Does a difference in ice sheets between Marine Isotope Stages 3 and 5a affect the duration of stadials~~?~~?: Implications from hosing experiments

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Abstract. Glacial periods undergo frequent climate shifts between warm interstadials and cold stadials on a millennial time-scale. Recent studies ~~have shown~~show that the duration of these climate modes varies with the background climate; a colder background climate and lower CO_2 generally results in a shorter interstadial and a longer stadial through its impact on the Atlantic Meridional Overturning Circulation (AMOC). However, the duration of stadials ~~was~~is shorter during the Marine Isotope Stage 3 (MIS3) compared with MIS5, despite the colder climate in MIS3, suggesting potential control from other climate factors on the duration of stadials. In this study, we ~~investigated~~investigate the role of glacial ice sheets. For this purpose, freshwater hosing experiments ~~were~~are conducted with an atmosphere–ocean general circulation model under MIS5a~~,~~ ~~MIS3~~ and MIS3 boundary conditions, and MIS3 boundary conditions with MIS5a ice ~~sheet conditions.~~sheets. The impact of ice sheet differences on the duration of the stadials ~~was~~is evaluated by comparing recovery times of the AMOC after freshwater forcing ~~was~~is reduced. Hosing experiments ~~showed~~show a slightly shorter recovery time of the AMOC in MIS3 compared with MIS5a, which ~~was~~is consistent with ice core data. We ~~found~~find that larger glacial ice sheets in MIS3 ~~shortened~~shorten the recovery time. Sensitivity experiments ~~showed~~show that stronger surface winds over the North Atlantic ~~shortened~~shortens the recovery time by increasing the surface salinity and decreasing the sea ice amount in the deepwater formation region, which set favourable conditions for oceanic convection. In contrast, we also ~~found~~find that surface cooling by larger ice sheets ~~tended~~tends to increase the recovery time of the AMOC by increasing the sea ice thickness over the deepwater formation region. Thus, this study suggests that the larger ice sheet in MIS3 compared with MIS5a could have contributed to the shortening of stadials in MIS3, despite the climate being colder than that of MIS5a, when the effect of surface wind ~~played~~plays a larger role.

1 Introduction

Reconstructions from ice cores reveal that the climate varied frequently on a millennial time-scale over the glacial period (Kawamura et al. 2017). These millennial-scale climate variabilities are known as Dansgaard–Oeschger (DO) cycles, and occurred more than 20 times over the last glacial period (DO cycles, Fig. 1, Dansgaard et al. 1993, Huber et al. 2006, Capron et al. 2010, Kindler et al. 2014). The DO cycles are famous for their abrupt and large temperature increases over Greenland from stadial to interstadial, followed by gradual cooling and a drastic return to the stadial conditions. These two contrasting climate modes ~~persisted~~persist for more than several hundred years, and in total, ~~resulted~~result in periodicity from one thousand years to more than five thousand years (Buizert and Schmittner 2015, Kawamura et al. 2017). The DO cycles are often attributed to reorganizations of the Atlantic meridional overturning circulation (AMOC) between a vigorous mode and a weak mode (Ganoploski and Rahmstrof 2001, Piotrowski et al. 2005, Menviel et al. 2014, Henry et al. 2016, Menviel et al. 2020). For example, it ~~has been~~is shown that the shift of the AMOC from a vigorous mode to a weak mode ~~caused~~causes a reduction of northward oceanic heat transport in the Atlantic, expansion of sea ice and drastic cooling over the North Atlantic and warming over the Southern Ocean (Kageyama et al. 2010, 2013).

To better understand the dynamics of DO cycles as well as the spread in the duration of DO cycles, previous studies ~~investigated~~investigate possible relations between the frequency of these cycles and the background climate such as glacial ice sheet amounts and atmospheric CO_2. For example, McManus et al. (1999) ~~suggested~~suggest that DO cycles ~~occurred~~occur most frequently when the size of the glacial ice sheets ~~was~~is at an intermediate level between interglacial and full glacial. They ~~suggested~~suggest that intermediate ice sheets ~~could~~can be unstable, and that the frequent release of freshwater ~~could~~can cause drastic weakening of the AMOC. On the other hand, ice core and modelling studies ~~have suggested~~suggest the importance of global cooling in determining the frequency of DO cycles (Buizert and Schmittner 2015, Kawamura et al. 2017). Kawamura et al. (2017) ~~showed~~show that DO cycles ~~occurred~~occur most frequently when the Antarctic temperature and global cooling ~~were~~are at intermediate levels between interglacial and full glacial periods over the last 720 thousand years. It ~~was~~is further demonstrated based on climate modelling experiments that the vigorous AMOC becomes more vulnerable to perturbations such as freshwater hosing when the global or Southern Ocean climate is colder than the modern climate but not as cold as the full glacial climate, resulting in a more unstable vigorous AMOC mode during mid-glacial periods (Buizert and Schmittner 2015, Kawamura et al. 2017). These results suggest that the spread of the frequency of DO cycles may not purely result from chaotic behaviour of the AMOC, but rather may be modulated by changes in the background climate (Buizert and Schmittner 2015, Kawamura et al. 2017, Mitsui and Crucifix 2017).

Recent studies of ice cores from both Greenland and Antarctica further ~~explored~~explore the relation of the background climate and the frequency of DO cycles by separating the durations of interstadials and stadials. With respect to interstadials, Buizert and Schmittner (2015) ~~showed~~show that the duration ~~decreased~~decreases as the Antarctic temperature ~~decreased~~decreases from interglacial to full glacial conditions (Fig. 1). Lohmann and Ditlevsen (2019) also ~~showed~~show, based on ice core data from Greenland, that the duration of interstadials ~~was~~is highly correlated with the surface cooling rate over the northern North Atlantic; the duration ~~decreased~~decreases as the cooling rate of the Greenland temperature ~~increased~~increases. These studies are supported by experiments with climate models showing an increased sensitivity of the vigorous AMOC to freshwater hosing under colder climates (Zhang et al. 2014b, Kawamura et al. 2017), and by climate model studies showing shortening of the duration of interstadials in their intrinsic millennial-scale climate variability with lower CO_2 levels (Brown and Galbraith 2016, Klockmann et al. 2018).

With respect to stadials, the situation is different. Buizert and Schmittner (2015) ~~found~~find a weak relation between the durations of stadials and Antarctic temperature; the durations of the stadials ~~were~~are extremely long during the full glacial interval (MIS2, 4, Fig. 1a), short in the early glacial interval (Marine Isotope Stage 5 (MIS5)), and even shorter in the mid-glacial period (MIS3, Fig. 1b), which ~~contributed~~contributes to the short periodicity of DO cycles during mid-glacial periods. In addition, Lohmann (2019) ~~analyzed~~analyze the dust record in Greenland ice cores and ~~found~~find that the durations of stadials ~~correlated~~correlate with the decreasing trend of dust during the first 100 years of the stadials. Although the factors controlling the trend of dust remain unclear, these results suggest that another type of climate forcing over the North Atlantic ~~played~~plays a role in modulating the durations of stadials in combination with surface cooling. In addition, these results suggest that the processes modulating durations of interstadials and stadials may differ. Nevertheless, it still remains unclear why the durations of stadials ~~were~~are generally shorter in MIS3 compared with MIS5, despite colder conditions in MIS3.

