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Key Points:

- Ice sheet/climate feedbacks can occur on a decadal scale in the future
- Greenland melting causes the deep ocean circulation to decrease significantly
- The discrepancy caused by including an ice sheet causes cooling of up to 30%

Supporting Information:

- Supporting Information S1

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Response of Atlantic overturning to future warming in a coupled atmosphere-ocean-ice sheet model

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Abstract Climate change can influence sea surface conditions and the melting rates of ice sheets; resulting in decreased deep water formation rates and ultimately affecting the strength of the Atlantic Meridional Overturning Circulation (AMOC). As such, a detailed study of the interactive role of dynamic ice sheets on the AMOC and therefore on global climate is required. We utilize a climate model in combination with a dynamic ice sheet model to investigate changes to the AMOC and North Atlantic climate in response to Intergovernmental Panel on Climate Change scenarios for RCP4.5 and RCP6. It is demonstrated that the inclusion of an ice sheet component results in a drastic freshening of the North Atlantic by up to 2 practical salinity units, enhancing high-latitude haloclines and weakening the AMOC by up to 2 sverdrup (10^6 m^3/s). Incorporating a bidirectionally coupled dynamic ice sheet results in relatively reduced warming over Europe due to the associated decrease in heat transport.

1. Introduction

The AMOC is one of the key drivers for heat transport within the climate system [*Boccaletti et al.*, 2005]. It has been well established that this system of deep ocean circulation is sensitive to both freshwater perturbations and changes in ocean temperature [*Rahmstorf*, 2002]. Previous work has demonstrated that freshwater input to the North Atlantic by so-called Heinrich events had triggered abrupt climate changes due to a sudden collapse of the AMOC system [*McManus et al.*, 2004]. Abrupt climate change of this nature has occurred in the past, as shown by several paleoclimate studies [*Naafs et al.*, 2013]. While previous research has demonstrated that an increase in atmospheric greenhouse gas (GHG) concentrations and temperature alone can trigger an AMOC slowdown [*Stocker and Schmittner*, 1997], the additional disturbance caused by large-scale melting of the Greenland ice sheet (GIS) could result in an even more dramatic slowdown. It has been speculated that melting of the GIS could be one of the driving factors responsible for weakening of the circulation system in the future [*Hu et al.*, 2011] and that some effects can already be seen today [*Rahmstorf et al.*, 2015]. However, the extent of this weakening may still be unclear, and it appears to crucially depend on the strength of the freshwater flux [*Hu et al.*, 2013].

Up until now, the scenarios as documented in the Intergovernmental Panel on Climate Change (IPCC) have examined many possible future climate projections [*Moss et al.*, 2010], and there have been several investigations regarding the GIS stability in the light of future climate warming. *Robinson et al.* [2012] found that the GIS is multistable but that a complete loss and an essentially ice-free state is possible with a surface warming of only 1.6°C. The corresponding freshwater effects in the North Atlantic, and the possibility of a muted AMOC have also been investigated with prescribed freshwater perturbations representing GIS melt; *Jungclaus et al.* [2006] and *Driesschaert et al.* [2007] both found that melt water inputs of 0.1 sverdrup (10^6 m^3/s) (Sv) can weaken the AMOC in studies using an Earth System Model of Intermediate Complexity coupled to an ice sheet model. General circulation models with prescribed freshwater perturbations have also been used; *Swingedouw et al.* [2013] studied multiple coarse resolution models and found that all models displayed a reduction of the AMOC when forced by 0.1 Sv of freshwater input of freshwater forcing distributed around Greenland. *Weijer et al.* [2012] found that model complexity may indeed play a role on the transient response of the AMOC to such a freshwater forcing, yet both strongly eddying and coarse resolution ocean models produce a similar quantitative response on decadal time scales; however, work here has been limited to ocean-only models.

There has also been work performed using fully coupled climate-ice sheet models, such as the studies performed by *Fichefet et al.* [2003], *Ridley et al.* [2005], *Mikolajewicz et al.* [2007], *Charbit et al.* [2008], and

Vizcaíno et al. [2008]. However, each of these studies has had limitations, falling back upon coarser resolutions, inconsistent coupling, or idealized forcing scenarios. While these findings have provided a solid basis, there has yet to be a conclusive discussion regarding the connection between GIS melting, AMOC weakening, and the resulting long-term evolution of the climate system utilizing the current state-of-the-art forcing scenarios as presented in the IPCC. We attempt to fill this gap using a dynamic, high-resolution Ice Sheet model (ISM) bidirectionally coupled to an atmosphere-ocean coupled general circulation model (AOGCM).

