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Impact of the Tibetan Plateau and Rocky Mountains on deep ocean circulation during the Middle Miocene

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Abstract.

The stages of deep ocean circulation during the Miocene remain uncertain, but palaeogeographic changes likely played a role in its evolution to the Atlantic-dominated overturning state of today. Regarding orographic changes, the uplift of the Tibetan Plateau is thought to be conducive to a shift from Pacific to Atlantic deep water formation, with flattening of the Rocky Mountains having the opposite effect. Here, we perform a suite of fully coupled climate model simulations using the Community Earth System Model version 1.2 (CESM1.2) with middle Miocene palaeogeography to assess the impact of orographic and CO_2 forcing on the meridional overturning circulation (MOC). The control simulation exhibits a strong Pacific MOC (PMOC; ~20 Sv) and no Atlantic MOC (AMOC). Flattening or widening the Tibetan Plateau has no significant effect on either basin's overturning. Flattening the Rocky Mountains strengthens the PMOC by 4 Sv by altering freshwater routing into the Arctic, but does not affect AMOC. A lower CO_2 simulation (2x PI CO_2) yields no qualitative change in overturning structure, indicating that the PMOC is not solely a consequence of warm climate forcing. Our results suggest that Miocene orography influenced Pacific deep water formation but was insufficient to trigger a shift toward modern-like AMOC conditions. This implies that other tectonic and ocean gateway changes were likely necessary to enable the development of the modern Atlantic-dominated overturning regime.

1 Introduction

Earth's climate is influenced by the deep ocean circulation known as the Meridional Overturning Circulation (MOC; Buckley & Marshall, 2016; Liu et al., 2020; Lynch-Stieglitz, 2017). Its strength is linked to the intensity of formation of dense water at the surface due to cooling, evaporation, and sea-ice formation (Rhein et al., 2011). Today, deep water formation takes place in the subpolar North Atlantic and the Southern Ocean. The MOC comprises the complete cycle of polar deepwater formation, its meridional transport to other latitudes, and the eventual upwelling and return to the surface. Its Atlantic upper branch, where deep water forms in the North Atlantic, is called the Atlantic MOC or AMOC. There is some evidence for a deep water formation and overturning in the North Pacific in the past, called the Pacific MOC or PMOC (Burls et al., 2017; McKinley et al., 2019; Naik et al., 2025). The strength and

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structure of the MOC are sensitive to various factors, such as atmospheric freshwater fluxes, basin geometry, and ocean salinity distribution, all of which influence surface water density and thus modulate deep water formation (Böning et al., 2016; de Boer et al., 2008; Ferreira et al., 2018; Naik et al., 2025; Rhein et al., 2011; Roquet et al., 2025). In addition to these, orography has received increasing attention in recent years, and in particular, the evolution of the Tibetan Plateau and the Rocky Mountains during the Cenozoic has been linked to the development of the deep circulation to its modern Atlantic-dominated state (Maffre et al., 2018; Su et al., 2018).

The Tibetan Plateau has a complex tectonic history, beginning with mountain-building events in central and southern Tibet during the Cretaceous, followed by the India–Asia collision around 60–56 million years ago (Ma) and continued uplift of different regions throughout the Paleogene and Neogene (Ding et al., 2022). Substantial uplift of the southern Tibetan Plateau and the Himalayan Ranges occurred during the Miocene (~23-5 Ma; Ding et al., 2017; Spicer et al., 2021). This uplift period coincides with an intensification of the AMOC (Cramer et al., 2009; Uenzelmann-Neben & Gruetzner, 2018; Woodruff & Savin, 1989). Some studies suggest a cessation of overturning in the Pacific around the same time (Kender et al., 2018). The Rocky Mountains, part of the North American Cordillera, also exhibit a complex tectonic and uplift history (Copeland et al., 2017; Fan et al., 2021; Li et al., 2021). Proxy records, including $\delta^{18}O$ records and geological indicators, suggest that the Rocky Mountains were at higher elevations before the Miocene, with surface lowering likely occurring during the Miocene (Cassel et al., 2014; Chamberlain et al., 2012; Colgan & Henry, 2009).

Previous simulations using modern paleogeography and pre-industrial boundary conditions have shown that removing the Tibetan Plateau can weaken the trade winds over the Pacific and collapse the Asian Summer Monsoon, altering interbasin moisture transport and ocean salinity patterns (Maffre et al., 2018; Su et al., 2018; Wen & Yang, 2020). Specifically, in this scenario, when the Tibetan Plateau is removed, a large amount of atmospheric moisture is transported to the North Atlantic from the tropical Pacific and this increased freshwater input into the North Atlantic would lead to surface freshening and a shutdown of the AMOC (Su et al., 2018; Yang et al., 2020; Yang & Wen, 2020). Simultaneously, reduced rainfall over the Pacific increases sea surface salinity, enhancing deep water formation and strengthening the PMOC (Wen & Yang, 2020; Yang & Wen, 2020). Conversely, adding the Tibetan Plateau to a flat global topography has been shown to increase net precipitation and Ekman upwelling in the North Pacific, leading to a shutdown of the PMOC, while reducing moisture export from the tropical Pacific to the North Atlantic, resulting in a slight strengthening of the AMOC (Tong et al., 2025; Yang et al., 2024).

The Rocky Mountains, on the other hand, are thought to block atmospheric moisture transport from the North Pacific to the North Atlantic. Their removal enhances moisture transport to the North Atlantic, decreasing its salinity and weakening the AMOC, while increasing salinity in the Pacific and favouring the establishment of a PMOC (Maffre et al., 2018). Thus, the uplift of the Tibetan Plateau and the lowering of the Rocky Mountains may have exerted opposing influences on Northern Hemisphere overturning

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circulation during the Miocene. However, the role of the Rocky Mountains remains debated, as some studies suggest it plays only a minor or negligible role in deep ocean circulation (Jiang & Yang, 2021; Wen & Yang, 2020; Yang & Wen, 2020).