From a climate modelling point of view, previous studies ~~have shown that~~investigate dependences of the recovery time of the AMOC and the duration of stadials ~~depend on~~to the background climate, based on freshwater hosing experiments~~ conducted under different background climate conditions.~~. While the timing of freshwater input and DO cycles is still debated, and that freshwater hosing may not be the cause of the AMOC weakening (Barker et al. 2015), these studies provide useful information to study DO cycles. For example, Weber and Drijhout (2007) ~~showed in simulations with an earth system model of intermediate complexity (EMIC)~~and Bitz et al. (2007) show that the recovery time of the AMOC ~~was~~is longer under glacial conditions (Last Glacial Maximum, LGM) compared with preindustrial (PI) conditions. ~~Bitz et al. (2007) also showed with a comprehensive climate model that the recovery time became longer under the LGM climate than under the PI climate and a doubled CO_2 climate.~~ These studies suggest that a larger expansion of sea ice over the North Atlantic in the LGM ~~would cause~~causes an increase in the recovery time of the AMOC. Extensive sea ice ~~covered~~covers the original deepwater formation regions and ~~suppressed~~suppresses atmosphere–ocean heat exchange in the deepwater formation region (Oka et al. 2012, Sherriff-Tadano and Abe-Ouchi 2020), which ~~made~~makes it difficult for the AMOC to recover after freshwater hosing ~~had~~is ceased (Bitz et al. 2007, Weber and Drijhout 2007). In contrast, Gong et al. (2013) ~~compared~~compare the recovery time of the

AMOC under PI, mid-glacial and LGM conditions in a comprehensive climate model and ~~found~~find that the recovery time ~~was~~is shortest in the mid-glacial case and longest in the PI case. They ~~suggested~~suggest that greater subsurface ocean warming over the deepwater formation region, which affects ocean stratification (Mignot et al. 2007), ~~was~~is important in causing a shorter recovery time of the AMOC in the mid-glacial period. Furthermore, Goes et al. (2019) recently ~~showed~~show that the recovery time of the AMOC ~~became~~becomes shorter when they ~~forced~~force their Earth system model of intermediate complexity (EMIC) with LGM winds compared with modern winds. ~~Similarly, Sherriff-Tadano and Abe-Ouchi (2020) showed from sensitivity experiments with a comprehensive climate model that stronger surface winds shortened the duration of the weak AMOC state by increasing sea surface salinity over the deepwater formation region.~~ These results support the inference that changes in the background climate (e.g. ice sheet configurations and insolation) can modify the duration of stadials, although the processes and results may depend on the models used. However, in most studies, because the boundary conditions such as ice sheet configurations, CO_2 concentration and insolation are all modified at the same time, the impacts of individual boundary conditions on the durations of stadials and the recovery time of the AMOC remain elusive. A better understanding of the individual roles of boundary conditions and their mechanism in modifying the recovery time is necessary to understand the changes in the durations of stadials across glacial periods, as well as to interpret model discrepancies.

Previously, it ~~has been~~is shown that large Northern Hemisphere glacial ice sheets increase sea surface salinity over the North Atlantic Deepwater (NADW) formation region by increasing surface winds and decreasing precipitation (Eisenman et al. 2009, Smith and Gregory 2012, Brady et al. 2013, Zhang et al. 2014a, Gong et al. 2015, Klockmann et al. 2016, Galbraith and de Lavergne 2019, Guo et al. 2019). In addition, it ~~has been~~is shown that stronger surface cooling by ice sheets increases the amount of sea ice in the NADW formation region and the Southern Ocean, the latter of which is induced by colder NADW outcropping in the Southern Ocean (Sherriff-Tadano et al. 2021). These results imply that differences in glacial ice sheets may play a role in modifying the durations of stadials during glacial periods. Recently, Sherriff-Tadano et al. (2021) ~~performed~~perform simulations of MIS3 and MIS5a and ~~explored~~explore the impact of ice sheet differences on the AMOC and climate. In their simulations, differences in the ice sheets ~~exerted~~exert small impacts on the vigorous mode of the AMOC, because of a compensational balance between the increase in sea surface salinity in the northern North Atlantic (strengthening effect) and the increase in sea ice in the North Atlantic and Southern Ocean (weakening effect). However, the impact of mid-glacial ice sheets on the duration of stadials and the recovery time of the AMOC remains elusive. Because the important processes affecting the stability of the AMOC may differ between vigorous and weak AMOC modes (Buizert and Schmittner 2015, Lohmann 2019), a different response of the AMOC to ice sheet forcing under a weak AMOC state may be found.

In this study, we ~~explored~~explore the impacts of differences in the ice sheets between the MIS3 and MIS5a on the recovery time of the AMOC and the durations of stadials. For this purpose, we ~~performed~~perform freshwater hosing experiments under three background climates that have been simulated previously, MIS3, MIS5a and MIS3 with the ice sheet forcing of MIS5a (Sherriff-Tadano et al. 2021). By comparing the recovery time of the AMOC after the cessation of freshwater hosing in each experiment, we ~~assessed~~assess the impact of the ice sheets on the recovery time of the AMOC. Furthermore, to explore the mechanism by which the ice sheets modify the recovery time of the AMOC, we ~~performed~~perform partially coupled experiments. In these experiments, the atmospheric forcing, which is passed to the oceanic component of the model, ~~was~~is replaced with a different forcing. By this method, individual effects of changes in surface wind, atmospheric freshwater flux, or surface cooling on the AMOC can be estimated (Mikolajewicz et al. 1997, Schmittner et al. 2002, Gregory et al. 2005, Sherriff-Tadano et al. 2021).

We should note that, in the hosing experiments, we focus on the situation how climate system recovers from the cessation of external forcing. In contrast, recent studies with AOGCMs show intrinsic oscillations of AMOC, which resemble DO cycles, without any external forcing. For example, Vettoretti and Peltier (2016) and Sherriff-Tadano and Abe-Ouchi (2020) show in their intrinsic oscillations of AMOC that the recovery of the AMOC from weak mode to strong mode is determined by the balance among sea ice, surface salinity and subsurface ocean warming over the deepwater formation region in the North Atlantic. From the viewpoint of mechanisms, the recovery process of the AMOC in the present hosing experiments is similar to that in the intrinsic oscillations of AMOC. Therefore, our findings may not be confined to the hosing experiments or DO cycles induced by external forcing, but may also be applied to those obtained via intrinsic oscillations of the AMOC.

This paper is organized as follows. Section 2 describes the model and the experimental design. In section 3, the impacts of the ice sheet configurations on the recovery time of the AMOC and its mechanism are assessed. Section 4 discusses the results, and section 5 presents the conclusion.

