Determinant Role of the Tibetan Plateau and the Antarctic in the Atlantic Meridional Overturning Circulation Formation

Mingjun Tong[a], Haijun Yang*[a], Rui Jiang[b], and Peili Wu[c]

[a]*Department of Atmospheric and Oceanic Sciences and Key Laboratory of Polar Atmosphere-ocean-ice System for Weather and Climate of Ministry of Education, Fudan University, Shanghai, 200438, China*

[b]*Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, 100871, China*

[c]*Hadley Centre, Met Office, UK*

Journal of Climate
Submitted, April 2, 2024

**Corresponding author address*: Haijun Yang, Department of Atmospheric and Oceanic Sciences, Fudan University, 2005 Songhu Road, Shanghai, 200438, China.

Email: yanghj@fudan.edu.cn

ABSTRACT

Our recent research revealed the pivotal roles of the Tibetan Plateau and Antarctic orography in the formation of the Atlantic Meridional Overturning Circulation (AMOC). Through detailed investigations employing coupled model experiments that progressively incorporate the Tibetan Plateau followed by Antarctica (TP2AT) and vice versa (AT2TP), this study elucidates their combined impact on the AMOC. The uplift of the Tibetan Plateau significantly modifies atmospheric moisture transport in the Northern Hemisphere, leading to a less saline North Pacific and a more saline North Atlantic. This alteration is essential for the transition of deep-water formation from the North Pacific to the North Atlantic, which activates the AMOC. Antarctic topography's role is chiefly associated with its influence on the atmospheric westerlies over the Southern Hemisphere's subpolar regions. This influence strengthens the AMOC by boosting Ekman pumping and Agulhas leakage in the Southern Ocean. The cooperative influence of the Tibetan Plateau and Antarctica is crucial for establishing the current configuration of the AMOC. The sequence of introducing the Tibetan Plateau followed by Antarctica (TP2AT) is found to be more effective in setting up the AMOC than the reverse sequence (AT2TP). In the AT2TP scenario, a strong Pacific Meridional Overturning Circulation (PMOC) preexists the introduction of the Tibetan Plateau, necessitating the termination of the PMOC before the AMOC can commence. This process leads to a longer evolution time of the AMOC in AT2TP than in TP2AT.

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

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a crucial part of the global climate system, with its variations and potential reactions to global warming significantly affecting vast regions worldwide. It's also considered as a critical tipping point within the climate system. Both observational data and model simulations have indicated a weakening AMOC and the consequent accumulation of salinity in the South Atlantic (Zhu and Liu. 2020). Some projections suggest that this trend of weakening may persist over the coming decades due to ongoing freshwater influx from the melting of Greenland's ice sheets (Weijer et al. 2012). Moreover, certain researchers have even posited that a transition of the AMOC could happen as early as 2025 (Ditlevson, P. and Ditlevson, S. 2023). The future of the AMOC is a matter of considerable concern and remains a focal point in climate research discussions.

To accurately forecast the AMOC change, it's essential first to grasp the primary factors influencing it. Traditionally, the AMOC has been understood to be maintained by buoyancy forces in the North Atlantic and wind forces over the Southern Ocean (Johnso et al. 2019; Bryden. 2021). In more recent studies, the significance of large continental orography, such as massive mountain ranges, in shaping the modern AMOC has been increasingly recognized (Maffre et al. 2018; Sinha et al. 2012; Stouffer et al. 2022; Yang and Wen 2020; Jiang and Yang 2021). Numerous simulations have 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). In today's world, however, there is no deep-water formation in the North Pacific, primarily because the surface seawater in that region 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 North Atlantic deep-water (NADW), suggesting 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 TP's significant elevation can dramatically impact the mid-latitude westerlies, thereby altering atmospheric moisture transport patterns (Tang et al. 2022; Liu et al. 2007). These changes can profoundly influence buoyancy-driven thermohaline circulations (Yang and Wen, 2020). In our prior studies, 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 revealed 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.

Polar regions are sensitive in the climate system and the interactions between polar regions and ocean circulation may potentially trigger cascading effects (Dekker et al. 2018). Around 3 million years ago (Ma), the expansion of the Antarctic ice-sheet 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). The Warmer Southern Ocean tend to lead a stronger AMOC through three ways: (1) Deep water seesaw effect. The warmer Southern Ocean reduces the formation of Antarctic Bottom Water (AABW), which increases the NADW formation indirectly. Thus, AMOC is enhanced during this interaction. (2) Agulhas leakage. Warming of the Southern Ocean may increase much warm water move from the Indian Ocean to the Atlantic Ocean, leading to a stronger AMOC. (3) Density gradient effect. Warming of the Southern Ocean reduces the density of water bodies in the region, further driving the strengthening of the AMOC by increasing the north-south pressure gradient (Buizert and Schmittner 2015). Additionally, a strong meridional gradient in Southern Ocean westerlies significantly impacts deep ocean circulation, linked to the upwelling of deep-water masses and strengthened North Atlantic Deep Water (NADW) formation (Delworth and Zeng, 2008). Despite the recognized importance of physical processes in the Southern Ocean for the AMOC, research focusing specifically on Antarctica's impact on the AMOC has been limited. In PMIP4 simulations, a connection between Antarctic sea-ice and abyssal ocean circulation has been identified, providing evidence of the role Antarctic sea-ice plays in reorganizing glacial-interglacial ocean circulation patterns (Marzocchi and Jansen, 2017). Antarctica's influence extends to the global climate system at large (Singh et al., 2016), underscoring the interconnectedness of these critical Earth system components.

Researchers have long acknowledged the influence of continental orography on the modern ocean circulation. Prior investigations have typically concentrated on understanding how the presence or absence of global mountain ranges impacts oceanic currents or have explored the influence of individual topographical features. However, the combined effects of multiple topographies have received relatively scant attention. Yang et al. (2024) (hereafter, Y24) conducted a brief examination of the collective impact of different mountainous regions on the GMOC. The findings from Y24 suggest that the TP and Antarctica, through their respective influences on deep-water formation and Ekman pumping, can collaboratively facilitate the complete establishment of the AMOC. Building upon the groundwork laid by Y24, this paper aims to delve deeper into the synergistic effects of these two significant topographies on the AMOC, providing a more comprehensive understanding of their joint role.

This paper is organized as follows: Section 2 presents 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. The mechanisms underlying the synergistic effects of the TP and Antarctica on the AMOC are thoroughly analyzed in Section 4. Section 5 provides a summary of the findings and a discussion on their implications.

2. Model and experiments

The Community Earth System Model (CESM) version 1.0.4 is employed in this study. CESM is developed by the United States' National Center for Atmospheric Research and the climate research community. CESM is a fully coupled climate model that enables simulation of the past, present and future climate of the Earth. It is widely used in examining the atmospheric processes, ocean circulation, and the interaction between them. It comprises six components: atmosphere, land, ocean, sea ice, land ice, and a coupler. The resolution utilized here is T31_gx3v7, with CAM4 as the atmospheric module and POP2 as the oceanic module. The atmosphere and land models have 48 and 96 points in latitude and longitude on a spectral grid with 26 vertical levels, while the horizontal grid of POP2 is gx3v7 with 60 layers in depth. More details of CESM1.0 can be found in Hurrell et al. 2013.

Some experiments analyzed in this work were performed in Y24, including the “Real”, “Flat”, “OnlyTP”, and “OnlyAT” simulations. The “Real” simulation incorporates realistic terrestrial topography and was run for 2400 years, serving as a benchmark for comparing the effects of topography on ocean circulation. Conversely, the “Flat” simulation models a hypothetical Earth with a uniform global altitude of 10 meters above sea level and was integrated for 1200 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 tailored experiments, designed to isolate the effects of individual topographies, were run for 1600 years, starting from year 801 of the “Flat” simulation.

To explore the combined influence of the TP and Antarctica on the AMOC, we initiated 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). Conversely, the “AT2TP” experiment involves introducing the TP into the “OnlyAT” scenario and is conducted over the same duration as “TP2AT”. The primary distinction between “TP2AT” and “AT2TP” lies in the sequence in which the terrains are incorporated. Our analysis concentrates on the equilibrium stages of these experiments: model years 801-1200 for “Flat”, years 2001-2400 for the individual terrain experiments, and years 4401-4800 for the combined terrain experiments.

All experiments maintain consistency in boundary conditions aside from topographical height. The geographical setup reflects modern-day conditions, without adjustments for plate tectonic movements. Atmospheric CO2 levels are kept constant at preindustrial levels (285 ppm), and the model does not account for changes in river routing or vegetation types. Continental ice sheets are represented as inert “bright rocks” within the model, allowing planetary albedo to self-adjust according to thermal conditions.

