τ_{ao}) were kept at their CTL values. In EXP_To, τ_{ai} was kept at its CTL value, while τ_{io} and τ_{ao} were taken from EXP_T, thereby applying the LGM wind stress anomaly over the open ocean.

Third, we conducted experiments in which LGM thermal conditions were combined with spatially limited wind stress anomalies to examine whether the effects of wind stress depend on the background thermal state. EXP_HTnl, EXP_HTnh, and EXP_HTs applied the LGM wind stress anomalies over 0°–60°N, 60°–90°N, and 0°–90°S, respectively, together with the LGM thermal conditions. EXP_HTi and EXP_HTo applied the wind stress anomalies over sea ice and the open ocean, respectively, under the LGM thermal conditions. EXP_HTonl and EXP_HTonh further isolated the effects of open-ocean wind stress in the low- and high-latitude Northern Hemisphere, respectively.



135 Finally, EXP_HmT, EXP_HmTi, and EXP_HmTo were conducted using the LGM thermal anomalies from MIROC3.2.2 together with the LGM wind stress anomalies from each PMIP model. These experiments were designed to compare the effects of wind stress anomalies among the PMIP models under an identical thermal background. EXP_HmTi and EXP_HmTo further separated the effects of wind stress acting on sea ice and the open ocean, respectively.

Name	Thermal conditions	Wind stress	Freshwater flux	AMOC index (Sv)
EXP_Hn series	LGM (0°-90°N, fc=0.2-1.0)	CTL	CTL	11.6 (fc=1.0)
EXP_Hs series	LGM (0°-90°S, fc=0.2-1.0)	CTL	CTL	6.7 (fc=1.0)
EXP_Tnl	CTL	LGM (0°-60°N)	CTL	14.2
EXP_Tnh	CTL	LGM (60°-90°N)	CTL	15.6
EXP_Ts	CTL	LGM (0°-90°S)	CTL	14.4
EXP_Ti	CTL	LGM (sea ice)	CTL	14.8
EXP_To	CTL	LGM (open ocean)	CTL	17.6
EXP_HTnl	LGM	LGM (0°-60°N)	CTL	12.4
EXP-HTnh	LGM	LGM (60°-90°N)	CTL	12.2
EXP-HTs	LGM	LGM (0°-90°S)	CTL	6.6
EXP-HTi	LGM	LGM (sea ice)	CTL	11.1
EXP-HTo	LGM	LGM (open ocean)	CTL	12.5
EXP_HTonl	LGM	LGM (0°-60°N, open ocean)	CTL	11.0
EXP-HTonh	LGM	LGM (60°-90°N, open ocean)	CTL	8.4
EXP_HmT	LGM (MIROC3.2.2)	LGM	CTL	12.6
EXP_HmTi	LGM (MIROC3.2.2)	LGM (sea ice)	CTL	9.6
EXP_HmTo	LGM (MIROC3.2.2)	LGM (open ocean)	CTL	9.7

140 **Table 3: Summary of the additional sensitivity experiments conducted in this study.**

3 Results

The maximum AMOC transport at 25°N in the CTL experiment was 14.1 Sv (Fig. 3a), slightly weaker than the 15.9 Sv in the original MIROC3.2.2 preindustrial simulation. Nevertheless, COCO reproduced the overall structure of the AMOC and the deep-water formation regions in the Labrador and Irminger Seas.

Figure 4 summarizes the AMOC responses to the LGM anomalies of the surface boundary conditions. The thermal anomalies generally weakened the AMOC, with a mean AMOC strength of 7.0 Sv in EXP_H (Fig. 4). In contrast, the wind stress anomalies generally strengthened the AMOC. When the thermal and wind stress anomalies were combined, the resulting AMOC strength varied substantially among the PMIP models and could be either stronger or weaker than in the



150 CTL experiment. The freshwater-flux anomalies had relatively small effects on the AMOC in most cases, although the freshwater anomaly from CNRM-CM33 caused a substantial weakening.

These results show that differences in LGM surface boundary conditions among the PMIP models can substantially affect the simulated AMOC. In the following sections, the role of thermal, wind, and freshwater forcing is further discussed individually. We also examine the spatial dependence of the thermal and wind stress effects and the dependence of the wind

155 stress effect on the background thermal state.

