



## RESEARCH LETTER

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## Key Points:

- The AMOC weakens greatly in response to deglacial lowering ice sheet topography
- This weakening follows a strikingly linear relationship with ice sheet volume
- The weakening is caused by a wind-driven sea ice expansion process

## Supporting Information:

- Readme
- Figures S1–S4
- Text S1–S4

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## Linear weakening of the AMOC in response to receding glacial ice sheets in CCSM3

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**Abstract** The transient response of the Atlantic Meridional Overturning Circulation (AMOC) to a deglacial ice sheet retreat is studied using the Community Climate System Model version 3 (CCSM3), with a focus on orographic effects rather than meltwater discharge. It is found that the AMOC weakens significantly (41%) in response to the deglacial ice sheet retreat. The AMOC weakening follows the decrease of the Northern Hemisphere ice sheet volume linearly, with no evidence of abrupt thresholds. A wind-driven mechanism is proposed to explain the weakening of the AMOC: lowering the Northern Hemisphere ice sheets induces a northward shift of the westerlies, which causes a rapid eastward sea ice transport and expanded sea ice cover over the subpolar North Atlantic; this expanded sea ice insulates the ocean from heat loss and leads to suppressed deep convection and a weakened AMOC. A sea ice-ocean positive feedback could be further established between the AMOC decrease and sea ice expansion.

## 1. Introduction

Ice sheets actively influence the climate system because of their orographic features, their albedo, and their function as the largest readily exchangeable reservoir of fresh water on Earth [e.g., Clark *et al.*, 1999]. Paleoclimate records have shown that global ice sheet volume during the late Quaternary has varied significantly with the glacial-interglacial cycles, possibly driven by variations in Earth's orbit [Hays *et al.*, 1976; Shackleton, 2000]. Along with the waxing and waning of ice sheets, the Atlantic Meridional Overturning Circulation (AMOC) is also thought to have experienced significant changes [McManus *et al.*, 2004; Rahmstorf, 2002], with a possible contribution to the abrupt climate changes in the North Atlantic region and the globe [Clark *et al.*, 2002].

Previous studies regarding the influence of ice sheet retreat on the AMOC have focused on the effects of meltwater discharge [Broecker, 1994; Hu *et al.*, 2009, and references therein], while the role of the associated reorganization of atmospheric circulation induced by the changing orography has been largely neglected. Recently, a modeling study [Eisenman *et al.*, 2009] suggested that anomalous rainfall over the northern North Atlantic Ocean associated with orographic forcing from the receding glacial ice sheets could cause a decrease in the AMOC and a possible abrupt climate change. However, other studies that also used coupled climate models postulated different mechanisms for the weakening of the AMOC, e.g., the adjustment of sea ice coverage [Vettoretti and Peltier, 2013; Zhang *et al.*, 2014] and variations in wind-driven ocean circulations [Zhang *et al.*, 2014] caused by ice sheet changes. Therefore, basic questions remain regarding the AMOC response to the orographic effects of receding ice sheets, and the underlying mechanisms are still open to debate. Furthermore, in studies only using fully coupled models the mechanism driving a response typically remains ambiguous due to the complicated feedbacks involved and the coupled nature of the climate system, and companion simulations in which some components of the climate system are inactivated help elucidate physical mechanisms [Eisenman *et al.*, 2009].

Another question of great interests related to the ice sheet retreat is whether a gradual variation in the ice sheet volume could trigger abrupt shifts in the AMOC [Wunsch, 2006] through factors such as freshwater forcing [Rahmstorf, 1995] or heat flux forcing [Oka *et al.*, 2012]. Zhang *et al.* [2014] has recently demonstrated that, in their coupled general circulation model, variations in intermediate ice sheet volume could cause abrupt changes in the AMOC and rapid glacial climate shifts via the northern westerly shifts associated with the ice sheet orographic changes. Given the model uncertainty on simulating glacial ocean

circulation [Otto-Bliesner *et al.*, 2007], this nonlinear behavior of the AMOC should be carefully examined across multiple climate models.

