Amplified North Atlantic warming in the late Pliocene by changes in Arctic gateways

Bette L. Otto-Bliesner[1], Alexandra Jahn[2], Ran Feng[1], Esther C. Brady[1], Aixue Hu[1], and Marcus Löfverström[1]

[1]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO 80305, USA.

[2]Dept. of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, Univ. of Colorado Boulder, Boulder, CO 80309, USA.

Corresponding Author: Bette L. Otto-Bliesner (ottobli@ucar.edu)

Key Points:

- Closure of Arctic gateways in a new reconstruction of mid-Piacenzian paleogeography reduces simulated Arctic freshwater exports to the North Atlantic and enhances the AMOC
- Simulated regional patterns of temperature show better correspondence with proxy-indicated warm sea surface temperatures in the North Atlantic
- The climatic response to the closure of Arctic gateways is not a linear combination to the closure of the individual straits.

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Abstract

Under previous reconstructions of late Pliocene boundary conditions, climate models have failed to reproduce the warm sea surface temperatures reconstructed in the North Atlantic. Using a reconstruction of mid-Piacenzian paleogeography that has the Bering Strait and Canadian Arctic Archipelago Straits closed, however, improves the simulation of the proxy-indicated warm sea surface temperatures in the North Atlantic in the Community Climate System Model. We find that the closure of these small Arctic gateways strengthens the Atlantic Meridional Overturning Circulation, by inhibiting freshwater transport from the Pacific to the Arctic Ocean and from the Arctic Ocean to the Labrador Sea, leading to warmer sea surface temperatures in the North Atlantic. This indicates that the state of the Arctic gateways may influence the sensitivity of the North Atlantic climate in complex ways, and better understanding of the state of these Arctic gateways for past time periods are needed.

1 Introduction

Data reconstructions and Pliocene Model Intercomparison Project Phase 1 [PlioMIP1] climate model simulations of the Pliocene sea surface temperatures (SSTs), specifically during the mid-Piacenzian [mP, 3.264 – 3.025 Ma], are in good agreement in most regions except at sites in the North Atlantic [*Dowsett et al.*, 2013]. Higher levels of ocean heat transport, based on micropaleontological evidence [*Dowsett et al.*, 1992] and carbon isotopic composition of marine organic matter [*Raymo et al.*, 1996], have been invoked to explain the origin of this Pliocene warmth, but coupled climate models have failed to consistently reproduce the magnitude or agree even on the sign of the change in the Atlantic Meridional Overturning Circulation (AMOC) [*Haywood and Valdes*, 2004; *Zhang et al.*, 2013]. Furthermore, an alternate explanation, which invokes the higher reconstructed concentrations of atmospheric carbon dioxide (CO_2) during the Pliocene [*Budyko et al.*, 1985; *Crowley*, 1991], is also not sufficient and calls into question whether coupled climate models adequately simulate polar amplification.

Experiments have also explored the AMOC responses to replacing the Barents Sea with land [*Hill*, 2015], a deepening of the sills along the eastern and western limbs of the Greenland-Scotland-Iceland ridge [*Robinson et al.*, 2011], and an extended drainage basin of the Hudson Bay and Baltic rivers [*Hill*, 2015]. Among these changes, only changes to the Greenland-Scotland-Iceland ridge have led to a significant strengthening of the AMOC. A new reconstruction of mP paleogeography [*Dowsett et al.*, 2016] includes closure of the Bering and Canadian Arctic Archipelago Straits. The impacts of the representation of these gateways and influences on pathways of present-day ocean currents have been investigated with ocean-only [e.g. *Wadley and Bigg*, 2002] and coupled ocean-sea ice models [e.g. *Komuro and Hasumi*, 2005]. Recent studies have also investigated the climate-system response to the closure of Bering Strait [e.g. *Hu et al.*, 2015]. However, the climate response to both ocean gateways closed during the Pliocene has yet to be explored.

Here we conduct a series of medium-resolution, coupled atmosphere-ocean-sea ice-land simulations to better understand the North Atlantic climate response (particularly the AMOC and sea-surface temperature field) to the configuration of open and closed ocean gateways in the Bering Strait and the Canadian Arctic Archipelago. We quantify the changes to freshwater transport to the North Atlantic with closure of these gateways and subsequent impacts on the AMOC. The new simulation compares favorably to proxy reconstructions of North Atlantic temperatures. This is important, as the mP warm period has been suggested as a geologic example for the long-term response of the future Earth to present levels of global atmospheric CO_2.