The Miocene was a warm epoch of the Neogene, characterized by elevated CO_2 levels (~400-800 ppm) and warmer temperatures (~5-8 °C) globally, compared to modern times (Steinthorsdottir et al., 2021; Steinthorsdottir et al., 2025). Previous works mentioned above have looked at the role of the Tibetan Plateau and the Rocky Mountains on the ocean circulation using modern boundary conditions. However, many studies have shown the importance of using a realistic palaeogeography on the sensitivity of the ocean circulation to factors such as ocean gateway changes (Hutchinson et al., 2019; Toumoulin et al., 2020). In this study, we utilize a fully coupled climate model, set up with realistic mid-Miocene palaeogeography and a 3x pre-industrial (PI) CO_2 level (854.1 ppm), to investigate the influence of the Tibetan Plateau and Rocky Mountains on deep ocean circulation during the Miocene. We perform a control simulation with the Getech mid-Miocene palaeogeography along with three sensitivity experiments: one with Tibetan Plateau removal, a second with western Tibetan Plateau uplift, and a third with Rocky Mountains removal. Additionally, we compare these with a 2x PI CO_2 experiment to compare the impact of atmospheric CO_2 with the impact of orography. Section 2 describes the climate model and experimental design, Section 3 presents the simulation results, and Section 4 discusses the findings, limitations, and conclusions.

2 Model and Experiments

2.1 Model

We utilize the fully coupled Community Earth System Model version 1.2 (CESM1.2; Hurrell et al., 2013), which has been widely used by the community for paleoclimate simulations (e.g., Li et al., 2022; Lin et al., 2024). The atmospheric component is the Community Atmosphere Model version 4 (CAM4; Neale et al., 2013), with 26 vertical levels and a horizontal resolution of 1.9x2.5°. The oceanic component is Parallel Ocean Program version 2 (POP2; Smith, 2010), with 1° resolution and 60 vertical levels. The land model is version 4 of the Community Land Model 4 (CLM4; Lawrence et al., 2011), which includes dynamic vegetation for all the simulations in this study, and the sea-ice model is version 4 of the Community Ice Code (CICE4; Hunke & Lipscomb, 2008). Further details of the model set-up and initialisation can be found in Renoult et al. (2026).

2.2 Experimental design

We performed a control simulation using CESM1.2 with middle Miocene paleogeography, representing the Langhian stage (15.97–13.82 Ma), provided by Getech Plc. This control simulation is called Mio_Ctrl. In addition, we performed 3 sensitivity experiments to examine the influence of orography on ocean

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circulation. The topography and bathymetry used in both the control and sensitivity experiments are shown in Fig. 1, and the experiments are described in detail below. These runs were initiated from a middle Miocene simulation used in Renoult et al. (2026), which is the same as our simulations except for a slightly higher bare-soil albedo. The control simulation from Renoult et al. (2026) is referred to as MioDS_Ctrl in this study, where DS indicates 'dark soil'.

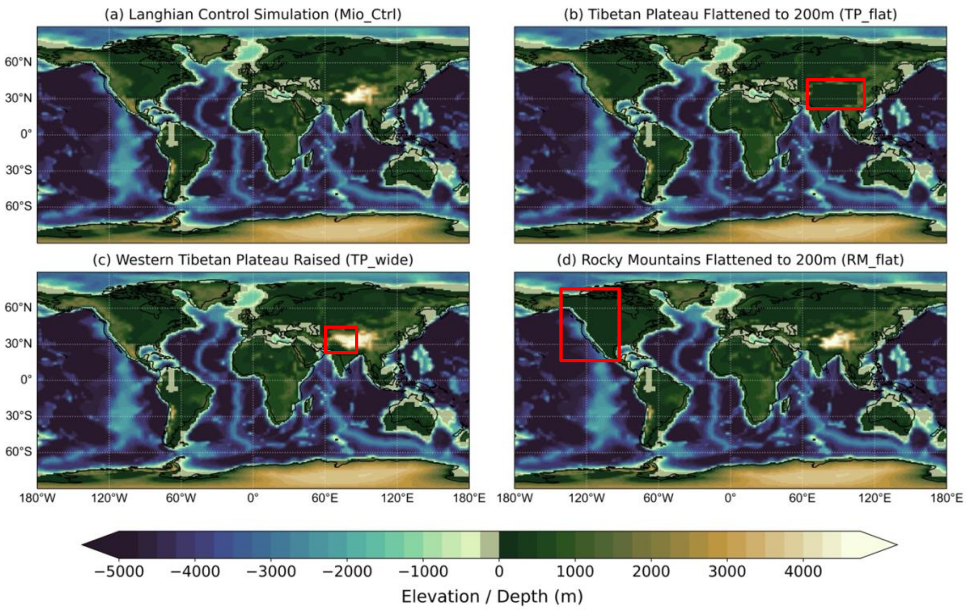

Figure 1. The topography of the Miocene simulations is shown with the simulation name in parentheses in the panel titles. (a) Control simulation for the Langhian (Mio_Ctrl) (b) Tibetan Plateau flattened to 200 m (TP_flat) (c) Western Tibetan Plateau raised higher (TP_wide) (d) Rocky Mountains flattened to 200 m (RM_flat). The regions where the topography is changed compared to Mio_Ctrl are marked with red squares in b, c & d. The topography of the 2xCO2 experiment (Mio_2xCO2) is the same as Mio_Ctrl.

The CO_2 level for all simulations is set to 854.1 ppm, which falls within the range of CO_2 estimates for the middle Miocene (Rae et al., 2021; Steinthorsdottir et al., 2025). While some recent studies suggest lower mid-Miocene CO_2 concentrations, models have struggled to reproduce the warm, proxy-derived Miocene temperatures, particularly at high latitudes, using these lower values (Burls et al., 2021; Hossain et al., 2023). To assess whether the circulation is sensitive to the uncertainty in CO_2 levels, we compare MioDS_Ctrl with an equilibrium simulation at a lower 2x PI CO_2 concentration (~569.4 ppm), which aligns more closely with recent proxy estimates (e.g., Consortium*† et al., 2023; Ji et al., 2018; Steinthorsdottir et al., 2021). This simulation is also from Renoult et al. (2026); however, they did not investigate the ocean overturning circulation in their study. We refer to this simulation as Mio_2xCO2. Given that these simulations are identical to Mio_Ctrl except for the bare soil colour, and that the corresponding control simulation produces a virtually unchanged MOC, we infer that soil colour exerts a

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negligible influence on the large-scale overturning circulation. Consequently, we deemed it unnecessary to rerun these simulations for analysis in this study.