2. Model and Experimental Setup

The AOGCM simulations in this study are examined with both fixed (designated as *ao* configuration) and dynamic (*aoi* configuration) ice sheets, simulating both Greenland and Antarctica. Both the Earth system and the ice sheet models are run synchronously, exchanging information at the end of every simulated year. The AOGCM and ISM are coupled bidirectionally and exchange information about the orography, surface temperature, precipitation, and ice melt. The methodology for this coupling is described by *Barbi et al.* [2014]. The *aoi* configuration and *ao* configuration both use identical forcings and boundary conditions. The AOGCM used is COSMOS, which includes an atmospheric component ECHAM5, run at T31L19 resolution (3.75° × 3.75°); and a dynamic ocean-sea ice model MPIOM, run on a GR30 grid (approximate average resolution 3.0° × 1.8°, significantly higher at polar latitudes). A dynamic vegetation module is not included, and while vegetation feedbacks are naturally important, the land use changes projected by the IPCC are included in our forcing scenarios. COSMOS has been extensively used for both present day and paleoclimate studies, such as experiments performed to investigate the Last Glacial Maximum [*Zhang et al.*, 2013; *Gong et al.*, 2013], the Holocene [*Wei and Lohmann*, 2012], and the Pliocene [*Stepanek and Lohmann*, 2012]. The ISM RIMBAY [*Thoma et al.*, 2014] was run on a 20 km resolution and applied the shallow ice approximation to both the Greenland and Antarctic ice sheets.

Explicit consideration of a dynamic ice sheet in the model enables us to determine the influence of melting of the GIS on the ocean, the influence of changed ice sheet orography on the atmosphere, and cumulatively, on the entire climate system. Four simulations following the IPCC Representative Concentration Pathway (RCP) scenarios are performed (RCP4.5-*aoi*, RCP4.5-*ao*, RCP6-*aoi*, and RCP6-*ao*). We start from an initial concentration of 280 ppm CO_{2eq}, which corresponds to a preindustrial climate state, simulate the prescribed historic period, and then follow the IPCC guidelines for RCP4.5 (583 ppm CO_{2eq}) and RCP6 (808 ppm CO_{2eq}) as well as the extensions of these scenarios for time periods beyond the 21st century. All forcings are prescribed in units of ppm CO_{2eq}, which transforms all possible forcings utilized in the IPCC experiments into equivalent amounts of GHG based on the resulting radiative forcing.

3. Ice Sheet Response

In response to the increase of GHG concentrations (Figure 1a) and increasing atmospheric temperatures, the dynamic ice sheet begins to melt. For the extension of scenario RCP4.5, the globally averaged temperature increase for the last 30 years relative to the historic simulation is $\approx$4°C (calendar year 2370–2400), and for RCP6, it is $\approx$7°C. These temperature increases are comparable with the RCP Extensions published by the IPCC yet are slightly warmer than the multimodel ensemble presented, which shows a mean warming of 2.5°C for RCP4.5 and 4.2°C for RCP6 [*Stocker et al.*, 2013]. This discrepancy is understandable, as the AOGCM used in our study has a high climate sensitivity [*Haywood et al.*, 2013]. Figure 1b shows the total ice sheet mass decrease. By the end of extension scenario RCP4.5, the GIS mass decreases from an initial state of $\approx 3.1 \times 10^6$ Gt to $\approx 3.0 \times 10^6$ Gt, corresponding to a loss of $\approx$3% of its mass; resulting in $\approx$ 0.3 m of sea level rise. In scenario RCP6 , it loses $\approx$6%, with a final ice mass of $\approx 2.9 \times 10^6$ Gt, or $\approx$ 0.7 m of sea level rise. These values fit well compared to the published findings in the IPCC [*Stocker et al.*, 2013], which suggest a long-term sea level increase of 0.11 m to 0.65 m due to runoff from the GIS in models using intermediate radiative forcing. However, it should be noted that this sea level estimate does not include the thermal expansion of the ocean or isostatic adjustment of the Earth's mantle. For both scenarios, the slope of the total ice mass time series and the mass balance time series indicates that melting would likely continue if the simulation were extended, and it is possible that an irreversible melting has been triggered by crossing a threshold point, as suggested by *Robinson et al.* [2012], yet this determination would require further research. A comparison with other model studies is also possible; *Vizcaino et al.* [2015] performed a similar fully coupled study for RCP4.5, focusing primarily on the ice sheet response. While the ISM used in that work was different from ours, both the ice sheet volume change in sea level equivalent as well as the surface mass balance for the GIS are comparable to our simulation results.

