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# Impact of Mid-Pliocene Boundary Conditions on the Atlantic Meridional Overturning Circulation (AMOC)

Julia E. Weiffenbach[1], Wing-Le Chan[2], Ayako Abe-Ouchi[2], and Anna S. von der Heydt[1,3]

[1]Institute for Marine and Atmospheric Research Utrecht, Department of Physics, Utrecht University, Utrecht, The Netherlands, [2]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan, [3]Centre for Complex Systems Science, Department of Physics, Utrecht University, Utrecht, The Netherlands

**Key Points:**

- Mid-Pliocene orography and vegetation leads to a stronger Atlantic Meridional Overturning Circulation
- Approximately 80% of the strengthening by mid-Pliocene orography and vegetation is a consequence of closed Arctic gateways
- Elevated $CO_2$ levels and smaller ice sheets levels during the mid-Pliocene partly compensate for the strengthening

**Supporting Information:**

Supporting Information may be found in the online version of this article.

**Correspondence to:**

J. E. Weiffenbach,
j.e.weiffenbach@uu.nl

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**Author Contributions:**

**Conceptualization:** Julia E. Weiffenbach, Wing-Le Chan, Ayako Abe-Ouchi, Anna S. von der Heydt
**Data curation:** Wing-Le Chan
**Formal analysis:** Julia E. Weiffenbach
**Funding acquisition:** Ayako Abe-Ouchi, Anna S. von der Heydt
**Investigation:** Julia E. Weiffenbach, Wing-Le Chan
**Methodology:** Julia E. Weiffenbach, Wing-Le Chan, Ayako Abe-Ouchi, Anna S. von der Heydt
**Project administration:** Ayako Abe-Ouchi, Anna S. von der Heydt
**Resources:** Wing-Le Chan, Ayako Abe-Ouchi
**Software:** Wing-Le Chan



**Abstract** We use the coupled atmosphere-ocean model MIROC4m to investigate the effect of mid-Pliocene boundary conditions on the Atlantic Meridional Overturning Circulation (AMOC), studying the impact of increased $CO_2$, reduced ice sheets and altered orography and vegetation. We find that a higher $CO_2$ concentration and smaller ice sheets both weaken the AMOC with respect to the pre-industrial. The stronger mid-Pliocene AMOC is therefore a consequence of mid-Pliocene orography and vegetation, where the closed Arctic gateways are responsible for approximately 80% of the AMOC strengthening. The main mechanism for mid-Pliocene AMOC strengthening is reduced transport of freshwater from the Arctic into the North Atlantic, enhanced by a decrease of surface freshwater flux into the high-latitude North Atlantic.

**Plain Language Summary** The mid-Pliocene warm period, approximately 3 million years ago, was a warm geological time period during which the $CO_2$ level was similar to today. While the ice sheets were smaller and the geography was different over parts of the globe, this period is often considered analogous for a possible future warm climate. Studies show that the AMOC, a large-scale ocean circulation that transports heat and salt from the tropics to the high-latitude North Atlantic, was likely stronger during this time and that this may have led to warm North Atlantic sea surface temperatures. We use a global climate model to investigate which factors in the mid-Pliocene lead to strengthening of the AMOC. Our results show that the higher $CO_2$ and smaller ice sheets weaken the AMOC. The geography and vegetation is therefore responsible for the strengthening of the AMOC during the mid-Pliocene. This is mainly due to Bering Strait and Canadian Archipelago being closed, reducing the transport of freshwater from the Arctic into the North Atlantic.

## 1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a critical component of the Earth's climate system. The AMOC functions as a large-scale oceanic conveyor belt, transporting warm, salty water from the tropics to the North Atlantic, where it cools, sinks, and returns southward at depth. This process regulates the global climate by distributing heat and has a critical influence on weather patterns (Jackson et al., 2015), sea level (Little et al., 2019), and the carbon cycle (Pérez et al., 2013). Proxy evidence suggests that during the mid-Pliocene, approximately 3 million years ago, the AMOC was likely stronger than at present (Dowsett et al., 1992; Ravelo & Andreasen, 2000; Raymo et al., 1996), contributing to relatively warm sea surface temperatures (SSTs) in the high-latitude North Atlantic (Dowsett et al., 2013; McClymont et al., 2020). This is supported by results from the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) which focuses on the mid-Pliocene warm period (mPWP; 3.205 Ma). They show that most models consistently simulate a stronger than modern AMOC in the mPWP and amplified North Atlantic SST warming (Zhang et al., 2021), agreeing with proxy reconstructions (Haywood et al., 2020).