In the first sensitivity experiment, we flattened the Tibetan Plateau, from elevations exceeding 4000 m in the control, to 200 m (Fig. 1b). This simulation is referred to as TP_flat and represents an earlier topographic state than that of the Miocene. The Himalayan and Karakoram mountain ranges were also included in the flattened region to capture the full influence of Asian orography.

In the second experiment, we increased the elevation of the western Tibetan Plateau to match the broader topographic extent shown in the palaeogeographic reconstruction of Burls et al. (2021). This experiment is called TP_wide, and represents a later state when the Tibetan Plateau was wider (Fig. 1c).

In the third experiment, we flattened the Rocky Mountains to an elevation of 200 m; this is referred to as RM_flat (Fig. 1d). It represents an extreme test case of the Rocky Mountains lowering across the Miocene. Previous studies have also tested the impact of Rocky Mountains removal on ocean circulation, although using PI boundary conditions (Jiang & Yang, 2021; Maffre et al., 2018). Thus, our RM_flat experiment allows us to investigate the effect of a possible lowering of the Rocky Mountains during the Miocene and also assess whether our results are consistent with these prior findings.

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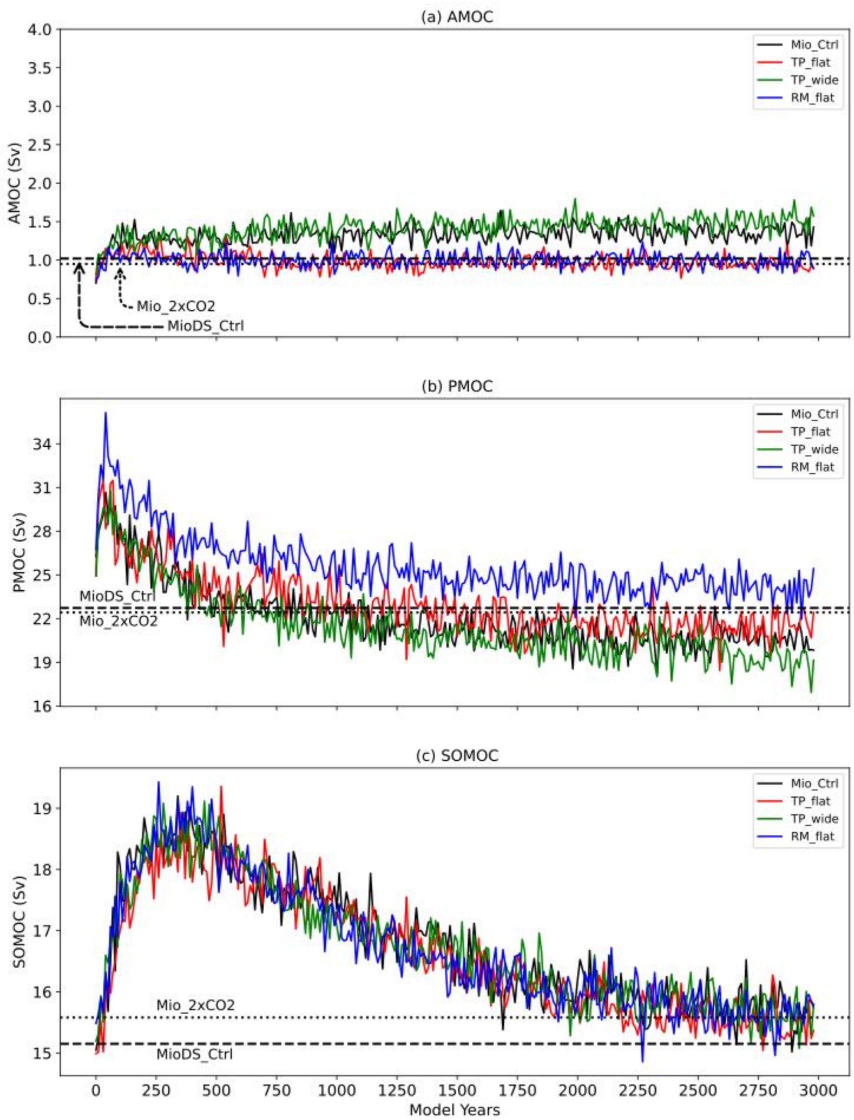

Figure 2. The spin up of the (a) Atlantic Meridional Overturning Circulation (AMOC), (b) Pacific MOC (PMOC), and (c) Southern Ocean MOC (SOMOC) over the 3000 years of the simulations, for the three sensitivity experiments, TP_flat (red), TP_wide (green), and RM_flat (blue), and the Miocene control simulation Mio_Ctrl (black). The dashed and dotted lines show the average value of the MOCs in MioDS_Ctrl and Mio_2xCO2, respectively, over the final 100 years.

The MioDS_Ctrl and Mio_2xCO2 simulations from Renoult et al. (2026) were run for 3222 years. The control and sensitivity experiments for this study were branched off from the final year of MioDS_Ctrl and run for an additional 3000 years. The climatological mean is computed from the last 100 years of each simulation for analysis.

To check that the simulations are in quasi-equilibrium, we follow the criteria recommended by De Boer et al. (2025), which is that the trends in AMOC, PMOC, and Southern Ocean MOC (SOMOC) should be

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less than 1 Sv/1000 years and the deep ocean temperature (DOT) trend should be less than 0.1°C/century for the final 1000 years of the simulations. AMOC is defined as the maximum of the North Atlantic overturning streamfunction, north of 45°N and below 500 m. PMOC is defined as the maximum of the North Pacific overturning streamfunction, north of 30°N and below 500 m. SOMOC is defined as the absolute value of the negative minima of the global overturning streamfunction, south of 20°S and below 2000 m. Table 1 confirms that almost all of the criteria are fulfilled by our simulations, except for the PMOC in TP_wide, which has a trend only slightly above (-1.08 Sv/1000 years) the recommended value.