The objective of this paper is to study the transient response of the AMOC to a realistic deglacial lowering of ice sheets in the Community Climate System Model version 3 (CCSM3) and further investigate the underlying mechanisms by using both atmosphere-alone and fully coupled simulations. Our study suggests that the retreat of the Northern Hemisphere ice sheets induces a northward shift of the westerlies in the northern North Atlantic. This shift causes a rapid sea ice expansion and enhanced insulation against oceanic heat loss to the atmosphere, which then leads to a reduction of deep convection and eventually a weaker AMOC. The transient weakening of the AMOC is gradual in CCSM3 with respect to the ice sheet topographic forcing, with no evidence of nonlinear thresholds. The remainder of this paper is arranged as follows: Section 2 briefly describes the model and experiments. The evolution of the AMOC to a realistic deglacial lowering of ice sheets is shown in section 3. We then investigate the underlying mechanisms in section 4. A summary and further discussion is given in section 5.

## 2. Model and Experiments

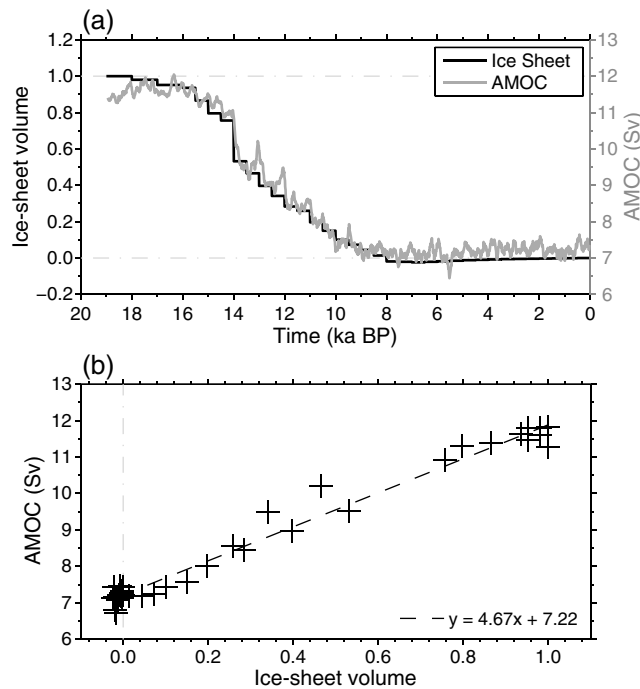
We analyze a transient simulation of climate evolution over the last 21,000 years forced only by the receding ice sheets (TraIS, hereafter) in a low-resolution version of CCSM3 [Yeager *et al.*, 2006]. The model components include the Community Atmosphere Model 3 (CAM3) at T31 horizontal resolution with 26 vertical levels, the Community Land Model 3 also at T31 resolution, the Parallel Ocean Program at a nominal 3° horizontal resolution with 25 vertical levels, and the Community Sea Ice Model 5 on the same horizontal grid as the ocean. TraIS is branched off from a transient simulation of the last 21,000 years [Z. Liu *et al.*, 2009] at 19 ka before present (A.D. 1950) and is integrated to the present day [He *et al.*, 2013; Shakun *et al.*, 2012]. The ice sheet configuration in the simulation is altered every 500 years based on the ICE-5G reconstruction [Peltier, 2004]; the solar insolation, greenhouse gases (GHGs), and ocean bathymetry are prescribed at the value of 19 ka, and the effect of freshwater flux associated with the ice sheet melting is not included.

In addition to the transient simulation with the fully coupled CCSM3, two atmosphere-only simulations using the same atmosphere component model (CAM3) are employed in this study (LARGEatm and MEDIUMatm [Eisenman *et al.*, 2009]). The sea surface temperature and sea ice cover in both simulations are specified to follow the seasonal cycle from a coupled simulation at 21 ka. The two runs only differ in the ice sheet configuration and GHG concentrations: LARGEatm uses the ice sheets and GHGs at 21 ka while MEDIUMatm makes use of those at 12 ka. Readers are referred to Eisenman *et al.* [2009] for the details of these two experiments. The difference in an atmospheric variable between MEDIUMatm and LARGEatm mainly represents its response to receding ice sheets excluding the possible feedbacks from other components involving sea ice and ocean (the contribution from difference GHG concentrations is expected to be small since both runs use the same prescribed sea surface temperature and sea ice) [Eisenman *et al.*, 2009].