2. Methodology

2.1 Model

Numerical experiments ~~were~~are performed with the Model for Interdisciplinary Research on Climate 4m (MIROC4m; Hasumi and Emori 2004), an atmosphere–ocean coupled general circulation model (AOGCM). This model consists of an atmospheric general circulation model (AGCM) and an oceanic general circulation model (OGCM). The AGCM and OGCM include a land surface model and a sea ice model, respectively. The AGCM solves the primitive equations on a sphere using a spectral method. The horizontal resolution of the atmospheric model is ~2.8°, and there are 20 layers in the vertical direction. The OGCM solves the primitive equations on a sphere, with the Boussinesq and hydrostatic approximations adopted. The horizontal resolution is ~1.4° in longitude and 0.56°–1.4° in latitude (latitudinal resolution is finer near the equator). There are 43 layers in the vertical direction. Note that the coefficient of horizontal diffusion of the isopycnal layer thickness in the OGCM ~~was slightly~~is increased to 700 m^2 s^{-1} compared with the original model version (300 m^2 s^{-1}) that was submitted to Paleoclimate Model Intercomparison Project 2. These two model versions ~~were~~are referred to as Model B and Model A, respectively, by Sherriff-Tadano and Abe-Ouchi (2020). Here, we ~~used~~use Model B. The model version used in this study has been used extensively for modern climate, palaeoclimate (Obase and Abe-Ouchi 2019, O'ishi et al. 2021, Chan and Abe-Ouchi 2020) and future climate studies (Yamamoto et al. 2015). It also reproduces the AMOC of the present, LGM (Sherriff-Tadano and Abe-Ouchi 2020), MIS3 and MIS5a (Sherriff-Tadano et al. 2021) reasonably well. See Hasumi and Emori (2004) and Chan et al. (2011) for detailed information on the parameterizations used in the model.

2.2 Model simulations

This study ~~was~~is based on three climate simulations that have been performed previously (Sherriff-Tadano et al. 2021, Table 1). The first climate simulation ~~was~~is that of MIS5a, which ~~was~~is forced with a CO$_2$ concentration of 240 ppm, insolation of 80 ka and the ice sheet boundary configuration of 80 ka taken from Ice sheet model for Integrated Earth system Studies (IcIES, Abe-Ouchi et al. 2007, Abe-Ouchi et al. 2013, Fig. 2a). The second and third climate simulations ~~were~~are those of MIS3, both of which ~~were~~are forced with CO$_2$ of 200 ppm and insolation of 35 ka, but forced with ice sheets of either 36 ka (MIS3, Fig. 2b) or 80 ka (MIS3-5aice, Table 1). The volumes of the ice sheet ~~were~~are 40 metre sea level equivalent for 80 ka and 96 metre sea level equivalent for 36 ka (Abe-Ouchi et al. 2013). ~~The Antarctic ice sheet was fixed to the modern configuration, and the Bering Strait~~The volume of the MIS3 ice sheets exceeds the range of reconstructions (40- to 90-meter sea level equivalent, Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017, Gowan et al. 2021), hence may cause an overestimation of the ice sheet effect. Nevertheless, the ice sheet forcing used in this study at least captures the characteristics suggested by reconstructions, which show larger ice sheets at MIS3 compared to MIS5a (Pico et al. 2017, Gowan et al. 2021). The Antarctic ice sheet is fixed to the modern configuration, and the Bering Strait is remained open in all experiments. For methane and other greenhouse gases, the concentration of the LGM ~~was~~is used (Dallenbach et al. 2000). These three simulations ~~were~~are initiated from a previous LGM experiment by Kawamura et al. (2017), and ~~were~~are integrated for 2,000 years (MIS5a) or 3,000 years (MIS3 and MIS3-5aice). The decreasing trends of deep ocean temperature of the last 100 years ~~were~~are 0.002 ˚C in ~~MIS5~~MIS5a, 0.011 ˚C in MIS3 and 0.007 ˚C in MIS3-5aice, respectively (Sherriff-Tadano et al. 2021).

To cause drastic weakening of the AMOC and shift the climate into stadial, a freshwater flux of 0.1 Sv ~~was~~is applied uniformly over the northern North Atlantic (50˚–70˚ N) for 500 years (Fig. 3). Subsequently, the freshwater flux ~~was~~is stopped and the experiments ~~were~~are further integrated for 1,000 years to assess the dependence of the recovery time on the background climate. These experiments are named MIS3H, MIS5aH and MIS3-5aiceH, respectively~~.~~ (Table 1). The impact of the mid-glacial ice sheet on the duration of stadials ~~was~~is assessed by comparing the recovery time of the AMOC between MIS3H and MIS3-5aiceH~~.~~ (Table 1). The effect of the differences in CO$_2$ and insolation ~~could~~can be assessed by comparing the recovery time of the AMOC between MIS3-5aiceH and MIS5aH~~.~~ (Table 1).

2.3 Partially coupled experiments

To clarify the mechanisms by which glacial ice sheets modify the recovery time of the AMOC, partially coupled experiments ~~were~~are conducted (Table 2). In these experiments, the atmospheric forcing – wind stress and atmospheric freshwater flux (precipitation, evaporation and river runoff) ~~—that drove the ocean was~~is replaced with monthly ~~climatology.~~climatologies. The heat flux ~~was~~is unchanged in these experiments, as it ~~was~~is strongly coupled with the sea surface temperature and fixing the surface heat conditions has an unrealistic impact on the AMOC (Schmittner et al. 2002, Gregory et al. 2005, Marozke 2012). Atmospheric forcing ~~was~~is replaced with monthly ~~climatology~~climatologies of the last 100 years of the hosing period in each experiment. Thus, this forcing ~~did~~does not include atmospheric noise, which itself can induce a mode shift of the AMOC (~~Ganopolski and Rahmstrof 2001,~~ Kleppin et al. 2015). Nevertheless, similar conclusion is obtained when raw daily fields obtained from the last 100 years of the hosing period are used instead of monthly climatologies (Fig. S1). Understanding the role of atmospheric noise is beyond the scope of this study, but should be explored in other studies.