2 Model and Experimental Design

To identify the sensitivity of the late Pliocene climate to uncertainties in reconstructions of the Arctic Ocean gateways, we conducted five coupled climate simulations with the Community Climate System Model version 4 (CCSM4) [Methods, Text S1] [*Gent et al.*, 2011]. The baseline Pliocene simulation uses the standard PlioMIP1 forcing protocol: atmospheric CO_2 set to 405 ppmv (parts per million by volume) and the Pliocene Research, Interpretation, and Synoptic Mapping, Version 3 (PRISM3) vegetation, ice sheets, and topography [*Haywood et al.*, 2011; *Rosenbloom et al.*, 2013]. The land-sea geography is kept at its modern configuration except for the filling of Hudson Bay. The updated PRISM4 mP paleo-environmental reconstruction, which considers change in dynamic topography associated with mantle flow and glacial isostatic adjustment due to Piacenzian ice loading and will be used in PlioMIP2 (centered on an interglacial peak MIS KM5c: 3.205 Ma), closes the Bering Strait (BS) and the straits through the Canadian Arctic Archipelago (CAA: Northwest Passage and Nares Strait) [*Haywood et al.*, 2016b]. We conduct three sensitivity simulations, for comparison to our baseline PlioMIP1 simulation and a preindustrial simulation [PI with 1850 conditions]: (1) only the BS closed, (2) only the CAA closed, and (3) both the BS and CAA closed. The first two sensitivity simulations allow us to assess the linearity of the effects of the individual straits on the Arctic and North Atlantic.

3 Proxy Reconstructions

The model simulations are compared to the reconstructions of North Atlantic SSTs compiled by Dowsett et al., 2012, 2013 (Table S1). The confidence level of the proxy-data records were evaluated by these authors based on semi-quantitative measure of confidence accounting for quality of the age control of the samples at each site, number of samples at each site, fossil preservation and abundance, reliability of proxy method or technique used; we retain only records with high to very high confidence level in this study. The model-proxy comparison is conducted on the anomalies of the simulated Pliocene and preindustrial temperatures. In order to ensure the consistency of model-proxy data comparison, published proxy anomalies (reference to modern) are corrected with preindustrial minus present-day anomalies (*Rayner et al.,* 2003; *Reynolds et al.,* 2002).

4 Results

4.1 Impacts of closing Arctic gateways on North Atlantic Ocean

CCSM4 reasonably reproduces observed SST and sea surface salinity (SSS) in the North Atlantic with warm and saline conditions extending across the basin south of

~45°N and northward into the eastern Greenland-Iceland-Norwegian (GIN) Sea (Fig. S1). Cold and fresher conditions extend from the Fram Strait southward along the eastern Greenland coast to the Labrador Sea. The baseline PlioMIP1 simulation is warmer and saltier in the North Atlantic than the PI simulation (Fig. 1). In the PI and PlioMIP1 simulations, deep-water formation extends from the Labrador Sea to Irminger Sea, and the Greenland-Iceland-Norwegian Seas, similar as in observations (Figs. 1 and S1, e.g., Smethie et al., 2000; Danabasoglu et al., 2012). The maximum AMOC in the PlioMIP1 simulation is indistinguishable from the PI control (Fig. 2), also the case in PlioMIP1 simulations by several other models [*Zhang et al.*, 2013]. Areal sea ice extent in the CCSM4 PlioMIP1 simulation decreases in the Arctic as compared to PI (Fig. S2) but persists through the summer [*Rosenbloom et al.*, 2013].

With a closed Bering Strait at the Pliocene, saltier water in the Labrador and GIN Seas favors increased deep-water formation in both regions (Fig. 1). The AMOC strengthens by about 2.5 Sv and meridional heat transport (MHT) convergence in the Atlantic between 40 – 60°N increases by 0.036 PW, or 10% as compared to the PlioMIP1 simulation with the BS open (Fig. 2). The strengthened AMOC is consistent with modeling results for modern [*Goosse et al.*, 1997; *Wadley and Bigg*, 2002] and Quaternary [*Hu et al.*, 2015] ocean circulations for a closed BS. Annual sea ice concentrations are reduced by up to 15% in the waters west of Greenland (including Baffin Bay, the Davis Strait, and Labrador Sea) and east of Greenland (including the East Greenland Current region and in the Barents Sea) as compared to the PlioMIP1 simulation (Fig. S2).

Closure of only the CAA straits, on the other hand, results in a significant freshening and cooling of the Labrador and GIN seas (Fig. 1) and thus a large expansion of sea ice in these basins (Fig. S2), as compared to the PlioMIP1 simulation. Deep-water formation is shutdown except in the eastern North Atlantic (Fig. 1), resulting in a reduction of the AMOC by about 5 Sv or 20% (Fig. 2) and a decrease of MHT convergence in the Atlantic between 40 – 60°N of -0.017 PW or -5% as compared to the PlioMIP1 simulation with the CAA straits open. This contrasts with results from previous studies using a low-resolution ocean model [*Wadley and Bigg*, 2002] and an ocean model with flux corrections [*Goosse et al.*, 1997], but it is consistent with results from an ocean-sea ice model [*Komuro and Hasumi*, 2005].

With the closure of both the Bering and Canadian Arctic Archipelago straits, there is a freshening of and decreased deep-water formation in the Norwegian Sea (Fig. 1), and a displacement of the region of deepwater formation southeastward into the Irminger Sea and the subpolar North Atlantic, resulting in more saline water emanating from the Labrador Sea even compared to the closed BS case. The model responds with an even greater strengthening of the AMOC (~4.5 Sv or 18%), approximately doubling the response with only the Bering Strait closed. As compared to the closed BS case, the strengthening of the AMOC is primarily confined to between 40 and 60°N (Fig. 2). MHT convergence in this latitudinal band increases by 0.098 PW or 30% as compared to the PlioMIP1 simulation. Sea ice has a dipole response, with large decreases west of Greenland and increase from the tip of Greenland to the northern North Atlantic (Fig. S2).