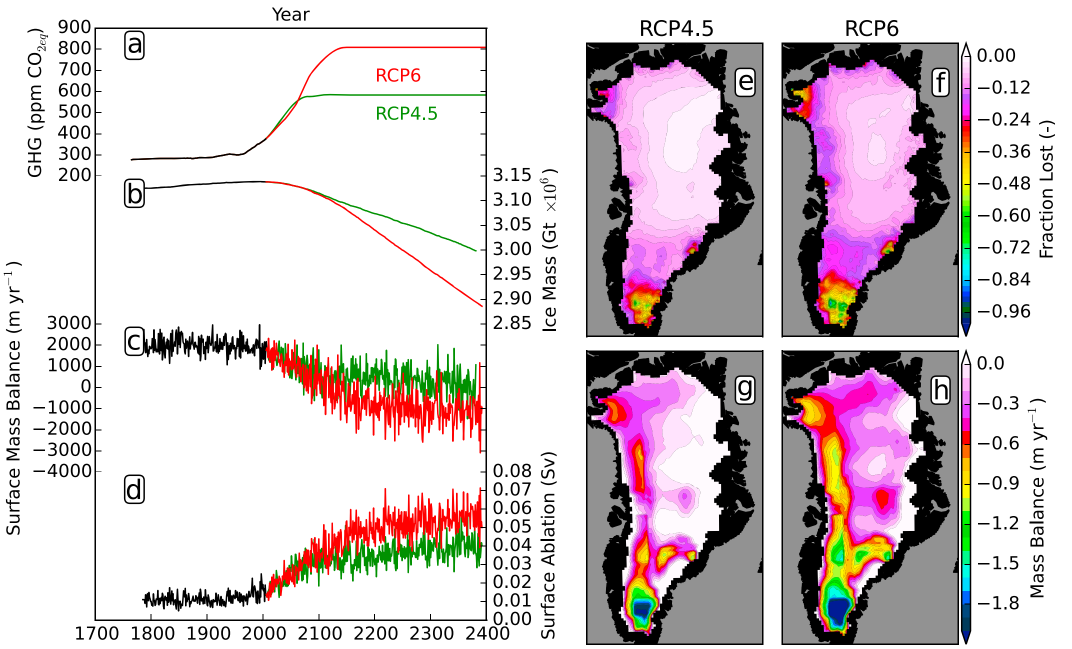

Figure 1. Time series and spatial response of the GIS in the *aoi* simulations. (a) The radiative forcing used in the model scenarios in equivalent amounts of CO_2, (b) the ice sheet's total mass, (c) summed mass balance of the GIS, (d) amount of ablated ice in terms of freshwater discharge to the ocean, (e and g) spatial response of the ice sheet in scenario RCP4.5, and (f and h) response for RCP6. Figures 1e and 1f show the fraction of ice lost at the end of the simulation with -1 corresponding to a complete loss of ice thickness. Figures 1g and 1h show the spatial distribution of mass balance of the ice sheet, as a sum of ablation, calving, and ice dynamics.

Spatially, the variability of the ice sheet's response to the atmospheric warming is diverse. Figures 1e and 1f show the amount of ice remaining as a percentage of the initial ice thickness for RCP4.5 and RCP6. Most of the ice melt occurs along the southern margin of Greenland, suggesting that a majority of the meltwater is introduced to the ocean in the Greenland Sea. The center of the ice sheet is less susceptible to ice melt, as much of central Greenland remains intact at the end of the simulation. These findings are supported by the spatial distributions of melting rates (Figures 1g and 1h).