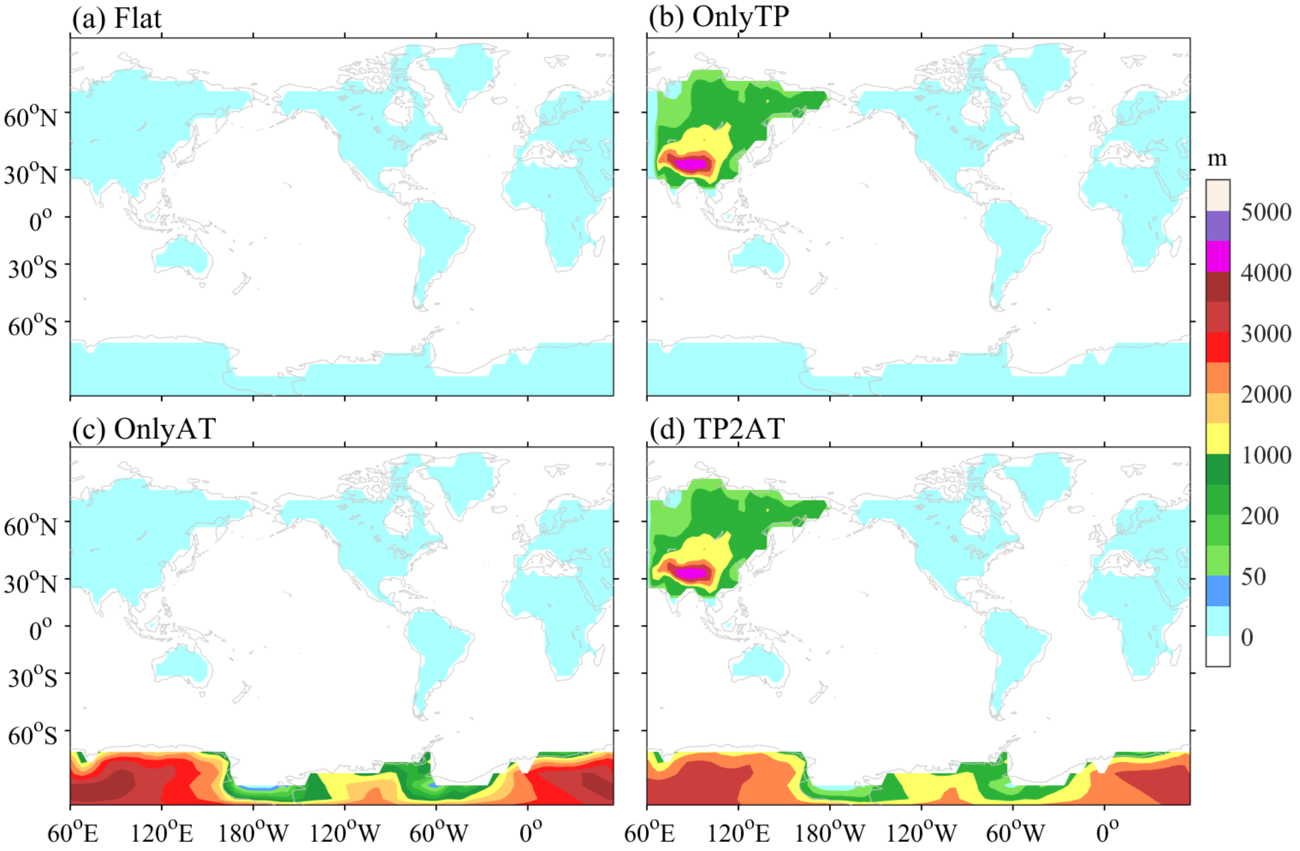


Figure 1. Schematic diagram of topography experiments. (a) Flat, (b) Only TP, (c) Only AT, and (d) TP2AT. The topography scheme of AT2TP is the same as TP2AT. Shading represents surface geopotential heights (units: m)

Annual mean model outputs are used for analysis. When examining the collaborative influence of TP and Antarctic, the contribution of TP can be discerned by considering AT2TP minus OnlyAT and that of Antarctic can be discerned by considering TP2AT minus OnlyTP. The individual role of the TP and Antarctica can be also obtained by comparing OnlyTP with Flat, and comparing OnlyAT with Flat, respectively. It's noted that some experiments exhibit an initial adjustment phase marked by a sudden jump in variables when topography is introduced abruptly; however, these initial fluctuations have minimal impact on the equilibrium state. We use student-t test to examine the statistical significance of our results. Most changes are significant at the 95% confidence level. For visual clarity, significance test is not shown in any figures

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

Previous studies have reached a consensus that mountains on the Earth nowadays matter in the formation of AMOC, of which the TP matters the most and the Antarctic plays as an assistant role (Y24). This can also be seen in the evolution of AMOC and PMOC index 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 Antarctic topography. However, this maturation process takes several hundred years longer in the AT2TP scenario (Fig. 2a). The basic idea is that in TP2AT the uplift of TP leads to immediately 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 Antarctic orography subsequently supports NADW formation by enhancing Ekman pumping in the Southern Ocean. Conversely, in AT2TP, the PMOC is bolstered due to increased Ekman pumping in the Southern Ocean within the Flat scenario. The uplift of the TP then has to first counteract this enhanced PMOC before it can begin the process of NADW formation. The specifics of these processes will be discussed in detail in Section 4.

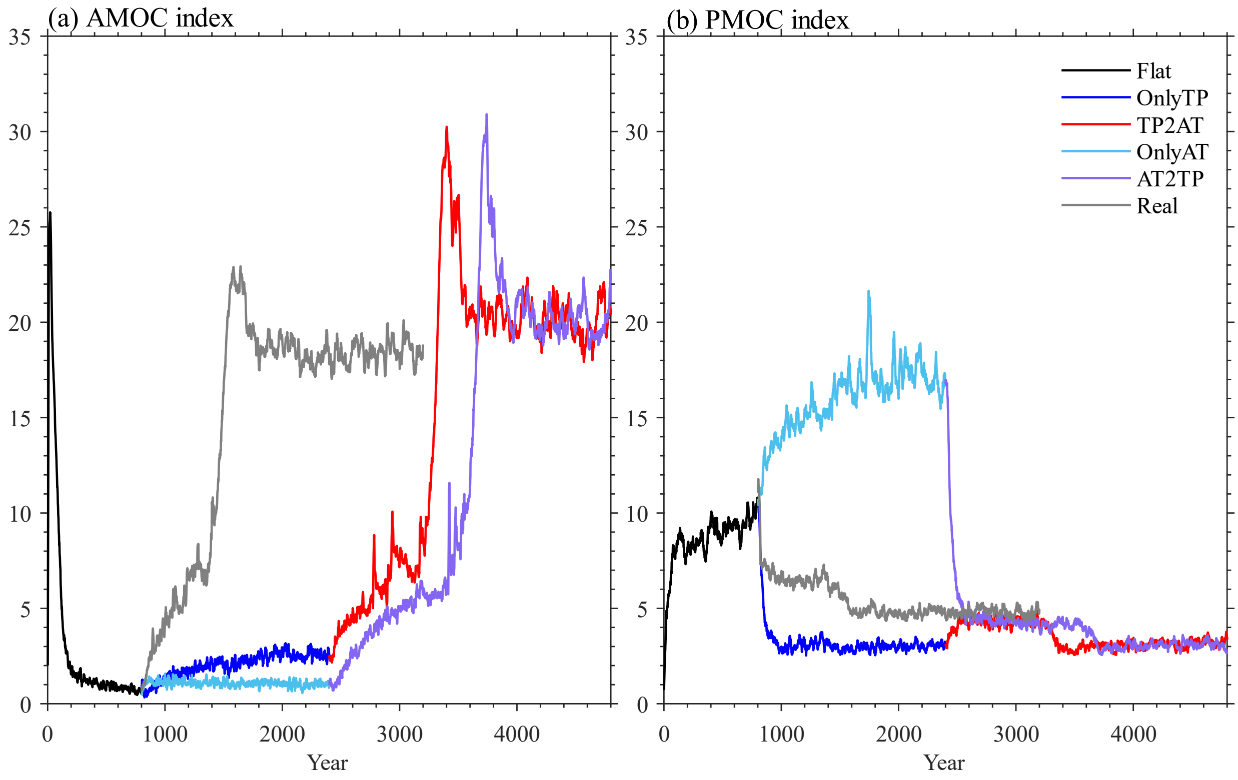


Figure 2. (a) AMOC and (b) PMOC index (Unit: Sv; $1Sv = 10^6 m^3 Sec^{-1}$) evolution is presented for Flat, OnlyTP, OnlyAT, TP2AT, AT2TP and Real experiment. AMOC index is defined as the maximum stream

function at depths of 0-2000m in the Atlantic Ocean (Jiang and Yang. 2021). PMOC index is calculated in the Pacific Ocean similarly. All the curves are smoothed by a 10-year running mean.