Table 1. The mean trends in AMOC, PMOC, SOMOC, and the centennial trend of DOT for the three sensitivity experiments, TP_flat, TP_wide, and RM_flat, over the final 1000 years of the simulation.

Experiment	AMOC trend (Sv/1000 years)	PMOC trend (Sv/1000 years)	SOMOC trend (Sv/1000 years)	DOT trend (°C/century)
Mio_Ctrl	-0.05	-0.19	0.42	-0.01
TP_flat	-0.03	0.15	0.42	-0.01
TP_wide	0.05	-1.08	0.35	-0.01
RM_flat	-0.03	-0.15	0.46	-0.01

3 Impact of orography and CO_2 on the overturning circulation

3.1 Impact of the Tibetan Plateau

The control experiment, Mio_Ctrl, exhibits a strong PMOC of approximately 20 Sv (Fig. 3b; Table 2). In contrast, the North Atlantic overturning strength is only ~1 Sv (Fig. 4b; Table 2), indicating an AMOC-off state. Earlier studies have suggested that the uplift of the Tibetan Plateau arrested the PMOC in favour of an AMOC (Tong et al., 2025; Yang et al., 2024). The persistence of a PMOC in the Mio_Ctrl simulation despite a substantial Tibetan Plateau suggests that other factors may have played a stronger role in determining the state of Northern Hemisphere overturning during this period. If this Miocene control simulation is realistic, then it suggests that the PMOC may have been more robust than previously thought. Given that the control already has a PMOC and no AMOC, the removal of the Tibetan Plateau cannot produce the results of a switch to a PMOC-dominated state. At most, it would strengthen the PMOC. On the other hand, a higher or wider Tibetan Plateau may weaken the PMOC here. Nevertheless, one could investigate if the atmosphere and ocean (e.g., winds, freshwater fluxes) react in the same fashion as suggested by previous studies that removed the Tibetan Plateau in models with modern paleogeography.

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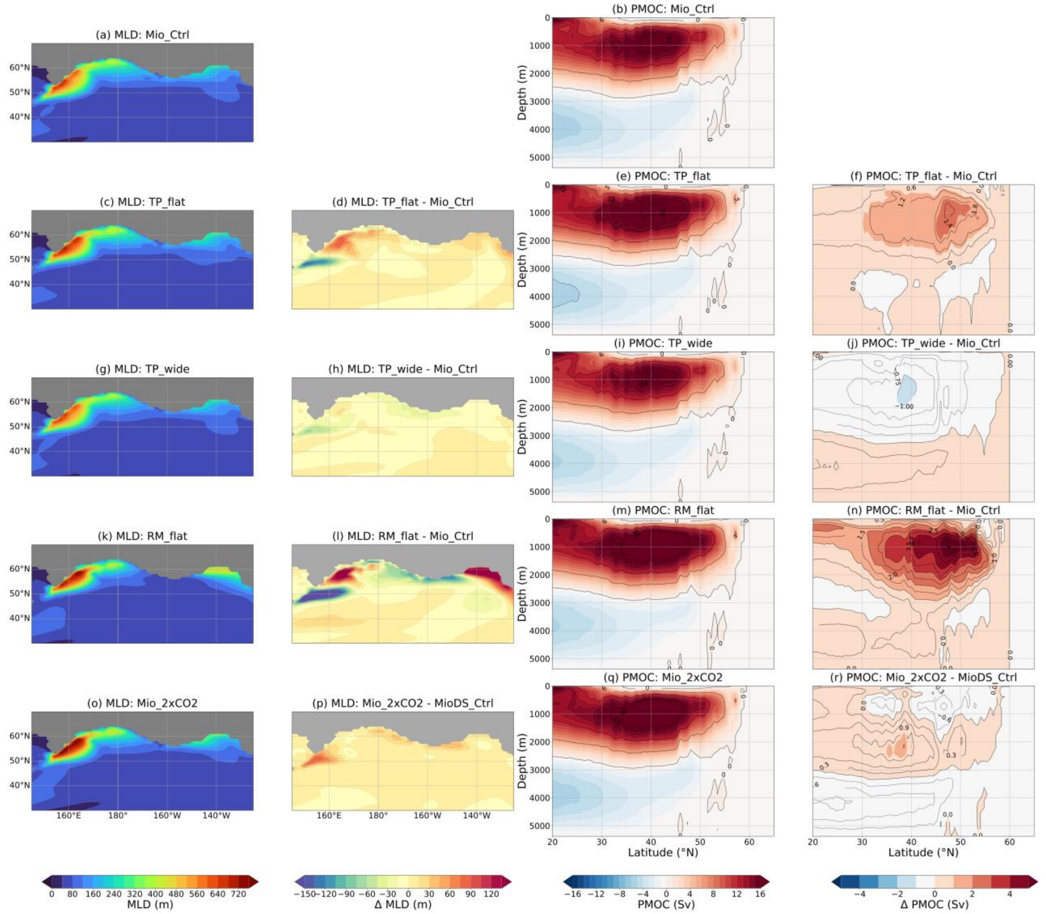

Figure 3. North Pacific Mixed Layer Depth (MLD) and PMOC in all the experiments. Experiments are arranged in rows (Mio_Ctrl, TP_flat, TP_wide, RM_flat, and Mio_2xCO2, respectively). Column 1 is the North Pacific MLD, column 2 is the difference in MLD between the sensitivity and control experiments. Column 3 is the overturning streamfunction in the North Pacific, and column 4 is the difference in PMOC in the sensitivity and control experiments. In the PMOC streamfunctions (column 3), the positive streamfunction (red) values denote a clockwise circulation and the negative streamfunction (blue) values denote an anticlockwise circulation.