4.2 A mechanism for responses

The simulated responses can be understood by changes in the Arctic freshwater (liquid and sea ice) transports and subsequent effects on the SST, SSS, and deep-water formation in the North Atlantic. At present [*Aagaard and Carmack*, 1989] and in the PlioMIP1 simulation, relatively fresh seawater is transported through the Bering Strait into the Arctic, with additional freshwater being added to the Arctic Ocean through river runoff and net precipitation (Fig. 3, Table S2). This freshwater is then exported from the Arctic to the North Atlantic via two routes. The short route is through the Canadian Arctic Archipelago straits (Northwest Passage and Nares Strait) into Baffin Bay and out along the northeast coast of the Canadian Arctic. A major portion of the Pacific water transported through the Bering Strait leaves the Arctic through the straits of the Canadian Arctic Archipelago [*Jahn et al.*, 2010]. The long route is through the Fram Strait, with a large contribution from sea ice export. Previous work has shown that the CCSM4 represents the Arctic freshwater fluxes reasonably well in present-day simulations [*Jahn et al.*, 2012], and that changes in the Arctic freshwater export affect the simulated deep convection in the North Atlantic in the CCSM4 more strongly than SST changes [*Jahn and Holland*, 2013].

With a closed Bering Strait in the Pliocene, the total freshwater (liquid and solid, FW) transported to the North Atlantic through the Fram Strait decreases by about 39% and through the CAA Straits by 36%, with a total reduction of the Arctic FW export of about 30% (Fig. 3, Table S2), resulting in a saltier Labrador and GIN Seas (Fig. 1). With an open BS but closed CAA, the total FW export stays about the same as in the baseline Pliocene experiment, but all freshwater must be exported through the Fram Strait (Fig. 3, Table S2). This more-than-doubled FW export by the long route explains the significant freshening and cooling of the Labrador and GIN seas (Fig. 1), increased sea ice cover (Fig. S2) and sea ice melt, and a shutdown of deep-water formation except in the eastern North Atlantic (Fig. 1).

For the mP simulation with closed BS and closed CAA straits, Arctic FW is transported entirely through the Fram Strait and is sourced only from the local Arctic FW budget (P-E+R), as no Pacific FW is entering the Arctic. Compared to the baseline PlioMIP1 experiment, this leads to a 30% reduction of the total FW export from the Arctic, similar to the closed BS case. In contrast to the closed BS case, however, this reduction is entirely due to a 36% decrease in the total liquid FW export from the Arctic (Table S2). The total sea ice export stays at the same level as in the PlioMIP1 simulation. As all FW now leaves the Arctic east of Greenland, it leads to a freshening of and decreased deep-water formation in the Norwegian Sea (Fig. 1). At the same time, the strongly reduced total liquid FW export together with the cutoff of the short export route through the CAA results in a more saline Labrador and south Greenland Sea with increased deep convection, even compared to the closed BS case (Fig. 1). The stronger AMOC in the mP simulation with closed BS and closed CAA straits is therefore due to the phase and pathway of the Arctic FW export, rather than being a linear combination of the AMOC response in the individual closure cases of the Bering and CAA straits (Fig. 2).

4.3 Impact on North Atlantic and Arctic temperatures

Our PlioMIP1 simulation, with open BS and CAA straits, has a 1.9°C increase in global mean annual temperature compared to the PI control, with a polar amplification of ~3 times the global warming [*Rosenbloom et al.*, 2013]. Compared to proxy data, the PlioMIP1 simulation underestimates the reconstructed warm mid-latitudes (40 – 60°N) of the North Atlantic (Fig. 4). The model simulates on average 1.4°C warming (range 0.7 to 1.8°C) at mid-latitude proxy sites characterized as high and very high confidence [*Dowsett et al.*, 2012] relative to the PI simulation (Fig. 4, Table S1), while the warming is 5.1°C (range -0.2 to 8.8°C) derived from proxy reconstructions. This data model mismatch is worsened in the closed CAA experiment with an average cooling of 0.8°C (range -3.0 to 0.8°C), but is improved by closing the BS and further by closing both the BS and the CAA straits, featuring a 2.4°C (range 1.8 to 4.0°C) and 3.2°C (range 1.9 to 5.5°C) warming, respectively (Table S1).

With the new mP PRISM4 reconstruction of Arctic gateways, the model still underestimates pan-Arctic (greater than 60°N) warming. None of the simulations capture the strong warming reconstructed for ODP 907 near Iceland, a site assessed to be high confidence (Table S1). Other pan-Arctic sites provide less confident temperature estimates due to dating and calibration uncertainties. In particular, the large age range of many terrestrial records mean that the proxy mean annual temperatures may represent periods in the Pliocene with higher CO_2 than prescribed in the CCSM4 Pliocene simulations and/or could represent periods within the Pliocene with high summer insolation anomalies in the Arctic [*Haywood et al.*, 2016a; *Prescott et al.*, 2014; R. Feng, pers. comm.]. Similarly, other differences in the paleogeography [*Hill*, 2015] or bathymetry in the North Atlantic [*Robinson et al.*, 2011] from modern could be important. Previous modeling has shown that an ice-free Arctic in the summer provides a better match to the proxy temperature data [*Ballantyne et al.*, 2013; *Howell et al.*, 2016]. Whether this speaks to models such as CCSM4 underestimating the sensitivity of Arctic sea ice to warming, or the need to include the chemistry-climate feedbacks [*Unger and Yue*, 2014] associated with the changed vegetation not commonly included in paleoclimate simulations, remains an open question.

