Pivotal Role of Tibetan Plateau and Antarctic in Shaping Present-day Atlantic Meridional Overturning Circulation

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ABSTRACT

Our recent study has shown key roles of the Tibetan Plateau and Antarctic orography in the formation of the Atlantic Meridional Overturning Circulation (AMOC). This is a follow-up investigation to elucidate physical processes of the combined effect by comparing two different sets of experiments: starting from a global flat orography, one to incorporate the Tibetan Plateau (TP) first followed by the Antarctica (TP2AT) and the other to introduce the Antarctica first followed by the TP (AT2TP). The uplift of the TP significantly modifies moisture transport in the Northern Hemisphere, leading to a fresher North Pacific and a more saline North Atlantic. This alteration of atmospheric moisture transport is essential for the transition of deep-water formation from the North Pacific to the North Atlantic, which activates the AMOC. The role of Antarctic orography is mainly associated with its influence on the atmospheric westerlies over the subpolar Southern Hemisphere, which can strengthen the AMOC by boosting Ekman pumping and Agulhas leakage in the Southern Ocean. The combined influence of the TP and the Antarctica is the key driving factor for establishing the current configuration of the AMOC. The sequence of the TP going before the Antarctica (TP2AT) is more effective in setting up the AMOC than the other way around (AT2TP). This is because in AT2TP it takes time to terminate a strong Pacific Meridional Overturning Circulation (PMOC) before the AMOC gets into a full swing.

KEYWORDS: Atlantic Meridional Overturning Circulation, Pacific Meridional Overturning Circulation, Tibetan Plateau, Antarctica, Coupled Model

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a crucial part of the present-day global climate system. Its fluctuations and potential responses to ongoing global warming are a global concern. The AMOC is also considered to hold a tipping point within the climate system (van Westen et al. 2024). Both observational data and model simulations have indicated a weakening AMOC during the recent period and the consequent accumulation of salinity in the South Atlantic (Zhu and Liu 2020). Some model projections suggested that this weakening trend of the AMOC may persist over the coming decades due to ongoing freshwater influx from the melting of Greenland's ice sheets (Weijer et al. 2012). Some researchers even suggested that a transition of the AMOC could happen as early as 2025 (Ditlevson and Ditlevson 2023). The future of the AMOC remains a hot topic in climate research.

To assess potential future changes of the AMOC, it is essential to understand the fundamental factors driving it. Traditional views of the AMOC are that it is maintained by buoyancy forcing in the North Atlantic and by wind stress forcing over the Southern Ocean (Johnson et al. 2019; Bryden 2021). The significance of large continental orography, such as massive mountain ranges, in shaping the modern-day AMOC has also been increasingly recognized (Sinha et al. 2012; Maffre et al. 2018; Yang and Wen 2020; Jiang and Yang 2021; Schmittner et al. 2011; Stouffer et al. 2022). Numerous simulations suggested that on a hypothetical Earth without significant topographical relief, the Pacific Meridional Overturning Circulation (PMOC) would predominate rather than the AMOC (Sinha et al., 2012). If all the giant mountains are removed, the modern-day MOC would be switched from the Atlantic to the Pacific (Maffre et al. 2018). In today's world there is no deep-water formation in the North Pacific, primarily because the surface seawater in that ocean basin is not dense enough to sink.

Geological evidence indicates that the uplift of the Tibetan Plateau (TP), the highest plateau in the world, coincides with the formation of the North Atlantic Deep Water (NADW), illustrating a potential role of the TP in shaping the AMOC (Ivanova 2009; Ferreira et al. 2018; Yang and Wen 2020; Liu et al. 2022). The significant elevation of the TP can dramatically impact the mid-latitude westerlies, thereby altering moisture transport patterns (Liu et al. 2007; Tang et al. 2022). These changes can profoundly influence buoyancy-driven thermohaline circulations (Yang and Wen 2020). Previously, we conducted a series of orography sensitivity experiments using coupled models, focusing on the impact of continental orography on the global meridional overturning circulation (GMOC) (Yang et al. 2024). Our findings show that the rise of the TP is indispensable in the formation of the AMOC. However, the TP alone is insufficient to fully establish the AMOC, which requires the contribution of other significant orography. Specifically, only the Antarctic has the capability to complement the TP's influence and achieve the complete establishment of the AMOC, as we will demonstrate in this paper.

Polar regions are sensitive to changes in the climate system; and the interactions between polar regions and ocean circulations may potentially trigger cascading effects on global climate (Dekker et al. 2018). Around three million years ago (Ma), the expansion of the Antarctic ice-sheets initiated changes in deep ocean circulation, hastening glaciation in the Northern Hemisphere (Woodard et al. 2014). Wind-induced upwelling process in the Southern Ocean can drive the AMOC (Kuhlbrodt et al. 2007). A strong meridional gradient in the westerlies over the Southern Ocean can significantly enhance the upwelling of deep-water masses and thus strengthen the NADW formation (Delworth and Zeng 2008). Additionally, a warmer Southern Ocean is usually linked to a stronger AMOC through a reduction in the formation of the Antarctic Bottom Water (AABW) and strengthening of the Agulhas leakage (Buizert and Schmittner 2015). Despite the recognized importance of physical processes in the Southern Ocean for the AMOC, research focusing specifically on Antarctica’s impact on the AMOC is limited.

Researchers have long acknowledged that the influence of continental orography on modern-day ocean circulations. Prior investigations typically concentrated on understanding how the presence or absence of global mountain ranges impacts ocean currents and on isolating the influence of individual topography. Sinha et al. (2012) and Maffre at al. (2018) concluded the global large orography’s importance on shaping modern-day MOC. Both of these studies emphasized that mountains matter in changing the heat and freshwater fluxes over the ocean, thus altering the ocean circulation mode. Maffre et al. (2018) argued that Rocky Mountain is critical to shift the area of strong precipitation and change the river runoff towards the tropical Atlantic, which leads to the change of AMOC. These conclusions are consistent with Schmittner et al. (2011)’s work, who argued that the existence of the Andes and the Rocky Mountains reduce atmospheric moisture transport from the Pacific to the Atlantic. So, the North Atlantic becomes saltier and the North Pacific becomes fresher. However, as the whole continental orography is removed in the above studies, it is hard to conclude the reason for the MOC shift being caused by mountains in North America. Maroon (2016) utilized the Geophysical Fluid Dynamics Laboratory (GFDL) model and revealed a significant enhancement of the PMOC in a removing-Rocky experiment. However, this change was not attributed to the traditionally assumed influence on the wind field (Maffre et al. 2018; Sinha et al. 2012), but rather to the effect of river runoff. Furthermore, it was found that keeping the Rocky Mountain while altering the direction of river runoff would also modify the MOC pattern. A previous work in our research group conducted Rocky Mountain-only experiment and found that Rocky Mountain's existence has a weak effect on AMOC (Jiang and Yang. 2021). Since the locations of deep-water formation and variations in river runoff differ across models, the role of the Rocky Mountains in influencing the MOC remains a subject of ongoing debate. Yang et al. (2024; hereafter Y24) then conducted a brief examination of the collective impact of different mountainous regions on the GMOC. Their findings suggested that the TP and Antarctica, through their respective influences on deep-water formation and Ekman pumping, can jointly facilitate a complete establishment of the AMOC. Building upon the groundwork laid by Y24, this paper aims to investigate detailed processes translating the synergistic effects of the TP and the Antarctic into the establishment of the AMOC.

This paper is organized as follows. In Section 2, we present the models and experiments used in this study. In Section 3, we detail the changes in the AMOC resulting from the uplift of the TP and Antarctica orography, in different orders. The mechanisms underlying the combined effects of the TP and Antarctica on the AMOC are thoroughly investigated in Section 4. A summary of our findings is presented in Section 5, together with a discussion on their implications.