3.3.1 Flattening the Tibetan Plateau

Reducing the height of the Tibetan Plateau to 200 m in TP_flat has no significant impact on the overturning circulation compared to the control simulation (Fig. 3e,f; Fig. 4e,f; Table 2). Specifically, the AMOC and SOMOC are unchanged, and the PMOC strengthens by 1 Sv (Table 2). This result is similar to, but considerably weaker than, that suggested by several earlier studies that have found a strong response of the PMOC to the removal of the Tibetan Plateau. However, since the PMOC is already strong in Mio_Ctrl, this result is not unexpected. We investigate which of the mechanisms at play in those studies are active or absent in this study. Specifically, the removal of the Tibetan Plateau has been found to alter

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the atmospheric circulation, diverting moisture from the Pacific to the North Atlantic due to weakening of trade winds and the Asian Summer Monsoon, which freshens the North Atlantic and affects deep water formation in both ocean basins (Maffre et al., 2018; Su et al., 2018; Wen & Yang, 2020).

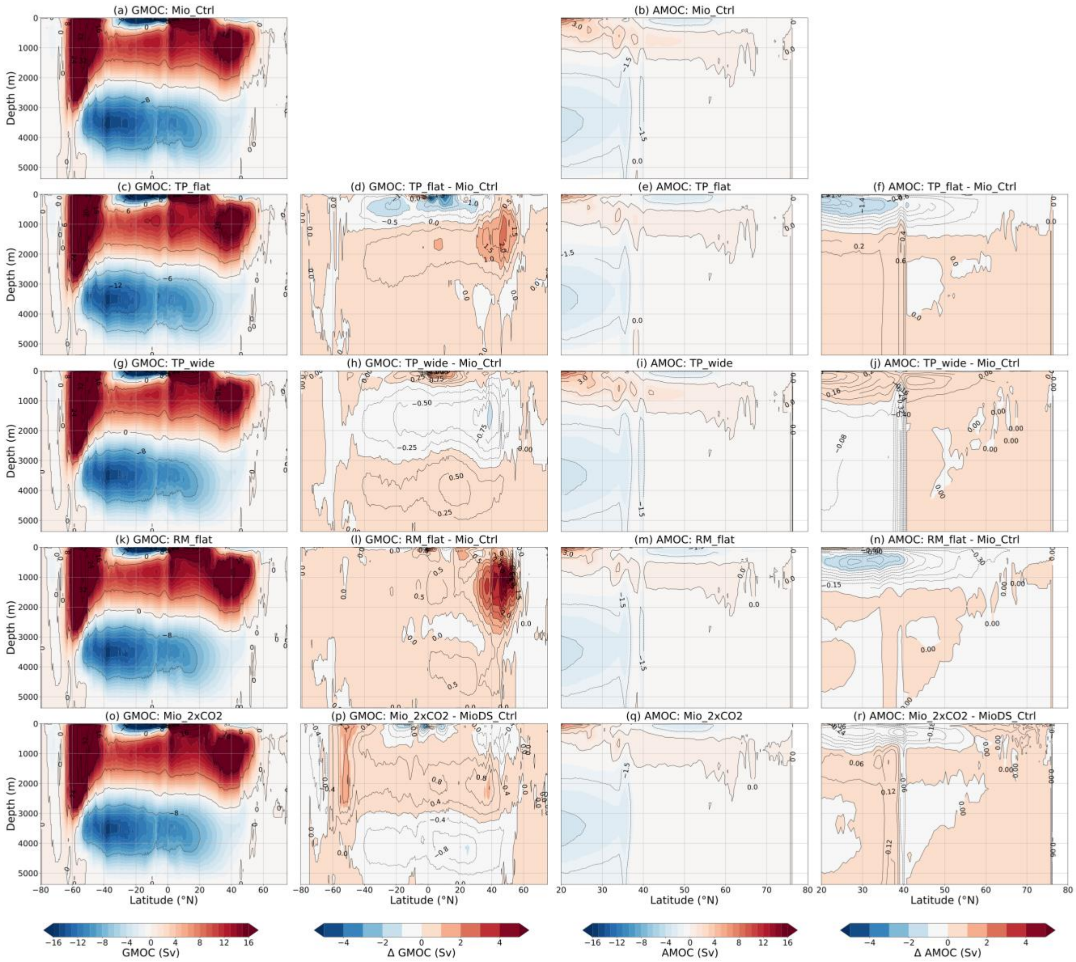

Figure 4. GMOC and AMOC in all simulations. Experiments are arranged in rows (Mio_Ctrl, TP_flat, TP_wide, RM_flat, and Mio_2xCO2, respectively). Column 1 is the GMOC, column 2 is the difference in GMOC between the sensitivity and control experiments. Column 3 is the AMOC, and column 4 is the difference in AMOC between the sensitivity and control experiments. Similar to Fig. 3, the positive streamfunction (red) values denote a clockwise circulation and the negative streamfunction (blue) values denote an anticlockwise circulation in columns 1 and 3.

In our TP_flat simulation, the changes in freshwater flux over the North Pacific are limited (Fig. 5d). The Indian Ocean and western tropical Pacific exhibit a strong reduction in freshwater flux, while the eastern and central tropical Pacific exhibit an increased freshwater flux (Fig. 5d). The reduction in freshwater flux over the Indian Ocean points towards the collapse of the Asian Summer Monsoon, as also indicated

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by the changes in winds over the Indian subcontinent (Fig. 6b,c). The reduced freshwater flux in the North Pacific results in a similarly small strengthening of the PMOC (by 1.3 Sv; Table 2, Fig. 3f).

Table 2: The strength of overturning in the North Atlantic (AMOC), North Pacific (PMOC), and Southern Ocean (SOMOC), North Pacific Sea Surface Salinity for all the experiments, and the difference in the strengths between the sensitivity experiments and the control experiment.