The mPWP featured a $CO_2$ concentration of approximately 400 ppm (e.g., de la Vega et al., 2020; Pagani et al., 2010; Seki et al., 2010), periods of near-modern orbital forcing (Haywood et al., 2013), reduced land ice sheets (Dolan et al., 2015; Dowsett et al., 2010; Koenig et al., 2015) and altered vegetation and orography (Dowsett et al., 2016). While the mPWP has been recognized as a potential climate analog for a future warm climate (Burke et al., 2018; Tierney et al., 2019), several studies have investigated and highlighted the importance of non-$CO_2$ effects on features of the mPWP climate (e.g., Burton et al., 2023; Feng et al., 2022; Han et al., 2024). The impact of the complete set of mPWP boundary conditions on the AMOC in the PlioMIP2 ensemble has been studied (Weiffenbach et al., 2023; Zhang et al., 2021), as well as the effect of Arctic gateway closure in the mPWP

**Supervision:** Ayako Abe-Ouchi, Anna S. von der Heydt
**Validation:** Ayako Abe-Ouchi, Anna S. von der Heydt
**Visualization:** Julia E. Weiffenbach
**Writing – original draft:** Julia E. Weiffenbach
**Writing – review & editing:** Julia E. Weiffenbach, Wing-Le Chan, Ayako Abe-Ouchi, Anna S. von der Heydt

(Otto-Bliesner et al., 2017). While Otto-Bliesner et al. (2017) have shown that closure of the Canadian Archipelago and Bering Strait during the mPWP lead to strengthening of the AMOC and warming in the North Atlantic, the separate influence of mPWP $CO_2$, ice sheet extent and combined orography and vegetation on the AMOC has not yet been studied. In the context of this study, "orography and vegetation" refers to the combined orography, bathymetry, land-sea mask, vegetation, soils and lakes as per the PlioMIP2 protocol (Haywood et al., 2016).

We conduct a series of coupled atmosphere-ocean simulations to investigate and quantify the individual impact of $CO_2$, reduced ice sheets, and orographic boundary conditions on the AMOC during the mPWP. Furthermore, we conduct an extra experiment where we implement the mPWP orography and vegetation reconstruction without closing the Arctic gateways. This allows us to determine the effect of Arctic gateway closure in a mPWP background climate, separating the relative contributions of the Arctic gateways closure and other mPWP boundary conditions. The study contributes to our understanding of the changes in Atlantic Ocean conditions and circulation during the mPWP, and helps us assess the potential and limitations of the mPWP for understanding long-term future climate change.

## 2. Model Setup and Methods

We carry out experiments with the coupled atmosphere-ocean general circulation model MIROC4m (K-1 model developers, 2004). The atmospheric model has a horizontal resolution of $\sim 2.8°$ and 20 vertical levels. The ocean model has a horizontal resolution of $\sim 1.4°$ in longitude and $0.56 - 1.4°$ in latitude, with a finer resolution near the equator, and 43 vertical levels. This model has been widely used to study modern climates (e.g., Greve et al., 2023) and paleoclimates such as the mid-Holocene (Sueyoshi et al., 2013), the last interglacial (O'ishi et al., 2021) and the mid-Pliocene (Chan & Abe-Ouchi, 2020; Chan et al., 2011). We employ the same model set-up as used for the mid-Pliocene experiments in Chan and Abe-Ouchi (2020), with an updated cloud parametrization following Sherriff-Tadano et al. (2023). The update involves a reduction of the temperature below which cloud water becomes cloud ice, accounting for the observed underestimation of supercooled cloud liquid water under cold conditions (Yoshida et al., 2010). The modification has been shown to reduce the model's warm SST bias over the pre-industrial Southern Ocean (Sherriff-Tadano et al., 2023), and leads to warmer SSTs globally in mPWP simulations (Figure S1 in Supporting Information S1). As a result, the root mean square error with absolute mPWP and mPWP minus pre-industrial SST reconstructions by McClymont et al. (2020) is reduced with respect to the simulations using the original cloud parametrization.

### 2.1. Experiments

To be able to separate the forcing of different boundary conditions in the mPWP, we perform a total of six experiments, of which four are sensitivity experiments. Experiments take the form $Ex^c$, where $c$ is the $CO_2$ concentration in ppm and $x$ is a combination of applied mPWP boundary conditions. With present-day boundary conditions, $x$ is null; otherwise it can be $o$ (mPWP orography, bathymetry, land-sea mask, vegetation, lakes and soils combined) and/or $i$ (mPWP ice sheets). The pre-industrial $E^{280}$ and mPWP $Eoi^{400}$ experiments are the core experiments of PlioMIP2. The mPWP $Eoi^{400}$ experiment implements the PRISM4 reconstruction (Dowsett et al., 2016), as prescribed by the PlioMIP2 protocol (Haywood et al., 2016). A more detailed description of the implemented mPWP boundary conditions can be found in Text S1 in Supporting Information S1 and Figures S2-S4 in Supporting Information S1.

The experiments performed are $E^{280}$, $E^{400}$, $Ei^{400}$, $Eo^{400}$ and $Eoi^{400}$ and an additional sensitivity experiment, $Eo^{400}_{open}$. Table 1 gives an overview of the experiments and their boundary conditions. $Eo^{400}_{open}$ is identical to the $Eo^{400}$ experiment with mPWP orography and vegetation, except the Bering Strait and Canadian Archipelago remain open. All experiments are run to equilibrium for at least 2,500 model years. We analyze the last 500 years of the experiments to avoid any biases due to multi-centennial fluctuations in the AMOC (Figure S5 in Supporting Information S1). The deep ocean temperature change is less than 0.01°C per century for the last 500 years of all experiments.