## 3. Linear Weakening of the AMOC to Receding Ice Sheets

In the transient ice sheet simulation, the maximum AMOC decreases following the lowering of the Northern Hemisphere ice sheets, as shown in Figure 1. At 19 ka, the AMOC maximum is 11.5 sverdrup (Sv), comparable to that at the Last Glacial Maximum (LGM, 22–19 ka) in the transient simulation with all climatic forcing, including GHGs, insolation, ice sheets, and freshwater fluxes [Z. Liu *et al.*, 2009]. In response to the deglacial receding of ice sheets, the AMOC weakens by 41%, a significant amount compared with glacial variations and changes that result from other climatic factors as suggested by paleoclimate reconstructions [McManus *et al.*, 2004] and numerical simulations [He *et al.*, 2013; Z. Liu *et al.*, 2009; Shakun *et al.*, 2012; Zhu *et al.*, 2014]. These results imply that the orographic effects alone associated with glacial variations in ice sheets can cause significant changes in the AMOC and, in turn, the climate at regional and global scales (Figure S1 and Text S1 in the supporting information).

Notably, the AMOC strength and the Northern Hemisphere ice sheet volume exhibit a strikingly linear relationship with a correlation coefficient larger than 0.9 (Figure 1b). The linear regression coefficient (with a 95% confidence interval) is  $4.7 \pm 0.2$  Sv per total deglacial change of ice sheets. Although the temporal evolution of the AMOC strength shows an abrupt reduction at 14 ka, it is accompanied by the



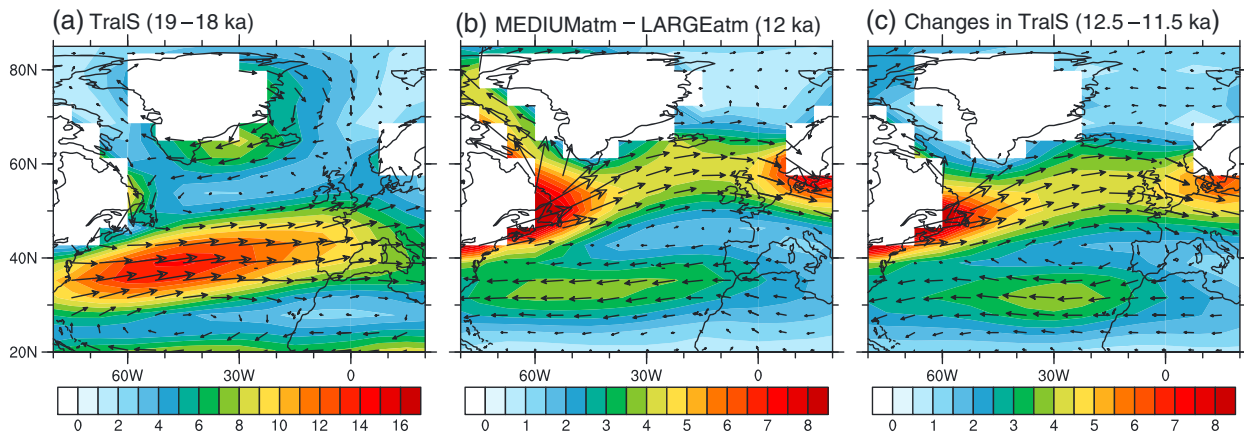
**Figure 1.** (a) Time series of the Northern Hemisphere ice sheet volume (black, left axis) and the maximum AMOC in the transient simulation (gray, right axis, units:  $Sv = 10^6 m^3 s^{-1}$ ). (b) Scatterplot of the maximum AMOC and the Northern Hemisphere ice sheet volume. Note that the ice sheet height/volume is altered every 500 years in the transient simulation, the time series of the AMOC is from the decadal mean data, and the mean values of the maximum AMOC over the last 100 years within each interval are used to produce the scatterplot in Figure 1b. For illustration purpose, the ice sheet volume has been rescaled between 0 and 1.

largest retreat of ice sheets (22% by volume, corresponding roughly to meltwater pulse 1A). Therefore, their linear relationship is still evident. Our CCSM3 simulation results do not support the possibility that the ice sheet orographic forcing is able to trigger a nonlinear “switch-like” response in the AMOC, at odds with Zhang et al. [2014].