2. Model and experiments

The Community Earth System Model (CESM) is developed by the United States' National Center for Atmospheric Research (NCAR) and the climate research community. It is a fully coupled climate model that enables simulations of the past, present, and future climate of the Earth. It is widely used in examining atmospheric processes, ocean circulations, and the interactions between them. The model comprises six components: atmosphere, land, ocean, sea ice, land ice, and a coupler. The CESM version 1.0.4 is employed in this study, with a resolution of T31_gx3v7. Specifically, the CAM4 is the atmospheric module, and the POP2 is the oceanic module. The atmosphere and land models have 48 and 96 grid points in the horizontal direction with a resolution of approximately 3.75° × 3.75°, and the atmosphere has 26 vertical levels. The ocean model POP2 employs the gx3v7 grid, with a uniform zonal grid spacing of 3.6° and non-uniform meridional grid. The meridional resolution is 3.4° around 35°N and 35°S, and gradually increases towards the equator and poles, reaching 0.6° near the equator. The ocean has 60 vertical layers. The horizontal resolution of the sea ice model is the same as that of the ocean model. Further details on CESM1.0 can be found in Hurrell et al. (2013).

Some experiments analyzed in this paper were performed previously (see Y24), including the "Real," "Flat," "OnlyTP," and "OnlyAT" simulations. The "Real" simulation incorporates realistic terrestrial topography; it was run for 2400 years, serving as a benchmark for comparing the effects of topography on ocean circulations. Conversely, the "Flat" simulation assumes an Earth with a uniform altitude of 10 meters above sea level globally; it was integrated for 1600 years (Fig. 1a). The simulations "OnlyTP" (Fig. 1b) and "OnlyAT" (Fig. 1c) modify the "Flat" scenario by incorporating the topography of the TP and Antarctica, respectively. These two experiments, designed to isolate the effects of individual topographies, were run for 1600 years each, starting from year 801 of the "Flat" simulation.

To explore the combined influence of the TP and Antarctica on the AMOC, we use two distinct sets of topographical experiments: "TP2AT" and "AT2TP." The "TP2AT" experiment involves adding Antarctic terrain to the "OnlyTP" setup, and is integrated for an additional 2400 years starting from year 2401 of the "OnlyTP" run (Fig. 1d). The "AT2TP" experiment introduces the TP into the "OnlyAT" scenario, and is integrated for the same duration as "TP2AT." The primary distinction between "TP2AT" and "AT2TP" lies in the sequence in which the terrains are incorporated. Our analysis focus on the quasi-equilibrium stages of these experiments using annual mean fields: model years 801-1200 for "Flat," years 2001-2400 for the individual terrain experiments, and years 4401-4800 for the combined terrain experiments of TP2AT" and "AT2TP."

All experiments use the same boundary conditions except for topographical height. The geographical setup reflects modern-day conditions, without adjustments for plate tectonic movements. Atmospheric CO_2 level is kept constant at the preindustrial level (285 ppm); and the model does not account for changes in river routes or vegetation types. Continental ice sheets are represented as inert "bright rocks" within the model, allowing planetary albedo to self-adjust according to changing thermal conditions. Annual mean model outputs are used for analysis.

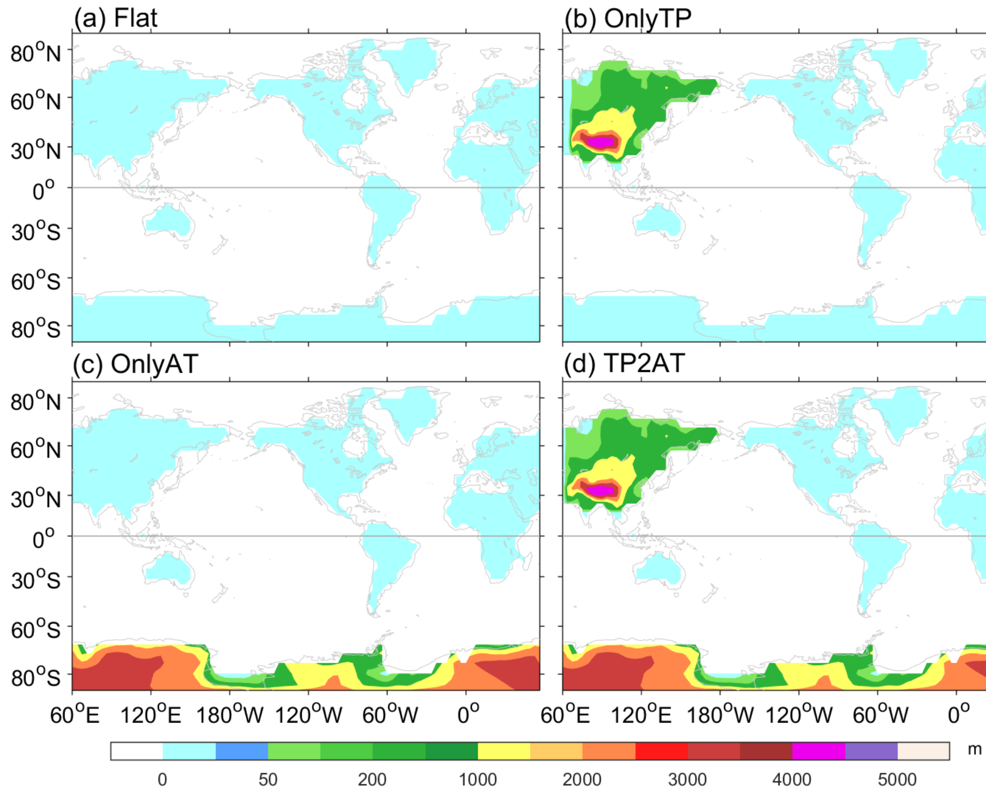

FIG. 1. Topography configuration in coupled model experiments. (a) Modified topography with flat global topography used in Flat, (b) modified topography with the inclusion of the Tibetan Plateau (TP) used in OnlyTP, (c) modified topography with the inclusion of Antarctic (AT) topography used in OnlyAT, and (d) modified topography with the TP and AT used in TP2AT and AT2TP. Shading represents surface geopotential heights (units: m)

When examining the combining influence of the TP and Antarctica, the contribution of the TP can be discerned by using AT2TP minus OnlyAT; and that of the Antarctica, by using TP2AT minus OnlyTP. The individual roles of the TP and Antarctica can be obtained by comparing OnlyTP with Flat and by comparing OnlyAT with Flat, respectively. Note that some experiments exhibit an initial adjustment marked by a sudden jump in variables when topography is introduced abruptly. These initial fluctuations have minimal effects on the quasi-equilibrium state.

3. Effects of the TP and Antarctica on meridional overturning circulation

Previous studies reached a consensus that current mountains on the Earth matter in the formation of the AMOC, of which the TP matters the most and the Antarctic plays as a secondary role (Y24). This can also be seen in the evolutions of the AMOC and PMOC indices in TP2AT and AT2TP clearly (Fig. 2). In TP2AT, the AMOC reaches its peak value by the 3400th year, approximately 1000 years after the introduction of the Antarctic orography. However, this maturation process takes several hundred years longer in the AT2TP scenario (Fig. 2a). The basic idea is that the uplift of the TP in TP2AT immediately leads to anomalous atmospheric moisture transport from the North Atlantic to the North Pacific, shutting down the PMOC quickly (Fig. 2b) and initializing the NADW formation. The introduction of the Antarctic orography subsequently supports the NADW formation by enhancing Ekman pumping in the Southern Ocean. In AT2TP, the PMOC is bolstered due to increased Ekman pumping in the Southern Ocean in response to the Antarctic orography. The uplift of the TP has to first counteract this enhanced PMOC before it can begin the process of the NADW formation. The specifics of these processes will be discussed in Section 4.