Five partially coupled experiments ~~were~~are conducted under MIS3H and MIS3-5aiceH (Table 2). All of the experiments ~~were~~are initiated from the first year of the cessation of freshwater hosing, which ~~corresponded~~correspond to the period when the climate and AMOC ~~had~~have settled to the stadial state (see Figs. 11 and 12). The first two experiments ~~served~~serve as a validation of the method; the atmospheric forcing ~~was~~is replaced with the ~~climatology~~monthly climatologies in MIS3H and MIS3-5aiceH. These experiments are named PC-MIS3H and PC-MIS3-5aiceH, respectively. We ~~regarded~~regard the method as valid when these experiments ~~reproduced~~reproduce the general difference of MIS3H and MIS3-5aiceH. In the other three experiments, the atmospheric forcing ~~was~~is replaced with different forcing~~.~~ (Table 2). In PC-MIS3H_wind, the surface wind stress of MIS3-5aiceH ~~was~~is applied to MIS3H. In PC-MIS3H_water, the atmospheric freshwater flux of MIS3-5aiceH ~~was~~is applied to MIS3H. In PC-MIS3H_windwater, the atmospheric freshwater flux and surface wind stress of MIS3-5aiceH ~~were~~are applied to MIS3H. From these experiments, the impact of differences in the wind ~~was~~is estimated as the difference between PC-MIS3H_wind and PC-MIS3H, the impact of differences in the atmospheric freshwater flux ~~was~~is estimated as the difference between PC-MIS3H_water and PC-MIS3H, and the impact of differences in the surface cooling ~~was~~is estimated as the difference between PC-MIS3H_windwater and PC-MIS3-5aiceH~~.~~ (Table 2). Note that the effect of surface cooling (heat flux) ~~was~~is estimated as a residual, following previous studies (Gregory et al. 2005). The surface cooling effect ~~included~~includes the effects of changes in freshwater flux of sea ice.

In conducting partially coupled experiments, the location of atmospheric freshwater flux needs to be adjusted following differences in land sea mask between MIS3 and MIS5a ice sheets (Fig. S2). Largest changes appear over the Barents Sea, where new ice sheets expand. In contrast, changes in land sea mask near the Labrador Sea and Norwegian Sea, where the main oceanic convections take place (Fig. 5), are small (Fig. S2). We adjust the location of river runoff and atmospheric freshwater flux in the partially coupled experiment by shifting it to closest ocean grid points.

3. Results

Simulated climates of unperturbed MIS5a, MIS3 and MIS3-5aice are displayed in Figs. 3–5. The simulated global air temperatures ~~were~~are 10.6 ˚C in MIS5a, 7.9 ˚C in MIS3 and 8.9 ˚C in MIS3-5aice (Sherriff-Tadano et al. 2021). The maximum strength of the AMOC ~~was~~is 18.4 Sv in MIS5a, 15.6 Sv in MIS3 and 15.1 Sv in MIS3-5aice (Fig. 4). The slightly weaker AMOC in MIS3 than in MIS5a is consistent with a reconstruction based on ^{231}Pa/^{230}Th (Bohm et al. 2015). Associated with the vigorous AMOC, deepwater ~~formed~~forms in the Greenland Sea and the Irminger Sea, and most parts of the northern North Atlantic ~~remained~~remain ice-free in all experiments (Fig. 5). These characteristics are consistent with proxy data suggesting ice-free conditions in the Norwegian Sea during interstadials (Dokken et al. 2013, Sadazki et al. 2019).

3.1 Responses to freshwater hosing

To shift the climate and AMOC into stadial states, freshwater hosing experiments ~~were~~are performed under these background climate conditions. These experiments all ~~showed~~show drastic weakening of the AMOC in response to hosing (Figs. 3 and 4). The strength of the AMOC ~~decreased~~decreases to 3 Sv in MIS5aH and MIS3-5aiceH, and ~~decreased~~decreases to 5 Sv in MIS3H. In addition, the Antarctic bottom water further ~~penetrated~~penetrates into the North Atlantic compared with unperturbed conditions (Fig. 4). Associated with the weakening of the AMOC, sea ice ~~expanded~~expands farther south and ~~reached~~reaches 50˚ N (Fig. 5). As a result, the deepwater formation region ~~was~~is covered by sea ice and the sea surface temperature over the northern North Atlantic ~~was~~is drastically reduced (Fig. 6). In addition, the surface salinity ~~decreased~~decreases drastically at high latitudes (Fig. 6) because of freshwater hosing, cessation of convective mixing and a reduction in northward salt transport by the AMOC. In contrast, the subsurface ocean temperature ~~increased~~increases at high latitudes because of the suppression of convective mixing. These characteristics are consistent with proxies (Rasmussen and Thomsen 2004, Dokken et al. 2013). In the tropics, the subsurface ocean temperature and salinity ~~increased~~increase because of the weakening of the northward transport of heat and salt by the AMOC (Gong et al. 2013).

The weakening of the AMOC and the expansion of sea ice ~~induced~~induce drastic cooling over Greenland (Fig. 7a). In particular, the February temperature decreases by 12 ˚C in MIS3H, 10 ˚C in MIS3-5aiceH and 12 ˚C in MIS5aH, which are within the range of ice core data (Kindler et al. 2014). Over the Antarctic, the temperature increases by 1–2 ˚C because of the bipolar seesaw (Kawamura et al. 2017). In terms of precipitation (Fig. 7b), the model ~~reproduced~~reproduces a southward shift of the tropical rain belt (Wang et al. 2004) and weakening of the Indian monsoon (Deplazes et al. 2014). Therefore, the model ~~reproduced~~reproduces the overall characteristics of the climate shift into stadial reasonably well.

3.2 Recovery

The AMOC ~~recovered~~recovers from the weak state to the vigorous state in all experiments after the cessation of freshwater hosing (Fig. 3), although the recovery time ~~differed~~differs among the experiments. In MIS5aH, the AMOC ~~started~~starts to recover abruptly 200 years after the cessation of hosing. In MIS3H, the AMOC first ~~increased to~~increases by 4.5 Sv over the first 80 years and then ~~intensified~~intensifies abruptly to the vigorous mode ~~of~~by 7.1 Sv in 70 years (the recovery speed nearly doubled compared with the first 80 years). The recovery time ~~was~~is slightly shorter in MIS3H compared with MIS5aH, which is consistent with the ice core data showing slightly shorter durations of stadials during MIS3 compared with MIS5a-d (Buizert and Schmittner 2015). In contrast, the recovery time ~~was~~is much longer in MIS3-5aiceH; it ~~took~~takes approximately 600 years to start the drastic recovery. Before that, the AMOC ~~recovered~~recovers gradually by 3 Sv over the first 560 years. Around model year 1065, the AMOC ~~was~~is abruptly enhanced and its strength ~~reached~~reaches 10 Sv. The strength of the AMOC once ~~decreased~~decreases to 7 Sv, although 100 years after the first abrupt strengthening, the AMOC ~~started~~starts to recover abruptly to the interstadial state. These results reveal three important points. First, the larger mid-glacial ice sheets in MIS3 compared with those of MIS5a ~~shortened~~shorten the recovery time of the AMOC~~.~~ (comparisons of MIS3H and MIS3-5aiceH). Second, the lowering of the CO_2 and the changes in insolation from MIS5aH to MIS3-5aiecH ~~contributed~~contribute to the increase in the recovery time of the AMOC in our experiments. This is consistent with other studies showing an increase in the durations of stadials under lower CO_2 concentrations (Brown and Galbraith 2016, Klockmann et al. 2018). Third, the recovery time of the AMOC ~~could not~~cannot be predicted based on the original strength of the AMOC because the recovery time ~~was~~is shorter in MIS3H compared with MIS5aH, even though the original AMOC ~~was~~is weaker. In MIS3H, the effect of the glacial ice sheet ~~was stronger than that of CO_2,~~is strong and thus ~~caused~~causes shortening of the recovery time compared with MIS5aH, despite having lower CO_2 concentration. Below, we further compare the recovery process in MIS3-5aiceH and MIS3H to understand how glacial ice sheets modify the recovery time, which ~~remained~~remains unclear in previous studies.