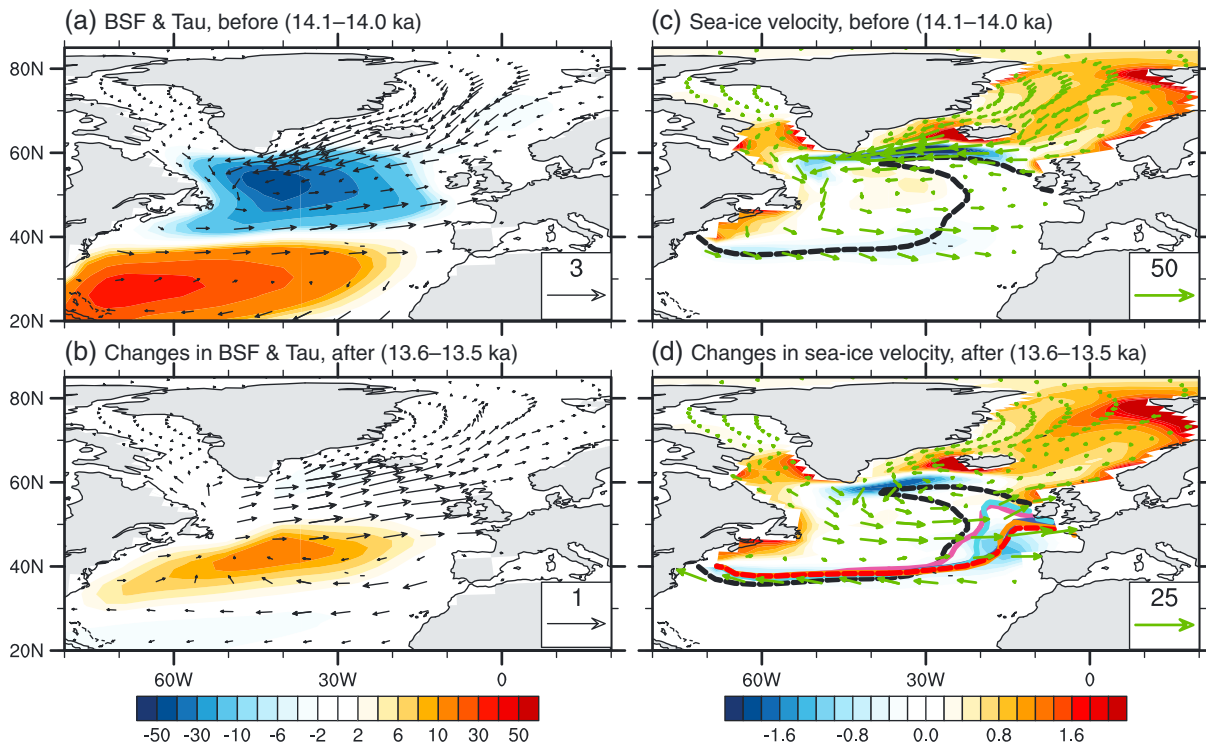
#### 4. Changes in Low-Level Winds and Sea Ice Transport

To understand the dynamic mechanisms of the AMOC response to receding ice sheets, we examine the changes in low-level winds in both the atmosphere-only simulations and fully coupled transient simulation. At the LGM (19–18 ka in TraIS), the model simulates a westerly jet across the Atlantic that is nearly zonal along  $\sim 40^\circ N$ , with cyclonic and anticyclonic winds to the north and south, respectively (Figure 2a). In response to ice sheet retreat, the atmosphere-only simulations (MEDIUMatm – LARGEatm) reveal anticyclonic wind changes over the North Atlantic with changes in magnitude up to  $5 m s^{-1}$  (Figure 2b),

which is a manifestation of the northward shift of the westerly jet [Kutzbach and Guetter, 1986; Manabe and Broccoli, 1985]. Comparable anticyclonic wind changes also stand out in TraIS at 12 ka (Figure 2c), suggesting the same origin for the atmospheric response to ice sheets as the orographic effects [Pausata et al., 2011]. The pattern of wind response at 850 hPa is robust across the entire transient simulation (see also Figure 4b) and is coherent with the surface wind stress (Figure 3b). It is worth noting that, in