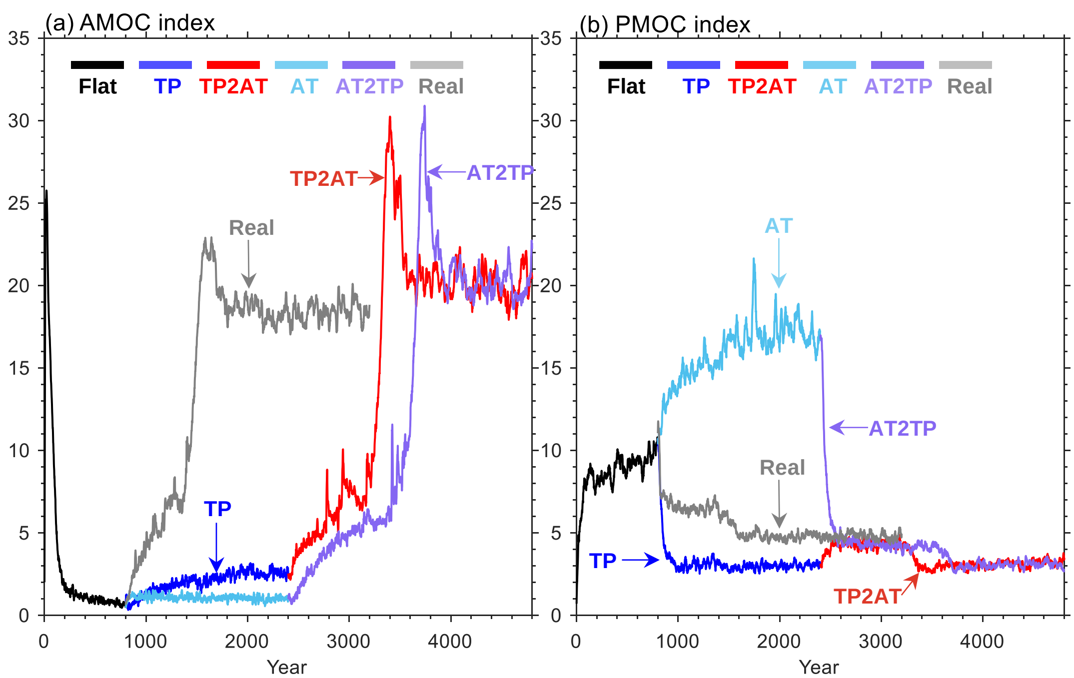

FIG. 2. Temporal evolutions of (a) the Atlantic meridional overturing circulation (AMOC) and (b) Pacific meridional overturning circulation (PMOC) in different topography experiments (units: Sv; 1Sv = 10^6 m^3s^{-1}). The AMOC index is defined as the maximum stream function at depths of 400-2000 m and 20°-70°N in the North Atlantic. The PMOC index is calculated similarly, except in the North Pacific. All the curves are smoothed by a 10-year running mean.

Spatial patterns of the AMOC, PMOC, and GMOC under four different scenarios are illustrated in Fig. 3. The presence of the TP suppresses thermohaline circulation in the Pacific (comparing Figs. 3b2 and b1), while the Antarctic orography generally enhances thermohaline circulation. (Evident in the comparison between Figs. 3b1 and b3, and between Figs. 3a2 and a4). However, neither the TP or Antarctic orography alone can lead to the establishment of the AMOC (Figs. 3a2 and a3). It is established only through the presences of both TP and Antarctica. This is clearly seen in the similar patterns and strengths of the meridional overturning circulation across the TP2AT, AT2TP, and Real experiments (Figs. 3a4-c6), indicating that the orography of other continents does not significantly impact the formation of the AMOC. This underscores the unique and complementary roles of the TP and Antarctic orography in shaping the modern-day AMOC.

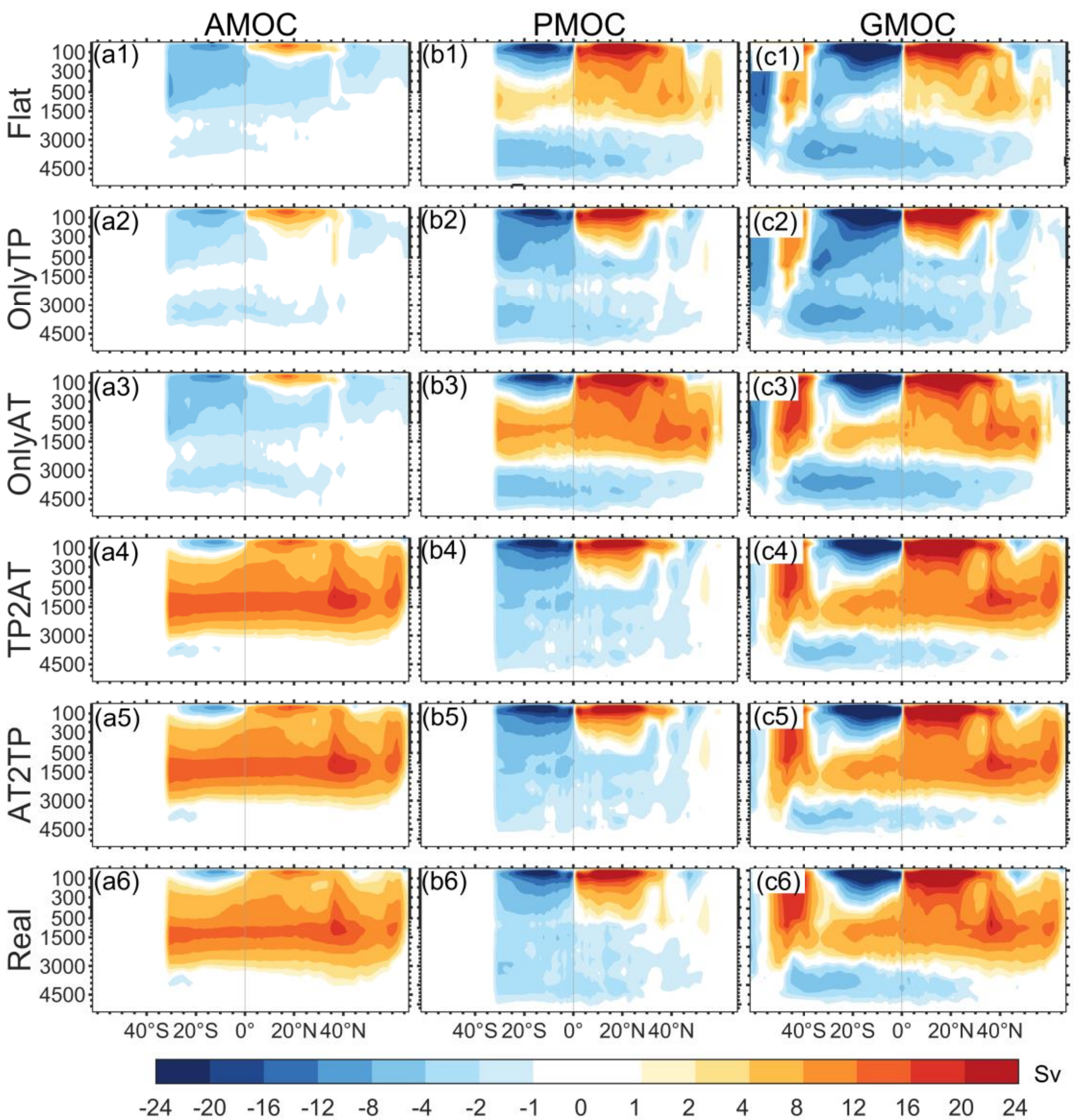

FIG. 3. Patterns of (a) the AMOC, (b) PMOC, and (c) GMOC in different experiments (units: Sv). The MOCs are averaged over years 801-1200, 2001-2400, 4401-4800, and 2601-3000 in Flat, OnlyTP and OnlyAT, TP2AT and AT2TP, and Real, respectively.

4. Mechanisms behind the joint effect of the TP and Antarctica

a. Ocean buoyance change

The changes in buoyancy across the global surface ocean are shown in Fig. 4. The uplift of the TP causes significant freshening in the North Pacific compared to the Flat scenario (Fig. 4a1), which is the key factor leading to the shutdown of the PMOC. Concurrently, most areas of the Atlantic exhibit surface salinization, with a mild freshening occurring in the NADW formation region. This mild freshening prevents the establishment of the AMOC. It is observed that the change in sea-surface salinity (SSS) predominantly influences the changes in sea-surface density (SSD), as illustrated in Fig. 4a1. While the changes in sea-surface temperature (SST) shown in Fig. 4b1 tend to increase SSD, they only slightly counterbalance the impact of SSS on SSD. The critical role of SSS in affecting SSD, and thereby influencing deep-water formation in both North Pacific and North Atlantic, was studied theoretically as early as in Stommel (1961). Additionally, geographical differences between the Atlantic and Pacific basins affect salinity distribution, contributing to the Atlantic's stronger deep-water formation compared to the Pacific (Ferreira et al. 2018; Yang and Wen 2020).