To understand the recovery process of MIS3-5aiceH, time series of sea ice, deepwater formation, surface salinity, surface density and subsurface ocean temperature ~~were~~are analyzed (Renold et al. 2010, Vettoretti and Peltier 2016, Brown and Galbraith 2016). Figure 8 shows time series of these variables in the Irminger Sea (35–25° W, 55–63° N) and Greenland Sea (1° W–5° E, 65°N–70°N), where deepwater ~~formed~~forms at the onset of the abrupt recovery of the AMOC. In MIS3–5aiceH, after the cessation of hosing, surface salinity and density first ~~increased drastically~~ increase in the Irminger Sea and Greenland Sea (red line in Fig. ~~8), followed by a gradual increase afterwards.~~8d, e, j, k). In association, the AMOC ~~strengthened~~strengthens slightly by 3 Sv over the first 560 years and ~~increased~~increases the northward transport of salt and heat~~, which induced~~. This induces a slight increase in the subsurface temperature and surface salinity and a decrease in sea ice~~. Formation of~~ (Fig. 8). During this period, no deepwater ~~occurred~~forms in Irminger Sea and Greenland Sea, except for one case in the Irminger sea approximately 300 years after the cessation of hosing~~, but~~ (Fig. 8c, year 800 in the figure). Nevertheless, the AMOC ~~did~~does not start to recover at this point (Fig. 3) because the surface salinity and subsurface ocean temperature ~~were~~are not sufficiently high to maintain convection. Four hundred years after the cessation of hosing, the surface salinity and sea ice thickness ~~reached a quasi-equilibrium~~reach an apparently steady state~~,~~ (Fig. 8a, e), whereas the subsurface temperature continuously ~~increased.~~increases (Fig. 8f, year 900 in the figure). When the subsurface ocean ~~warmed~~warms sufficiently, vigorous convective mixing ~~initiated~~initiates again in the Irminger Sea (Figs. ~~8~~8c and 9, regions circled by black contours). As a result, a positive salinity anomaly ~~spread~~spreads over the subpolar gyre regions (Fig. 9), which ~~caused~~causes a second deepwater formation in the north-western North Atlantic in the Greenland Sea, where the surface salinity ~~was~~is sufficiently high and subsurface ocean sufficiently warm (Figs. ~~8~~8f and 9). These deepwater formations ~~did~~do not occur continuously and they ~~ceased~~cease once, possibly associated with decadal variability in deepwater formation (Oka et al. ~~2006). Note that the emergence of enhanced decadal variability prior~~2006), and are similar to~~ the full AMOC recovery is in line with~~ the observation of early warning signals for DO events (i.e., signs of a tipping point) in a high-resolution ice core record (Boers 2018). However, the deepwater formation in the Greenland Sea ~~induced~~induces southward flow through the Denmark Strait in the deep ocean and ~~enhanced~~enhances the AMOC via downward flow along the slope (Reynolds et al. 2010). As a result, a compensational northward surface flow ~~transported~~transports salt into the deepwater formation and ~~caused~~causes a second occurrence of convection in the Greenland Sea (Fig. 9, years 1075 to 1079). Subsequently, the AMOC ~~recovered~~recovers abruptly to its original strength with an overshoot (Fig. 3). These recovery processes show that the balance of sea ice thickness, sea surface salinity and subsurface ocean temperature ~~determined~~determine the recovery time of the AMOC in this experiment. The recovery process observed here is also similar to the recovery process of AMOC in intrinsic AMOC oscillations observed in Vettoretti and Peltier (2016) and Sherriff-Tadano and Abe-Ouchi (2020).

In contrast, the recovery process ~~differed~~differs in MIS3H (black line in Fig. 8). At first, during the hosing period, sea surface salinity ~~was~~is higher and sea ice thickness ~~was~~is thinner compared with MIS3-5aiceH~~,~~ (Fig. 8a, d, e), which ~~were~~are favourable conditions to induce deepwater formation. ~~Then, after~~Note that at this point, no deepwater forms at northern North Atlantic (Fig. 5d and Fig. 8b, h). After the cessation of freshwater hosing, ~~deepwater formation initiated, triggered by~~however, the initial increase of surface salinity~~.~~ triggers a deepwater formation over Irminger Sea (Fig. 8b, e). Because the surface salinity ~~was~~is already sufficiently high in the ~~weak phase~~ last 100 years of the ~~AMOC,~~hosing period (Fig. 8e), deepwater ~~could~~can form continuously~~.~~ over Irminger Sea (Fig. 8b). As a result, vertical mixing ~~occurred~~occurs continuously and further ~~increased~~increases surface salinity and ~~decreased~~decreases sea ice thickness over the Irminger Sea and Greenland Sea~~, causing~~. The increase in sea surface salinity and density then induce a gradual strengthening of the AMOC~~. Then, the~~ by 4.5 Sv in 80 years (Fig. 3). This gradual increase in the AMOC ~~induced a~~ further helps to increase ~~in~~the surface salinity and ~~a~~ decrease ~~in~~ sea ice ~~(Fig. 8)~~thickness over the Greenland Sea~~.~~ (Fig. 8g, j, k). As a result, 80 years after the cessation of hosing, deepwater formation ~~initiated~~initiates in the Greenland Sea~~,~~ (Fig. 8h), and the AMOC abruptly ~~recovered.~~recovers by 7.1 Sv in 70 years (Fig. 3). Thus, in MIS3H, changes in the surface salinity and sea ice thickness ~~played~~play a larger role in controlling the recovery time of the AMOC, whereas the changes in subsurface ocean temperature ~~played~~plays a minor role in the recovery~~.~~ (Fig. 8f, l).

The above analysis suggests that the differences in surface salinity and sea ice between MIS3H and MIS3-5aiceH under the hosing phase ~~caused~~cause the difference in the recovery time; in MIS3H, surface salinity ~~was~~is higher and sea ice thickness ~~was~~is thinner compared with MIS3-5aiceH, which ~~favoured~~favour a shorter recovery time. The differences in sea ice and surface salinity may be attributed to a difference in the surface wind (Sherriff-Tadano et al. 2018). Figure 10a and d show how the surface wind ~~differed~~differs in the two experiments. Anomaly fields in Fig. 10d reveal the enhancement of cyclonic wind over the northern North Atlantic and southward displacement of the westerly winds in MIS3H compared with MIS3-5aiceH, which ~~were~~are induced by the topography of the Laurentide ice sheet (Pausata et al. 2011, Sherriff-Tadano et al. 2021). ~~With the~~The southward-shifted westerly wind and strong northerly wind over the western North Atlantic~~, less~~ act to reduce the eastward transport of sea ice ~~was transported~~ to the deepwater formation region in MIS3H (Fig. 10c, f). Therefore, even though the atmosphere ~~was~~is colder~~,~~ (Fig. S5), less sea ice ~~existed~~exists over the ~~deepwater formation region.~~Irminger Sea. In terms of surface salinity, the ~~wind intensified~~stronger cyclonic surface winds enhance the Ekman upwelling and gyre circulation that transport~~ warm and~~ saline water to the deepwater formation region and support convection through increasing the surface salinity ~~and decreasing the sea ice~~ (Fig. 10b, e, Montoya et al. 2011, Muglia and Schmittner 2015, Sherriff-Tadano et al. 2018). In fact, a positive wind stress curl ~~was~~is larger in the subpolar region and the Irminger Sea in MIS3H compared with MIS3-5aiceH (Fig. 10d). Therefore, differences in winds over the northern North Atlantic ~~seemed~~seem to contribute to the difference in the recovery time between the two experiments by modulating the surface salinity and sea ice in the stadial period.