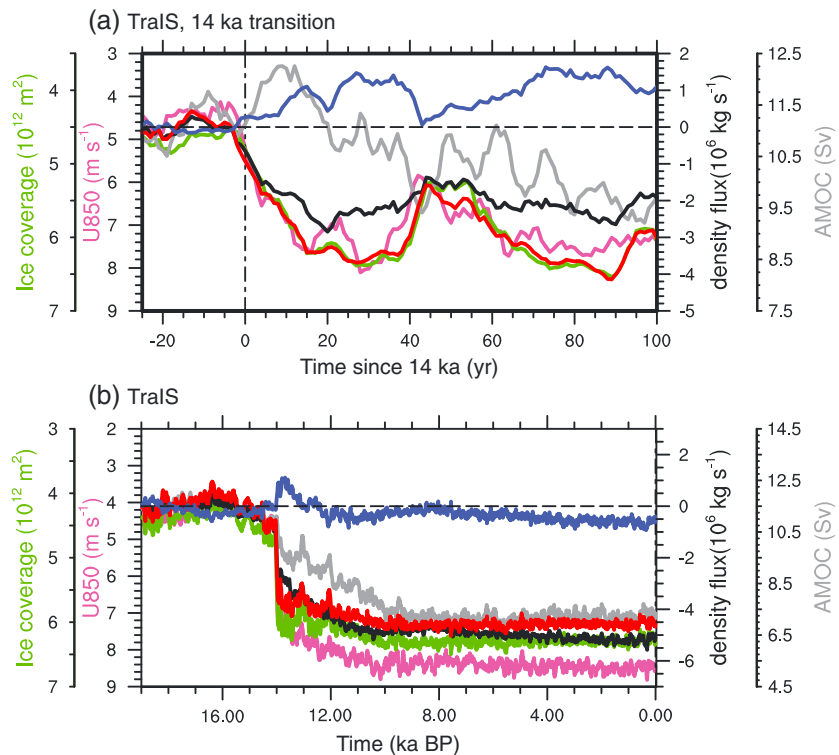
**Figure 2.** (a) Climatological annual mean winds at 850 hPa (vectors, units:  $m s^{-1}$ ) over the North Atlantic before the lowering of ice sheets (averaged between 19 and 18 ka). (b) Differences in the annual mean winds at 850 hPa in the atmosphere-alone simulations with the ice sheet volume at 12 and 21 ka respectively. (c) The same as Figure 2b, but for the fully coupled transient simulation. Shading denotes the magnitude of the wind vectors.



**Figure 3.** (a) Last 100 year (14.1–14.0 ka) average before the 14 ka transition of the annual mean barotropic stream function (BSF, shading, units: Sv) and surface wind stress (black vectors, units:  $\text{dyn cm}^{-2}$ ). (b) 401–500 years (13.6–13.5 ka) average after the 14 ka transition of the changes in barotropic stream function and surface wind stress. (c) Last 100 year (14.1–14.0 ka) average before the 14 ka transition of the annual mean sea ice formation rate (shading, units:  $\text{cm d}^{-1}$ ), sea ice velocity (green vectors, units:  $\text{cm s}^{-1}$ ), and the February sea ice margin (defined as the 15% sea ice coverage) (black dashed). (d) 401–500 years (13.6–13.5 ka) average after the 14 ka transition of the sea ice formation rate, changes in sea ice velocity, and the progression of the February sea ice margin (black dashed, before the transition; magenta, the first year; blue, years 5–15; cyan, years 45–55; dark orange, years 95–105; red dashed, years 401–500).

response to receding ice sheets, TraIS is characterized by a marked cooling in the northern high latitudes, especially over ocean in the Labrador Sea and the Greenland, Iceland, and Norwegian Seas, as well as a weaker warming in the Southern Hemisphere (Figure S1), indicating important feedbacks from ocean and sea ice adjustments.