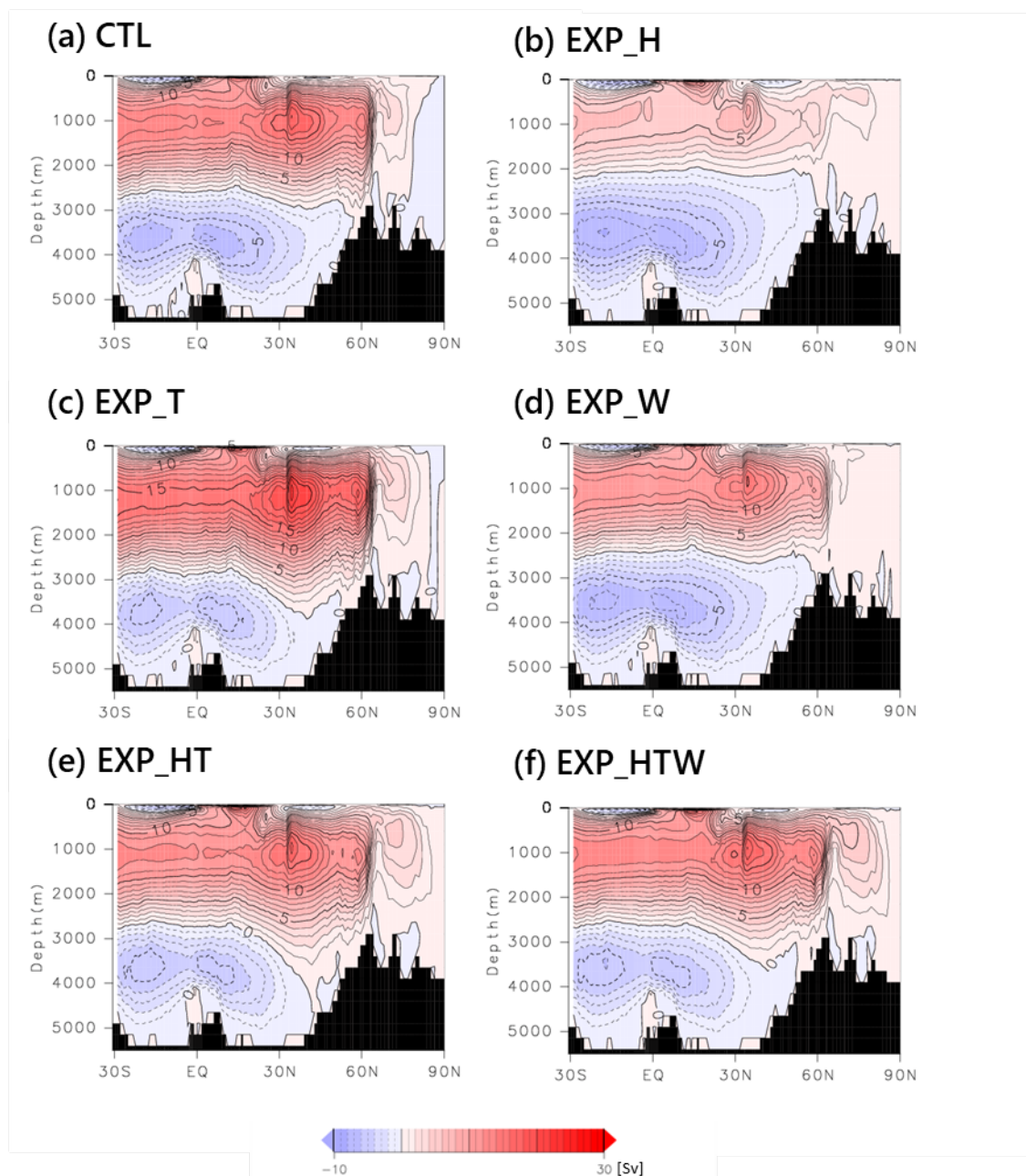


Figure 3: The Atlantic meridional streamfunction in (a) the CTL experiment and (b–f) the anomaly experiments, averaged over the corresponding integration periods.