4. Ice Sheet Feedbacks

As the GIS melts, its surface elevation will decrease, causing changes to the wind fields (Text S1 in the supporting information) which in turn will change how much momentum is transferred to the ocean. It has been suggested that these changes to wind strength could induce changes in the local climate [*Ridley et al.*, 2005], and we wish to see if there are any changes in the wind-induced surface ocean circulation. Based upon Figure 1, the primary elevation changes in the ice sheet occur along its southern edge. This change is minimal at the AOGCM resolution, as was also found by *Vizcaino et al.* [2015]. Examining the horizontal barotropic stream function of the ocean gives an indication of surface gyres, and we discover that the orographic changes caused by ice sheet melting have a minimal effect on surface ocean circulation (Figure S3 in the supporting information). Since these changes are less than 10% of the absolute magnitude of the gyre strength, we conclude that the primary influence of the ice sheet on the atmosphere-ocean system at this resolution is the surface ablation and meltwater. It should, however, be noted that ice sheet orgraphy effects have been suggested to play a critical role in the climate system, both on paleoclimatological time scales [*Eisenman et al.*, 2009; *Zhu et al.*, 2014], as well as in hypothetical sensitivity studies of the present day climate [*Davini et al.*, 2015].

In the coupled *aoi* model configuration, the ice sheet meltwater discharges into the surface layers of the North Atlantic and the Nordic Seas. As a result, the sea surface salinity is decreased by up to 2 practical salinity units (psu) relative to the initial state (Figures 2a and 2b). Comparing the *aoi* and *ao* setups at the end of the simulations shows that including the dynamic ice sheet in the coupled climate simulation significantly increases the freshwater anomaly in the upper ocean layers of the North Atlantic, as *aoi* simulates an additional