In the presence of Antarctic orography only, the SSS values in both Pacific and Atlantic are increased slightly compared to those in the Flat scenario (Fig. 4a2), which apparently helps enhance the PMOC in Flat. When the TP and Antarctic orography coexist, the surface freshening in the Pacific is almost similar compared to that in OnlyTP (Figs. 4a3, a4), while in the Atlantic basin north of 30°S the SSS increases significantly, which is particularly clear in the subtropical-subpolar North Atlantic. This SSS change is critical to the establishment of the AMOC. Note that the subpolar North Atlantic undergoes significant warming (Figs. 4b3 and b4), which is the consequence of the AMOC's formation. Additionally, the buoyancy patterns in the TP2AT and AT2TP experiments are nearly identical, suggesting that the climate system’s quasi-equilibrium responses do not vary based on the sequence of topographical introductions in our sensitivity experiments. This also indicates a robustness in the climate system’s reaction to these large-scale orographic features.

The changes in March mixed layer depth (MLD) (Fig. 4c) are consistent with the changes in the deep-water formation region and thus the meridional overturning circulation. In OnlyTP, the MLDs in both North Pacific and North Atlantic shoal, compared to that in the Flat scenario (Fig. 4c1), consistent with the PMOC shutdown and the weak AMOC. In OnlyAT, the MLD is deepened in the North Pacific (Fig. 4c2), consistent with the enhanced PMOC. In TP2AT and AT2TP, the MLD changes are nearly identical, shoaling in the North Pacific and deepening in the North Atlantic (Figs. 4c3, c4), consistent with the PMOC shutdown and AMOC establishment.

Regarding the Pacific basin north of the equator, the changes in SSS, SSD, and MLD in OnlyTP closely mirror those in TP2AT and AT2TP, suggesting that the TP alone has an important influence on the ocean state across much of the Pacific, including both the wind-driven and thermohaline circulations. The TP's impact in this region appears to be decisive and substantial. In contrast, when considering the ocean state in the North Atlantic, the involvement of Antarctic orography becomes necessary to complement the effects of the TP. The Antarctic's contribution is crucial for adjusting the North Atlantic's conditions to facilitate the establishment of the AMOC. This interplay between the TP and Antarctica highlights combined dynamics where the influence of one is enhanced or modulated by the presence of the other, particularly in influencing the characteristics of global ocean circulations and, by extension, the global climate system.

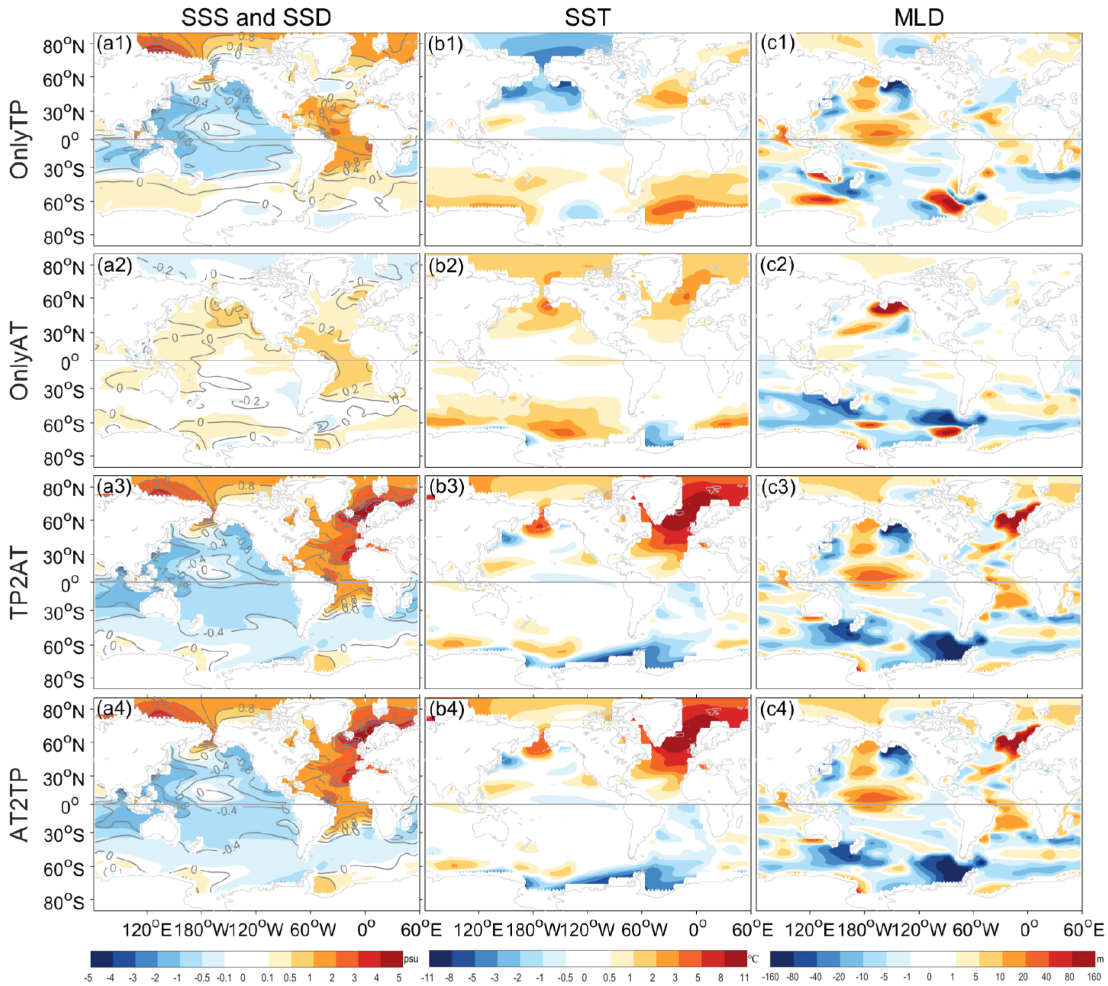

FIG. 4. Changes of (a) sea-surface salinity (SSS) (shading; units: psu) and sea-surface density (SSD) (contour; units: kg/m^3), (b) sea-surface temperature (SST) (units: °C), and (c) March mixed layer depth (MLD) (units: m) in different experiments, with respect to Flat. March MLD represents the site of the deepest vertical mixing and convection, and thus deep-water formation, which is defined the same way as in Large et al. (1997).

b. Atmospheric moisture transport

The SSS changes in the North Pacific and North Atlantic are largely caused by the net surface freshwater flux (i.e., evaporation minus precipitation, or EMP). This has been examined in details in similar sensitivity experiments of our previous study (Yang and Wen 2020). For a steady state, the EMP across the ocean surface is equivalent to the vertically integrated moisture transport divergence over the entire atmosphere column, when neglecting the freshwater flux on land surface and in river runoff (Jiang and Yang. 2021). Figure 5 shows the changes in moisture transport and convergence in four different experiments, with respect to the Flat scenario. It is clear that the TP has significant effects on the global hydrological pattern in the Northern Hemisphere (Figs. 5a, c, d), while the effect of Antarctic orography on the Northern Hemisphere is negligible (Fig. 5b).

The uplift of the TP attracts a large amount of moisture from the Western Hemisphere, tropical Pacific, and Indian Ocean (Fig. 5a), which converges over East China and the western subtropical Pacific. The accumulation of freshwater in the western Pacific, coupled with its northward transport by the Kuroshio and subsequent eastward transport around 40°N by the Kuroshio Extension, ultimately leads to the shutdown of the PMOC. Similar processes were illustrated in Wen and Yang (2020). Concurrently, less freshwater converges in the North Atlantic surface due to the enhanced westward moisture transport across the ocean and North American continent. It is noteworthy that the moisture changes over the North Atlantic in OnlyTP are similar to those in TP2AT and AT2TP, in terms of both pattern and magnitude. This suggests that changes in surface freshwater flux alone are insufficient to induce strong NADW formation. In TP2AT and AT2TP, significant Ekman pumping occurs in the Southern Ocean, which serves an essential auxiliary role in the processes leading to the full establishment of the AMOC.