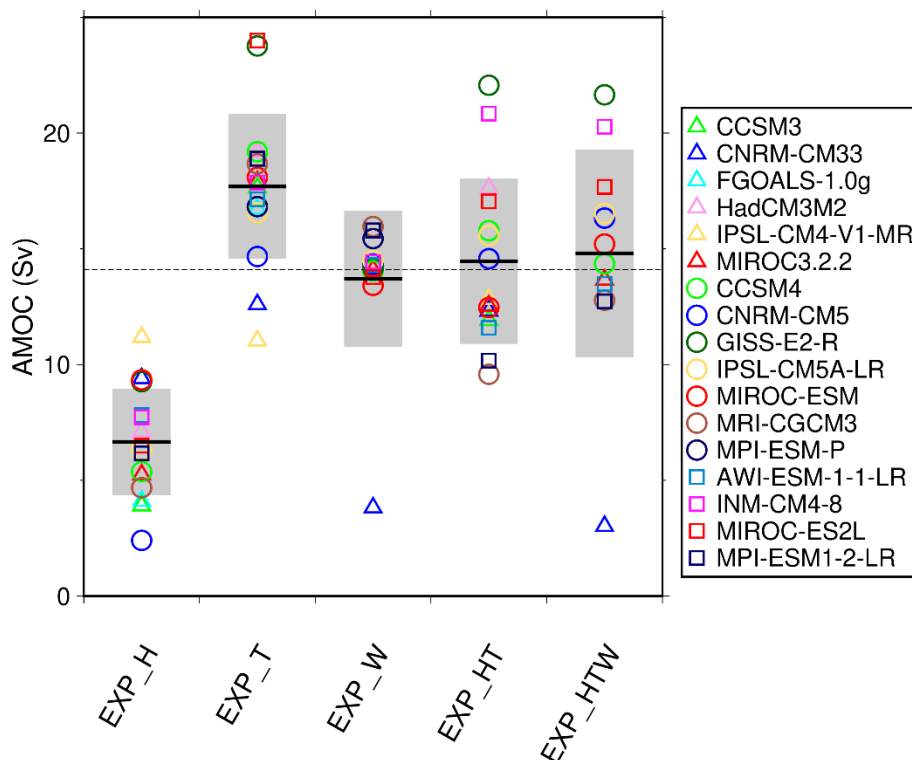


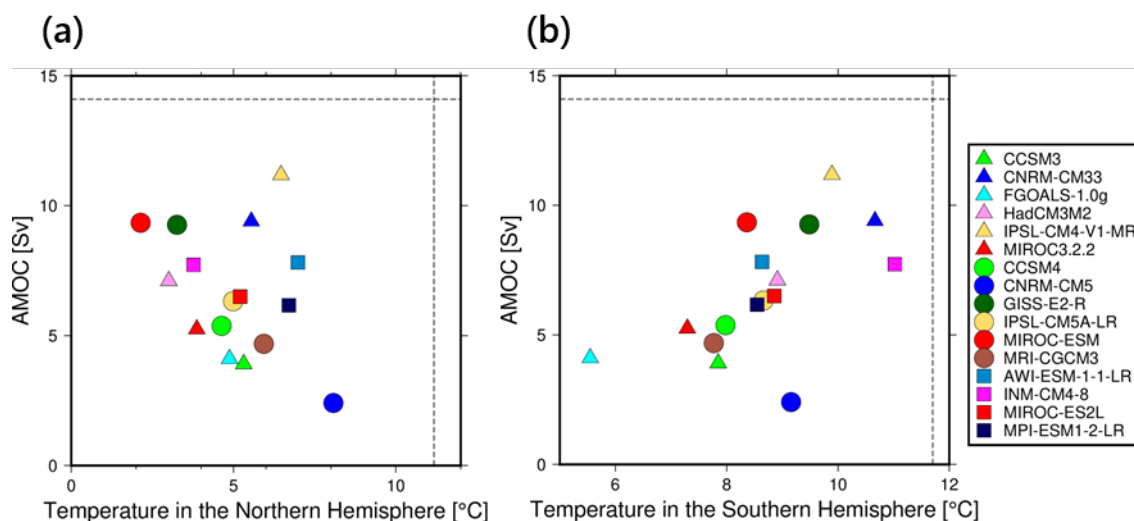
Figure 4: The AMOC index (maximum overturning circulation at 25°N) of the anomaly experiments. Black lines and gray boxes show the mean value and standard deviation of each anomaly experiment, respectively. The dashed line indicates the CTL value of 14.1 Sv.

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3.1 Thermal effect

Figure 5 shows the relationship between the AMOC strength and the mean surface air temperature (SAT) over the ocean grids in the Northern and Southern Hemispheres for EXP_H. The AMOC shows only a weak relationship with the mean Northern Hemisphere SAT ($r = -0.32$; Fig. 5a), and no robust relationship is found when the mean SAT is calculated over the North Atlantic instead of the entire Northern Hemisphere. In contrast, the AMOC tends to weaken as the Southern Hemisphere becomes colder ($r = 0.59$; Fig. 5b). These results suggest that the thermal conditions in the Southern Hemisphere have a stronger relationship with the AMOC strength than those in the North Atlantic in the EXP_H experiments.

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175 **Figure 5: Scatterplot of EXP_H simulations between the AMOC index and the surface air temperature over the (a) Northern and**
 180 **(b) Southern Hemisphere. Dashed lines indicate the CTL value.**

We next conducted sensitivity experiments in which the LGM thermal anomalies were applied separately to the Northern and Southern Hemispheres to examine the spatial dependence of the thermal effect (Fig. 6a). Figure 7 shows the changes in AMOC strength as the magnitude of the thermal anomaly was gradually increased from the CTL state. The magnitude of the applied anomaly was scaled by a factor (f_c), ranging from 0.2 to 1.0. The AMOC decreases monotonically as the Southern Hemisphere is cooled, with an abrupt reduction occurring at approximately 3–4°C of mean Southern Ocean cooling in most cases (Fig. 7a). The mean LGM SAT anomaly over the Southern Ocean (30°–90°S) ranges from 0.7 to 6.2°C among the PMIP models. Thus, some PMIP models cross the range of cooling associated with the abrupt AMOC reduction (Oka et al., 2021), whereas others do not. The different degrees of Southern Ocean cooling among the PMIP models therefore result in substantially different AMOC strengths in EXP_Hs.