Experiment	Mio_Ctrl	TP_flat	TP_flat – Mio_Ctrl	TP_wide	TP_wide – Mio_Ctrl	RM_flat	RM_flat – Mio_Ctrl
AMOC Strength (Sv)	1.4	1.0	-0.5	1.5	0.1	1.0	-0.5
PMOC Strength (Sv)	20	21	1.3	19	-1.0	24	4
SOMOC Strength (Sv)	16	16	-0.3	15	-0.3	16	-0.2
North Pacific FWF (10^{-5}) ($kg/m^2/s$)	1.21	1.13	-0.08	1.24	0.03	0.99	-0.22
North Pacific SSS (PSU)	34.82	35	0.18	34.65	-0.17	35.02	0.2

Earlier studies have reported a persistent El Niño state and a weakened Walker circulation in the Pacific–indicated by weakening of the easterly trade winds and a shift in freshwater flux, where the central tropical Pacific receives higher freshwater flux while the western tropical Pacific receives lower freshwater flux–linked to the removal of the Tibetan Plateau (Naiman et al., 2017; Wen et al., 2020). We observe similar shifts on our TP_flat experiment, supporting these previous theories (Figs. 5d, 6c).

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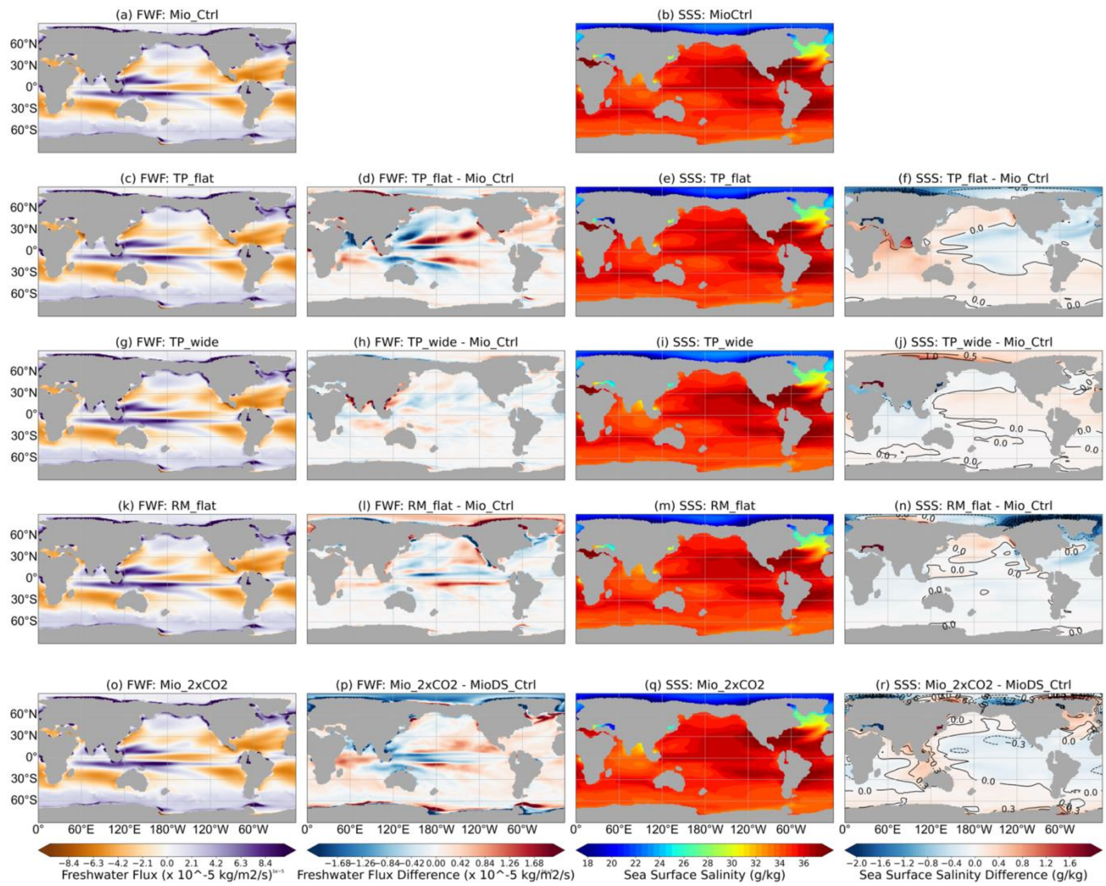

Figure 5. Surface oceanic freshwater flux and Sea Surface Salinity (SSS) for all the experiments. Experiments are arranged in rows (Mio_Ctrl, TP_flat, TP_wide, RM_flat, and Mio_2xCO2, respectively). The surface freshwater flux is calculated as $\boldsymbol{Precipitation - Evaporation + Runoff + Sea\ Ice\ Melt + Snow}$. Column 1 is the surface freshwater flux, column 2 is the difference in freshwater flux between the sensitivity and control experiments. Column 3 is the SSS, and column 4 is the difference in SSS between the sensitivity and control experiments.

3.1.2: Widening the Tibetan Plateau

A common experiment to investigate the role of the Tibetan Plateau in ocean circulation involves adding the Tibetan Plateau to a globally flat orography. This typically leads to a shutdown of the PMOC, caused by increased net precipitation in the North Pacific, while simultaneously strengthening the AMOC due to increased salinity in the North Atlantic (Tong et al., 2025; Yang et al., 2024). Instead of adding the Tibetan Plateau to a flat orography, in our TP_wide experiment, we raise the western Tibetan Plateau in our palaeogeography to match that of Burls et al. (2021) leading to a wider Tibetan Plateau overall (Section 2.2). Raising the western region of the Tibetan Plateau has a very limited influence on the PMOC (Fig. 3j). It weakens by ~1 Sv, while the AMOC and SOMOC remain essentially unchanged (Table 2; Fig. 3j; Fig. 4h,j).

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In TP_wide, only the Indian Ocean and the coastal western tropical Pacific exhibit a noticeable change, with an increase in freshwater flux and a subsequent reduction in salinity (Fig. 5h,j). This points towards a strengthening of the Asian Summer Monsoon system, as theorised previously (Zhang et al., 2015). Overall, the widening of the Tibetan Plateau only has local effects, likely due to the fact that it is a relatively small change in orography compared to the TP_flat simulation.