Spatial patterns of the AMOC, PMOC, and GMOC under four different scenarios are depicted in Fig. 3. The presence of the TP is to suppress the thermohaline circulation in the Pacific (comparing Figs. 3b2 and b1), whereas Antarctic orography generally bolsters thermohaline circulation, irrespective of its origination (evident in the comparisons between Figs. 3b1 and b3, as well as 3a2 and a4). However, neither the TP or Antarctic topography alone can lead to the establishment of the AMOC (Figs. 3a2 and a3). It's only through the combined presence of both the TP and Antarctica that a robust AMOC can be established. This is clearly seen in the similar patterns and strengths of the MOC across the TP2AT, AT2TP, and Real experiments (Fig. 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 AMOC.

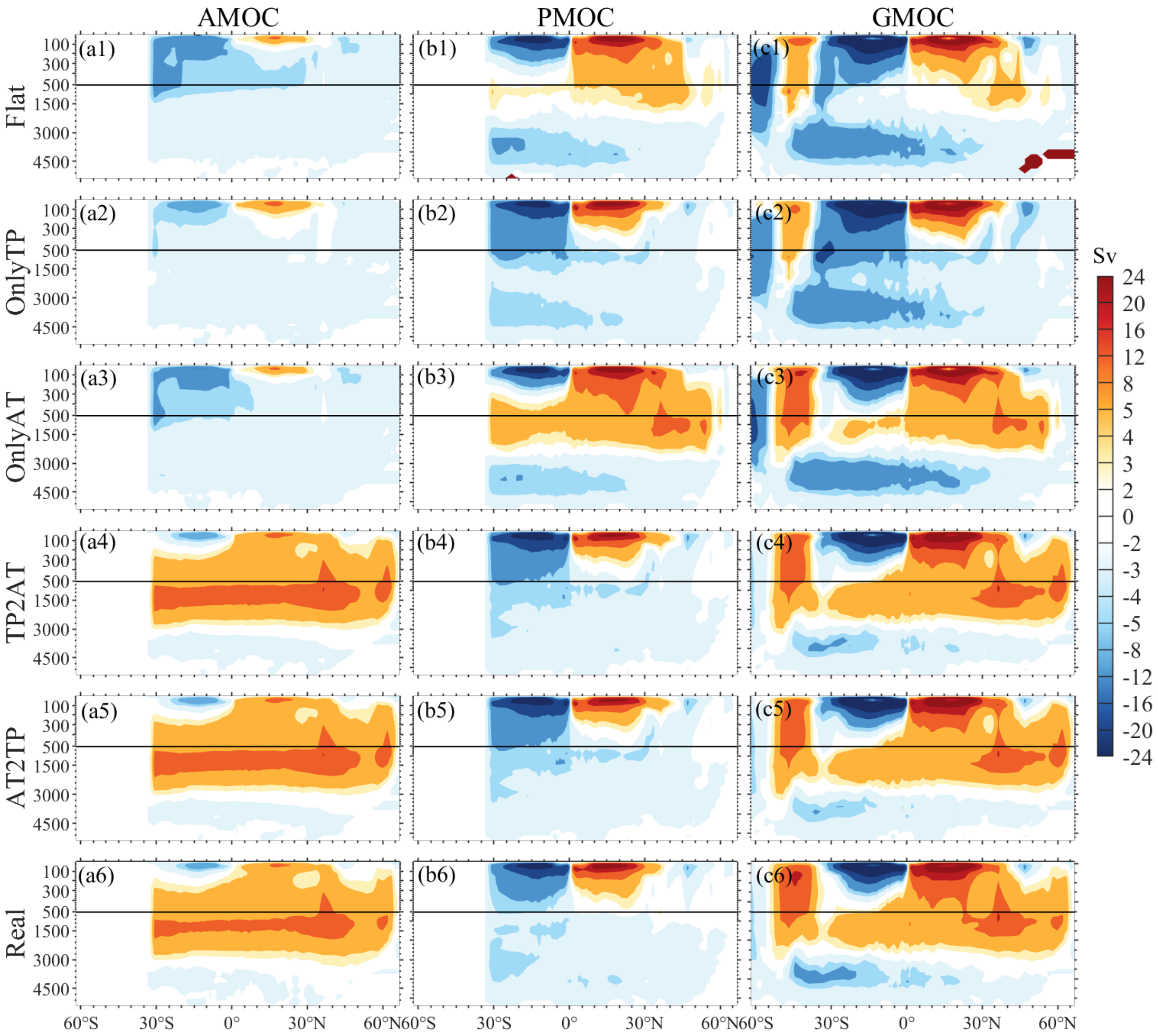


Figure 3. The spatial pattern of AMOC, PMOC and GMOC are shown from the Flat, OnlyTP, OnlyAT, TP2AT, AT2TP and Real experiment. The x-direction axis represents latitudes, and the y-direction axis is depth measured in meters.

4. Mechanisms of the TP and Antarctica synergistical effect

a. Ocean buoyance change

The changes in buoyancy across the global ocean surface are depicted 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, and a mild freshening occurs 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 the 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 the North Pacific and North Atlantic, has been documented in our previous studies (Yang and Wen 2020).

In the presence of Antarctic orography only, the SSS in both the Pacific and Atlantic are increased compared to the Flat scenario (Fig. 4a2), which apparently helps to enhance the PMOC in the Flat. When the TP and Antarctic orography coexist, the surface freshening in the Pacific is even stronger (Figs. 4a3, a4). Concurrently, north of 30°S in the Atlantic 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. It's also observed that the subpolar North Atlantic undergoes significant warming (Figs. 4b3 and b4), which is a 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 equilibrium response does 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 mixed layer depth (MLD) (Fig. 4c) are consistent with changes in the deep-water formation region and thus the meridional overturning circulation. In OnlyTP, the MLD depth in both the North Pacific and North Atlantic is shoaling, compared to 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 the AMOC establishment.

Regarding the Pacific north of Equator, the changes in SSS, SSD and MLD in OnlyTP closely mirror those in TP2AT and AT2TP, suggesting that the TP alone have a controlling influence on the ocean state across much of the Pacific, including both the wind-driven and thermohaline circulation. 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 a synergistic dynamic where the influence of one is enhanced or modulated by the presence of the other, particularly in dictating the characteristics of the global ocean circulation and, by extension, the global climate system.