4.4 Implications for Pliocene Greenland Ice Sheet

Ice-rafted detritus records suggest a significant expansion of the Greenland ice sheet (GrIS) during the M2 glacial event (~3.3 Ma) [*Flesche Kleiven et al.,* 2002; *Bierman et al.,* 2016] that temporarily punctuated the relatively stable warm climate of the late Pliocene. The driver of this glaciation is not well understood, though insolation and CO_2 variations are thought to have played important roles for the ice sheet formation [*Contoux et al.*, 2015; *Dolan et al.*, 2015; *Koenig et al.*, 2015]. The results presented here suggest that the cold SST feedback (when only closing the CAA straits but leaving BS open) may have been important for this transition as well, and possibly also for subsequent glaciations in the Pleistocene. These results highlight the importance of further studies with coupled climate-ice-sheet models for understanding GrIS responses to the Arctic gateway configurations.

5 Conclusions

Our simulations show that closure of the relatively small Arctic gateways critically influences the AMOC, by inhibiting freshwater transport from the Pacific to the Arctic Ocean and from the Arctic Ocean to the Labrador and Greenland-Iceland-Norwegian (GIN) Seas. The net result is a stronger AMOC and an improved simulation of the proxy-indicated warm SSTs across the North Atlantic from south of Greenland to the British Isles with closure of both the Bering Strait and straits in the Canadian Arctic Archipelago. These results indicate the need to have better assess the climate impact of these Arctic gateways when using models in comparison to data for past time periods.

The Pliocene has been used as a geologic analogue to assess the long-term climate response to modern CO_2 levels. Pliocene proxy reconstructions consistently show greater high latitude warmth, and possibly more sensitive climate [*Pagani et al.*, 2010] than simulated by state-of-the-art Earth system models [*Haywood et al.*, 2013]. Our results indicate that the state of the Arctic gateways may influence the sensitivity of the North Atlantic climate in complex ways, making the Pliocene a better process than geologic analogue to study the ability of models to realize the full sensitivity to processes and feedbacks that may affect the Earth system sensitivity in the future.