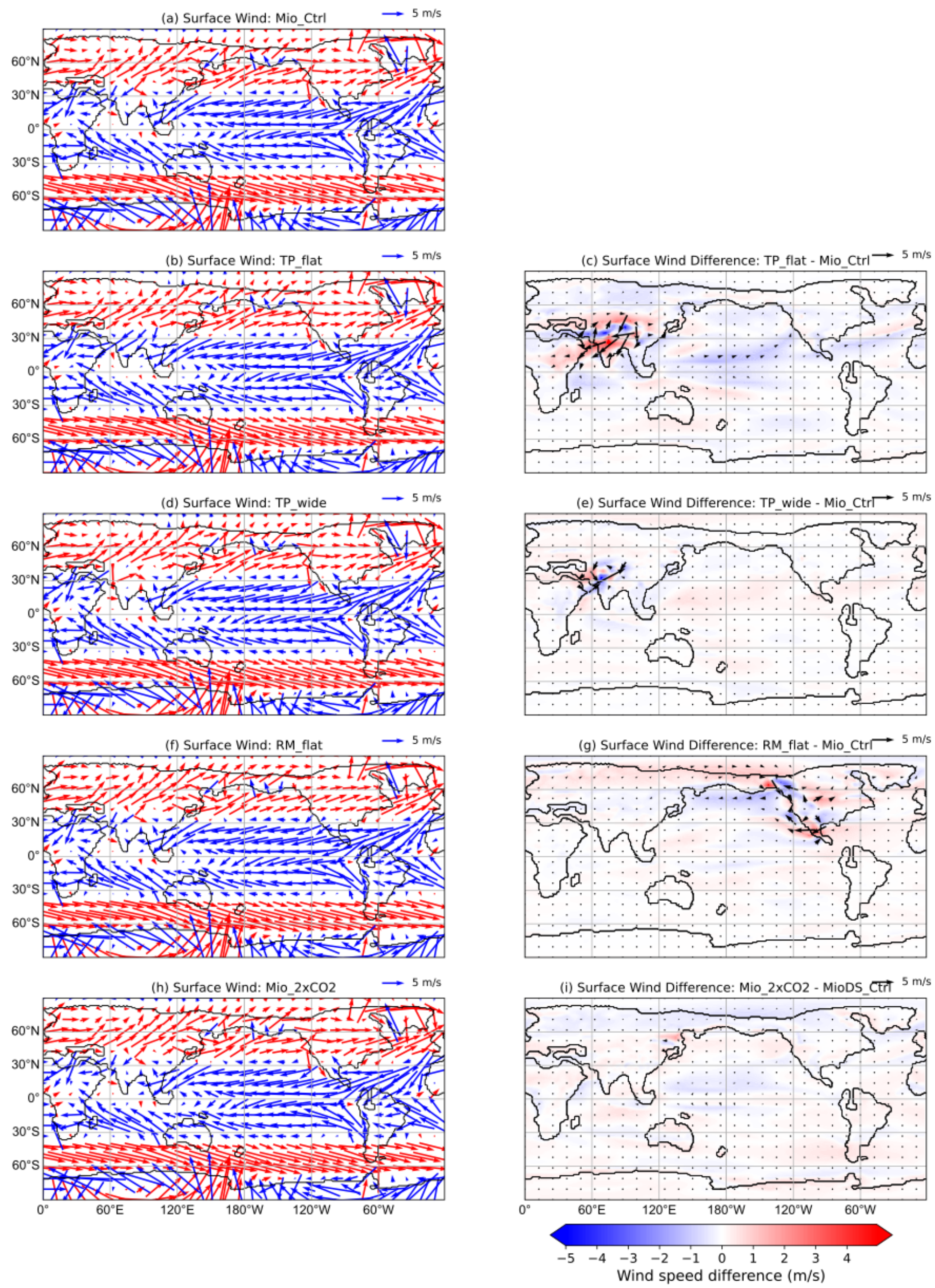

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Figure 6. Surface winds in all the experiments. Experiments are arranged in rows (Mio_Ctrl, TP_flat, TP_wide, RM_flat, and Mio_2xCO2, respectively). Column 1 is surface winds with the red arrows representing westerly winds and blue arrows representing easterly winds. Column 2 is the difference in surface winds of the sensitivity and control experiments. The contour is the difference in wind speed, and the quivers represent the difference in wind direction, calculated as the resultant vector of $\boldsymbol{U_{diff}} = \boldsymbol{U_{exp}} - \boldsymbol{U_{Mio\_Ctrl}}$ and $\boldsymbol{V_{diff}} = \boldsymbol{V_{exp}} - \boldsymbol{V_{Mio\_Ctrl}}$, where $\boldsymbol{U_{exp}}$ and $\boldsymbol{U_{Mio\_Ctrl}}$ are the zonal component of the surface wind of the sensitivity experiments and control experiment (Mio_Ctrl), respectively, and $\boldsymbol{V_{exp}}$ and $\boldsymbol{V_{Mio\_Ctrl}}$ are the meridional components. Reference arrows for the wind speed are placed in the upper right corner of each panel, representing 5 m/s.

3.2 Impact of the Rocky Mountains (RM_flat)

In pre-industrial climate simulations, removing the Rocky Mountains has been shown to suppress the AMOC and enhance the PMOC by allowing increased atmospheric moisture transport from the Pacific into the North Atlantic (Maffre et al., 2018; Sinha et al., 2012). This altered freshwater flux is the result of changes in runoff leading to more freshwater reaching the Atlantic, which would have precipitated out into the Pacific or Indian Ocean in the presence of orography (Maffre et al., 2018). However, more recent studies suggest that removing the Rocky Mountains may not have a significant effect on the MOC (Jiang & Yang, 2021; Yang et al., 2024). To test this under Miocene boundary conditions, we conduct a sensitivity experiment where the Rocky Mountains are flattened to 200 m (RM_flat).