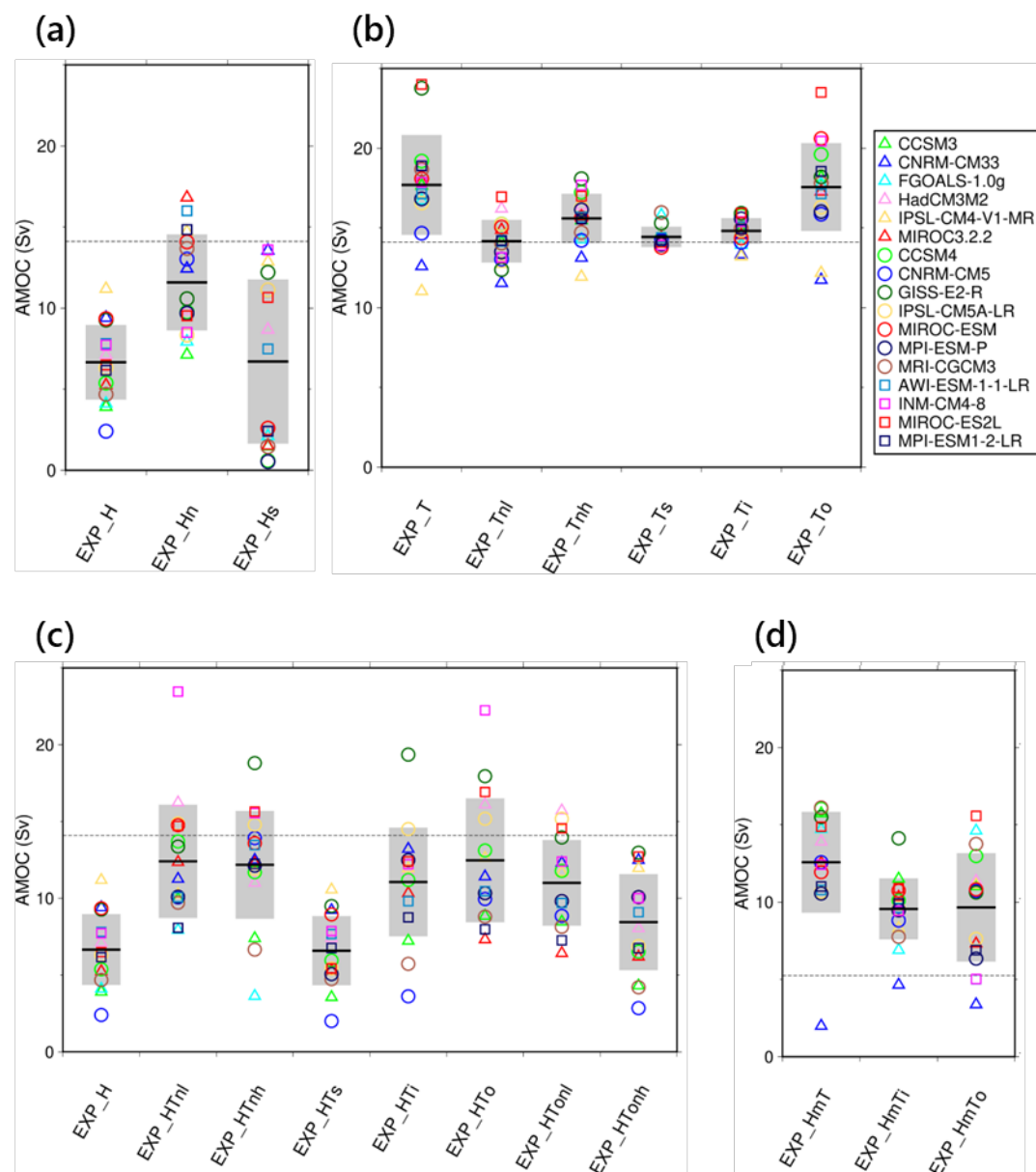


Figure 6: The AMOC index (maximum overturning circulation at 25°N) of the sensitivity experiments. Black lines and gray boxes show the mean value and standard deviation of each anomaly experiment, respectively. Dashed lines indicate (a–c) the CTL value of 14.1 Sv and (d) the AMOC index of EXP_H with the MIROC3.2.2 anomaly (5.3 Sv).

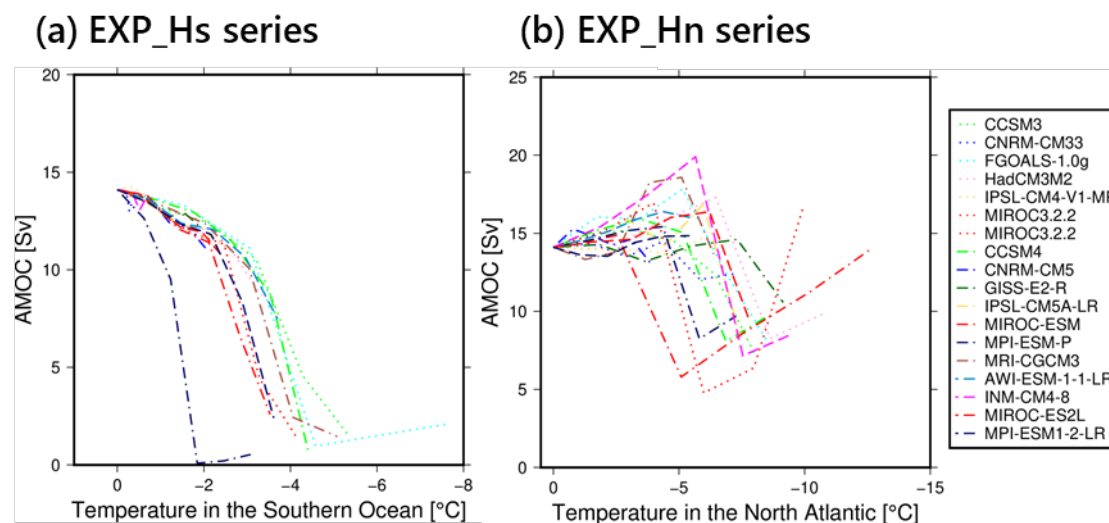


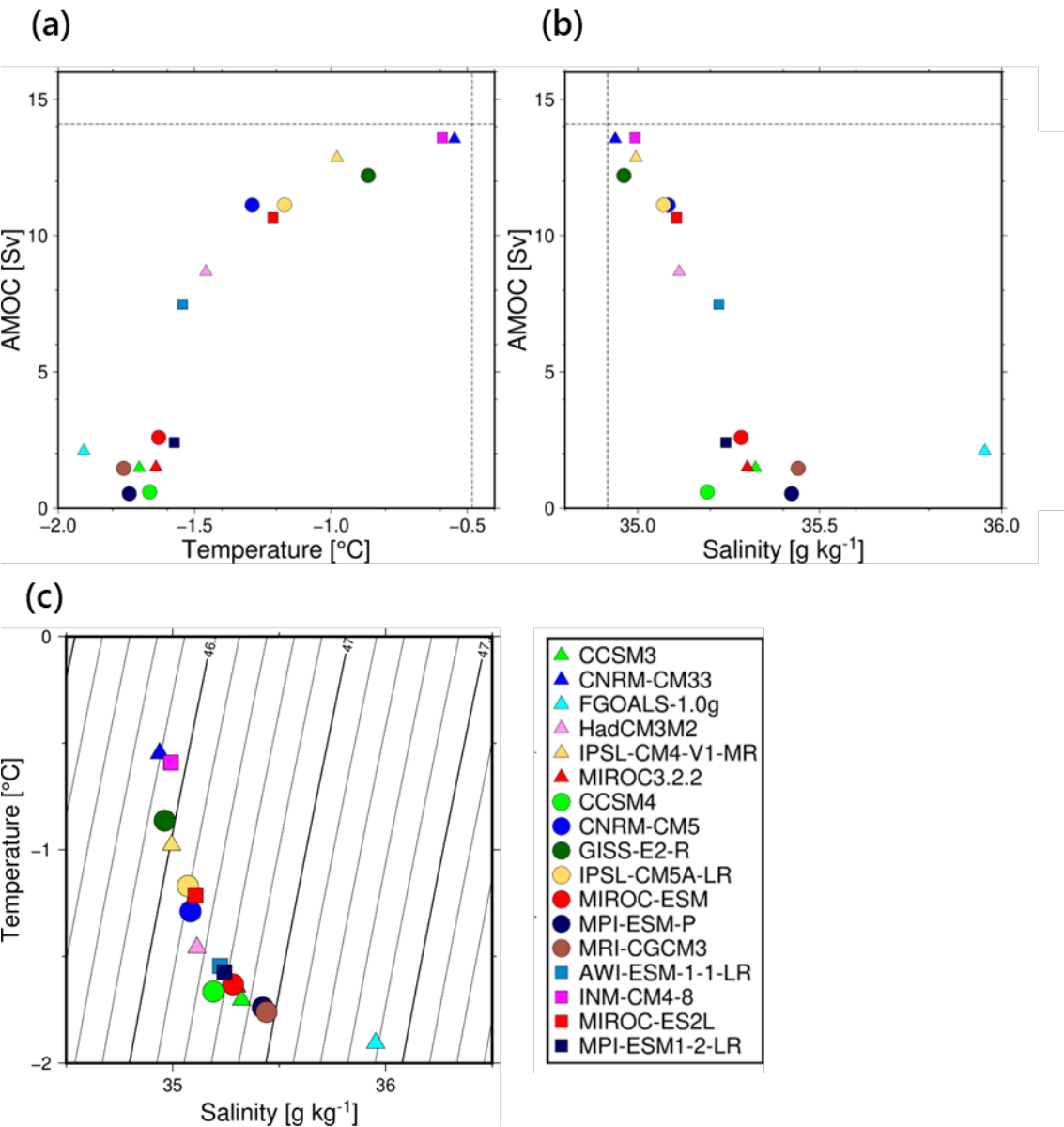
Figure 7: (a) The AMOC index of the EXP_Hs series ($f_c = 0.2-1.0$) with thermal anomalies from each PMIP model plotted against the mean surface air temperature anomaly over the Southern Ocean ($30^{\circ}-90^{\circ}\text{S}$). (b) Same as (a), but for the EXP_Hn series, with the horizontal axis indicating the mean surface air temperature anomaly over the North Atlantic ($30^{\circ}-75^{\circ}\text{N}$).