Acknowledgments and Data

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Figures

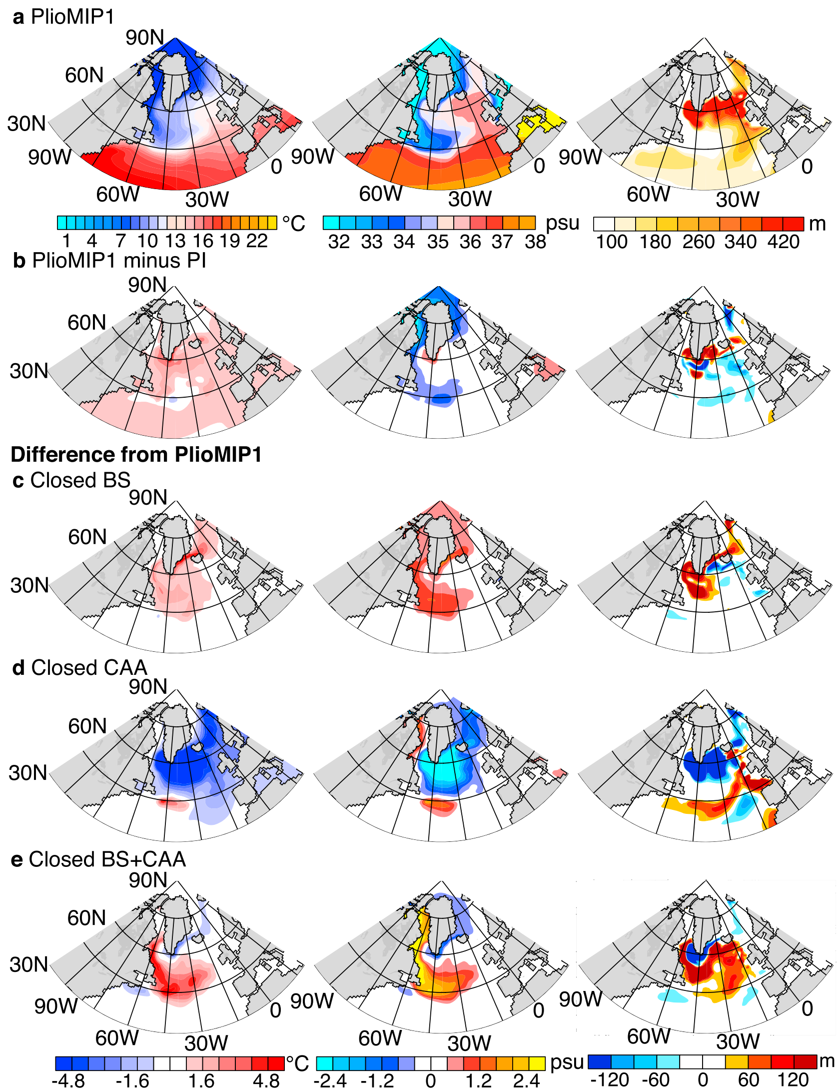

Figure 1. Comparison of SST (left), SSS (middle) and mixed layer depth (MLD, right). Panel a, annual-mean SST (°C), annual-mean SSS (psu), winter (December to February) MLD in the PlioMIP1 simulation. Panel b, PlioMIP1 minus PI changes in SST, SSS, and MLD. Panels c, d, e, changes in SST, SSS and MLD with respect to the PlioMIP1 simulation for the Closed BS, Closed CAA, and Closed BS+CAA experiments, respectively.

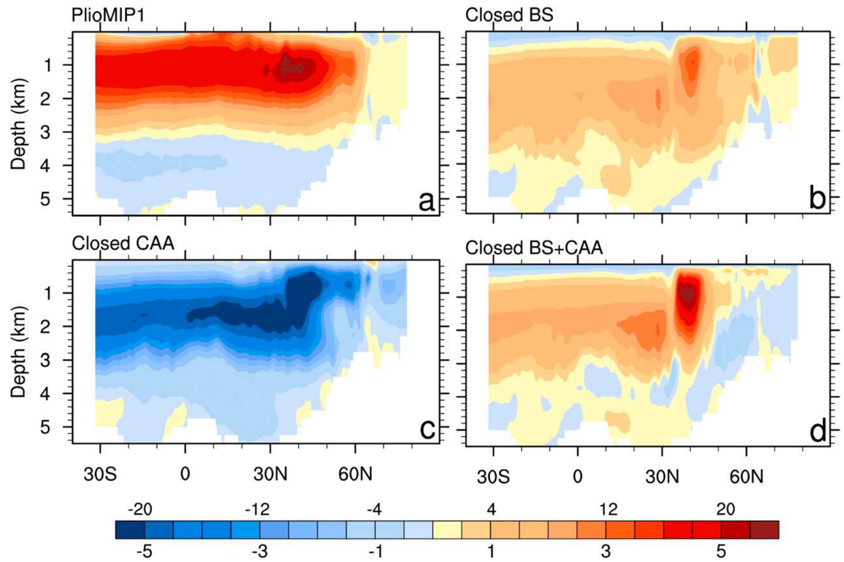

Figure 2. Comparison of AMOC in Pliocene simulations. a, Annual-mean AMOC (Sv) from PlioMIP1 simulation. Positive and negative contours indicate clockwise and counterclockwise circulation, respectively. b, c, d, Change in the AMOC as compared to the PlioMIP1 simulation for the Closed BS, Closed CAA, and Closed BS+CAA experiments, respectively. Top numbers in colorbar are used by panel a, and bottom numbers are used by panels b,c,d.

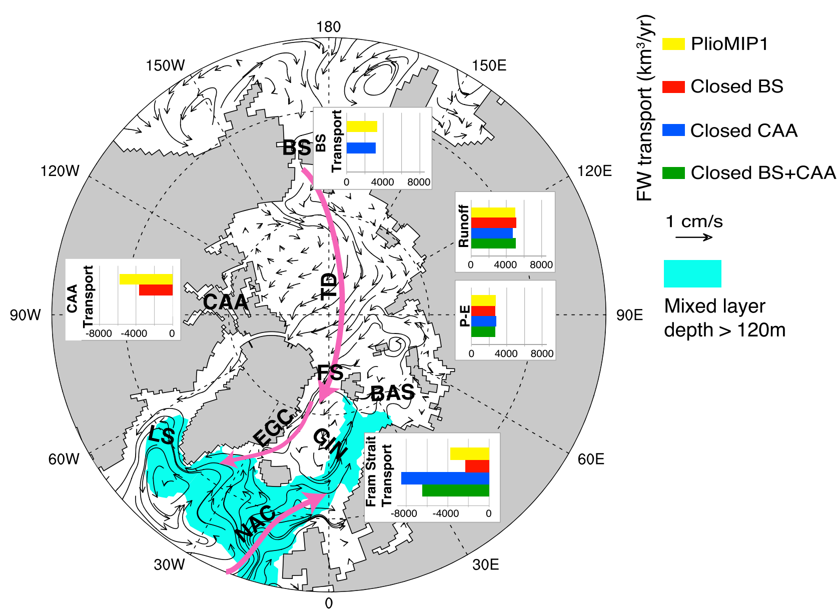

Figure 3. Arctic Ocean freshwater fluxes into and out of Arctic Ocean. Streamlines represent ocean surface circulation in the PlioMIP1 simulation. Net freshwater (solid plus liquid, in km^3/yr) input (positive values) and export (negative values) are shown for the

Pliocene simulations. Shaded blue area shows the region where winter ocean mixed layer depths are greater than 120m in the PlioMIP1 simulation. Other regions are labeled as BAS, Barents Sea; BS, Bering Strait; CAA, Canadian Arctic Archipelago; EGC, East Greenland Current; FS, Fram Strait; GIN, Greenland-Iceland-Norwegian Sea; LS, Labrador Sea; NAC, North Atlantic Current; TD, Transport Drift. 1 Sv equals 10^6 m^3/s and 3.1536 x 10^4 km^3/yr.