3.3 Partially coupled experiments

To clarify the impact of differences in surface wind between MIS3H and MIS3-5aiceH on the recovery time of the AMOC, partially coupled experiments ~~were~~are conducted from the first year after the cessation of freshwater hosing (Fig. 11). First, the reproducibility of the original experiments by the partially coupled experiments ~~was~~is assessed. In PC-MIS3H and PC-MIS3-5aiceH, the recovery time ~~was slightly~~is shorter compared with the corresponding original experiments. In particular, the recovery time ~~was~~is 200 to 300 years shorter in PC-MIS3-5aiceH compared with MIS3-5aiceH. This ~~was~~is related to the removal of sub-monthly variations in wind stress (Sherriff-Tadano et al. 2021, Supplementary information); removal of these variations ~~caused~~causes thinning of sea ice in the centre of the subpolar region by reducing sea ice transport in this region (Fig. 12b, c) and ~~created~~creates favourable conditions for deepwater to form. Nevertheless, even though PC-MIS3-5aiceH ~~underestimated~~underestimates the recovery time, PC-MIS3H and PC-MIS3-5aiceH at least ~~reproduced~~reproduce the main difference of the recovery time between MIS3H and MIS3-5aiceH.

Next, the effect of surface wind on the recovery time of the AMOC ~~was~~is explored. When the surface winds of the MIS5a ice sheet (MIS3-5aiceH) ~~were~~are applied to PC-MIS3H (PC-MIS3H_wind), the AMOC ~~did~~does not start to recover in the first 100 years, as seen in MIS3H~~.~~ (Fig. 11). This ~~was~~is related to the weaker cyclonic surface wind, which ~~reduced~~reduces the wind-driven oceanic transport of salt into the deepwater formation and caused a decrease of sea surface salinity there. Thus, partially coupled experiments ~~showed~~show that the stronger wind in MIS3H ~~created~~creates favourable conditions to cause an earlier recovery of the AMOC. This ~~was~~is also confirmed by another sensitivity experiment showing earlier recovery of the AMOC when the surface wind of MIS3H ~~was~~is applied to PC-MIS3-5aiceH (not shown).

Interestingly, the AMOC ~~did~~does not recover in PC-MIS3H_wind during the integration~~.~~, despite having the same surface wind forcing as in PC-MIS3-5aiceH, which recovers around year 900. A similar feature ~~was~~is also observed in PC-MIS3H_windwater~~,~~ (Table 2), where the model ~~was~~is forced with the ~~heat flux~~surface cooling of the MIS3 ice sheet (MIS3H) and the surface wind and atmospheric freshwater flux of the MIS5a ice sheet (MIS3-5aiceH). ~~This~~The long stadial ~~state was~~states observed in these two experiments are caused by the very thick sea ice over the deepwater formation region~~,~~ (green and blue lines compared to the red line in Fig. 12b, see also Fig. 12d), associated with stronger surface cooling by the MIS3 ice sheet (Fig. ~~12b, d~~S5). After the cessation of freshwater hosing and the replacement of the surface wind, the sea surface salinity as well as the subsurface ocean temperature ~~increased~~increase gradually in PC-MIS3H_wind and PC-MIS3H_windwater~~.~~ as in PC-MIS3-5aiceH. However, the thick sea ice over the deepwater region ~~prevented~~prevents the initiation of deepwater formation and ~~maintained~~maintains the weak AMOC (Loving and Vallis 2005, Bitz et al. 2007, Oka et al. 2012, Sherriff-Tadano et al. 2021). This result shows that the cooling effect of the MIS3 ice sheet ~~played~~plays a role in increasing the recovery time of the AMOC by increasing sea ice over the deepwater formation region.

Lastly, the effects of differences in atmospheric freshwater flux on the recovery time of the AMOC ~~were~~are explored for completeness. When the atmospheric freshwater flux of the MIS5a ice sheet (MIS3-5aiceH) ~~was~~is applied to PC-MIS3H (PC-MIS3H_water), the recovery time of the AMOC ~~increased~~increases slightly~~.~~ (Fig. 11). This ~~was~~is associated with a decrease of sea surface salinity over the deepwater formation region (Fig. 12a), which ~~was~~is linked to the northward shift of the rain belt in the mid-latitudes caused by the smaller ice sheet (Eisenman et al. 2009). Therefore, the larger ~~(smaller)~~ MIS3 ~~(MIS5a)~~ ice sheet ~~reduced (increased)~~reduces the recovery time of the AMOC by reducing ~~(increasing)~~ the input of atmospheric freshwater flux over the deepwater formation region~~.~~ when compared to MIS5a ice sheet. Nevertheless, the differences in atmospheric freshwater flux ~~had~~have less impact on the duration of the recovery compared with the effect of wind in these experiments. ~~To summarize, the shorter recovery time in MIS3H compared with MIS3-5aiceH was a result of the dominance of the surface wind effect caused by larger ice sheets, which promoted the recovery of the AMOC, compared with the surface cooling effect, which promoted increase in the recovery time of the AMOC.~~

To summarize, the shorter recovery time in MIS3H compared with MIS3-5aiceH is a result of the dominance of the surface wind effect caused by larger ice sheets. The stronger cyclonic surface winds at mid-high latitudes in MIS3H than in MIS3-5aiceH (Fig. 10d) enhance the wind-driven transport of salt to the deepwater formation in MIS3H (Fig. 10e). In addition, the strong northerly wind anomaly over the western North Atlantic and the southward shift of westerly wind cause a reduction of wind-driven transport of sea ice to the deepwater formation region over Irminger Sea in MIS3H (Fig. 10f). The higher surface salinity (Fig. 8d) and thinner sea ice thickness (Fig. 8a) over the deepwater formation region during the weak AMOC state then increase the probability of the recovery of the AMOC and cause an early recovery in MIS3H (Fig. 3).