Figure 8 shows the relationship between the AMOC and the temperature and salinity of Antarctic Bottom Water (AABW) in EXP_Hs. Both the temperature and salinity of AABW change systematically as the AMOC changes (Figs. 8a,b). The cooler atmospheric thermal forcing over the Southern Ocean leads to lower AABW temperatures, while increased sea-ice formation under colder conditions further increases the salinity of newly formed AABW through brine rejection (Fig. 8c), reflecting their common dependence on the thermal forcing over the Southern Ocean. These changes in AABW properties accompany the weakening of the AMOC associated with Southern Ocean cooling. The importance of AABW properties for the AMOC is consistent with recent model-based studies showing that the potential density of AABW plays a key role in determining the depth and strength of the AMOC (Song et al., 2025).

The response to Northern Hemisphere cooling is more complex (Fig. 7b). The response to modest cooling varies among the PMIP models, but most experiments show a substantial reduction in AMOC strength when the mean Northern Hemisphere SAT decreases by approximately $4-6^{\circ}\text{C}$. The evolution of the mixed layer depth indicates that this reduction is associated with the cessation of deep-water formation south of Greenland. The expansion of sea ice into this region reduces air–sea heat exchange and suppresses deep-water formation. This behavior is consistent with the thermal threshold of the glacial AMOC associated with a southward shift of the deep-water formation region (Oka et al., 2012, Ando and Oka, 2021). With further cooling, however, the AMOC begins to recover in some experiments, and some experiments eventually produce an AMOC stronger than that in the CTL experiment. In these cases, further cooling over the North Atlantic deepens the winter mixed layer south of the sea-ice edge, around 40°N . This region corresponds approximately to the northern rim of the NADW cell



215 in the Atlantic meridional streamfunction. The enhanced surface cooling therefore promotes deep-water formation at lower latitudes. Thus, Northern Hemisphere cooling produces two competing effects: sea-ice expansion suppresses deep-water formation by reducing air–sea heat exchange, whereas sufficiently strong cooling can enhance deep-water formation farther south in the open ocean by increasing surface heat loss.



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Figure 8: (a,b) Scatterplot of EXP_Hs simulations between the AMOC index and the temperature and salinity in the deep Southern Ocean (45°–90°S, below 4000 m). Dashed lines indicate the CTL value. (c) Relationship between the temperature and salinity in the deep Southern Ocean in EXP_Hs simulations.

225 3.2 Wind effect

Figure 6b shows the AMOC response to LGM wind stress anomalies applied over different latitude ranges. The wind stress anomaly over the Southern Hemisphere (EXP_Ts) has only a small effect on the AMOC. Wind stress changes over the low- and mid-latitude Northern Hemisphere (EXP_Tnl) produce substantial differences among the PMIP models, but do not lead to a robust strengthening or weakening of the AMOC as a whole. In contrast, wind stress changes over the high-latitude Northern Hemisphere (EXP_Tnh) generally strengthen the AMOC.

The AMOC strength in EXP_T shows little correlation with the maximum westerly wind stress over the North Atlantic ($r = 0.16$), indicating that the magnitude of the westerly wind stress alone does not explain the AMOC response under the PI thermal conditions. This result is consistent with previous studies showing that enhanced westerly winds over the North Atlantic do not necessarily strengthen the AMOC (Cessi, 2018; Lohmann et al., 2021). The sum of the AMOC changes in EXP_Tnl, EXP_Tnh, and EXP_Ts is also smaller than the AMOC change in EXP_T, indicating that the effects of wind stress are not simply additive.

The experiments separating wind stress over sea ice and the open ocean further show that the effect of wind stress over the open ocean is substantially larger than that over sea ice under the PI thermal conditions. The AMOC in EXP_To is close to that in EXP_T, whereas the effect in EXP_Ti is relatively small (Fig. 6b). Thus, wind-driven changes in the open-ocean circulation make a dominant contribution to the AMOC response to wind stress under the PI thermal conditions.