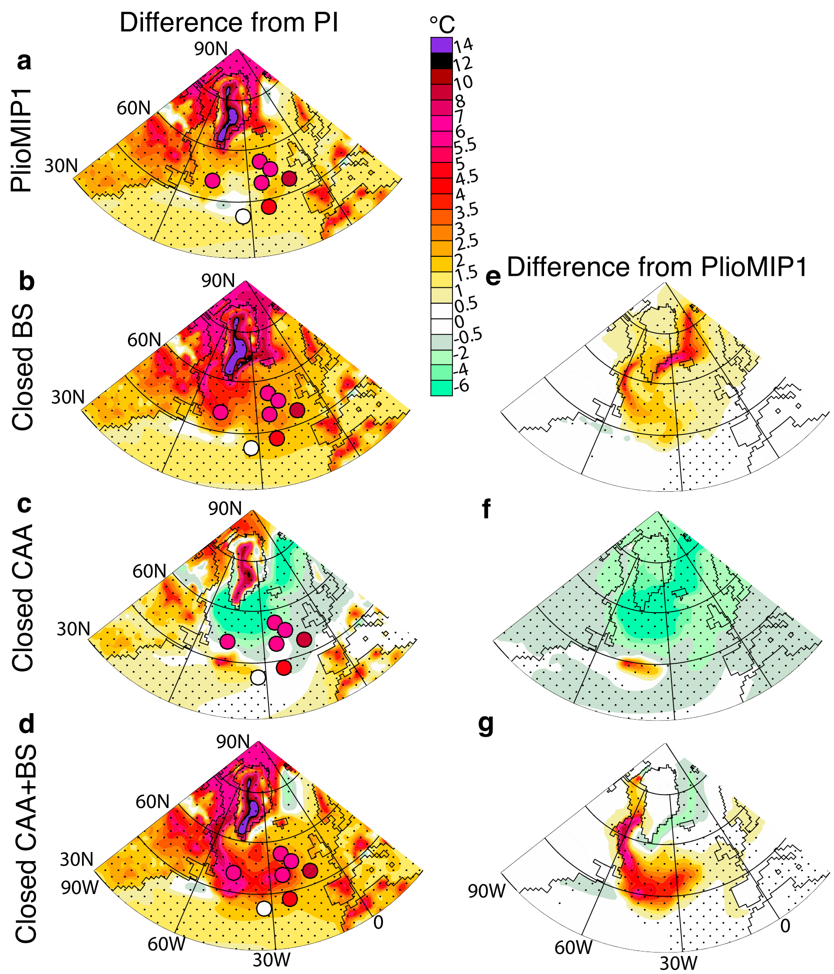

Figure 4. Annual surface temperature change (°C) in Pliocene simulations (contours) and proxy-data reconstructions (filled circles). Panels a-d, Change as compared to CCSM4 preindustrial simulation. Information about data points is presented in Table S1. Panels e-g, changes with respect to the PlioMIP1 simulation. Areas with differences significant above 99% (from Student's t-test) are dotted.

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Supporting Information for

Amplified North Atlantic warming in the late Pliocene by changes in Arctic gateways

Bette L. Otto-Bliesner[1], Alexandra Jahn[2], Ran Feng[1], Esther C. Brady[1], Aixue Hu[1], and Marcus Löfverström[1]

[1]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO 80305, USA.

[2]Dept. of Atmospheric and Oceanic Sciences and Institute for Arctic and Alpine Research, Univ. of Colorado Boulder, Boulder, CO 80309, USA.

Contents of this file

Introduction

Details of the CCSM4 model are included in the Methods (Text S1) and a comparison of the SST, SSS, and mixed-layer depths simulated by CCSM4 to observations (Figure S1). Also included in the SI is a supplementary figure showing the annual Arctic sea ice distributions simulated in the PI and Pliocene experiments (Figure S2). Tables S1 and S2 provide supporting information for results described in the main text.

Text S1. Methods

The simulations for this study used the CCSM4 (Gent et al., 2011), which has active atmosphere, land, ocean, and sea ice component models that are linked through a coupler that exchanges state information and fluxes between the components. The atmosphere component model is the Community Atmosphere Model, version 4 (CAM4) and the land component is the Community Land Model, version 4 (CLM4). Both adopt the FV1 version, which has a horizontal resolution of 0.9° in latitude and 1.25° in longitude, respectively. The ocean and sea ice components are the Parallel Ocean Program, version 2 (POP2), and the Community Sea Ice Model, version 4 (CICE4), with common grid of 320 x 384 points, a displaced-pole grid with poles in Greenland and Antarctica, and a nominal 1° resolution with finer resolution near the equator and North Atlantic. We adopt the alternate boundary conditions in our PlioMIP1 simulation. The PI simulation has been run for 1300 years; the PlioMIP1 simulation for 650 years, branching from the PI simulation at year 801 and with the ocean temperatures modified using the PRISM3 reconstructed SST and deep ocean temperature anomalies. The Pliocene gateways sensitivity experiments were started from year 451 of the PlioMIP1 simulation and run to year 650, except for CAA which was extended an additional 100 years to allow the AMOC to equilibrate. All results are shown for 50-year averages at the end of each simulation.