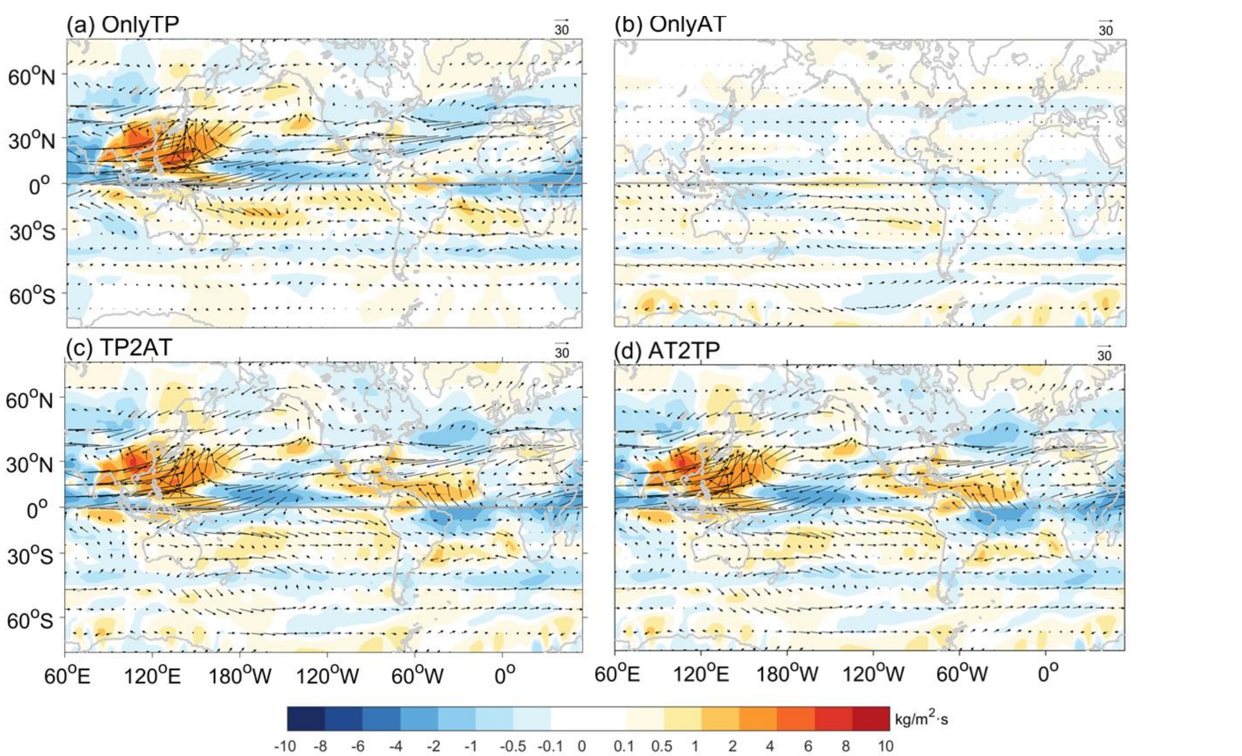

FIG. 5. Changes of vertically integrated moisture transport (vector; units: $\mathrm{kg}/m \cdot s$) and moisture convergence (shading; units: $10^{-5}\ \mathrm{kg}/m^2 \cdot s$) in (a) OnlyTP, (b) OnlyAT, (c) TP2AT, and (d) AT2TP, with respect to Flat.

Positive value in moisture convergence represents the freshwater flux from atmosphere to ocean, i.e., freshwater gain by the ocean.

c. Ekman pumping

Indeed, the increase of freshwater in the North Pacific surface and the decrease in the North Atlantic surface are primarily due to the weakening of mid-latitude westerlies (Fig. 6a), a response to the TP's uplift. The TP's elevation also leads to significant Ekman upwelling in the North Pacific (Figs. 6b, d, e), driven by changes in atmospheric circulations (figure not shown). This Ekman pumping creates conditions favorable for shutting down the PMOC. Additionally, the weakened westerlies result in reduced evaporation, contributing to the freshening of the North Pacific's surface waters and to diminished vertical mixing in the region, which further weakens deep-water formation in the North Pacific, thus playing a role in the PMOC's decline.

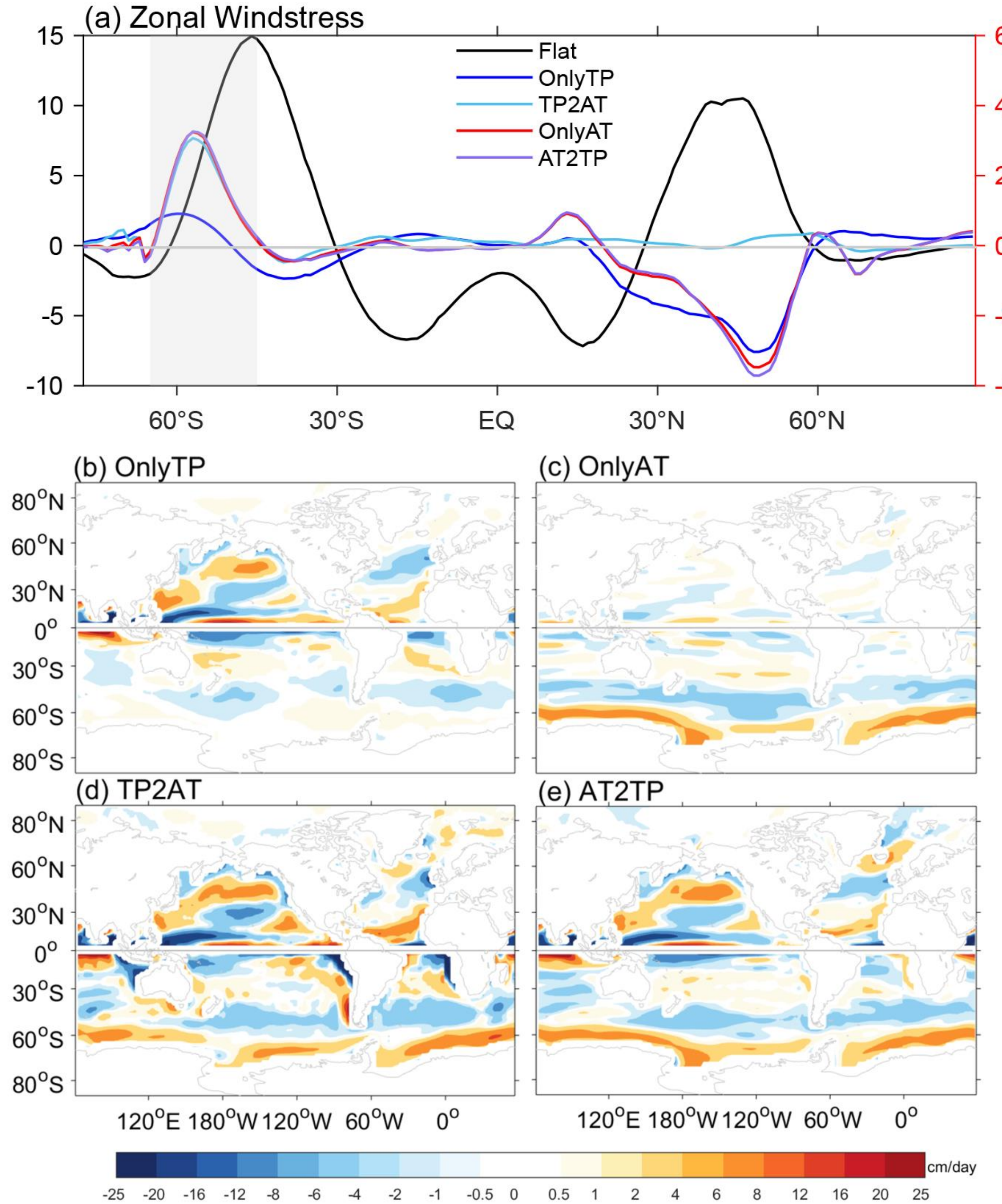

FIG. 6. (a) Mean westerlies in Flat (black curve; units: N/m^2; with the scale along the left ordinate) and its change in different experiments (with the scale along the right ordinate). Legends for curves are labeled. (b)-(e) Changes in Ekman pumping (units: cm/day) in OnlyTP, OnlyAT, TP2AT, and AT2TP, with respective to Flat, respectively. Positive (negative) value represents Ekman upwelling (downwelling).

Notable changes in Ekman pumping occur in the Southern Ocean along the Antarctic continent in AT, TP2AT, and AT2TP (Figs. 6c, d, e). The presence of the Antarctic orography results in stronger westerlies in the subpolar Southern Hemisphere compared to the Flat scenario (Fig. 6a), which in turn drives robust Ekman pumping near the Antarctic continent (Figs. 6c, d, e). This Ekman pumping induces a southward flow at depth while enhancing the northward Ekman flow at the surface, playing a pivotal role in facilitating deep-water formation in the Northern Hemisphere, albeit remotely.