The effects of wind stress change substantially when the LGM thermal conditions are imposed. Figure 6c summarizes the AMOC response to LGM wind stress anomalies under the LGM thermal conditions. The responses to wind stress over the low- and mid-latitude Northern Hemisphere, the Southern Hemisphere, and sea ice differ from those under the PI thermal conditions, indicating that the spatial distribution of the wind stress effect depends on the background thermal state. In particular, the effect of wind stress over sea ice (EXP_HTi) becomes more pronounced than under the PI thermal conditions. In EXP_HTi, the open ocean is still forced by the CTL wind stress. Nevertheless, the substantial strengthening of the AMOC in EXP_HTi relative to EXP_H demonstrates that wind stress acting on sea ice can contribute to the AMOC response under the LGM thermal conditions. These experiments indicate that LGM wind stress anomalies affect the AMOC through both wind-driven ocean circulation and changes in sea-ice distribution; the relative importance of these processes depends on the thermal background state and the associated deep-water formation and sea-ice distributions.

To isolate the effects of intermodel differences in wind stress from differences in thermal conditions, we used the LGM thermal anomaly from MIROC3.2.2 as a common LGM thermal background and imposed the LGM wind stress anomalies from each PMIP model (EXP_HmT, EXP_HmTo, and EXP_HmTi; Fig. 6d). These experiments also show that the LGM



wind stress anomalies generally strengthen the AMOC. In EXP_HmTo, a moderately positive correlation ($r = 0.45$) is found
 255 between the maximum westerly wind stress over the North Atlantic and the AMOC strength (Fig. 9), in contrast to EXP_T.
 This result suggests that enhanced westerly winds can strengthen the AMOC under the LGM thermal conditions. The deep-
 water formation region also differs between the PI and LGM thermal conditions. Under the LGM thermal conditions, deep
 convection in the GIN Seas is largely absent, and deep-water formation in the subpolar gyre becomes dominant. In this
 regime, enhanced wind stress can promote northward salinity transport into the subpolar gyre, strengthening the AMOC
 260 (Montoya et al., 2011). However, the magnitude of the westerly wind stress explains only part of the variation in AMOC
 strength in EXP_HmTo, indicating that the local spatial pattern of wind stress also plays an important role.

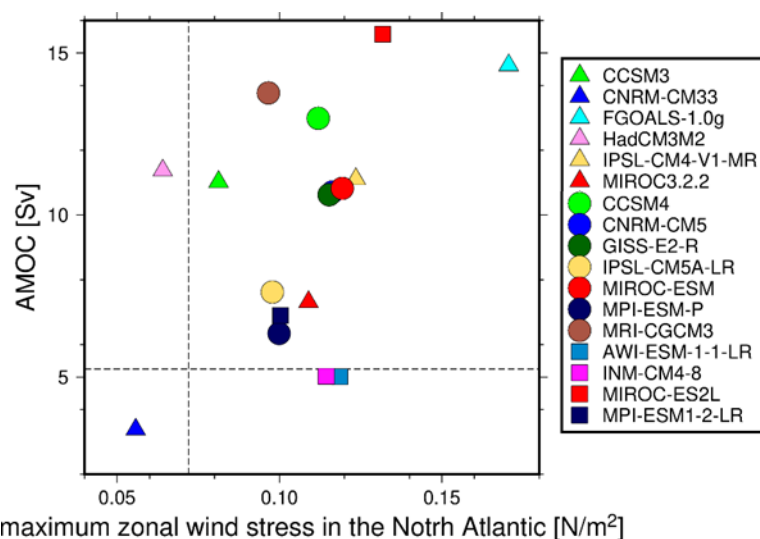


**Figure 9: Scatterplot of EXP_HmTo simulations between the AMOC index and the maximum westerly wind stress in the North
 265 Atlantic. Dashed lines indicate the CTL value.**

Wind stress anomalies also affect the AMOC through changes in sea-ice distribution. In EXP_HmTi, the southward sea-ice
 volume transport across 65°N increases by approximately 0.07 Sv on average, mainly owing to enhanced southward
 transport in the Labrador Sea (Fig. 10d). This transport change tends to increase sea-ice melt in the subpolar gyre, where
 270 deep-water formation occurs, which by itself would tend to weaken the AMOC. Nevertheless, the AMOC strengthens in
 EXP_HmTi. The strengthening is therefore associated not with the freshwater effect of sea-ice melt but with changes in
 surface heat exchange caused by the altered sea-ice distribution. In particular, intensified easterly winds around 60°N reduce
 sea-ice cover south of the Greenland–Scotland ridge (Fig. 10b,f), enhancing surface buoyancy loss in this region and
 promoting stronger deep-water formation.

275 The effect of a given LGM wind stress anomaly also depends strongly on the thermal background state. For example, the
 CNRM-CM33 wind stress anomaly weakens the AMOC when combined with the MIROC3.2.2 LGM thermal anomaly in



EXP_HmT, whereas it strengthens the AMOC when combined with the CNRM-CM33 LGM thermal anomaly in EXP_HT. Thus, the response to wind stress cannot be interpreted independently of the thermal conditions. Overall, the LGM wind stress anomalies tend to strengthen the AMOC through both wind-driven ocean circulation and changes in sea-ice distribution, while the magnitude and even the sign of the response depend on the local wind stress pattern and the background thermal state.