4. Discussion

Our results show that the recovery time of the AMOC largely ~~depend~~depends on the background climate. In MIS3H, the AMOC ~~started~~starts to recover soon after the cessation of freshwater hosing, whereas in MIS3-5aiceH, the AMOC first ~~recovered~~recovers gradually for several hundred years and then ~~recovered~~recovers abruptly~~. It was~~ (Fig. 3). From partially coupled experiments, it is found that the difference in surface wind ~~played~~plays a role in causing the ~~difference between~~shorter recovery of AMOC in MIS3H ~~and~~compared to MIS3-5aiceH~~. The cyclonic surface wind at mid-high latitudes was~~ (Fig. 11). In contrast, it is also found that the stronger ~~in MIS3H than~~ surface cooling by larger ice sheets promote to increase in ~~MIS3-5aiceH. In addition, a strong northerly wind anomaly was induced~~ the recovery time of the AMOC by increasing the amount of sea ice over the ~~western North Atlantic. As a result, the wind-driven transport of salt to the~~ deepwater formation region ~~was larger and wind-driven sea ice transport smaller in MIS3H compared with MIS3-5aiceH. This led to higher surface salinity and thinner sea ice thickness over the deepwater formation region, which increased the probability of the recovery of the AMOC.~~(Fig. 11). Thus, we find that the changes in the surface wind caused by the glacial ice sheet ~~could~~can contribute to a shorter stadial during MIS3 compared with MIS5, when its effect is stronger than that of surface cooling.

Previous studies ~~have shown~~show that the subsurface ocean temperature (Mignot et al. 2007, Gong et al. 2013), freshwater transport by the AMOC (de Vreis and Weber 2005, Weber and Drijfhout 2007, Liu et al. 2014) and surface winds (Goes et al. 2019) affect the recovery time of the AMOC. Our analysis of these parameters in hosing experiments ~~showed~~show results consistent with these studies. With respect to subsurface ocean temperature, the subsurface ocean temperature anomaly ~~was~~is larger in MIS3H than in MIS3H-5aiceH, which ~~favoured~~favours early recovery of the AMOC by destabilizing the water column in the deepwater formation region (Gong et al. 2013). With respect to freshwater transport by the AMOC, our analysis ~~showed~~shows a larger amount of freshwater transport into the Atlantic in MIS3H than in MIS3-5aiceH (0.073 Sv and 0.017 Sv, respectively, before freshwater hosing). Thus, the results ~~were~~are also consistent with previous studies in that the experiment in which the AMOC ~~transported~~transports more freshwater in the Atlantic ~~recovered~~recovers more quickly. Nevertheless, as shown in the partially coupled experiments, the AMOC ~~could not~~cannot recover in PC-MIS3H_wind when the surface wind ~~was~~is weak over the deepwater formation region. With respect to wind forcing, Goes et al. (2019) ~~showed~~show that the stronger surface wind in the LGM ~~caused~~cause a shorter recovery time of the AMOC compared with that from the modern climate. Our study is also in line with their study in that the stronger surface wind in MIS3 compared with MIS5a induced by ice sheet differences ~~caused~~causes a shorter recovery time of the AMOC. Therefore, together with Goes et al. (2019), this study reveals another important control on the recovery time of the AMOC: differences in localities of winds in the deepwater formation region. In this regard, this study supports the conclusion of Weber and Drijfhout (2007) and Bitz et al. (2007) that differences in atmospheric conditions play a role in controlling the recovery time of the AMOC.

Our findings can be used to interpret model discrepancies. Gong et al. (2013) ~~showed~~show that the recovery time of the AMOC ~~was~~is shorter under mid-glacial and LGM conditions compared with the PI climate, whereas Weber and Drijhout (2007) and Bitz et al. (2007) show that the recovery time ~~was~~is longer under LGM conditions compared with PI conditions. In these studies, all of the boundary conditions (e.g. glacial ice sheets and CO_2) ~~were~~are modified; thus, the reason for differences between the models remains elusive. Based on this study, we suggest that the wind effect of the glacial ice sheets ~~played~~plays the dominant role in the study of Gong et al. (2013), whereas the sea ice effect caused by lowering of the CO_2 concentration and by the glacial ice sheet ~~played~~plays a larger role in the studies of Weber and Drijhout (2007) and Bitz et al. (2007). In fact, the surface winds ~~were~~are strongest in the mid-glacial experiment compared with the other experiments of Gong et al. (2013, 2015). In contrast, the surface winds ~~were~~are not stronger in the LGM simulations compared with the PI simulation by Bitz et al. (2007, Otto-Bliesner et al. 2006), even under the existence of glacial ice sheets. Although the cause of the difference in surface wind remains elusive, differences in the strength of the surface winds between models may ~~have caused~~cause the difference in the recovery time. Because Weber and Drihout (2007) ~~used~~use an EMIC, the model may ~~have underestimated~~underestimate the wind change caused by the glacial ice sheets. Therefore, the wind effect may not have ~~had~~ a strong impact, and thus the sea ice effect played the dominant role.

Ice core studies ~~have~~ recently ~~suggested~~suggest a possibility that the relation between the background climate and the durations of climate states can differ between interstadials and stadials; although the durations of both interstadials and stadials are generally affected by global temperatures and surface cooling (Buizert and Schmittner 2015, Kawamura et al. 2017, Lohmann and Ditlevsen 2019), the durations of stadials may be affected by additional conditions over the Northern Hemisphere (Lohmann 2019) when the global climate is generally cold. A similar feature ~~was~~is also observed in climate model simulations of Sherriff-Tadano et al. (2021) and this study. For example, using the same ice sheet forcing, Sherriff-Tadano et al. (2021) ~~showed~~show that differences in the vigorous AMOC between MIS5a and MIS3 ~~were~~are mainly caused by the differences in CO_2. In their simulations, ice sheet differences ~~had~~have small impacts on the vigorous AMOC because of compensational balance between the strengthening effect of surface wind and the weakening effect of sea ice increase in the Northern and Southern Hemispheres. In contrast, in the hosing experiments of the present study, the effect of surface wind by the larger MIS3 ice sheets ~~appeared~~appears to be stronger compared with stronger surface cooling by the ice sheets and lower CO_2, causing shortening of the stadials in MIS3 compared with MIS5a. These results support the findings of ice core studies and suggest that the relation between the background climate and the durations of climate states can differ between interstadials and stadials.

Although the expansion of glacial ice sheets from MIS5a to MIS3 ~~could have contributed~~can contribute to short stadials during the mid-glacial period, we should keep in mind that there are still large uncertainties in reconstructions of the glacial ice sheets prior to LGM. For example, sea level reconstructions show a wide range of ice sheet volume from 40- to 90-meter sea level equivalent during MIS3 (Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017, Gowan et al. 2021). This can directly translate into uncertainties in the quantitative effect of the ice sheets on AMOC, and also can indirectly affect the AMOC by changing the timing of the closure of Bering Strait, which may be important when interpreting DO cycles and AMOC variabilities (Hu et al. 2015). Furthermore, uncertainties in the shape of ice sheet may affect the balance of the surface wind and surface cooling effects on AMOC. Hence, further studies on similar topic using other ice sheet reconstructions are important to better interpret the evolution of millennial-time scale climate and AMOC variabilities over the glacial period.