It is important to highlight that the specific location of deep-water formation is influenced by this mechanism in different ways. In scenarios where deep-water formation occurs in the North Pacific, such as in the Flat scenario, the Antarctic orography can augment the North Pacific Deep Water (NPDW) formation, thereby enhancing the PMOC. Conversely, when deep-water formation takes place in the North Atlantic, as seen in the scenarios involving the TP, the Antarctic orography can boost the NADW formation, and thus the AMOC. The direction of the southward pumping in the Southern Ocean, driven by the strong westerlies, does not inherently determine its source waters.

d. Agulhas leakage and meridional mass transport

When TP exist alone, it can affect the Southern Ocean through Rossby wave train (Fig. 7a1), leading to a slight enhancement of the Antarctic circumpolar current (ACC) and the Agulhas leakage (Fig. 7a2) in OnlyTP. The latter can contribute about 1~2 Sv water mass transport to the northward upper warm route of the AMOC (Beal et al. 2011). The TP's far-reaching effects on the Southern Ocean were revealed in Wang et al. (2023). The tropical Indian Ocean plays a role in the teleconnection between the TP and Southern Ocean, which occurs mainly in the austral winter. An anomalous high is generated to the south of Cape Agulhas in OnlyTP (Fig. 7a1), and the anomalous easterlies near Cape Agulhas enhances the Agulhas leakage by about 2-3 Sv (Fig. 7a2). The Agulhas Current is the western boundary current of the subtropical gyre in the southern Indian Ocean, primarily driven by the large-scale wind stress curl generated by the southeast trade wind and the westerlies in the Southern Hemisphere (Beal et al. 2011).

In OnlyAT, the role of the Antarctic in intensifying the westerlies and thus the ACC in the Southern Ocean is robust (Fig. 7b2). There is also an anomalous Rossby wave train over the Southern Ocean (Fig. 7b1). The anomalous ACC and Rossby wave train here are much stronger than those in OnlyTP in terms of magnitude. Due to the southward migration of the westerlies (Fig. 6a), the Agulhas leakage is also enhanced by about 1-2 Sv, indirectly reinforcing the AMOC.

We want to emphasize again that in OnlyTP, the AMOC is just slightly enhanced even with the help of the stronger Agulhas leakage, due to the lack of strong Ekman pumping in the Southern

Ocean. In OnlyAT, the enhanced Agulhas leakage does not help the AMOC, either, because the strong Ekman pumping pumps water mainly from the South Pacific. When the TP and Antarctic coexist, the Agulhas leakage can really contribute to the formation of the AMOC, which is estimated to be 2-3 Sv based on the TP2AT and AT2TP experiments (Figs. 7c2, d2).

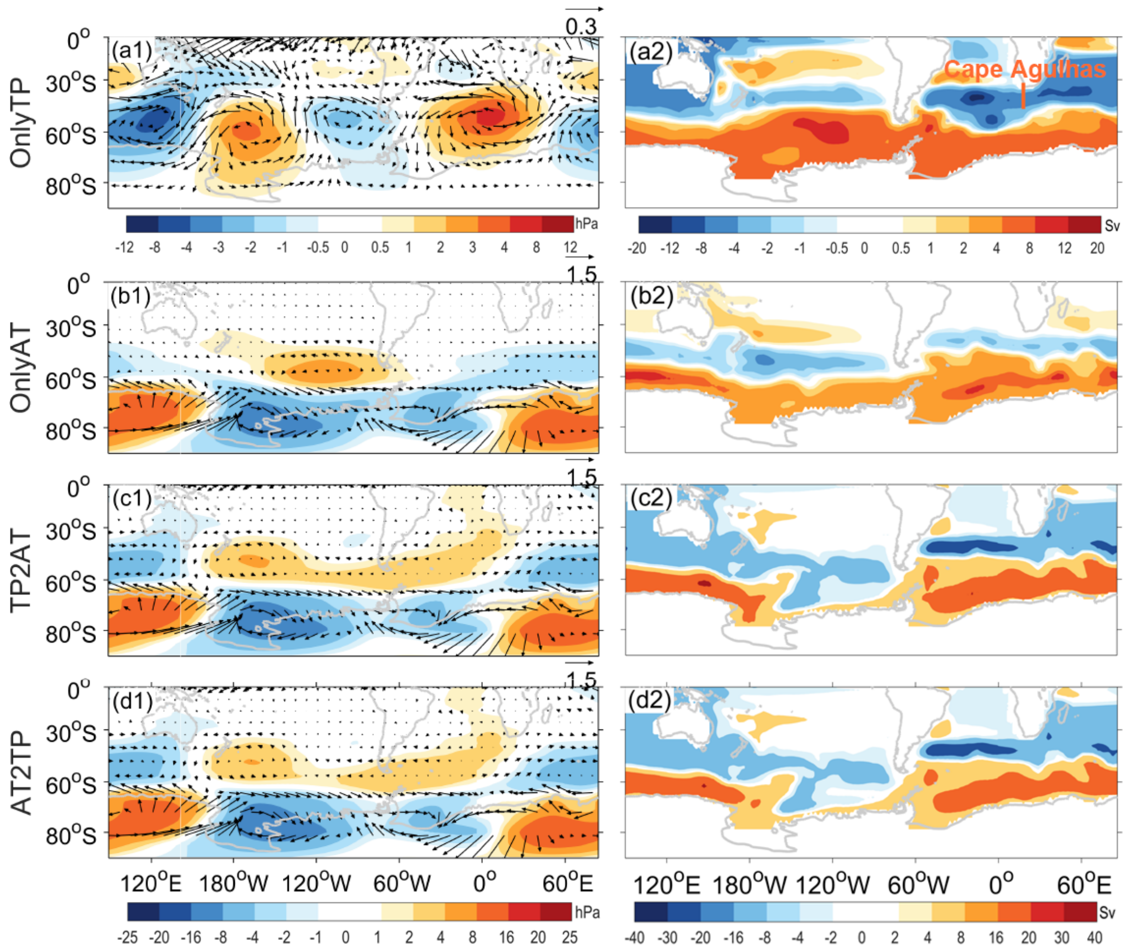

FIG. 7. Changes in (left panels) surface wind (vector; units: m/s) and sea-level pressure (shading; units: hPa) and (right panels) the barotropic streamfunction (units: Sv) in (a) OnlyTP, (b) OnlyAT, (c) TP2AT, and (d) AT2TP, with respect to Flat. In the left panels, all values are obtained by subtracting their corresponding zonal mean values; positive (negative) sea-level pressure represents anomalous high (low). In right panels, positive (negative) barotropic streamfunction represents clockwise (anticlockwise) flow. Note that the scales in (a1) - (a2) are different from those used in the other panels.

When either the TP or Antarctic is present in isolation, the southward mass transport across 30°S in the South Atlantic is very weak, suggesting a limited AMOC (Fig. 8a). However, a significant intensification in southward water mass transport within the Atlantic becomes evident only when both topographies are present simultaneously (Fig. 8a), thereby supporting a vigorous AMOC. In the Indo-Pacific region, the strength of thermohaline circulation is noticeably greater when influenced by the Antarctic alone, as opposed to the effect of the TP alone (Fig. 8b). This underscores the fact that the TP's presence disrupts the PMOC. With the concurrent presence of both the TP and Antarctic topography, the results show a strong northward water mass transport in the Indo-Pacific basin (Fig. 8b), indicating the collapse of the PMOC. The meridional water mass transports are calculated by integrating the meridional velocity zonally over the depth range of 2000-3000 m across 30°S in the Atlantic and Indo-Pacific basins.