**Table 1**
*Overview of Experiments Performed With MIROC4m*

| Experiment | Length (year) | $CO_2$ (ppm) | Ice | Topo | Veg | Land-sea mask | Arctic gateways | Global mean sea surface temp. (°C) | AMOC strength (Sv) |
|---|---|---|---|---|---|---|---|---|---|
| $E^{280}$ | 2,600 | 280 | PI | PI | PI | PI | Open | 13.0 | 19.2 |
| $E^{400}$ | 2,500 | 400 | PI | PI | PI | PI | Open | 15.5 | 17.8 |
| $Ei^{400}$ | 2,500 | 400 | mPWP | PI | PI | PI | Open | 15.7 | 16.5 |
| $Eo^{400}$ | 2,500 | 400 | PI | mPWP | mPWP | mPWP (PI Antarctica) | Closed | 16.8 | 21.3 |
| $Eo^{400}_{open}$ | 2,500 | 400 | PI | mPWP | mPWP | mPWP (PI Antarctica) | Open | 16.8 | 18.6 |
| $Eoi^{400}$ | 3,100 | 400 | mPWP | mPWP | mPWP | mPWP | Closed | 17.2 | 20.0 |

### 2.2. Factorization

We use the sensitivity experiments to separate the forcings of the mid-Pliocene climate. Our approach is a combination of a linear approach (e.g., Feng et al., 2022; Han et al., 2024; Lunt et al., 2010) and the Stein and Alpert (1993) approach, both of which are described in Lunt et al. (2012) in the context of mid-Pliocene climate forcing. We separate the total climate forcing ($F_{all}$) into a $CO_2$ forcing ($F_{CO2}$), an ice sheet forcing ($F_{ice}$) and a combined orography and vegetation forcing ($F_{oro+veg}$). $F_{res}$ is a residual nonlinear term, which considers the interaction or "synergy" (Stein & Alpert, 1993) between the ice and combined orography and vegetation forcings in this factorization.

$$F_{all} = F_{CO2} + F_{ice} + F_{oro+veg} + F_{res} \tag{1}$$

$$F_{all} = Eoi^{400} - E^{280} \tag{2}$$

$$F_{CO2} = E^{400} - E^{280} \tag{3}$$

$$F_{ice} = Ei^{400} - E^{400} \tag{4}$$

$$F_{oro+veg} = Eo^{400} - E^{400} \tag{5}$$

Our factorization assumes a certain distribution of state-dependent effects, in contrast to the symmetric factorizations by Lunt et al. (2012, 2021) (Text S2 in Supporting Information S1). It produces comparable results to the Lunt et al. (2012) and linear-sum factorization (Lunt et al., 2021) (Figure 1, Figures S6 and S7 in Supporting Information S1) while our factors are more easily interpretable. Specifically, $F_{CO2}$ represents the long-term effect of increasing $CO_2$ concentrations from 280 to 400 ppm under pre-industrial conditions, while $F_{ice}$ and $F_{oro+veg}$ capture the effects of reduced mPWP ice sheets and combined orographic and vegetation boundary conditions in a warm equilibrium climate with present-day boundaries.

We perform another linear factorization of $F_{oro+veg}$ into two components: a closed Arctic gateways forcing ($F_{Agw}$) and residual orography and vegetation forcing ($F^{open}_{oro+veg}$) using the experiment $Eo^{400}_{open}$. It is important to note that $F_{Agw}$ is only defined within the $Eo^{400}_{open}$ background climate. Meanwhile, $F^{open}_{oro+veg}$ constraints the response to the combined forcing of mPWP orography and vegetation without closed Arctic gateways.

$$F_{oro+veg} = F_{Agw} + F^{open}_{oro+veg} \tag{6}$$

$$F_{Agw} = Eo^{400} - Eo^{400}_{open} \tag{7}$$

$$F^{open}_{oro+veg} = Eo^{400}_{open} - E^{400} \tag{8}$$

### 2.3. Analyzed Variables

We analyze the forcing for different variables related to the AMOC and North Atlantic SSTs. These include the Atlantic meridional streamfunction (MSF), where we define the AMOC strength as the maximum streamfunction value below a depth of 500 m and at latitudes north of 0°N. For the Atlantic MSF, sea surface salinity, surface freshwater flux and SST, we calculate the annual average fields from a 500 year yearly time series. The December-January-February (DJF) mean ocean mixed layer depth (MLD) is calculated from a 500 year monthly time series. We perform student's *t*-tests on the yearly time series to determine significance. Ocean freshwater transports are calculated with respect to the reference salinity, which is taken as the average salinity of the Atlantic Ocean in each experiment, using 500 year climatologies. The transport of sea ice is included in the freshwater transport. As there is no ocean surface freshwater flux output in the ocean model, the surface freshwater flux is determined by closing freshwater budget after calculating the freshwater transports. The surface freshwater flux is therefore the sum of precipitation, evaporation, runoff and change in sea ice volume.