Also there is another unsolved problem: why ~~were~~are stadials very long during MIS2 and MIS4, when the glacial ice sheets ~~were~~are at their largest size (McManus et al. 1999, Buizert and Schmittner 2015, Kawamura et al. 2017)? During these periods, summer insolation over the North Atlantic ~~was~~is very low; therefore, this may be important. In fact, Turney et al. (2015) ~~showed~~show that lowering of the obliquity in MIS2 ~~weakened~~weakens the AMOC by increasing sea ice in the North Atlantic. In addition, very strong surface cooling by the glacial ice sheets may ~~have caused~~cause long stadials. In fact, we ~~found~~find that the strengthening of surface cooling by the larger ice sheets ~~could~~can increase the recovery time of the AMOC by increasing the amount of sea ice over the deepwater formation region. If there ~~was~~is a shift from a wind-dominated ice sheet effect, which ~~shortened~~shortens the recovery time of the AMOC, to a surface cooling-dominated ice sheet effect, the large ice sheets during MIS2 and MIS4 ~~could~~can contribute to the very long stadials. Further investigations of the roles of insolation and the ice sheet effect will be important for better understanding the glacial AMOC as well as interpreting the controlling parameters changing the duration of stadials over the glacial period.

Lastly, drastic weakening of the AMOC ~~was~~is induced by freshwater hosing in this study. ~~However, recent~~Recent studies ~~have shown~~, however, show that the large-scale freshwater hosing ~~was~~is a result of weakening of the AMOC, rather than the cause of the drastic weakening of the AMOC (Alvarez-Solas et al. 2011, Barker et al. 2015). Nevertheless, the main point of our results is that once the AMOC ~~was~~is weakened by external forcing, the recovery time of the AMOC ~~differed~~differs because of the ice sheet configurations. Thus, the external forcing that ~~induced~~induces the weakening of the AMOC ~~did~~does not have to be a large discharge from the ice sheet and ~~could have been~~can be other forcing, such as a small amount of freshwater flux from the ice sheet, or perhaps volcanic eruptions. ~~Thus~~Hence, our results are applicable for DO cycles forced by external forcing. ~~However~~On the other hand, previous studies ~~have shown~~show that DO cycles may be excited by internal oscillation of the atmosphere–sea ice–ocean system (Arzel et al. 2010, Peltier and Vettoretti 2014, Vettoretti and Peltier 2016, Brown and Galbraith 2016, Klockmann et al. 2018, Sherriff-Tadano and Abe-Ouchi 2020). ~~Although we have not explicitly investigated this case, we speculate that stronger winds in the northern North Atlantic could~~In Vettoretti and Peltier (2016) and Sherriff-Tadano and Abe-Ouchi (2020), the recovery of the AMOC is excited by the gradual warming of subsurface ocean and its balance with sea ice and surface salinity over deepwater formation region. From this point of view, the recovery process of the AMOC in the present hosing experiments is similar to that of the intrinsic oscillations of AMOC. Therefore, our findings may not be confined to the hosing experiments or DO cycles induced by external forcing, but also may be applicable to DO cycles associated with intrinsic oscillations of AMOC. Hence, although we have not explicitly investigated the case of intrinsic oscillations of AMOC, we speculate that stronger winds in the northern North Atlantic can increase the probability of deepwater formation during stadials by modifying the balance of sea ice, surface salinity and subsurface ocean temperature. Nevertheless, it is important to assess our findings in this case as well.

5. Conclusion

To understand the reason why the durations of stadials ~~were~~are shorter during MIS3 compared with MIS5 despite the generally colder climate in MIS3, we ~~explored~~explore the impact of the mid-glacial ice sheets on the durations of stadials. For this purpose, we ~~conducted~~conduct freshwater hosing experiments with the MIROC4m AOGCM under MIS3 and MIS5a conditions. Furthermore, to extract the impact of the difference in the glacial ice sheets on the recovery time of the AMOC, a sensitivity experiment ~~was~~is performed, which ~~was~~is forced with the MIS5a ice sheet under MIS3 CO_2 and insolation conditions (MIS3-~~5aice~~5aiceH). The ice sheets of MIS3 and MIS5a ~~were~~are taken from an ice sheet model, which ~~reproduced~~reproduces the evolution of the ice sheets over the last 400,000 years (Abe-Ouchi et al. 2013). Freshwater hosing of 0.1 Sv over the northern North Atlantic ~~induced~~induces collapse of the AMOC and southward expansion of sea ice, which ~~covered~~covers the deepwater formation region in all experiments. After the cessation of freshwater hosing, the AMOC ~~recovered~~recovers in all experiments, which ~~was~~is associated with the initiation of deepwater formation in both the Irminger Sea and the Greenland Sea. However, the recovery time of the AMOC ~~differed~~differs among the experiments; following the cessation of freshwater hosing, recovery ~~started~~starts after 80 years in MIS3, after approximately 200 years in MIS5a, and after approximately 600 years in MIS3-5aice. The slightly shorter recovery time in MIS3 compared with MIS5a ~~was~~is consistent with the ice core data. The sensitivity experiment (MIS3-~~5aice~~5aiceH) extracting the effect of the mid-glacial ice sheet ~~showed~~shows that a larger glacial ice sheet ~~caused~~causes a shorter recovery time in MIS3, whereas lowering of the CO_2 concentration and changes in insolation ~~caused~~cause an increase of the recovery time. The partially coupled experiments further ~~showed~~show that stronger surface winds over the North Atlantic ~~shortened~~shorten the recovery time by increasing the surface salinity and decreasing the sea ice amount in the deepwater formation region. In contrast, we also ~~found~~find that the surface cooling caused by larger ice sheets ~~tended~~tends to increase the recovery time of the AMOC by increasing the sea ice thickness over the North Atlantic. In our simulation, the effect of surface winds ~~appeared~~appears to be stronger than the effect of surface cooling, thus causing a shortening of the recovery time of the AMOC. Therefore, our results suggest that the expansion of glacial ice sheets ~~played~~plays a role in reducing the duration of stadials during MIS3 and thus ~~could~~can contribute to the frequent DO cycles during MIS3 when the effect of surface winds ~~dominated~~dominates. Nevertheless, the effect of surface cooling may be important when the long stadials during the MIS2 and MIS4 and the model discrepancies are considered.

Code and data availability

The MIROC code associated with this study is available to those who conduct collaborative research with the model users under license from copyright holders. The code of partially coupled experiments is available from the corresponding author (S. S.-T.) upon reasonable request. The simulation data will be available from https://ccsr.aori.u-tokyo.ac.jp/~tadano/.

Author contribution

S. S.-T. performed the climate model simulation and analyzed the results with the assistance of A. A.-O. S. S.-T. performed the partially coupled experiments with the assistance of A. O. The manuscript was written by S. S.-T. with contributions from all authors.

Competing interest

The authors declare no competing interests.

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