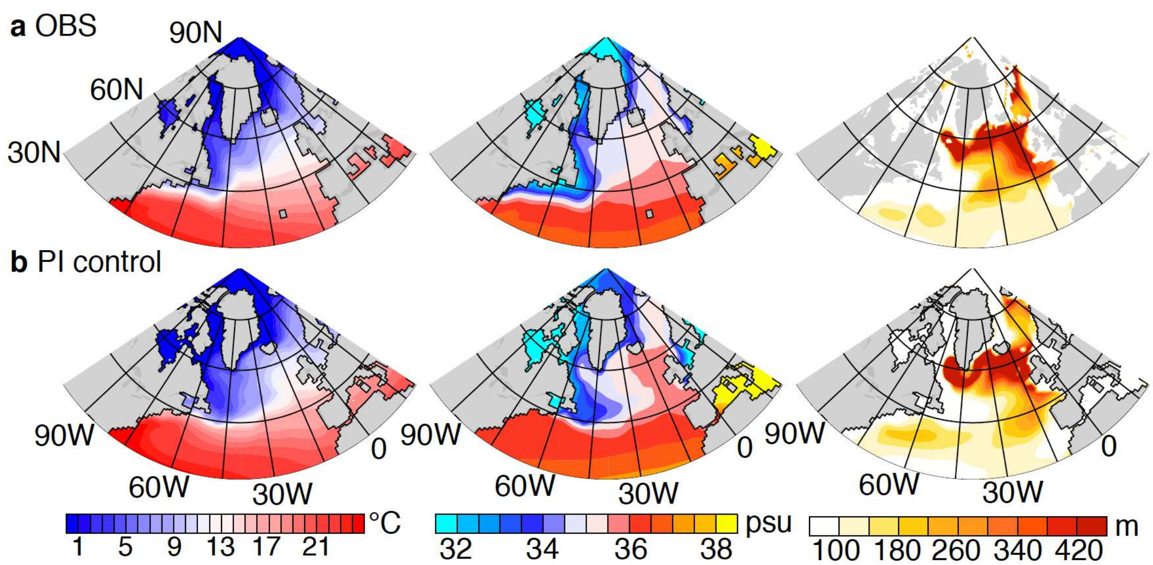

Figure S1. Comparison of SST (left), SSS (middle), and Mixed-layer Depths (right). (a) annual-mean SST (°C), SSS (psu) and winter (December to February) mixed layer depth [m] in observations (Monterey and Levitus, 1997; Locarnini et al., 2009; Antonov et al., 2010) and (b) the CCSM4 preindustrial (PI) simulation.