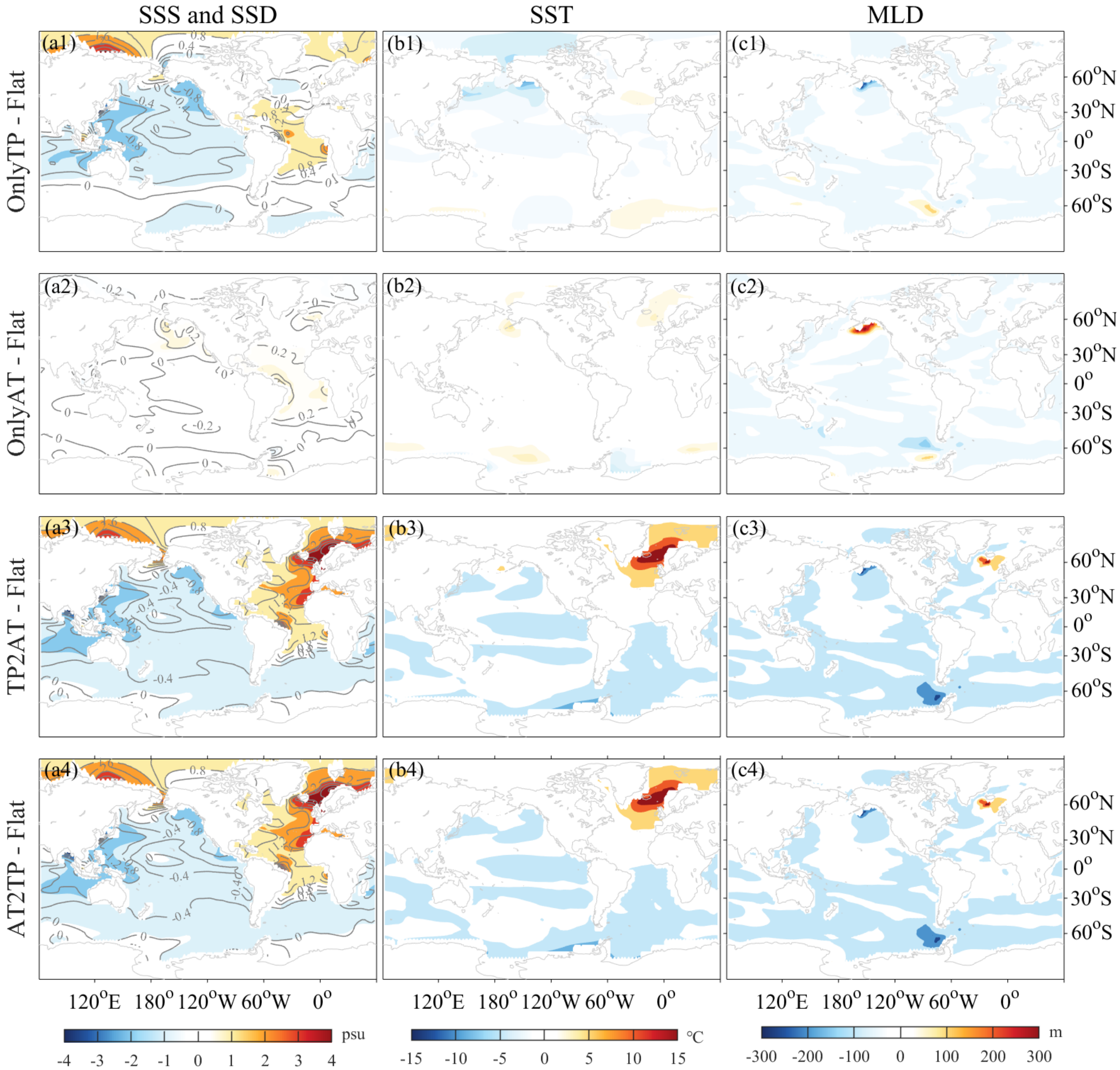


Figure 4 (a1) - (a4): The variations in sea surface salinity (shading, units: psu) and sea surface density (contour, units: kg/m^3); (b1) - (b4): Corresponding changes in sea surface temperature (units: ℃); (c1) - (c4): Mixed layer depth (MLD) changes. All the changes are respect to the Flat experiment.

b. Atmospheric moisture transport

The SSS change in the North Pacific and North Atlantic is largely caused by the net surface freshwater flux (i.e., Evaporation minus Precipitation, 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 at the land surface and river runoff (Yang et al. 2015). Figure 5 shows the changes in atmospheric moisture transport and convergence in four different experiments, with respect to the Flat scenario. It is clear that the TP have significant effect 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 atmosphere moisture from the Western Hemisphere, the tropical Pacific and the Indian ocean (Fig. 5a). This moisture converges over the Eastern China and the western subtropical Pacific. The accumulation of freshwater in these oceanic regions, coupled with its northward transport by the Kuroshio current and subsequent eastward transport around 40°N by the Kuroshio extension, ultimately leads to the shutdown of the PMOC. Similar processes have been deliberated in Wen and Yang (2020). Concurrently, less freshwater converges over the North Atlantic due to the enhanced westward moisture transport across the ocean and the 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 once again that changes in surface freshwater flux alone are insufficient to trigger robust 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 AMOC establishment.

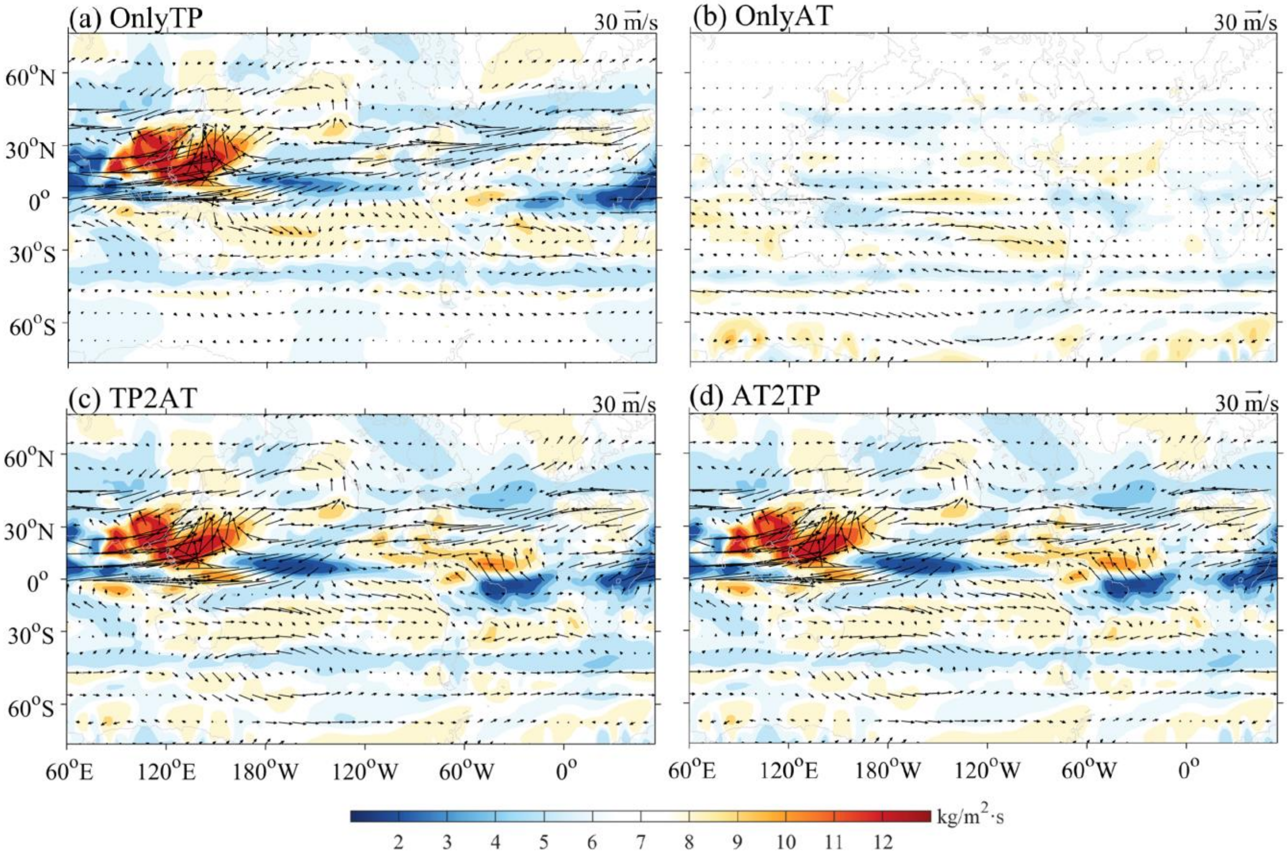


Figure 5. Changes of vertically integrated moisture transport (vector; units: $\mathrm{kg}/m \cdot s$), and shading represents moisture convergence (units: $10^{-5}\ \mathrm{kg}/m^2 \cdot s$).

c. Ekman pumping

Indeed, the increase in freshwater over the North Pacific and the decrease over the North Atlantic 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 circulation. 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 diminished vertical mixing in the region, further weakens deep-water formation, playing a role in the PMOC's decline.