## 3. Results

### 3.1. Factorization of the Mid-Pliocene AMOC

We show the effect of the total mPWP forcing on the AMOC and North Atlantic with respect to the pre-industrial in Figure 1a–1c. The total forcing $F_{all}$ shows a more saline North Atlantic surface and a deepening of the winter MLD south of Greenland concurrent with shallowing of the winter MLD in the Greenland, Iceland and Norwegian seas. The $F_{all}$ AMOC increase of 0.8 Sv is relatively small compared to the PlioMIP2 multi-model mean increase of 3.1 Sv (Weiffenbach et al., 2023). The qualitative $F_{all}$ response in AMOC MSF, sea surface salinity and SST is, however, similar to the PlioMIP2 ensemble (Figure S8 in Supporting Information S1). In addition, the AMOC response for all forcing terms except the residual forcing is significant according to a student's *t*-test ($p < 0.01$), allowing for a reliable analysis of relative changes induced by the mPWP forcings.

Both the $CO_2$ forcing and mPWP ice sheet forcing lead to weakening of the AMOC and limited to no salinity increase in the subpolar North Atlantic (Figures 1d–1i). While the effects of $F_{CO2}$ and $F_{ice}$ are similar in terms of AMOC strength, with a decrease of 1.4 and 1.3 Sv, respectively, the forcing mechanism is likely different as there are substantial spatial differences in the response. For instance, the AMOC weakening due to $CO_2$ is paired with significant shallowing of the AMOC (Figure 1d). Earlier individual model studies as well as multi-model comparisons involving LongRunMIP (Rugenstein et al., 2019) show that the AMOC's transient response to a $CO_2$ increase is weakening followed by (partial) recovery on longer timescales (Bonan et al., 2022; Curtis & Fedorov, 2024; Nobre et al., 2023), where some models eventually surpass the original AMOC strength (Bonan et al., 2022) while in others the AMOC remains weakened (Zhu et al., 2015). In the context of these studies, our model's AMOC remains weakened when the $CO_2$ concentration is increased in a pre-industrial background climate.

In contrast to the $F_{CO2}$ AMOC response, the weakened AMOC due to $F_{ice}$ is not accompanied by shallowing of the AMOC cell (Figure 1g). The magnitude and spatial response of the sea surface salinity and winter MLD also differs between $F_{CO2}$ and $F_{ice}$, where notably $F_{CO2}$ appears to be the main driver of freshening of the Arctic Ocean surface. It is likely that the $F_{ice}$ AMOC strength decrease is mostly a consequence of the reduced Greenland ice sheet, which leads to local warming (Figure S9 in Supporting Information S1) and widespread freshening of the North Atlantic surface. The role of the smaller Antarctic ice sheet in $F_{ice}$ is likely to be limited as it leads to no substantial changes in the zonal mean zonal wind stress at the Southern Ocean surface (Figure S10 in Supporting Information S1) that could affect upwelling of North Atlantic Deep Water.

Figure 1 reveals that it is the combined mPWP orography and vegetation forcing that is responsible for the stronger AMOC in the mPWP. $F_{oro+veg}$ leads to substantial strengthening of the AMOC of 3.5 Sv (Figure 1j). It is also the main contributor to the more saline North Atlantic surface in the mPWP (Figure 1k), as well as the above-average SST warming in the subpolar North Atlantic (Figure S11 in Supporting Information S1). The orography and vegetation forcing leads to substantial deepening of the winter MLD as well as enlargement of the area where winter deep water formation takes place (Figure 1l). We also find that $F_{res}$ of the AMOC strength is only −0.04 Sv (not shown here), suggesting that the interaction between the ice and orography and vegetation forcings does not lead to strengthening of the AMOC in the mPWP. There are some interaction effects on the Atlantic MSF, North Atlantic sea surface salinity and winter MLD, but they are generally small (Figure S12 in Supporting