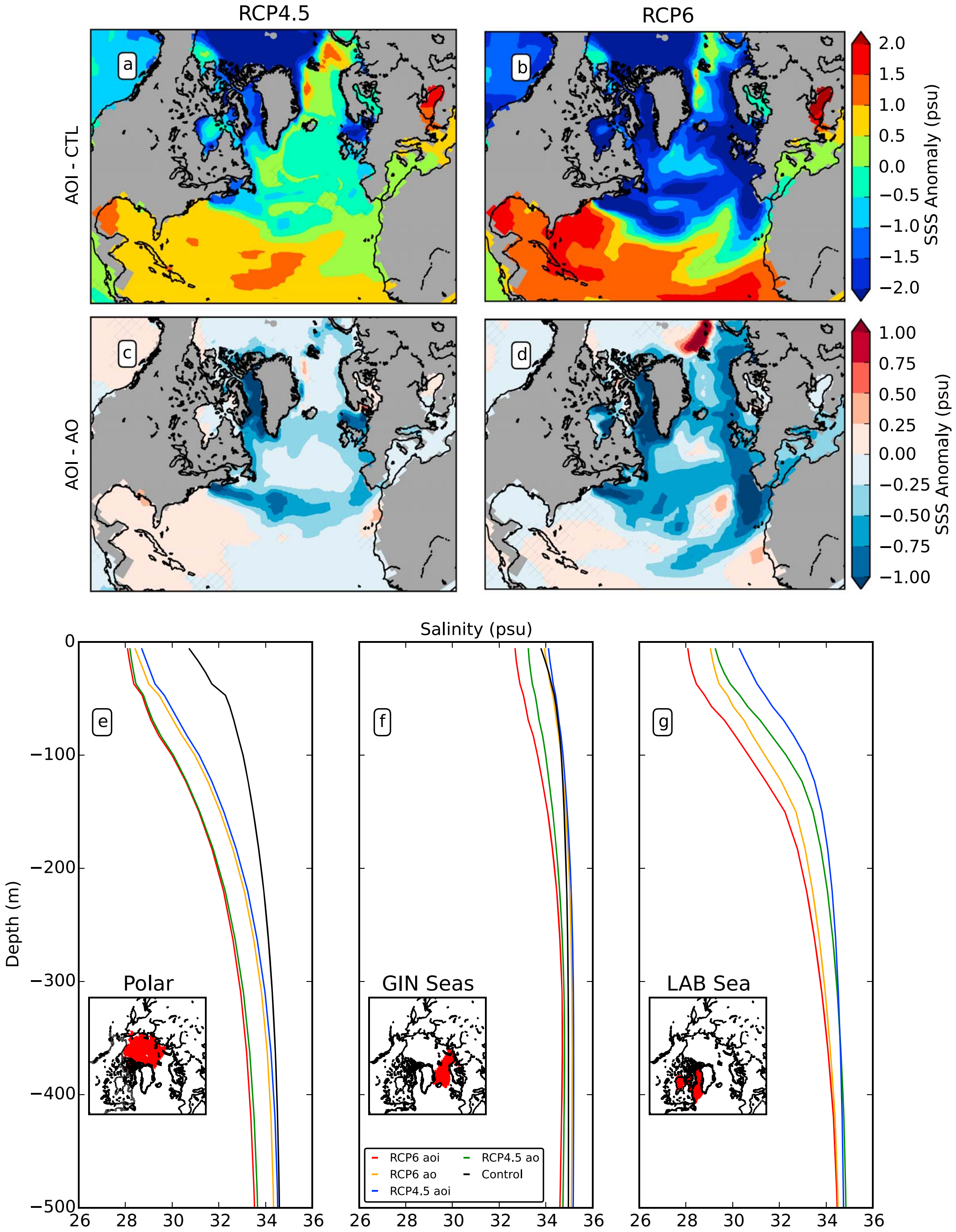

Figure 2. Salinity response of the North Atlantic. (a and b) Changes in sea surface salinity between the end of scenarios RCP4.5 and RCP6 as 30 year averages in the *aoi* simulation relative to the control state, respectively. (c and d) The anomaly between the *aoi* and *ao* simulations, together with hatching marking nonsignificant differences (95% level). (e, f, and g) The salinity profile of the Polar, GIN, and LAB seas, respectively, again as 30 year mean.

salinity decrease by up to 1 psu, doubling the signal relative to *ao* (Figures 2c and 2d). The magnitude of this anomaly implies that meltwater from the GIS plays an important role in determining the salinity budget of the North Atlantic in a warming world, which is a signal that has not been dynamically included in other state-of-the-art coupled atmosphere-ocean general circulation climate models. Previously, such effects were studied via the prescription of continental ice sheet melting in the form of ad hoc freshwater perturbation, whose strength had to be estimated rather than dynamically calculated from a bidirectionally coupled ISM.

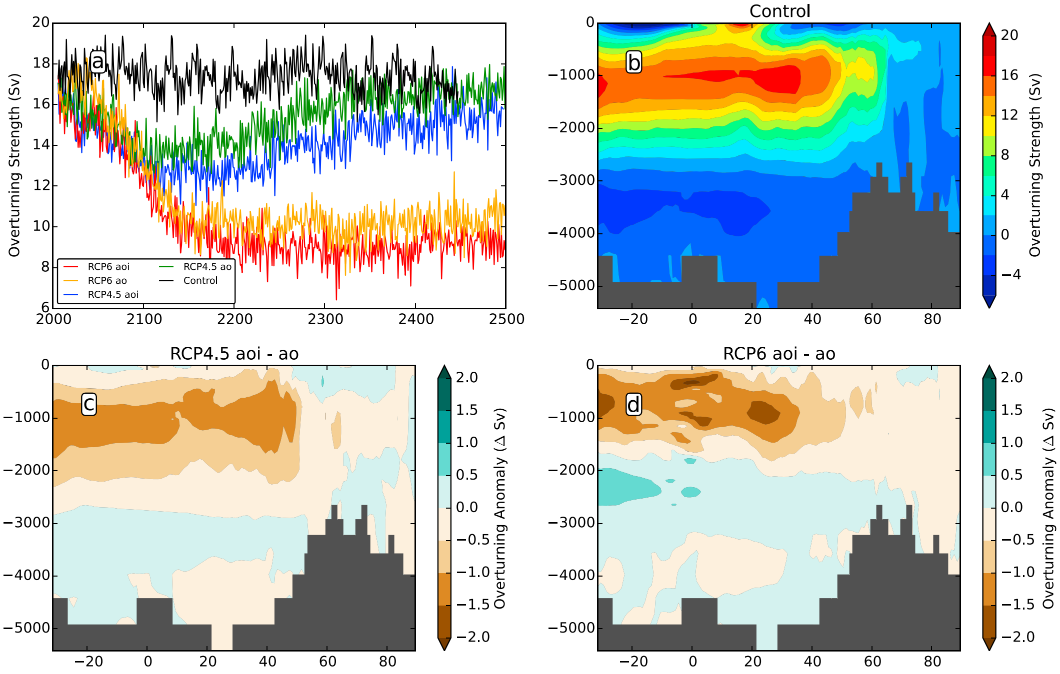

Figure 3. AMOC response. (a) The temporal evolution of the maximum AMOC strength in the upper cell. (b) The 30 year average of the AMOC in the control simulation in sverdrup (10^6 m^3/s). We can see a strong, upper circulation cell, transporting water from the high latitudes toward the south. (c and d) The anomaly between the model configurations of this overturning structure at the end of simulations RCP4.5 and RCP6, respectively.