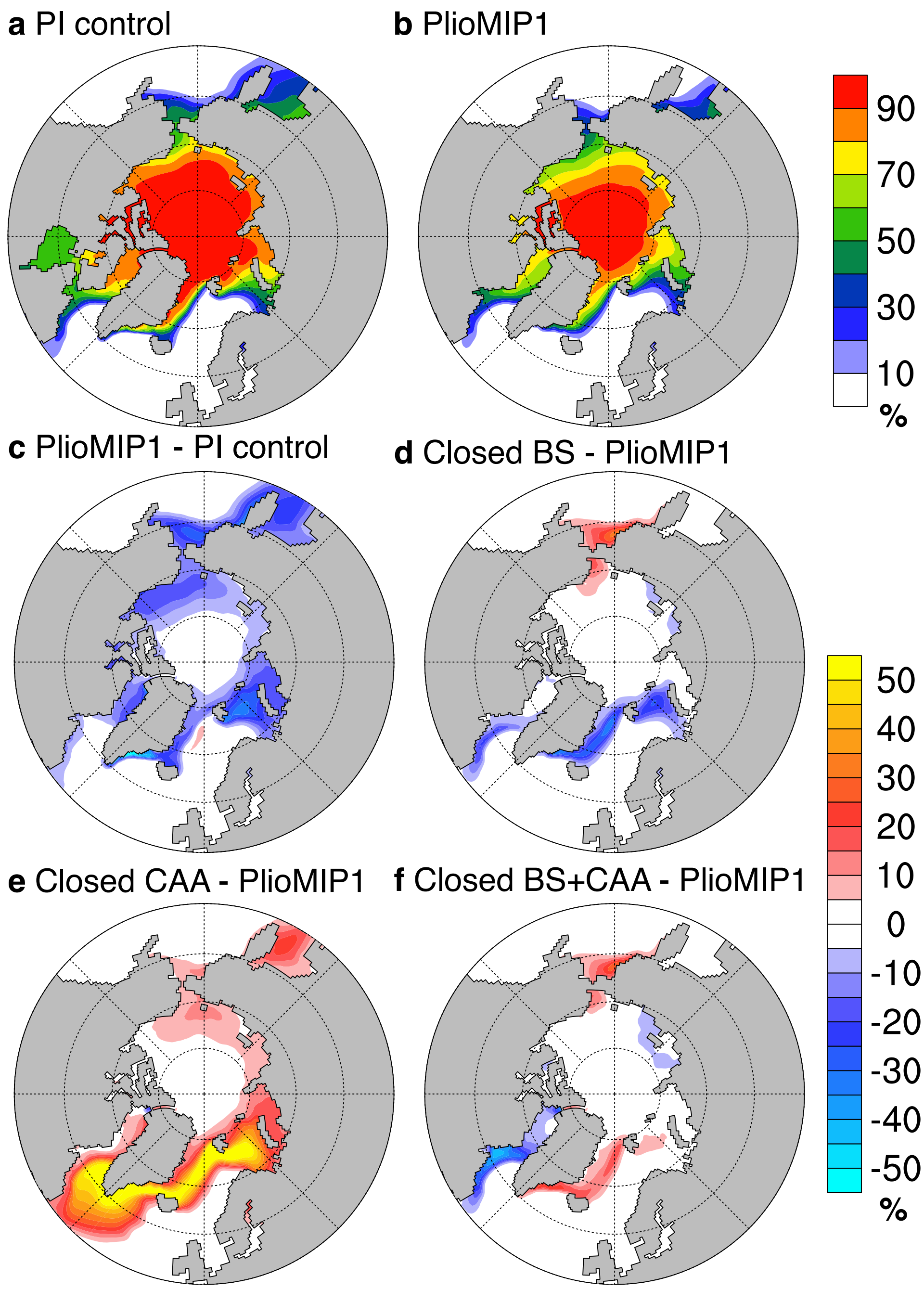

Figure S2. Comparison of Arctic sea ice concentrations (%) in CCSM4 simulations. a, Preindustrial simulation b, PlioMIP1 simulation. c, Change, PlioMIP1 minus preindustrial. d, e, f, Change as compared to the PlioMIP1 simulation for the Closed BS (d), Closed CAA (e), and Closed BS+CAA (f) experiments.

Sites	Lat	Lon	Conf	PRISM3	PlioMIP1	Closed BS	Closed CAA	Closed BS+CAA
DSDP_607	41.00	-32.96	4	-0.19	1.32	1.81	0.54	1.96
DSDP_608	42.84	-23.09	4	4.60	1.58	2.04	-0.30	1.96
DSDP_410	45.51	-29.48	3	4.30	0.67	2.15	-0.16	3.22
DSDP_609	49.88	-24.24	4	5.58	1.16	2.32	0.83	4.00
DSDP_111	50.43	-46.37	4	5.56	1.76	4.01	-1.86	5.49
DSDP_610	53.22	-18.89	4	6.61	1.41	2.28	-1.29	2.66
DSDP_552	56.04	-23.23	4	5.85	1.69	2.55	-3.00	2.84
DSDP_548	48.85	-12.00	4	8.79	1.31	1.96	-0.91	1.87
ODP_907	69.25	-12.70	3	9.44	1.25	5.04	-8.98	-0.98

Table S1. Mid- and high-latitude SST anomalies (°C) in North Atlantic region in PRISM3 reconstruction and Pliocene simulations. Sites are those with high (3) or very high (4) confidence levels from Dowsett et al., 2012, 2013. Confidence levels (Conf, increasing confidence from level 1 to 4) are provided by Dowsett et al., 2012 based on semi-quantitative assessments of proxy age control, number of samples, abundance and preservation of fossils, and reliability of reconstruction methods,. Model anomalies are Pliocene simulations minus preindustrial. Preindustrial (Rayner et al., 2003) minus present-day SST (Reynolds et al., 2002) corrections are added to the PRISM3 SST anomalies to ensure the consistency of data-model comparison.

	PlioMIP1	Closed BS	Closed CAA	Closed BS+CAA
Total net Arctic FW inputs	**11013**	**7748**	**10608**	**7733**
Bering Strait				
Liquid	3149	0	2957	0
Solid (ice)	151	0	200	0
River runoff	4981	5077	4649	5058
P-E	2732	2671	2802	2675
Total net Arctic FW exports	**-10377**	**-7241**	**-9712**	**-7387**
CAA				
Liquid	-5123	-3148	0	0
Solid (ice)	-650	-528	0	0
Fram Strait				
Liquid	-2011	-938	-5413	-4192
Solid (ice)	-1718	-1323	-3072	-2252
Barents Sea				

Liquid	-841	-1298	-661	-883
Solid (ice)	-34	-6	-566	-60
Total net Solid FW export	**-2402**	**-1857**	**-3638**	**-2312**
Total net Liquid FW export	**-7975**	**-5384**	**-6074**	**-5075**

Table S2. Annual means of the net Arctic Ocean freshwater (FW) fluxes from Pliocene simulations. All oceanic fluxes (km^3/yr) are net fluxes over the full depth of the water column at the boundaries. FW fluxes are calculated using monthly means relative to a reference salinity of 34.8 psu, with negative numbers indicating net FW exports from the Arctic Ocean, and positive numbers indicating net FW inputs. Small imbalances between total net Arctic FW inputs and outputs are associated with several factors including only calculating over a 50-year period for each experiment and using monthly means of velocity and salinity in the calculations.