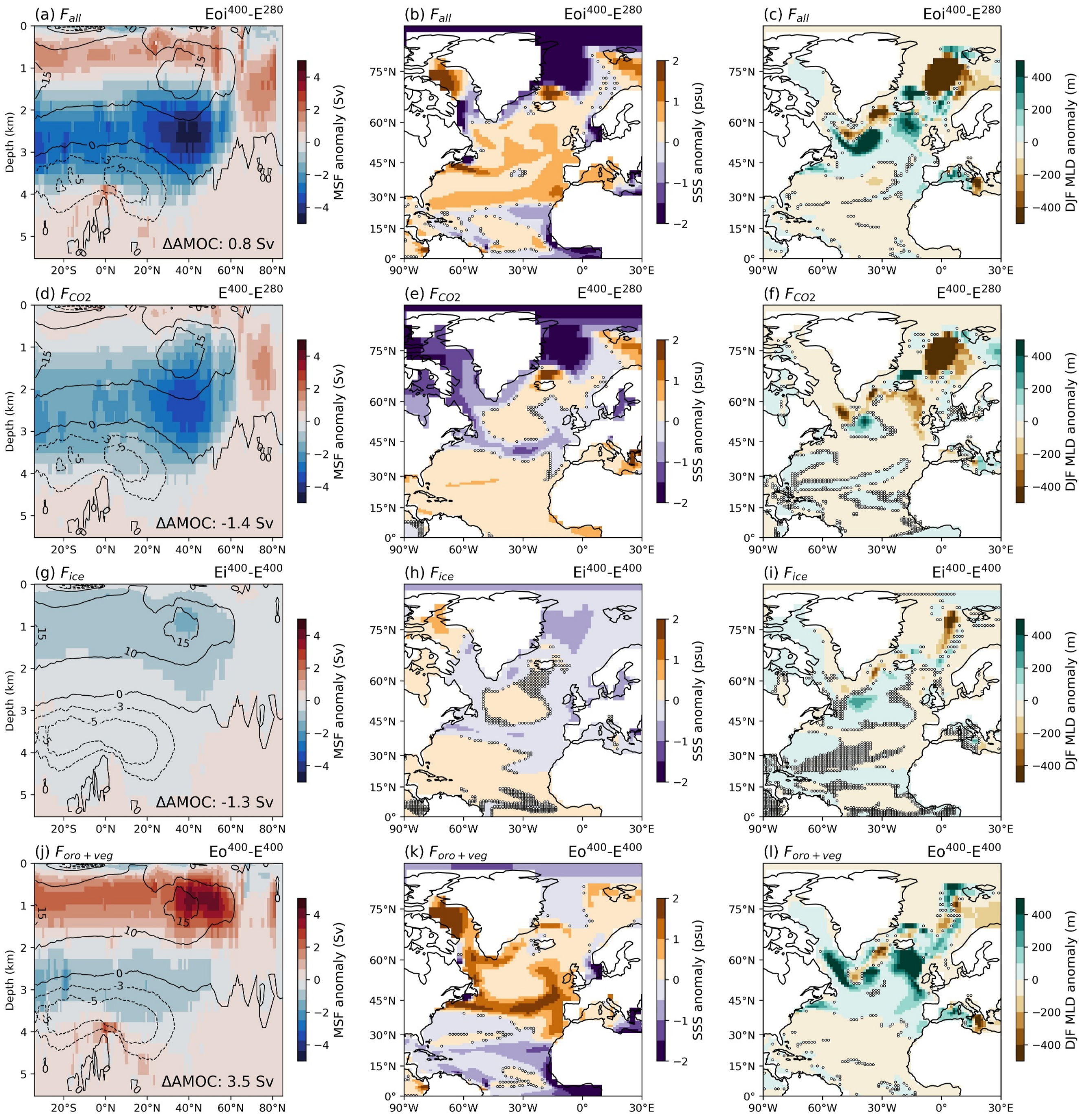


**Figure 1.** (a) The mid-Pliocene minus pre-industrial ($F_{all}$) Atlantic meridional streamfunction (MSF) anomaly. Contours show the background state Atlantic MSF. The Atlantic Meridional Overturning Circulation strength anomaly is indicated in bottom right corner, (b) $F_{all}$ sea surface salinity anomaly, (c) $F_{all}$ winter (DJF) mixed layer depth anomaly, (d)–(f) Same as panels (a)–(c) for increasing $CO_2$ ($F_{CO2}$), (g)–(i) Same as panels (a)–(c) for implementing reduced mid-Pliocene ice sheets ($F_{ice}$), and (j)–(l) Same as panels (g)–(i) for implementing mid-Pliocene orography and vegetation ($F_{oro+veg}$). Stippling indicates that anomalies are not significant according to a student's *t*-test ($p > 0.05$).

Information S1). $F_{res}$ does appear to lead to shallowing of the winter MLD in parts of the Labrador Sea, partly counteracting the deepening of the MLD there induced by $F_{oro+veg}$, but this does not have a significant impact on the AMOC.

Within the mPWP orography and vegetation forcing, the closure of the Bering Strait and Canadian Archipelago is the main contributor to the total increase in AMOC strength (Figure 2a). In our simulations, 77% of the stronger