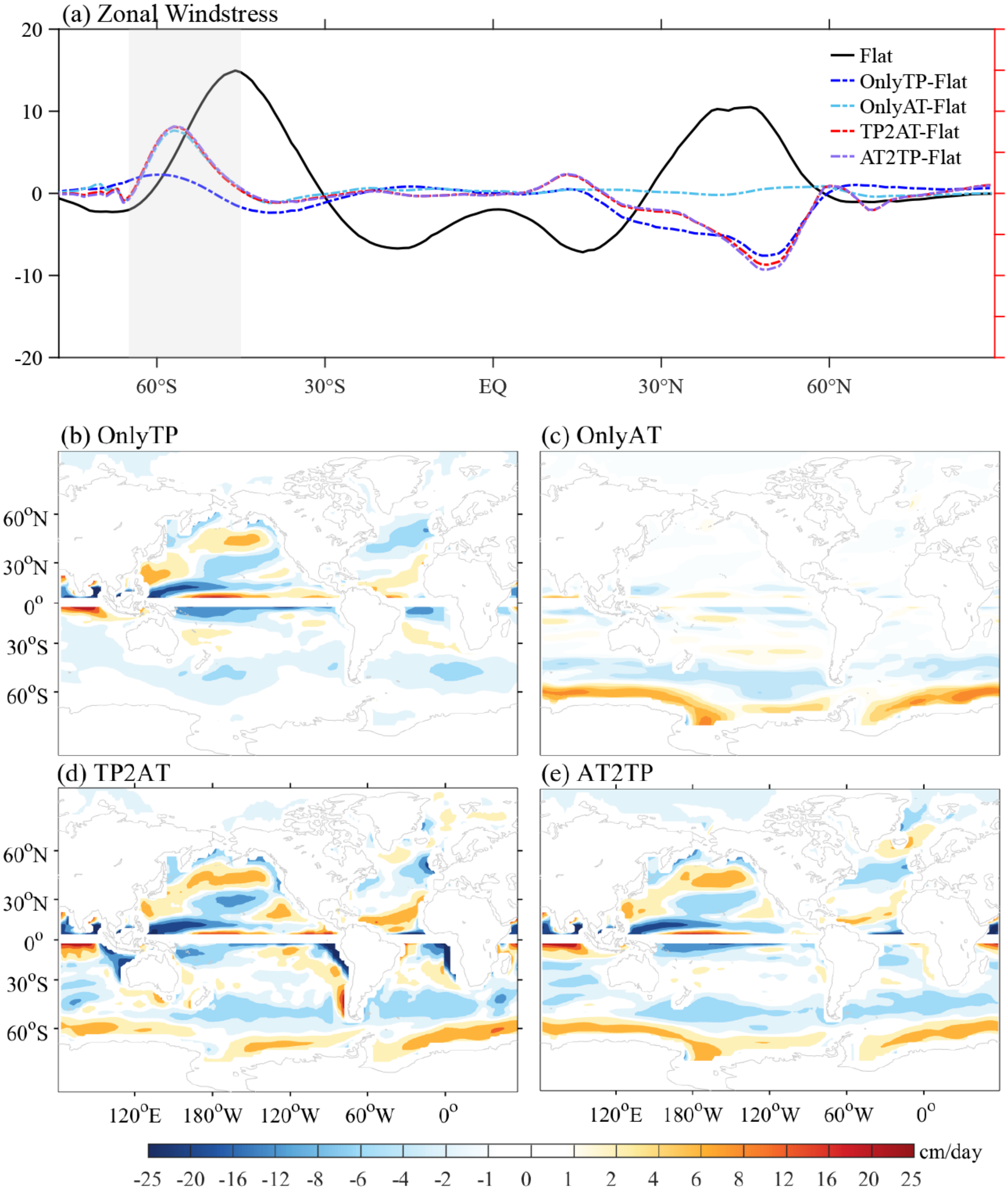


Figure 6. The curve of zonal wind stress changing with latitude in figure (a). Differences of zonal wind stress spatial pattern is shown in (b) OnlyTP minus Flat, (c) OnlyAT minus Flat, (d) TP2AT minus Flat and (e) AT2TP minus Flat. Units: N/m^2. Shadings in figure (b)-(e) represent Ekman pumping velocity (units: cm/day).

More notable change is the Ekman pumping in the Southern Ocean along the Antarctic continent in AT, TP2AT and AT2TP (Figs. 6c, d, e). The presence of 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 along the Antarctic coastline (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, Antarctic orography can augment North Pacific Deep Water (NPDW) formation, thereby enhancing the PMOC. Conversely, when deep-water formation takes place in the North Atlantic, as seen in scenarios involving the TP, Antarctic orography can boost 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, zonal and meridional mass transport

Beyond the Antarctic's role in intensifying the westerlies in the Southern Hemisphere, as previously discussed, there is a noticeable southward shift in the position of the westerlies relative to the Flat scenario (Fig. 6a). This southward migration of the westerlies can lead to a more pronounced Agulhas leakage, indirectly reinforcing the AMOC (Weijer et al., 2002). 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 winds and the westerlies in the Southern Hemisphere (Beal et al., 2011).

This enhanced Agulhas leakage involves the transfer of warm and salty waters from the Indian Ocean into the Atlantic, via the Agulhas Current around the Cape Agulhas (marked in Fig. 7a). This transfer contributes to the salinity of the Atlantic, an important factor in the density-driven process that underlies the AMOC (Schmittner et al. 2011). The southward shift of the westerlies, by amplifying the Agulhas leakage, thereby plays a role in potentially strengthening the AMOC.

It can be clearly seen from the zonal mass transport in Fig. 8b. In the shallower South Atlantic Ocean, zonal mass transport increases in all of the experiments, indicating that surface Agulhas leakage is intensified. Since the Agulhas leakage contributes to the salinity and temperature gradients, the changes in the Agulhas leakage can have profound effects on AMOC (Beal et al. 2011). This modulating process is linked to the northward flow of the AMOC, which is also referred as the surface “warming route” of AMOC. It is noted that Antarctic seems to play a more important role in enhancing Agulhas leakage (Fig. 7b). Due to the TP hardly affecting the wind field in the Southern Hemisphere (Fig. 6a), the increase of Agulhas leakage is only slight, suggesting that the TP contribute less than AT to “warming route” of AMOC.

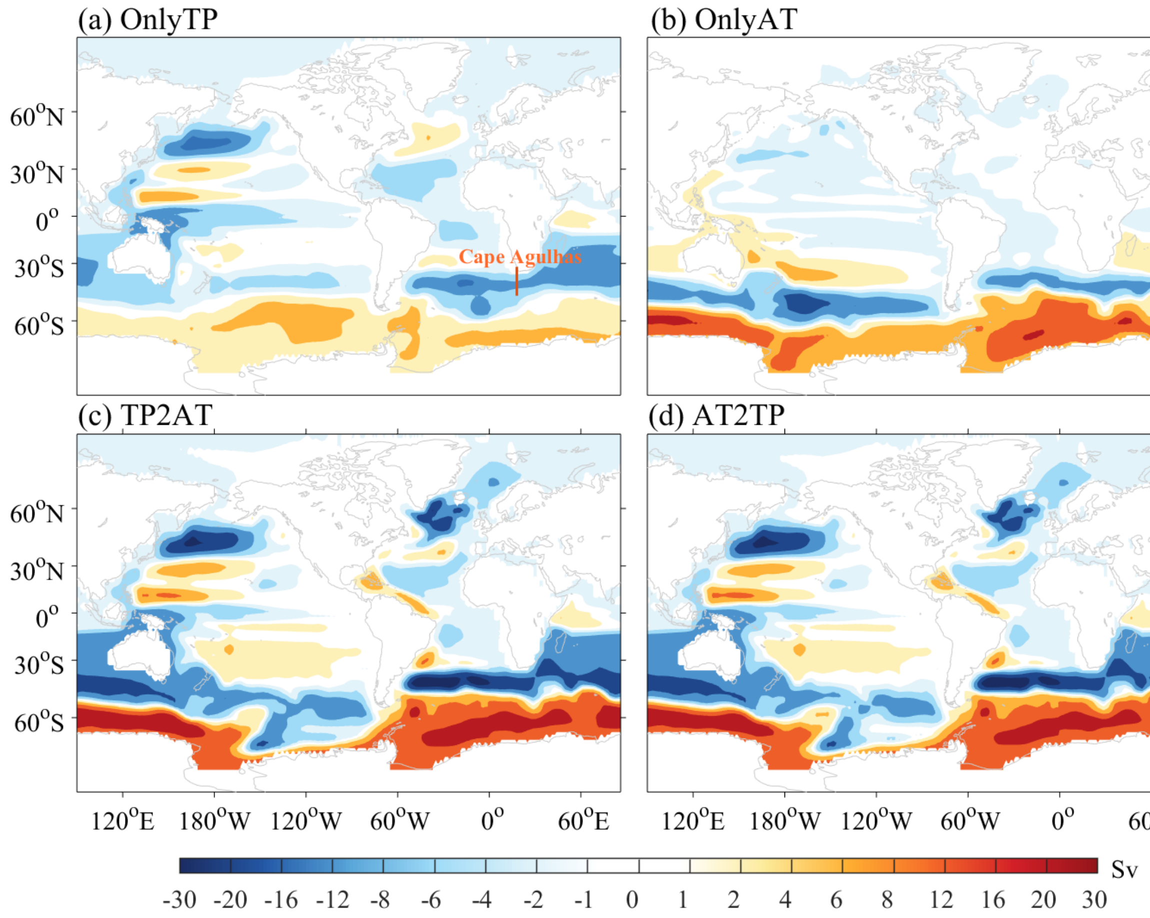


Figure 7. Changes of vertically integrated flow (barotropic stream function) between OnlyTP and Flat ((a) OnlyTP minus Flat). Figure (b), (c) and (d) are the same as figure (a), but for differences in (b) OnlyAT minus Flat, (c) TP2AT minus Flat, and (d) AT2TP minus Flat. Positive barotropic stream function (BSF) means clockwise flow, and negative BSF represents anticlockwise flow. Units: Sv.