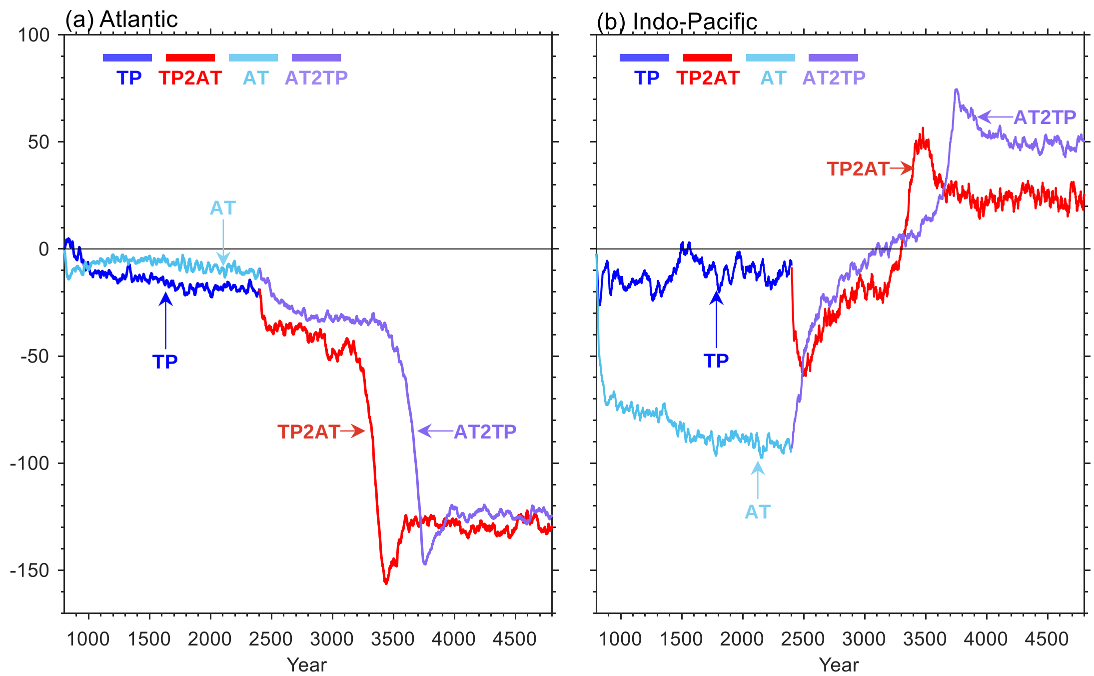

FIG. 8. Meridional mass transports across 30°S in (a) the Atlantic and (b) Indo-Pacific. The transport is calculated by integrating the meridional velocity over the depth range of 2000-3000 m along 30°S in the respective basin. Positive value represents northward transport, and vice versa. Blue, red, light blue, and purple lines represent OnlyTP, TP2AT, OnlyAT, and AT2TP, respectively.

e. Positive feedback in the subpolar North Atlantic

With the increased SSS in the North Atlantic, coupled with enhanced Agulhas leakage and stronger Ekman pumping in the Southern Ocean, the AMOC develops gradually during year 2400-3200 in TP2AT and year 2400-3600 in AT2TP. A sudden increase in the AMOC strength during its evolution results from a positive feedback mechanism involving sea ice after year 3200 in TP2AT, and it happens after year 3600 in AT2TP. As the AMOC strengthens, sea ice retreats northward, which in turn diminishes freshwater input into the North Atlantic, enhancing the NADW formation. The MLD over the North Atlantic deepens, and the AMOC develops further. This positive feedback between the AMOC and sea ice leads to rapid changes in both. After year 3200 in TP2AT and 3400 in AT2TP, the AMOC reaches its maximum, and correspondingly, sea ice reaches its minimum within approximately 200 years. The rapid MLD change is consistent with this feedback process as evidenced in Fig. 9a. This positive feedback between the AMOC and sea ice has been reported in numerous previous studies (e.g., Brady and Otto-Bliesner 2011; Yang and Wen. 2020).

Apart from the temporal evolution of sea ice, the spatial pattern of virtual salt flux change in the subpolar North Atlantic also supports this mechanism. Compared to the Flat scenario, the virtual salt flux resulting from sea-ice formation or melting in the North Atlantic is markedly elevated in TP2AT and AT2TP (Figs. 9e, f). The positive virtual salt flux signifies a net loss of freshwater from the North Atlantic, accompanied by the northward retreat of sea ice, which is denoted by the location of sea-ice margin. The resulting SSS increase in the North Atlantic is accompanied by a deepening of the MLD in that region (Fig. 4), which ultimately contributes to the strengthening of the AMOC. In OnlyTP and OnlyAT, the sea ice changes are minimal (Figs. 9c, d).

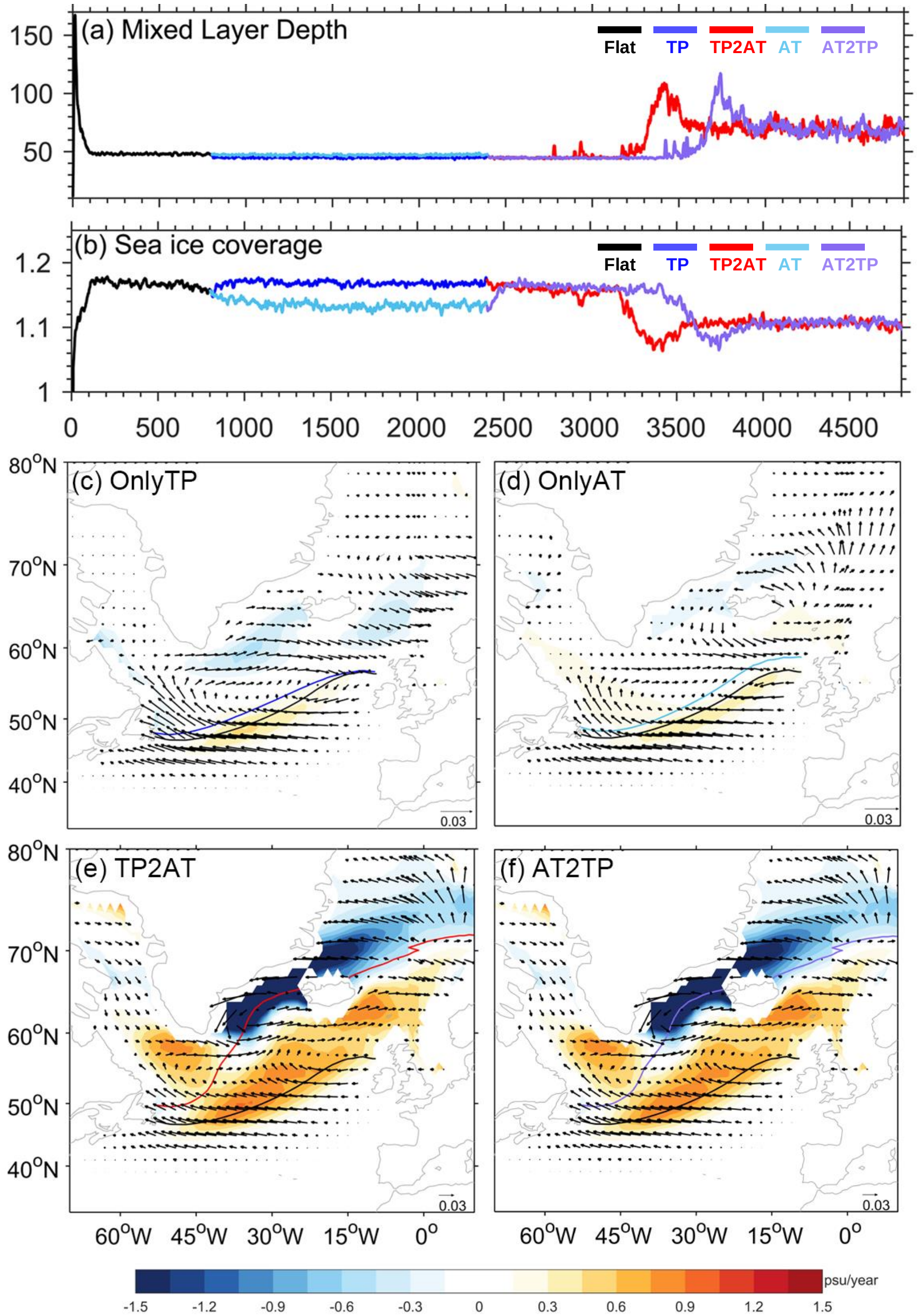

FIG. 9. Temporal evolution of (a) March MLD (units: m) and (b) sea-ice coverage (units: 10^6 km^2) in the Arctic. March MLD is averaged over 40°-65°N and 20°-60°W. The sea-ice cover is annual averaged. (c)-(f) Quasi-equilibrium change in virtual salt flux due to sea-ice formation or melting (shading; units: psu/year), and sea-ice velocity (vector; units: cm/s), with respect to Flat, in OnlyTP, OnlyAT, TP2AT, and AT2TP, respectively. These changes are annual averaged. Positive (negative) virtual salt flux indicates loss (gain) of freshwater in the ocean. The sea-ice margin is defined by the 15% sea-ice fraction and plotted as curves, with the black curve representing that in Flat.