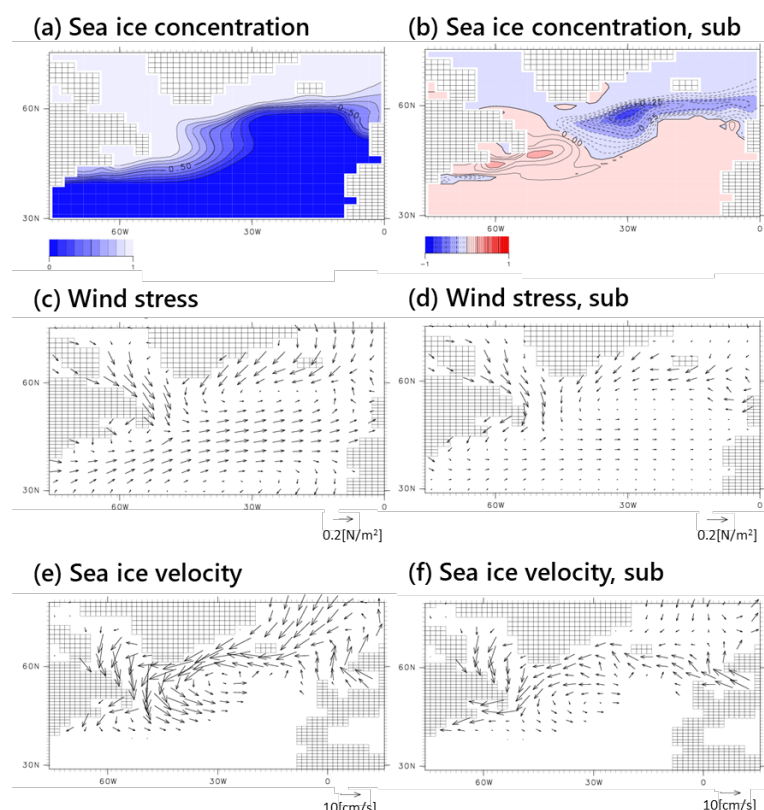


Figure 10: (a, c, and e) Average of EXP_HmTi simulations and (b, d, and f) its difference from EXP_H with MIROC3.2.2 anomaly. (a, b) Sea ice concentration in winter in the North Atlantic. (c, d) Wind stress boundary condition over the North Atlantic. (e, f) Sea ice velocity in the North Atlantic.

3.3 Freshwater effect

The LGM freshwater-flux anomalies have relatively small effects on the AMOC compared with the thermal and wind stress anomalies. The mean freshwater export from the Atlantic basin increases from 0.42 to 0.48 Sv, while net precipitation over the North Atlantic (45°–75°N) decreases from 0.32 to 0.17 Sv when the LGM E-P-R anomalies from the PMIP models are



applied. Both changes would tend to increase the salinity of the North Atlantic and thereby strengthen the AMOC. Nevertheless, the AMOC strength in EXP_W remains close to that in the CTL experiment.

295 The freshwater anomaly in CNRM-CM33 is an exception, with 0.44 Sv of freshwater export from the Atlantic basin and 0.18 Sv of freshwater input into the North Atlantic. This anomaly is associated with a substantial weakening of the AMOC in the CNRM-CM33 experiment. However, the freshwater-flux differences among the PMIP models do not explain the overall range of AMOC strengths in EXP_W or EXP_HTW, including the very weak AMOC in CNRM-CM33.

These results indicate that large-scale differences in E-P-R under LGM conditions have a relatively minor effect on the
 300 AMOC compared with differences in thermal conditions and wind stress, consistent with the results of Weber et al. (2007).

4 Discussions

The thermal anomaly in the Southern Hemisphere led to a weakening of the AMOC regardless of the PMIP model, and the magnitude of the weakening was primarily related to the degree of cooling over the Southern Ocean. This result is consistent
 305 with previous studies that have emphasized the importance of Antarctic Bottom Water (AABW) density for the strength of the AMOC (Jansen and Nadeau, 2016; Klockmann et al., 2016; Otto-Bliesner et al., 2007; Sun et al., 2020). The importance of Southern Ocean cooling for the glacial AMOC has also been identified in analyses of PMIP simulations (Marzocchi and Jansen, 2017; Sherrieff-Tadano et al., 2023). Our sensitivity experiments further demonstrate that differences in the magnitude of Southern Ocean cooling among climate models can lead to substantial differences in AMOC strength, even
 310 when the ocean model and its background state are held fixed. This suggests that uncertainties in the simulated Southern Ocean thermal conditions are an important source of the intermodel spread in the LGM AMOC.

Oka et al. (2012) demonstrated that cooling over the North Atlantic can cause a drastic weakening of the AMOC through sea-ice expansion that inhibits heat loss from the ocean in the deep-water formation region, a behavior referred to as the thermal threshold of the AMOC. Ando and Oka (2021) further showed that this thermal feedback can lead to hysteresis in
 315 the glacial AMOC through shifts in the deep-water formation region associated with atmospheric cooling and sea-ice changes. Our EXP_Hn experiments support the existence of this thermal threshold, with the expansion of sea ice and the associated suppression of deep-water formation in the subpolar North Atlantic. We newly demonstrate that the response to Northern Hemisphere cooling is not necessarily monotonic and depends on the spatial structure of the imposed thermal anomaly. In the EXP_Hn experiments, modest cooling can either weaken or strengthen the AMOC depending on the PMIP
 320 model anomaly. This behavior results from the simultaneous occurrence of two competing responses: shallowing of the winter mixed layer associated with sea-ice expansion in the Irminger Sea (Zhang et al., 2014) and deepening of the winter mixed layer south of the sea-ice edge due to enhanced surface heat loss (Smith and Gregory, 2012). These processes have opposite effects on deep-water formation and the AMOC. Thus, the response of the AMOC to North Atlantic cooling is sensitive not only to the magnitude of the cooling but also to its spatial distribution. Differences in the thermal boundary



325 conditions among climate models can therefore lead to substantially different AMOC responses even under a common ocean model.