Figure 8 illustrates the meridional mass transport (MMT) across the 30°. When either the TP or AT is present in isolation, the southward mass transport is relatively weak, suggesting a limited vigor in the thermohaline circulation. However, a significant intensification in southward mass transport within the Atlantic becomes evident only when both of two topographies are present simultaneously (solid lines in Fig. 8a), thereby supporting a vigorous AMOC. In the Indo-Pacific region, the strength of thermohaline circulation is noticeably greater when influenced by the AT alone, as opposed to the effect of the TP alone (dashed lines in Fig. 8a). This observation underscores the fact that the TP's presence disrupts the PMOC. With the concurrent presence of both the TP and AT torography, the results show a reduced northward mass transport in the Indo-Pacific basin, indicating a weakened wind-driven surface circulation.

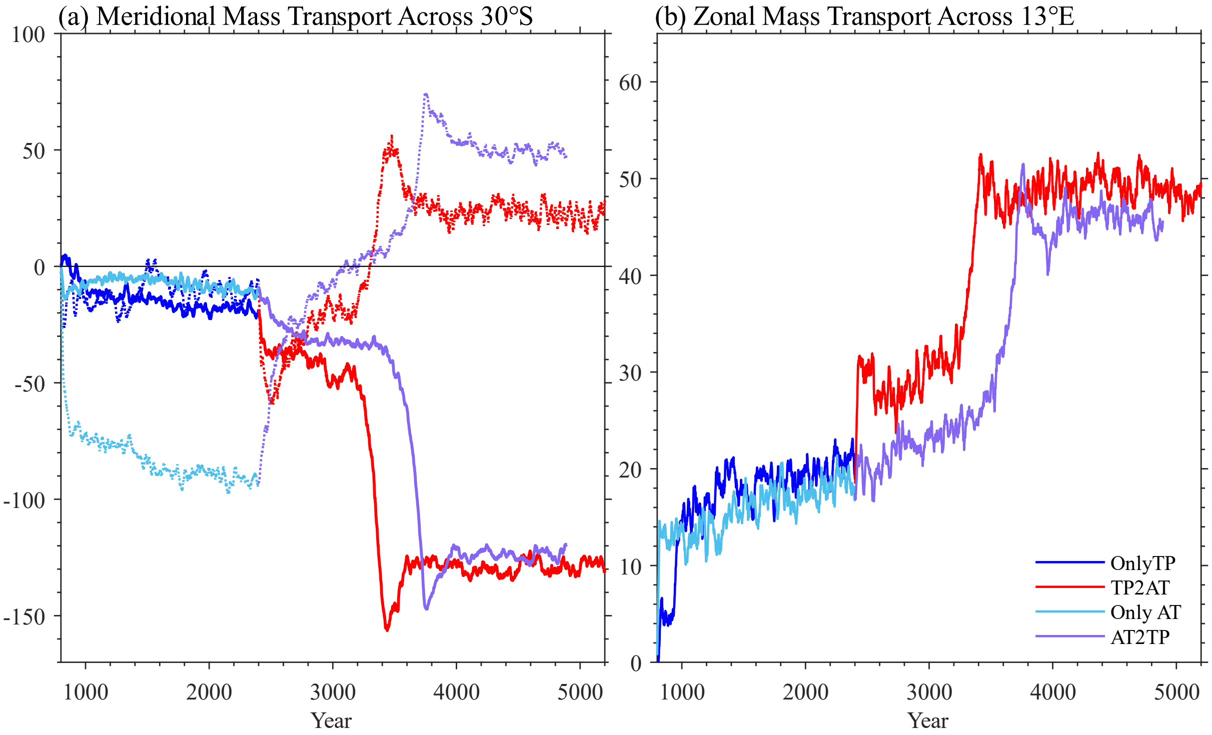
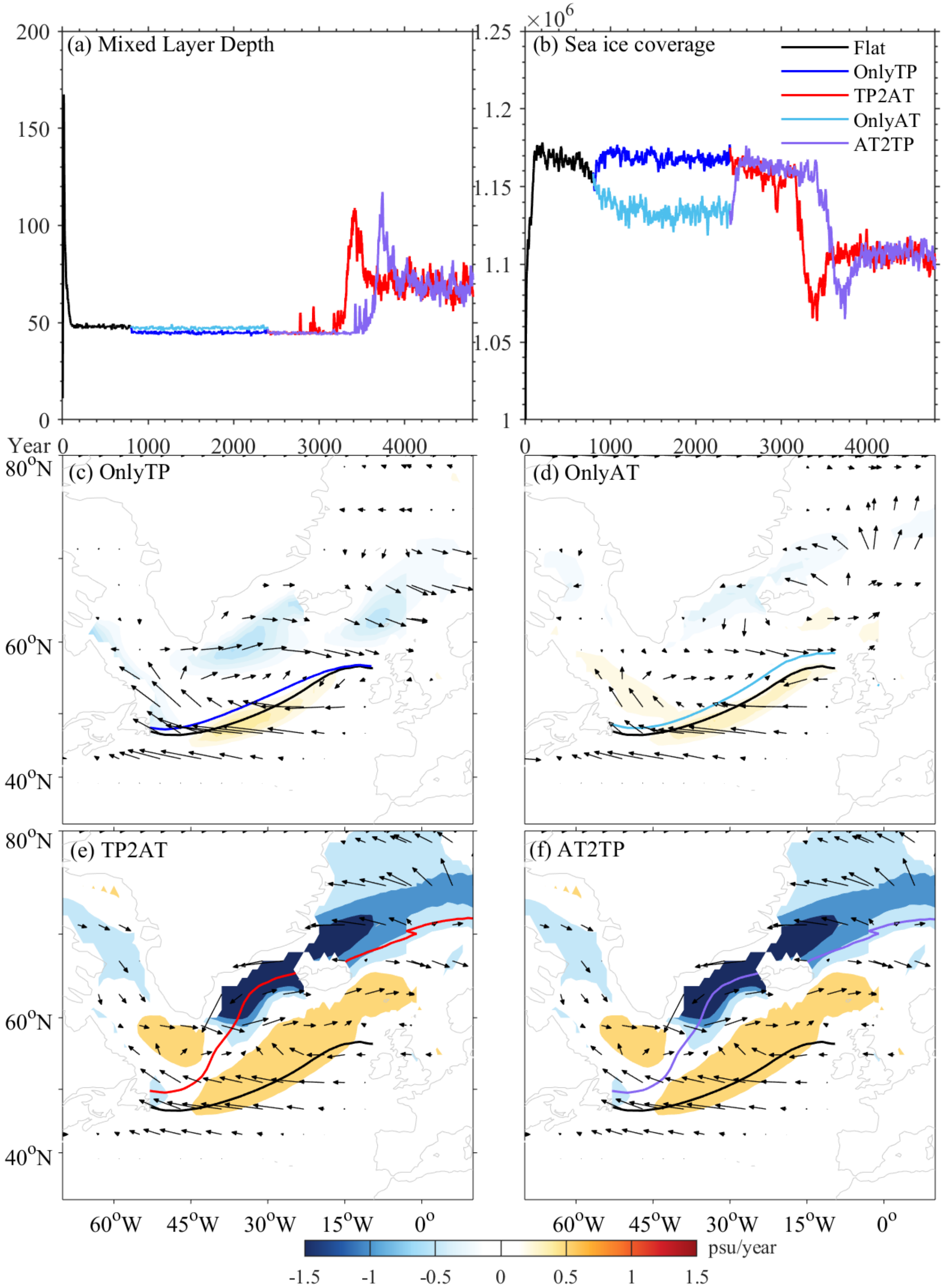


Figure 8. (a) Meridional mass transport (MMT) across 30 °S in the Atlantic (solid lines) and Indo-Pacific (dashed lines). The calculation of MMT is followed by Y24. Positive value represents northward transport, and vice versa. (b) Zonal mass transport across 13°E in the surface layer of the Atlantic (below 200m). The calculation method is similar to the MMT. Blue line, red line, light blue line and purple line represent OnlyTP, TP2AT, OnlyAT, and AT2TP respectively.

e. Positive feedback in the North Atlantic

With the increased salinity in the North Atlantic, coupled with enhanced Agulhas leakage and stronger Ekman pumping in the Southern Ocean, the AMOC begins to develop. An observed sudden increase in AMOC strength during its evolution highlights the critical role of positive feedback mechanisms involving sea ice. As the AMOC strengthens, sea ice retreats northward, which in turn diminishes freshwater input into the North Atlantic Ocean. This reduction initiates a positive feedback loop between the AMOC and sea ice, resulting in rapid changes in both systems. The consistency of changes in the mixed layer depth (MLD) with this feedback process is evident in Fig. 9a. This dynamic is observed around year 3200 in TP2AT and year 3400 in AT2TP (Figs. 2a, 9b), with the AMOC (and correspondingly, sea ice) reaching its maximum (minimum) within approximately 200 years. This phenomenon of positive feedback between the AMOC and sea ice has been corroborated by numerous previous studies (e.g., Brady and Otto-Bliesner, 2011; Yang et al., 2016).