5. Summary and discussion

In this study, we utilized four topographical experiments (OnlyTP, OnlyAT, TP2AT, AT2TP) and two reference experiments (Flat, Real) to investigate the combined effect of the TP and Antarctica on the formation of the AMOC. The results show that it is the combined influence of the TP and the Antarctic orography that maintains the modern day AMOC at its current strength. The presence of the TP is the key for the termination of the PMOC. The fundamental process is the orographic alteration of the atmospheric water cycle that distribute net freshwater fluxes across the world's oceans. It is the current regime of the atmospheric water cycle that enables the high salinity of the northern North Atlantic and the low salinity of sea water within the North Pacific. The presence of the Antarctic has an important role by enhancing southward water mass transport at depth in the South Atlantic and Agulhas leakage south of Africa. The existence of the TP alone, without the Antarctica, is insufficient for the full establishment of the AMOC, underscoring the indispensable role of both topographical features in the dynamics of Earth's climate system. A schematic summary is presented in Fig. 10.

The role of the TP is to suppress the NPDW formation, and to provide a favorable condition for the NADW formation, through changing the hydrological pattern in the Northern Hemisphere. The role of the Antarctic orography is to intensify the southward transport of seawater in the intermediate-deep ocean, through enhancing the Ekman pumping in the Southern Ocean. Nonetheless, it does not specify the origin of the southward-flowing water in terms of which ocean basin it comes from. With the addition of the Antarctic to the TP, the NADW formation can literally develop. We stress that the quasi-equilibrium response in these topography experiments does not depend on the manner in which order the topography is introduced; however, the transient response does. The slower evolution of the AMOC in AT2TP than that in TP2AT is mainly due to the difference in the location of deep-water formation.

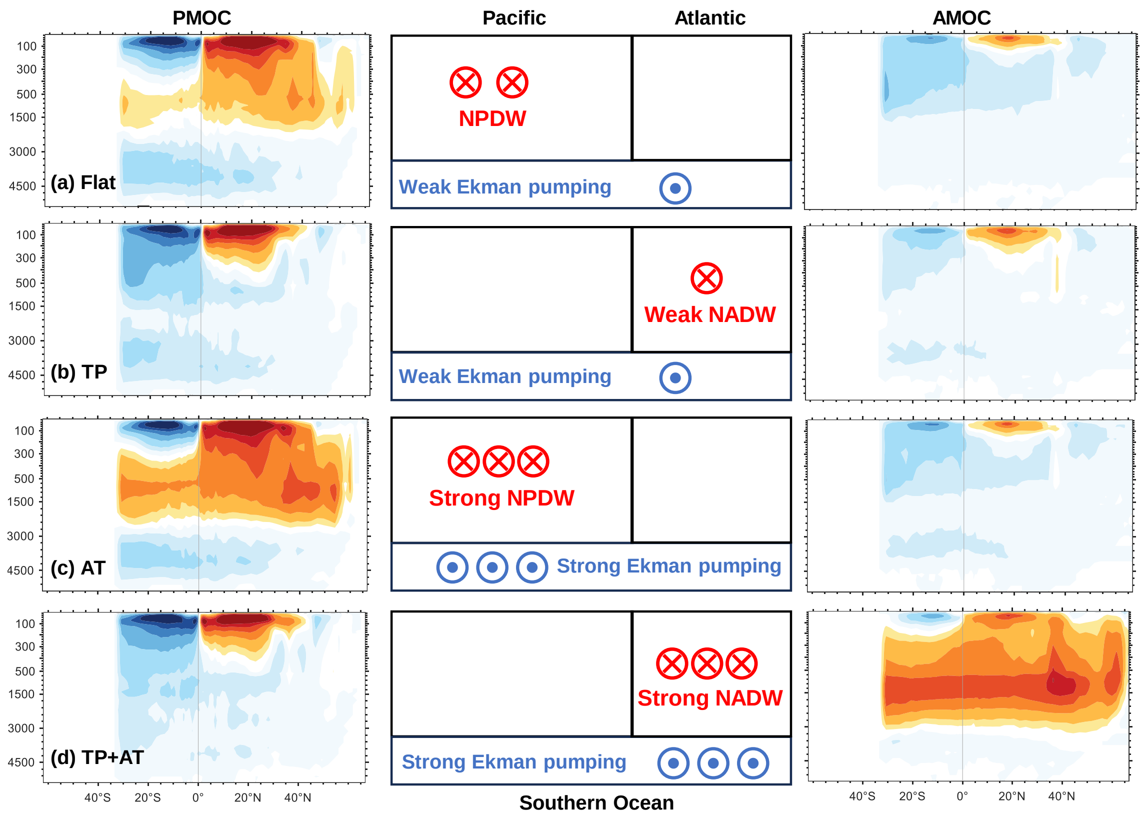

FIG. 10. Schematic diagram showing the combined role of the TP and Antarctica. The left (right) panels show the quasi-equilibrium pattern of the PMOC (AMOC) in respective experiments. The middle panels show schematically the deep-water formation in the North Pacific and North Atlantic, and the Ekman pumping in the Southern Ocean. "⊗" represents downward motion of seawater, while "⊙" represents Ekman upwelling.

The results presented here have important implications for our fundamental understanding of the AMOC mechanisms and its potential role in paleoclimate. The TP uplift span a wide geological timescale, from its initial uplift around 40 Ma to its mature state around 8 Ma (Chung et al. 1998; Spicer et al. 2003), which may have played a role in the initial development of Antarctic ice-sheet around 34 Ma (Bo et al. 2009), the retreat of the continental ice-sheets during 16-10 Ma, and the development of Arctic sea-ice around 2~3 Ma (Polyak et al. 2010), shaping the climate from the Oligocene to Pliocene (Li et al. 2019). The gradual TP uplift led to deflection of the atmospheric jet stream, intensified monsoonal circulation and increased rainfall over the Eurasian continent, and ultimately restructured the global hydrological cycle and provided favorable conditions for the NADW formation (Ruddiman and Kutzbach 1989; Raymo and Ruddiman 1992; Wu et al. 2022).

Our experiments here explored how the TP and Antarctica influence global ocean circulations. To isolate these effects, we maintain the modern-day configuration of bathymetry, continental layout, greenhouse gas concentration, incident solar radiation, and orbital parameters in our experimental design. Consequently, the findings of this study are subject to these limitations. Additionally, our conclusions might be influenced by the specific model used, including its resolution and river-runoff magnitudes. As discussed in the Introduction, a sensitivity experiment removing the Rocky Mountains, conducted by GFDL, shows that the PMOC is significantly enhanced (Maroon. 2016), which is not as apparent in CESM simulations (Jiang and Yang. 2021). It is important to note that we did not dynamically simulate the Antarctic glaciation. Our use of the modern-day land-sea distribution and ocean gateways could potentially overstate the TP's impact on the formation of the AMOC. Significant oceanic and climatic shifts, such as the closure of the Tethys Seaway, the formation of the Isthmus of Panama, and the opening of the Bering Strait, all post-date the TP's uplift (Zhang et al. 2022) and have profound implications for ocean circulations and the NADW formation (Schneider and Schmittner 2006; Hamon and Sepulchre 2013; Hu et al. 2015). Moreover, our experiments are set against a backdrop of preindustrial conditions with a stable CO_2 level, disregarding the influence of chemical erosion in rapidly uplifting regions on atmospheric CO_2. The uplift of the TP might have led to reduced atmospheric CO_2 levels, further encouraging the NADW formation through the expansion of continental ice sheets in the Northern Hemisphere (Raymo and Ruddiman 1992). A comprehensive understanding of the uplift's impact on global climate necessitates a quantitative insight into the long-term carbon cycle. Given the complex interplay of factors influencing long-term climate evolution, their contributions need to be further examined.

Despite these caveats, we want to underscore the significant role that the TP and Antarctica may have played in the evolution of global thermohaline circulations. This study highlights the importance of coupling among the oceans, the atmosphere and the large-scale orography in shaping our climate. We hope these findings can help to better understand and interpret past and future climate states and transitions.

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Data Availability Statement:

Datasets from this research can be obtained at https://corp.fudan.edu.cn/Data4Paper.htm.

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