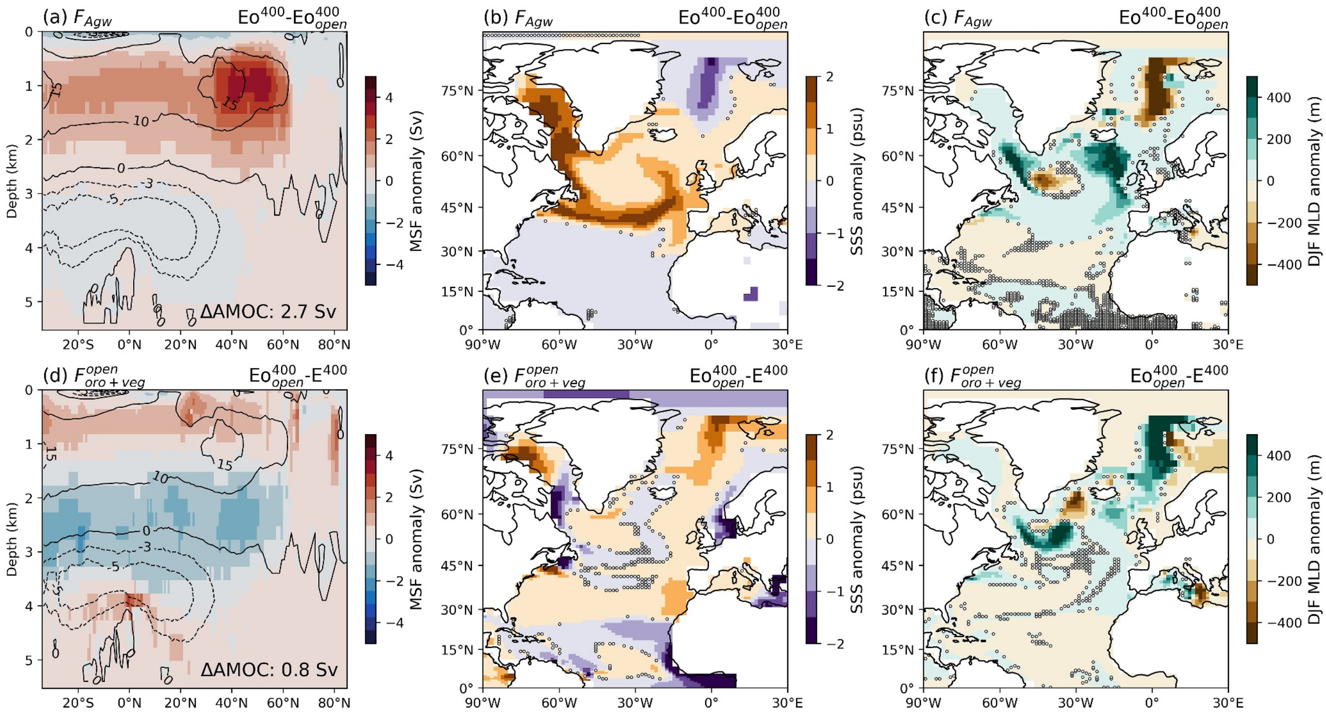


**Figure 2.** (a) The Atlantic meridional streamfunction (MSF) anomaly due to closure of the Arctic gateways ($F_{Agw}$). Contours show the background state Atlantic MSF. The Atlantic Meridional Overturning Circulation strength anomaly is indicated in bottom right corner, (b) $F_{Agw}$ sea surface salinity anomaly, (c) $F_{Agw}$ winter (DJF) mixed layer depth anomaly, (d)–(f) Same as panels (a)–(c) for the effect of mid-Pliocene orography and vegetation not including Arctic gateways closure ($F^{open}_{oro+veg}$). Stippling indicates that anomalies are not significant according to a student's *t*-test ($p > 0.05$).

AMOC in Eo$^{400}$ is related to the closed Arctic gateways. The remaining 23% is related to other boundary conditions such as vegetation, elevation differences and changes in non-Arctic gateways such as the Indonesian Throughflow. Both $F_{Agw}$ and $F^{open}_{oro+veg}$ lead to an increase in AMOC strength that is significant according to a student's *t*-test ($p < 0.01$) and contribute approximately equally to above-average SST warming in the subpolar North Atlantic by $F_{oro+veg}$ (Figure S11 in Supporting Information S1). Interestingly, the closure of the Arctic gateways leads to strengthening and deepening of the AMOC, whereas the other orographic and vegetation boundary conditions lead to strengthening concurrent with shallowing of the AMOC cell (Figure 2d). The stronger but shallower AMOC cell in the mPWP is a feature observed in more PlioMIP2 models (Zhang et al., 2021). Our results indicate that for MIROC4m, this shallowing is induced by both $F_{CO2}$ and $F^{open}_{oro+veg}$.

### 3.2. Mechanisms of AMOC Strengthening

Earlier studies have shown that for PlioMIP2, the stronger mPWP AMOC must be related to an increase in salinity in (parts of) the subpolar North Atlantic (Weiffenbach et al., 2023; Zhang et al., 2021). This is also what we observe in Figures 1 and 2, where the mPWP orography and vegetation in particular lead to an increase in sea surface salinity in the subpolar North Atlantic. To gain more insight into the mechanisms behind the AMOC strengthening due to the orographic and vegetation boundary conditions, we separate the contributions of freshwater transport and surface freshwater flux to the freshwater balance in the subpolar North Atlantic. Figure 3 examines the 500 year average input and export of freshwater in E$^{400}$, Eo$^{400}_{open}$ and Eo$^{400}$ in the high-latitude North Atlantic. The region is bounded by a transect at 45°N in the south, a transect at 65°N to the west of Greenland, and a transect at 80°N and 20°E to the east of Greenland (Figure 3). Nearly all North Atlantic deep water formation in winter takes place in this region (Figure 3a).