5. Ocean Response

Changes in the upper ocean's salinity also change the vertical density structure in the high latitudes. Vertical profiles of salinity at the end of the simulation period for the Greenland, Iceland, and Norwegian Seas (GIN), Labrador Sea (LAB), and Arctic Seas (ARC) basin are shown in Figures 2e–2g. The North Atlantic Deep Water (NADW) formation zones east of Greenland are particularly affected (Figure 2f) by the changes in the salinity budget and the ice sheet's meltwater contribution. In the RCP6 simulation, the formation of a strong halocline prevents new NADW formation due to the increased surface buoyancy. These findings are in accordance with the polar halocline catastrophe theory initially proposed by *Bryan* [1986], who suggested that strong high-latitude haloclines would severely impact vertical mixing within the ocean. We analyze some vertical mixing characteristic in more detail in the supporting information (Text S5).

The changes in the North Atlantic's freshwater budget and accompanying halocline formation in the high latitudes affect the NADW formation rate and therefore the AMOC strength. The circulation pattern, shown in its initial state in Figure 3b, weakens rapidly during the first 150 years of the simulation under the influence of increasing GHG concentrations. In the *aoi* experiments, this can be attributed not only to sea surface temperature increases and sea ice melting (these effects are expanded upon in Text S4 in the supporting information, along with a more thorough investigation of the complete freshwater budget) as is solely the case in the *ao* experiments but also to the explicit consideration of meltwater discharge from the GIS. The ice sheet meltwater causes an additional AMOC decrease by ≈2 Sv compared to the *ao* experiments. The difference of weakening of the NADW circulation cell can be seen in Figures 3c and 3d, shown as an average anomaly of the last 30 years of the simulation. The primary cause for this difference is the strong high-latitude halocline which develops, hindering vertical convection and causing the upper cell to weaken. In RCP4.5, the AMOC is able to recover again to a slightly depressed state, as the negative density perturbation caused by warming and freshening of the North Atlantic is not so severe. As seen in Figure 2f, the salinity change is not so large in RCP4.5, which may explain its recovery to the initial state. This suggests that the GIN seas likely play an important role in the AMOC strength and that the meltwater introduced here has a severe impact. We further examine the GIN seas in the supporting information (Text S5).

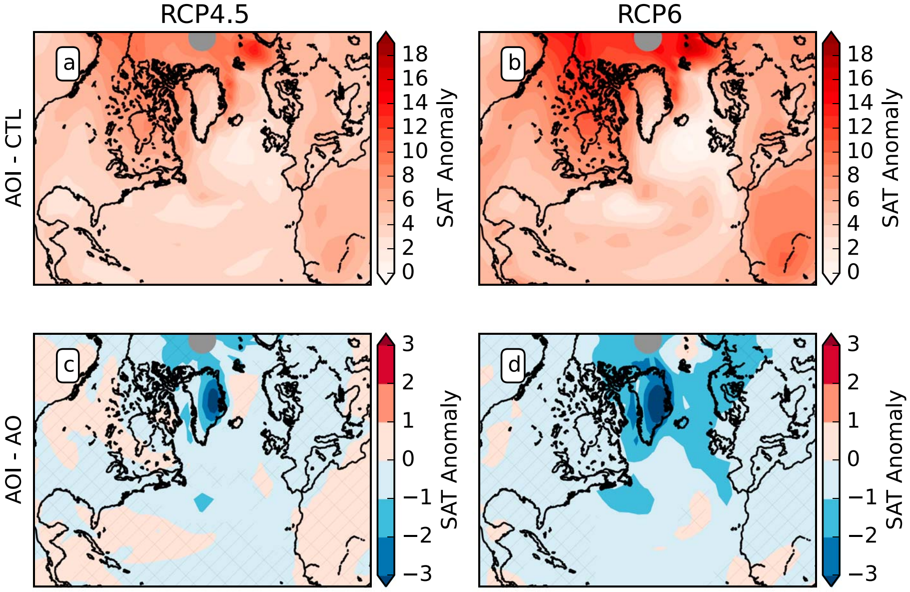

Figure 4. Resulting SAT differences. (a and b) The surface air temperature increase for scenarios RCP4.5 and RCP6 using the *aoi* model, respectively. (c and d) The differences between the model configurations. These differences are approximately 20–30% of the overall warming signal, suggesting that models without dynamic ice sheets may have partially overestimated climate warming in some regions. Hatching of insignificant regions is as in Figure 2.