Apart from the time evolution of sea ice, spatial pattern changes of sea ice in the Arctic also support 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 the presence of the TP (Fig. 9c, e, f). This increase signifies a net loss of freshwater from the North Atlantic, resulting in saltier ocean waters. The consequent increase in sea water salinity in the North Atlantic is accompanied by a deepening of the mixed layer depth in that region (Fig. 4), which ultimately contributes to the strengthening of the AMOC.


(a) Mixed Layer Depth
200
150
100
50
0
Year 0
1000
2000
3000
4000
×10^6
(b) Sea ice coverage
1.25
1.2
1.15
1.1
1.05
1
Flat
OnlyTP
TP2AT
OnlyAT
AT2TP
(c) OnlyTP
(d) OnlyAT
(e) TP2AT
(f) AT2TP
80°N
60°N
40°N
60°W
45°W
30°W
15°W
0°
psu/year
-1.5
-1
-0.5
0
0.5
1
1.5

358

Figure 9. Time evolution changes of mixed layer depth in the subpolar Atlantic (figure a, units: m) and sea ice coverage in the Arctic (figure b, units: m^2). Changes in Virtual Salt flux due to sea-ice formation or melting in (c) OnlyTP minus Flat, (d) OnlyAT minus Flat, (e) TP2AT minus Flat and (f) AT2TP minus Flat. Units: psu/year.

5. Summary and discussion

In this study we utilized four topographical experiments (OnlyTP, OnlyAT, TP2AT, AT2TP) and two reference experiments (Flat, Real) to delve into the combined effects of the TP and Antarctica on the AMOC. The results show that, under the synergistic influence of both the TP and Antarctica, the AMOC can achieve levels comparable to those observed in today's real world. Meanwhile, the presence of the TP disrupts the PMOC. Crucially, the TP and Antarctica together, by increasing the SSS in the North Atlantic, enhancing southward mass transport at depth in the South Atlantic and Agulhas leakage south of Africa, act as a pivotal factor for the AMOC's establishment. Therefore, we conclude that the combined impact of the TP and Antarctica is fundamental in determining the configuration of global ocean circulation. The individual presence of the TP, without Antarctica, is insufficient for the full establishment of the AMOC, underscoring the indispensable role of both these topographical features in the dynamics of Earth's climate system. A schematic figure exhibiting their combined role is shown in Fig. 10.

The role of the TP is to mainly suppress the NPDW formation, and 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 intensifying the southward transport of seawater in the 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 would like to emphasize that the equilibrium response in topography experiments does not depend on the manner in which 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 of location of deep-water formation.

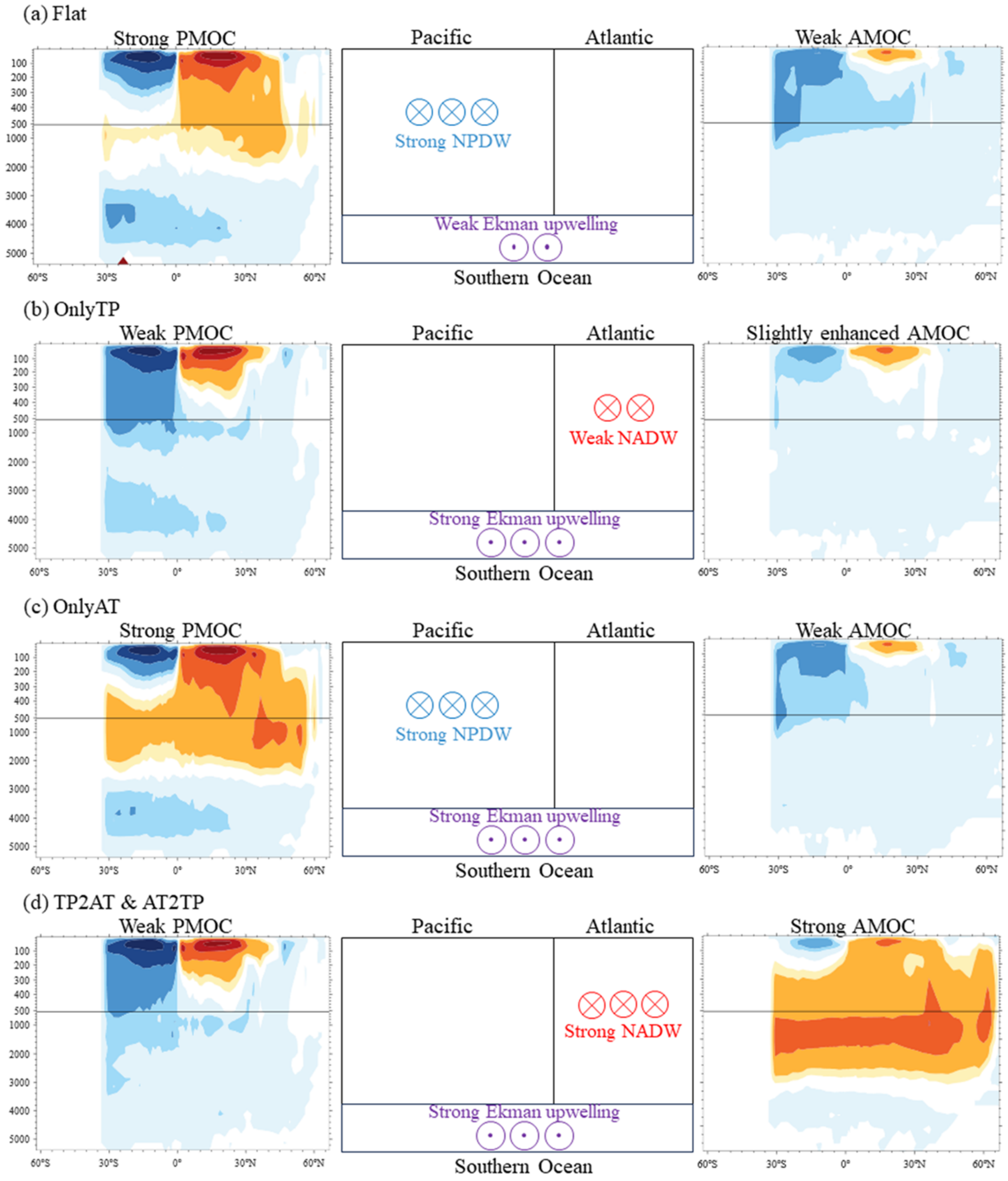


Figure 10. Schematic diagram showing

The results in this study may have important implications for the 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 15 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 5 Ma (references???), so that shaping the climate from Oligocene to Pliocene. The gradual TP uplift led to deflection of the atmospheric jet stream, intensified monsoonal circulation and increased rainfall over 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 specifically explore how the TP and Antarctica influence global ocean circulation. To isolate these effects, we maintain the modern configuration of bathymetry, continental layout, greenhouse gas concentrations, incident solar radiation, and orbital parameters in our experimental design. Consequently, the findings of this study are subject to certain limitations. Additionally, the conclusions might be influenced by the specific model used, including its resolution. It's important to note that we did not dynamically simulate Antarctic glaciation. Our use of the modern land-sea distribution and oceanic gateways could potentially overstate the TP's impact on 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 rise (Zhang et al. 2022) and have profound implications for ocean circulation and 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 stable CO2 levels, disregarding the influence of chemical erosion in rapidly uplifting regions on atmospheric CO2. The uplift of the TP might have led to reduced atmospheric CO2 levels, further encouraging 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 are still not fully understood

Despite the aforementioned caveats, we still wish to underscore the significant role that the TP and Antarctica have played in the evolution of global thermohaline circulation. These two colossal topographical features shape the fundamental structure of the global climate. Our aim is to provide a solid foundation to diminish the controversies surrounding the impact of these massive mountains on the AMOC, which is crucial for a deeper understanding of the ocean's role in past and future climate transitions.

Acknowledgement: This research is jointly supported by the NSF of China (Nos. 42288101, 42230403, and 41725021) and by the foundation at the Shanghai Frontiers Science Centre of Atmosphere-Ocean Interaction of Fudan University.

Data Availability Statement:

All data used in this study are available upon request.

References

Beal, L., De Ruijter, W., Biastoch, A. *et al*, 2011: On the role of the Agulhas system in ocean circulation and climate. *Nature*, **472**, 429–436. https://doi.org/10.1038/nature09983.

Buizert, C., and A. Schmittner, 2015: Southern Ocean control of glacial AMOC stability and Dansgaard-Oeschger interstadial duration. *Paleoceanography*, **30**, 1595–1612, https://doi.org/10.1002/2015PA002795.