The anomalous westerly winds in the Atlantic midlatitudes can cause a significant expansion of sea ice through wind-driven processes, as explained below. The abrupt transition at 14 ka provides an example. Before the transition, the wind-driven counterclockwise subpolar gyre and clockwise subtropical gyre are distinct in the ocean (Figure 3a). Sea ice generally forms in the northern and western parts of the subpolar region (Figure 3c, shading with warm color), moves southward and eastward (green vectors) due to wind-driven processes (Figure 3a), and melts to the south of Greenland ( $\sim 60^\circ\text{N}$ ) and the midlatitudes ( $\sim 40^\circ\text{N}$ ) (Figure 3c, shading with cold color), producing an “s-shaped” February sea ice margin (black dashed contour). After the sudden lowering of ice sheets, there is an evident northward shift of the gyre systems: a strengthening of the subtropical gyre along its northern edge and a weakening of the subpolar gyre along its southern edge ( $40^\circ\text{N}$ – $50^\circ\text{N}$ ) (Figure 3b). Consequently, sea ice is transported anomalously eastward in the northern part ( $\sim 50^\circ\text{N}$ ) and westward in the southern part ( $\sim 40^\circ\text{N}$ ) (Figure 3d, green vectors), causing rapid reorganization of the sea ice into a more zonal shape (contours). The blue, magenta, cyan, dark orange, and dashed red contours represent the February sea ice margin for the year 1, years 5–15, years 45–55, years 95–105, and years 401–500 average after the transition, respectively. The most striking feature is that a significant part of the sea ice expansion can be accomplished within 1 year. This rapid sea ice expansion implies the key role of the varied wind stress on sea ice transport, because the local sea ice formation (shading) is insignificant. Specifically, it is found that the change in the thermodynamic sea ice volume tendency over the northern North Atlantic is negative and smaller than the positive value in the dynamic volume tendency (Figure S2 and Text S2), supporting the interpretation that sea ice transport is the primary



**Figure 4.** (a) Time series of the annual mean area-averaged zonal wind at 850 hPa (magenta, first left axis), sea ice area (green, second left axis), area-integrated total, thermal, and haline surface density flux (black, red, and blue, respectively, first right axis) and the maximum AMOC (gray, second right axis) over the northern North Atlantic (50–70°N) near the 14 ka transition. (b) As in Figure 4a, but for the time series of decadal means in the entire transient simulation.

factor contributing to the expansion. Note that this rapid response in sea ice cover could not have resulted from the weakening of the AMOC, because the timescales of the latter is much longer than several years.

The wind-induced sea ice expansion, especially over the deep water formation region, can inhibit the deep convection and eventually weaken the AMOC through the sea ice insulating effect (Figure S3 and Text S3). Afterward, the weakened AMOC can further enhance the sea ice expansion through the reduced northward heat transport (Figure S4 and Text S4), forming a positive feedback between the sea ice expansion and the AMOC weakening [Jayne and Marotzke, 1999; Zhong *et al.*, 2011]. We note that changes in sea surface density from anomalous precipitation and evaporation (including river runoff, Figures S3g and S3h) are relatively small and therefore do not appear to play a dominant role in changing the AMOC. This is in contrast to the rain-driven mechanism proposed by Eisenman *et al.* [2009], and possible explanations are a topic for further study.

Our proposed mechanism involving wind-induced sea ice expansion and the subsequent insulating effect can be further supported by analyzing the evolution of the zonal wind, sea ice coverage, and surface buoyancy fluxes over the North Atlantic subpolar region (50–70°N). In TraIS, after the sudden ice sheet lowering at 14 ka (Figure 4a), both the zonal wind and sea ice cover exhibit a rapid adjustment in the first few years, with an increase of 62% in wind (from 4.5 to 7.3  $\text{m s}^{-1}$ , magenta, first left axis) and 32% in sea ice cover (from 4.7 to  $6.2 \times 10^{12} \text{ m}^2$ , green, second left axis). Simultaneously, the area-integrated thermal density flux (heat flux-induced density changes) decreases by 49% (red, first right axis), reducing the total density flux substantially (black, first right axis). In comparison, the AMOC does not decrease dramatically until almost 20 years after the sudden ice sheet lowering. Therefore, the initial expansion of sea ice does not appear to be caused by the weakening of the AMOC. We further hypothesize that the wind-driven sea ice expansion mechanism seems to be critical not only for the 14 ka transition but also for the entire deglaciation period in the transient weakening of the AMOC (Figure 4b). The evolution of the zonal wind at 850 hPa, the expansion of sea ice, and the reduction of surface density fluxes are all coherent with the weakening of the AMOC.