Figure 3a shows the temporal evolution of the maximum strength of the upper AMOC cell at a depth of 1020 m between 20°N and 40°N. The initial decrease in the AMOC occurs in the first 150 years, which is related to the degree of atmospheric warming. After the GHG levels have stabilized in RCP4.5, the AMOC slowly begins to recover again. This is in contrast to the situation in RCP6, where the warming and resulting freshening is too severe to allow for a recovery. It is also noticeable that the AMOC remains consistently 2 Sv weaker in the *aoi* case compared to the *ao* case. This consistent weakening is caused by the introduction of meltwater into the critical deep convection zones in the GIN seas (Figure 2f) via recirculation in the surface currents.

6. Discussion and Conclusion

The additional ≈2 Sv AMOC decrease simulated in both experiments RCP4.5 and RCP6 caused by including the ISM has major implications for future climate in a warming world. The anomalous reduction in *aoi* effectively decreases surface air temperature over the North Atlantic, Europe, and North America by ≈1–2°C when compared to the *ao* configuration (Figures 4c and 4d), which corresponds to a significant temperature decrease of up to 40%. The temperature decrease is caused by a relative reduction of heat transport from the mid to high latitudes between the two model configurations. This implies that the models included in the previous IPCC reports may have overestimated the Northern Hemisphere warming.

Comparing our results to previous work, we find that the estimates of other studies utilizing ad hoc freshwater perturbation compare reasonably well with the simulated meltwater input in our model, 0.04 Sv for RCP4.5 and 0.06 Sv for RCP6. *Hu et al.* [2013] use a range of ablation rates from the GIS; varying from 0.027 Sv to 0.192 Sv for their experiments; also finding that the AMOC is highly sensitive to continental ice melt. However, both *Jungclaus et al.* [2006] and *Driesschaert et al.* [2007] find that only in very strong perturbation cases of 0.1 Sv is a noticeable AMOC change induced. When examining systems with fully coupled ice sheets, *Mikolajewicz et al.* [2007] and *Vizcaíno et al.* [2008] found that a freshwater input of 0.02 to 0.03 Sv is sufficient to reduce the AMOC's ability to recover under idealized scenarios, a finding we support using a higher-resolution ice sheet model and the most recent IPCC scenarios. We therefore stress the fact that freshwater perturbation experiments should be viewed critically and may underestimate the sensitivity of the AMOC. However, a multimodel experiment is necessary to avoid systematic biases in the simulation of the AMOC, as has been previously discussed by *Weaver et al.* [2012]. One such study that addresses multimodel analysis is work performed by *Swingedouw et al.* [2015], who found an appreciable increased weakening of the AMOC in response to hosing experiments compared to radiative forcing of extreme future projections (RCP 8.5) alone yet that the sensitivity to freshwater input may be smaller than previously thought. The same multimodel approach is necessary for ice sheet models, which can display a variety of responses to identical forcings, as seen by *Dolan et al.* [2014]. Therefore, an ensemble style approach would be recommended in future studies.

In conclusion, we demonstrated that including a dynamic ice sheet component into an AOGCM forced by IPCC warming scenarios has immediate effects on the mass balance of the GIS. The resulting melt water from the ice sheet discharges into the North Atlantic, intensifying the formation of high-latitude haloclines. Furthermore, the reduction of the upper layer salinity inhibits NADW formation, reducing the AMOC by ≈2 Sv, and the associated changes in heat transport cause relatively less warming over the Northern Hemisphere when compared to simulations utilizing fixed ice sheets. As melting land ice and the corresponding effects on ocean salinity and heat distributions are a very likely possibility in a warming future climate [*Stocker et al.*, 2013], the inclusion of dynamic ice sheet components in climate models is of paramount importance to fully understand processes responsible for regulating and shaping future global climate.

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