The LGM wind stress anomalies generally strengthened the AMOC, consistent with previous studies (Muglia and Schmittner, 2015; Oka et al., 2012; Sherriff-Tadano et al., 2018). Our sensitivity experiments indicate that this effect arises from both changes in sea-ice distribution and wind-driven ocean circulation. Changes in sea-ice distribution can modify the air–sea
 330 heat exchange associated with deep-water formation (Born et al., 2010; Saenko et al., 2002; Zhu et al., 2014), while intensified westerly winds can enhance northward salinity transport and thereby strengthen the AMOC (Gong et al., 2015; Montoya et al., 2011; Montoya and Levermann, 2008; Sherriff-Tadano et al., 2018). However, the relationship between wind stress magnitude and AMOC strength is not necessarily straightforward. Cessi (2018) showed that North Atlantic wind stress can exert competing effects on the overturning circulation, while Lohmann et al. (2021) demonstrated a nonlinear AMOC
 335 response to enhanced and reduced wind stress forcing. Our results are consistent with these studies in suggesting that the AMOC response cannot be characterized solely by the magnitude of the wind stress anomaly. Our experiments further show that the relative importance of these mechanisms depends strongly on the thermal background state. Under the PI thermal conditions, the effect of wind stress over the open ocean dominates, whereas under the LGM thermal conditions, wind stress acting on sea ice also contributes substantially to the AMOC response. The dependence of the wind stress effect on the
 340 thermal background is also evident from the EXP_HmT experiments, in which wind stress anomalies from the same PMIP model can produce different AMOC responses when combined with different thermal anomalies. This result is consistent with the state dependence of wind-driven AMOC changes discussed by Montoya et al. (2011). It further indicates that the thermal background state can modify the pathways through which wind stress affects the AMOC. Therefore, differences in both the magnitude and spatial distribution of wind stress and the thermal background among PMIP models can contribute to
 345 the intermodel spread in the simulated LGM AMOC.

The results also highlight an important limitation in interpreting the differences among PMIP simulations. The experiments conducted here do not necessarily reproduce the LGM AMOC obtained in the corresponding PMIP models. In most PMIP models, the LGM AMOC is stronger than or comparable to that in the PI climate, whereas many of the EXP_HT and EXP_HTW experiments produce a substantially weaker AMOC. Moreover, the LGM surface boundary-condition anomalies
 350 derived from CCSM3, whose LGM simulation showed a considerable weakening of the AMOC, strengthened the AMOC when imposed on the common ocean model used here. Although the anomaly experiments and the original PMIP simulations cannot be compared directly, these differences indicate that the intermodel spread in the LGM AMOC arises not only from surface boundary conditions but also from ocean processes and model formulation. In addition, our experiments used preindustrial bathymetry with an open Bering Strait, whereas the Bering Strait was closed during the LGM. Previous
 355 studies have shown that closing the Bering Strait can strengthen the AMOC (Brierley and Fedorov, 2016; Hu et al., 2015). The use of preindustrial bathymetry in our experiments may therefore contribute to differences between our simulated LGM AMOC and those obtained in PMIP simulations that adopted LGM bathymetry. These differences emphasize that surface boundary conditions are an important, but not exclusive, factor controlling the simulated LGM AMOC.



5 Conclusions

360 We investigated the relative impacts of thermal conditions, wind stress, and freshwater flux on the AMOC during the LGM using an ocean general circulation model forced by surface boundary-condition anomalies derived from 17 PMIP models. By imposing these anomalies separately and in combination on a common ocean model, we isolated the effects of differences in surface boundary conditions among climate models.

The thermal anomalies generally weakened the AMOC, whereas the wind stress anomalies generally strengthened it, while 365 the freshwater-flux anomalies had relatively small effects in most experiments. Southern Ocean cooling weakened the AMOC through changes in AABW properties, and differences in the magnitude of Southern Ocean cooling among the PMIP models contributed to differences in AMOC strength. In contrast, the response to Northern Hemisphere cooling was non-monotonic. Sea-ice expansion suppressed deep-water formation by reducing air–sea heat exchange, whereas sufficiently strong cooling could enhance deep-water formation farther south by increasing surface heat loss.

370 The LGM wind stress anomalies strengthened the AMOC through both wind-driven ocean circulation and changes in sea-ice distribution. The magnitude and even the sign of the wind stress effect depended on the spatial distribution of the wind stress anomaly and the background thermal state. Thus, the effects of surface boundary conditions on the LGM AMOC are strongly state-dependent and cannot be understood solely from the magnitude of individual boundary-condition changes.

These results demonstrate that differences in surface boundary conditions among PMIP models can lead to substantial 375 differences in simulated LGM AMOC through both thermal and dynamical processes. At the same time, the anomaly experiments did not necessarily reproduce the AMOC of the corresponding PMIP simulations, indicating that differences in ocean processes and model formulation also contribute to the intermodel spread. A better understanding of both surface boundary conditions and ocean processes is therefore necessary for more reliable simulations of the LGM AMOC.

380 Code and data availability

The code of COCO is available from <https://github.com/COCO-Ocean-Model/coco>. The model output generated in this study is available from the corresponding author upon reasonable request because of the large volume of the model output data. The processed data underlying the figures and analyses are also available from the corresponding author upon reasonable request.

385 Author contributions

TA and AO designed the experiments, and TA performed the simulations. TA prepared the manuscript with contributions from AO.



Competing interests

The authors declare no competing interests.

390 Acknowledgements

Parts of this study are based on an extension of the results of the master's thesis by Kazuki Togawa at the University of Tokyo, and we would like to express our sincere gratitude for his contributions. This research was conducted using the FUJITSU Supercomputer PRIMEHPC FX1000 AND FUJITSU SERVER PRIMERGY GX2570(WISTERIA/BDEC-01) at the Information Technology Center, The University of Tokyo. The authors used ChatGPT (OpenAI) to improve English
395 grammar and language.

Financial support

This study was supported by JSPS KAKENHI Grant Number JP24H02346 and the Environment Research and Technology Development Fund (JPMEERF23S21109) of the Environmental Restoration and Conservation Agency provided by Ministry of the Environment of Japan.

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