## 5. Summary and Discussion

The evolution of the AMOC in response to a deglacial lowering of ice sheets is studied using a transient simulation in the CCSM3. Focus is placed on the effects of ice sheet orography, rather than the associated deglacial meltwater discharge. The simulation indicates that, as the Northern Hemisphere ice sheets recede, the AMOC weakens significantly. Furthermore, the AMOC weakening appears to be gradual during the entire deglaciation simulation, exhibiting an approximately linear response to the Northern Hemisphere ice sheet volume with no clear nonlinear thresholds. A wind-driven mechanism is proposed to explain this weakening: lowering of ice sheets induces a northward shift of the westerlies and a rapid eastward sea ice transport and expansion in the northern North Atlantic, which insulates the ocean from heat loss and eventually leads to suppressed deep convection and weakened AMOC. This AMOC reduction could be further sustained by a positive feedback between the sea ice expansion and the reduction of the northward heat transport by the AMOC at decadal and longer timescales. Our findings reveal that the response of wind fields, and in turn the induced sea ice transport, plays a key role in the reduction of the AMOC in response to the orographic effects of ice sheet retreat [cf. *Vettoretti and Peltier, 2013; Zhang et al., 2014*].

Our experiment suggests a linear weakening of the AMOC, in contrast to the nonlinear behavior described in *Zhang et al. [2014]*. This difference could be related to the different AMOC stability and initial background climates in the two models. In CCSM3, the AMOC is in a stable regime with a single equilibrium under the present day and the LGM climates [*W. Liu et al., 2013, 2014a*], and even during the last deglaciation [*W. Liu et al., 2014b*]. However, in *Zhang et al. [2014]*, they reported that their model (COSMOS, ECHAM5-JSBACH-MPIOM) is in a bistable regime with a strong and a weak AMOC mode coexisting. Furthermore, in comparison to the corresponding preindustrial control simulation, the LGM ocean circulation in CCSM3 is characterized by a shallower and weaker AMOC, while a slightly stronger and shallower AMOC is found in COSMOS [*Zhang et al., 2013*]. These discrepancies call for more modeling research on the AMOC dynamics and its response to the orographic effects of receding ice sheets in coupled models.

Findings in this study imply that in order to understand the role of ice sheets in glacial-interglacial climate change, we need to explicitly consider both the orographic effects and the traditional melting water discharge [cf. *Eisenman et al., 2009; Zhang et al., 2014*]. Furthermore, our experiments do not support the possibility that the ice sheet orographic forcing is able to trigger a nonlinear switch-like response in the AMOC. Nevertheless, they do demonstrate that a sufficiently fast lowering of the ice sheet topography alone (without meltwater discharge), like the 22% decrease by volume at 14 ka, can cause a large and rapid response in the thermohaline circulation and, therefore, regional and global abrupt climate change, through wind field changes [*Wunsch, 2006*]. Notably, in simulations incorporating the deglacial GHG forcing, the decreased AMOC in our study could be greatly overcompensated, as the AMOC at the LGM is suggested to increase more significantly in response to the sole forcing of deglacial GHGs [*Shakun et al., 2012; Zhu et al., 2014*], resulting in a stronger modeled AMOC at the present day.

It should be noted that the proposed mechanism involving sea ice expansion could depend on the background climate state. In a warmer climate with relative small sea ice coverage in the northern North Atlantic, other factors such as the anomalous precipitation and gyre salt transport [*Born et al., 2010; Schiller et al., 1997; Timmermann and Goosse, 2004*] could play a major role. It is also interesting to find that there is an evident tendency for the AMOC to recover for some steps of ice sheet lowering (e.g., at 13.5 and 12.5 ka), but not for others (e.g., 14.0 and 13.0 ka). Additional experiments are needed to study the dependence of the AMOC response on the background climate and details of ice sheet forcing, but are beyond the scope of this study.

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