We find that $F^{open}_{oro+veg}$ (Eo$^{400}_{open}$ minus E$^{400}$ in Figure 3a) leads to a 0.017 Sv reduction (−7%) in the surface freshwater flux within the defined region. The spatial distribution of this reduction is largely determined by the precipitation minus evaporation (PmE), as shown in Figure 3c for $F^{open}_{oro+veg}$. The $F^{open}_{oro+veg}$ PmE anomaly pattern is

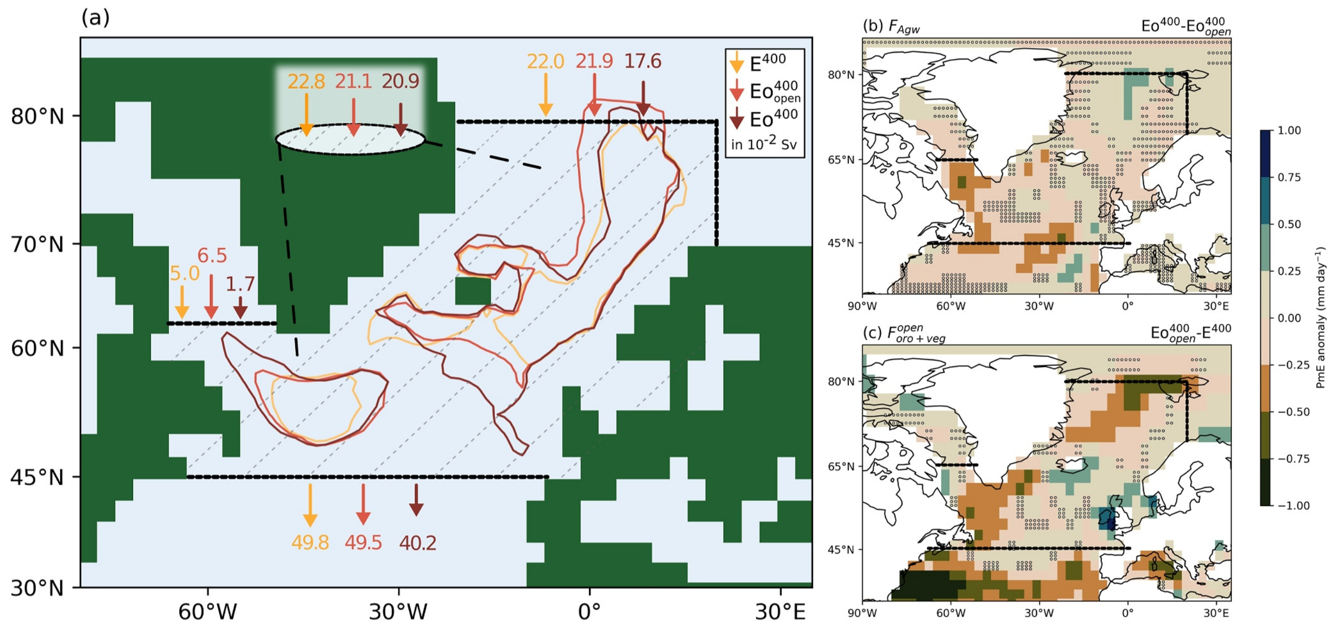


**Figure 3.** (a) $E^{400}$, $Eo^{400}_{open}$ and $Eo^{400}$ 500 year average freshwater transport, including sea ice transport, through indicated ocean transects, and the sum of the surface freshwater flux over the area contained by the transects. $E^{400}$ is a pre-industrial experiment at 400 ppm $CO_2$, $Eo^{400}_{open}$ implements mid-Pliocene orography and vegetation except closed Arctic gateways and $Eo^{400}$ implements all mid-Pliocene orography and vegetation boundary conditions. The transports and surface freshwater flux are given in $10^{-2}$ Sv. Contours show the winter (DJF) mixed layer depth >500 m for each experiment, (b) Precipitation minus evaporation (PmE) anomaly due to closure of Arctic gateways ($F_{Agw}$), and (c) PmE anomaly due to mid-Pliocene orography and vegetation excluding Arctic gateways closure ($F^{open}_{oro+veg}$). Stippling indicates that anomalies are not significant according to a student's $t$-test ($p > 0.05$).

likely related to altered atmospheric conditions and circulation, which lead to changes in both precipitation and evaporation patterns (Figure S13 in Supporting Information S1). The coastal run-off may also play a small role in the negative surface freshwater flux anomaly (Figure S14 in Supporting Information S1). The reduction in surface freshwater flux is almost completely compensated by an 0.015 Sv increase in southward freshwater transport into the Labrador Sea. Therefore, the net decrease of 0.003 Sv of freshwater input in $Eo^{400}_{open}$ with respect to $E^{400}$ will likely not translate to a widespread salinity increase in the subpolar North Atlantic. However, the distribution of the change in freshwater input can lead to local salinification, with as a result deepening of the winter MLD (Figure 2f) and moderate strengthening of the AMOC.

When considering $F_{Agw}$ ($Eo^{400}$ minus $Eo^{400}_{open}$) in Figure 3a, we see a substantial reduction in freshwater transport across both the Labrador Sea and Fram Strait transects. While the $F_{Agw}$ effect on the surface freshwater flux is minimal, the transports through the Fram Strait and Labrador Sea transects are drastically reduced with respectively 0.043 Sv (−20%) and 0.048 Sv (−73%). The total change in freshwater input is −0.093 Sv for $F_{Agw}$. This means that the Arctic gateways are responsible for 97% of the net decrease in subpolar North Atlantic freshwater input by the orographic boundary conditions. The link between a decrease in freshwater transport from the Arctic and an increase in North Atlantic salinity has been shown previously in studies considering the closure of the Bering Strait under different background climates (Brierley & Fedorov, 2016; Hu et al., 2010, 2015). As $F_{Agw}$ explains 77% of the AMOC strengthening by $F_{oro+veg}$, there should also be a role for $F^{open}_{oro+veg}$, likely related to decreases in surface freshwater flux that result in local salinification. This is in agreement with Weiffenbach et al. (2023), who find that the mPWP sea surface salinity anomalies with respect to the pre-industrial are correlated with the PmE surface flux anomalies in PlioMIP2. Paleogeographic changes in the Pliocene not related to the Arctic gateways, such as an altered Barents Sea land-sea mask, have also previously been shown to significantly affect the AMOC (Hill, 2015). While the changes explored by Hill (2015) have not been implemented in the mPWP PRISM4 reconstruction used in this study, their work illustrates that paleogeographic changes in the North Atlantic region can significantly impact the regional climate and ocean circulation.