RM_flat results in the strongest response to change in orography compared to the other experiments in this study, where the PMOC strengthens by 4 Sv (Fig. 3n, Table 2). The AMOC and GMOC, however, remain unchanged (Fig. 4l,n; Table 2). A likely mechanism for the enhanced PMOC is reduced surface runoff into the eastern North Pacific, which increases surface salinity and thus deepens convection in this region (Fig. 3l, 5n). This excess runoff appears to be redirected into the Arctic instead (Fig. 5l, n), supporting the idea that regional hydrological changes play a role in modulating deep water formation.

3.3 Impact of CO_2 forcing (Mio_2xCO2)

The control simulation, Mio_Ctrl, features a strong PMOC (~20 Sv) and no AMOC, as shown in Fig. 3b and Table 2. This ocean state is relatively uncommon among early to mid-Miocene simulations, where most models simulate either no PMOC or only a weakly emerging AMOC (Naik et al., 2025). A strong PMOC is more typically associated with the warmer climates of the Eocene and possibly the early Miocene, both from a dynamic perspective (de Boer et al., 2007; de Boer et al., 2008) and from a proxy perspective (Ferreira et al., 2018). Recent results from Hutchinson et al. (2025) further support the notion that PMOC is more favourable in warmer Miocene climates, while colder climates tend to support AMOC development.

Given that our CO_2 concentration in Mio_Ctrl (854.1 ppm) is at the upper end of proxy-based estimates, it raises the question of whether the strong PMOC seen in all our experiments is primarily driven by

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excessive greenhouse forcing. However, comparison with a lower 2xPI CO_2 level (Mio_2xCO2; CO_2 level: ~569.4 ppm) indicates that the PMOC is strong, even at this level of greenhouse forcing (Fig. 2q), while the AMOC is still off (Fig. 4q). Other relevant ocean-atmosphere fields, including freshwater flux, SSS, and wind patterns, show minimal changes between Mio_2xCO2 and MioDS_Ctrl (Fig. 5p&r; Fig. 6i). These results indicate that the presence of a PMOC in our simulations cannot be solely attributed to the high CO_2 forcing.

Thus, we conclude that the strong PMOC state is a robust feature of our Miocene model configuration, likely resulting from a combination of palaeogeographic boundary conditions, model-specific ocean and atmospheric dynamics, and CO_2 forcing, but not driven exclusively by the elevated CO_2 levels.

4 Discussion and Conclusions

We conducted climate model simulations using a middle Miocene palaeogeography to investigate the influence of the Tibetan Plateau and Rocky Mountains on deep ocean circulation. The control simulation (Mio_Ctrl) exhibits a strong PMOC of ~20 Sv and negligible overturning in the North Atlantic (~1 Sv), representing an AMOC-off state. Based on proxy evidence, this PMOC may be too strong for the middle Miocene, when the Pacific overturning was likely weaker or possibly absent (Naik et al., 2025; Steinthorsdottir et al., 2021). Even when CO_2 levels are reduced to a lower 2xPI value, the PMOC remains strong, and the AMOC does not recover.

The uplift of the Tibetan Plateau has been proposed to weaken the PMOC while strengthening the AMOC (Tong et al., 2025; Wen & Yang, 2020; Yang et al., 2024; Yang & Wen, 2020). In our simulations, we find limited support for this mechanism. Neither flattening nor widening the Tibetan Plateau has noteworthy effects on the AMOC or PMOC. That such an extreme experiment, where the Tibetan Plateau is flattened to 200 m, produces no discernible effect on the PMOC, is possibly because it is already strong in the control simulation. We do find that the removal of the Plateau weakens the tropical Pacific trade winds and the Walker circulation, leading to a more El Niño-like state, which is in agreement with previous studies (Naiman et al., 2017; Wen et al., 2020). Flattening the Rocky Mountains has the strongest effect on overturning in this study, where the runoff is redirected from the eastern North Pacific into the Arctic, leading to a saltier North Pacific and a fresher Arctic Ocean (Fig. 5l, n). Thus, our Miocene simulations suggest that the removal of the Rocky Mountains has important consequences for PMOC, in contrast with the previous studies, which suggest that the removal of the Rocky Mountains does not affect the PMOC significantly (Jiang & Yang, 2021; Yang et al., 2024). However, it should be noted that, overall, this impact is comparatively small relative to the strength of PMOC.

CESM1.2 under our Miocene boundary conditions shows a clear preference for sustaining a strong PMOC, even under substantially altered orographic and climatic conditions. The Miocene Arctic is very fresh compared to today, with Arctic SSS in Mio_Ctrl on average 20 PSU. The freshwater signal spreads through to the North Atlantic, where salinities in the present-day deep water formation regions of the

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Labrador Sea and Nordic Seas remain below 30 PSU in all the experiments. Such an open connection with a fresh Arctic inhibits the AMOC and is conducive to a PMOC through salinity feedback that is assisted by the open Panama gateway during the Miocene (Hutchinson et at., 2019). The impact of fresh Arctic and the Arctic-Atlantic connection on the deep overturning overrides that of the Tibetan Plateau and the Rocky Mountains, leaving their impacts to be primarily localized. It may be that our model has a salinity bias in the Arctic and North Atlantic that inhibits the impact of the orography. The experiment should be repeated in a model with Miocene paleogeography and a PMOC off and AMOC on control state. Whether this is realistic is uncertain, since most models feature a fresh Arctic and salinity and AMOC-off state in the early and mid-Miocene (Naik et al., 2025). Our study thus suggests that the orography played a minor role on the deep water formation during the Miocene, but that it may be equally or more important to establish first what the ocean circulation during the mid-Miocene looked like and what the importance of the fresh Arctic was. The upcoming Miocene intercomparison Project MioMIP2 will be a good opportunity for progress on this fundamental question.

Data and code availability

The model output for all the experiments and the Python code to analyse the dataset and reproduce the figures in this study will be made publicly available on Zenodo upon acceptance.

Competing interests

The authors declare that they have no conflict of interest.

Author contributions

TN and AdB conceptualized the study. TN and MR performed the simulations (investigation). TN conducted the formal analysis and wrote the original draft of the manuscript. AdB and MR reviewed and edited the manuscript. AdB provided resources and supervised the project.

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