Dekker, M. M., A. S. Von Der Heydt, and H. A. Dijkstra, 2018: Cascading transitions in the climate system. *Earth Syst. Dynam.*, **9**, 1243–1260, https://doi.org/10.5194/esd-9-1243-2018.

Delworth, T. L., and F. Zeng, 2008: Simulated impact of altered Southern Hemisphere winds on the Atlantic Meridional Overturning Circulation. *Geophys. Res. Lett.*, **35**, L20708, https://doi.org/10.1029/2008GL035166.

Ditlevsen, P., and S. Ditlevsen, 2023: Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat Commun*, **14**, 4254, https://doi.org/10.1038/s41467-023-39810-w.

Hamon, N., Sepulchre, P., Lefebvre, V. & Ramstein, G. The role of eastern Tethys seaway closure in the Middle Miocene Climatic Transition (ca. 14 Ma). Clim Past 9, 2687-2702 (2013).

Hu, A., Meehl, G. A., Han, W. et al. Effects of the Bering Strait closure on AMOC and global climate under different background climates. Progress in Oceanography 132, 174-196 (2015).

Hurrell, James W., Holland, M. M. *et al*, 2013: *The Community Earth System Model: A Framework for Collaborative Research*. United States. https://doi.org/10.1175/bams-d-12-00121.1.

Jackson, L.C., Biastoch, A., Buckley, M.W. *et al*, 2022: The evolution of the North Atlantic Meridional Overturning Circulation since 1980. *Nat Rev Earth Environ*, **3**, 241–25, https://doi.org/10.1038/s43017-022-00263-2

Jiang, R., and H. Yang, 2021: Roles of the Rocky Mountains in the Atlantic and Pacific Meridional Overturning Circulations. *J. Climate*, **34**, 6691–6703, https://doi.org/10.1175/JCLI-D-20-0819.1.

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf, 2007: On the driving processes of the Atlantic meridional overturning circulation. *Rev. Geophys.*, **45**, RG2001, https://doi.org/10.1029/2004RG000166.

Leutert, T. J., A. Auderset, A. Martínez-García, S. Modestou, and A. N. Meckler, 2020: Coupled Southern Ocean cooling and Antarctic ice sheet expansion during the middle Miocene. *Nat. Geosci.*, **13**, 634–639, https://doi.org/10.1038/s41561-020-0623-0.

Lu, M., B. Huang, Z. Li, S. Yang, and Z. Wang, 2019: Role of Atlantic air–sea interaction in modulating the effect of Tibetan Plateau heating on the upstream climate over Afro-Eurasia–Atlantic regions. *Clim Dyn*, **53**, 509–519, https://doi.org/10.1007/s00382-018-4595-3.

Maffre, P., J.-B. Ladant, Y. Donnadieu, P. Sepulchre, and Y. Goddéris, 2018: The influence of orography on modern ocean circulation. *Clim Dyn*, **50**, 1277–1289, https://doi.org/10.1007/s00382-017-3683-0.

Marzocchi, A., and M. F. Jansen, Connecting Antarctic Sea ice to deep-ocean circulation in modern and glacial climate simulations. *Geophys. Res. Lett., **44**, 6286–6295,* https://doi.org/10.1002/2017GL073936.

Meehl, G. A., A. Hu, J. M. Arblaster, J. Fasullo, and K. E. Trenberth, 2013: Externally Forced and Internally Generated Decadal Climate Variability Associated with the Interdecadal Pacific Oscillation. *Journal of Climate*, **26**, 7298–7310, https://doi.org/10.1175/JCLI-D-12-00548.1.

Patara, L., and C. W. Böning, 2014: Abyssal ocean warming around Antarctica strengthens the Atlantic overturning circulation. *Geophys. Res. Lett.*, **41**, 3972–3978, https://doi.org/10.1002/2014GL059923.

Pearson, P., Foster, G. & Wade, B. Atmospheric carbon dioxide through the Eocene–Oligocene climate transition. *Nature*, **461**, 1110–1113 (2009). https://doi.org/10.1038/nature08447.

Rahmstorf, S., Thermohaline circulation: The current climate. *Nature*, **421**, 699 (2003). https://doi.org/10.1038/421699a

Ruddiman, W. F. & Kutzbach, J. E. Forcing of late Cenozoic northern hemisphere climate by plateau uplift in southern Asia and the American West. J. Geophys Res 94, 18409–18427 (1989).

Raymo, M. E. & Ruddiman, W. F. Tectonic forcing of late Cenozoic climate. Nature 359, 117–122 (1992).

Schmittner, A., T. A. M. Silva, K. Fraedrich, E. Kirk, and F. Lunkeit, 2011: Effects of Mountains and Ice Sheets on Global Ocean Circulation. *J. Climate,* **24***,* 2814–2829, https://doi.org/10.1175/2010JCLI3982.1.

Schneider, B. & Schmittner, A. Simulating the impact of the Panamanian seaway closure on ocean circulation, marine productivity and nutrient cycling. Earth and Planetary Science Letters 246, 367-380 (2006).

Singh, H. K. A., C. M. Bitz, and D. M. W. Frierson, 2016: The Global Climate Response to Lowering Surface Orography of Antarctica and the Importance of Atmosphere–Ocean Coupling. *J. Climate,* **29**, 4137–4153, https://doi.org/10.1175/JCLI-D-15-0442.1.

Sinha, B., Blaker, A. T., Hirschi, J. J.-M., Bonham, S., Brand, M., Josey, S., Smith, R. S., and Marotzke, J. (2012), Mountain ranges favour vigorous Atlantic meridional overturning, *Geophys. Res. Lett.*, 39, L02705, https://doi.org/10.1029/2011GL050485.

Song, H., A. J. Miller, B. D. Cornuelle, and E. Di Lorenzo, 2011: Changes in upwelling and its water sources in the California Current System driven by different wind forcing. *Dynamics of Atmospheres and Oceans*, **52**, 170–191, https://doi.org/10.1016/j.dynatmoce.2011.03.001.

Stouffer, R. J., J. L. Russell, R. L. Beadling, A. J. Broccoli, J. P. Krasting, S. Malyshev, and Z. Naiman, 2022: The Role of Continental Topography in the Present-Day Ocean's Mean Climate. *J. Climate*, **35**, 1327–1346, https://doi.org/10.1175/JCLI-D-20-0690.1.

Toggweiler, J. R., 1994: The Ocean's Overturning Circulation. *Physics Today*, **47**, 45–50, https://doi.org/10.1063/1.881425.

Wang, L., H. Yang, Q. Wen, Y. Liu, and G. Wu, 2023: The Tibetan Plateau's Far-Reaching Impacts on Arctic and Antarctic Climate: Seasonality and Pathways. *J. Climate*, **36**, 1399–1414, https://doi.org/10.1175/JCLI-D-22-0175.1.

Weijer, W., 2002: Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy. *Global and Planetary Change*, **34**, 293–311, https://doi.org/10.1016/S0921-8181(02)00121-2.

Wen, Q., C. Zhu, Z. Han, Z. Liu, and H. Yang, 2021: Can the Topography of Tibetan Plateau Affect the Antarctic Bottom Water? *Geophysical Research Letters*, **48**, https://doi.org/10.1029/2021GL092448.

——, H. Yang, K. Yang, G. Li, Z. Liu, and J. Liu, 2022: Possible Thermal Effect of Tibetan Plateau on the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, **49**, https://doi.org/10.1029/2021GL095771.

Wood, R. A., A. B. Keen, J. F. B. Mitchell, and J. M. Gregory, 1999: Changing spatial structure of the thermohaline circulation in response to atmospheric CO2 forcing in a climate model. *Nature*, **399**, 572–575, https://doi.org/10.1038/21170.

Wu, F., Fang, X., Yang, Y. et al. Reorganization of Asian climate in relation to Tibetan Plateau uplift. Nat Rev Earth Environ 3, 684–700 (2022).

Yang, H., and Q. Wen, 2020: Investigating the Role of the Tibetan Plateau in the Formation of Atlantic Meridional Overturning Circulation. *J. Climate*, **33**, 3585–3601, https://doi.org/10.1175/JCLI-D-19-0205.1.

Zhang, Y., de Boer, A. M., Lunt, D. J., Hutchinson, D. K. et al. Early Eocene ocean meridional overturning circulation: The roles of atmospheric forcing and strait geometry. Paleoceanography and Paleoclimatology, 37, e2021PA004329 (2022).

Zhu, C., Liu, Z, 2020: Weakening Atlantic overturning circulation causes South Atlantic salinity pile-up. *Nat. Clim. Chang.* **10**, 998–100, https://doi.org/10.1038/s41558-020-0897-7.