Otto-Bliesner et al. (2017) state that the AMOC strengthens when closing the Canadian Archipelago and Bering Strait by reduced freshwater transports from the Arctic into the North Atlantic. However, in contrast to our results, they find that the freshwater transport through the Fram Strait increases and that a reduction in freshwater transport takes place only across the Canadian Archipelago. This discrepancy may arise from differences in the models or in the background climate conditions of the closed gateway experiments, which are likely to affect significant factors such as sea ice cover. Our results indicate that both the closure of the Arctic gateways and the reduced surface freshwater flux, driven by atmospheric changes caused by other mPWP orographic and vegetation boundary conditions, contribute to a decrease in freshwater input to the subpolar North Atlantic. The resulting higher salinity enhances deep water formation, strengthening the AMOC. The stronger AMOC then transports more heat and salt northwards into the subpolar North Atlantic (see transport by northward flow at 45°N, Table S1 in Supporting Information S1), leading to a saltier and warmer sea surface (Hu et al., 2010, 2015). The salt advection feedback leads to a further strengthening of the AMOC until an equilibrium is reached with the negative feedback by warming of the subpolar North Atlantic.

## 4. Conclusions and Discussion

We show that the simulated stronger AMOC in the mPWP with respect to the pre-industrial is a consequence of the mPWP combined orographic and vegetation boundary conditions. The higher $CO_2$ concentration and reduced ice sheets in the mPWP cause weakening of the AMOC but are compensated by the orography and vegetation forcing, resulting in a net strengthening in the mPWP. The closure of the Arctic gateways as part of the mPWP orographic boundary conditions is responsible for 77% of the total AMOC strengthening due to combined orographic and vegetation boundary conditions. The remaining 23% of strengthening can be attributed to decreased surface freshwater flux into the high-latitude North Atlantic by other mPWP orography and vegetation. The mechanism for the AMOC strengthening is therefore a combination of a reduction of freshwater transport from the Arctic into the North Atlantic due to the Arctic gateway closure and a decrease of the surface freshwater flux resulting from mPWP orography and vegetation changes. Positive salt advection feedback due to increased northward salt transport further strengthens the AMOC until a balance is reached with the negative thermal feedback induced by subpolar North Atlantic warming.

The results of this study align with Otto-Bliesner et al. (2017), who demonstrated that closing the Bering Strait and Canadian Archipelago strengthens the AMOC and can explain the amplified warming in the mPWP subpolar North Atlantic. With PlioMIP now using PRISM4 boundary conditions (Dowsett et al., 2016), our findings support that the Arctic gateways closure in these boundary conditions drive substantial AMOC strengthening. However, our results differ from Chandan and Peltier (2018), whose CCSM4 model showed an AMOC increase of 2.7 Sv from $F_{CO2}$ but decreases of 0.9 and 0.7 Sv from $F_{oro+veg}$ and $F_{ice}$, respectively, thereby attributing their stronger mPWP AMOC solely to $F_{CO2}$. This contrasts with five other PlioMIP2 models, which show an overall AMOC strengthening when non-$CO_2$ mPWP boundary conditions are applied (Figure S15 in Supporting Information S1). The MIROC4m model response aligns with those of other models, highlighting the importance of further testing of mid-Pliocene boundary conditions as PlioMIP progresses to its third phase, PlioMIP3 (Haywood et al., 2024).

Our study re-emphasizes the importance of considering the impact of non-$CO_2$ boundary conditions on paleoclimates that are considered to be potentially analogous to long-term future climates. Several studies have highlighted the importance of non-$CO_2$ boundary conditions in the mPWP, impacting both the ocean (Burton, Haywood, et al., 2024) and atmosphere (Chandan & Peltier, 2018; Feng et al., 2022; Han et al., 2024; Oldeman et al., 2024). Burton, Oldeman, et al. (2024) show that there are regions with large differences between the Pliocene and projected future climates, which are largely attributable to non-$CO_2$ boundary conditions. Our results provide further insight into the impact of separate mPWP boundary conditions on the AMOC and North Atlantic Ocean conditions. They thereby contribute to our process understanding of this region during the Pliocene and can aid the community when assessing similarities and differences between the Pliocene and a future warm climate.

## Data Availability Statement

The MIROC4m simulation data and Python code used to produce the results in this study are available at Weiffenbach et al. (2024).

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