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Intensified Atlantic vs. weakened Pacific meridional overturning circulations in response to Tibetan Plateau uplift

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Abstract: The role of the Tibetan Plateau (TP) in maintaining large-scale overturning circulation in the Atlantic and Pacific is investigated using a coupled atmosphere–ocean model. For the present day with a realistic topography, model simulation shows a strong Atlantic meridional overturning circulation (AMOC) but a near absence of a Pacific meridional overturning circulation (PMOC), which is in good agreement with present observations. In contrast, the simulation without the TP depicts a collapsed AMOC and a strong PMOC that dominates deep water formation. The switch in deep water formation between the two basins results from changes in the large-scale atmospheric circulation and atmosphere–ocean feedback in the Atlantic and Pacific. The intensified westerly winds and increased freshwater flux over the North Atlantic cause an initial slowdown of the AMOC, but the weakened East Asian monsoon circulation and associated decreased freshwater flux over the North Pacific enhance initial intensification of the PMOC. The further decreased heat flux and the associated increase in sea-ice fraction promote the final AMOC collapse over the Atlantic,

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while the further increased heat flux leads to the final PMOC establishment over the Pacific. Although the simulations were done in a cold world, it still importantly implicates that the uplift of the TP alone could have been a potential driver for the reorganization of PMOC–AMOC between the Late Eocene and Early Oligocene.

1. Introduction

The uplift of the Tibetan Plateau (TP) is a major tectonic event that has occurred throughout the Cenozoic, and its gradual growth has exerted a strong influence on atmospheric circulation and climate (Molnar et al., 2010). Since the pioneering work of Bolin (1950), the impacts of mountain uplift on regional and global climate have been investigated by a large body of studies. Nevertheless, although most studies have emphasized the role of mountain ranges on atmosphere dynamics, quantifications of the associated impact on ocean dynamics have been rare. For example, most previous works have taken atmospheric general circulation models to address regional climate effects, notably the Asian monsoon and arid environment evolutions (e.g., Ruddiman and Kutzbach, 1989; Ramstein et al., 1997; An et al., 2001; Liu and Yin, 2002; Jiang et al., 2008; Zhang et al., 2015). However, simulations have recently been applied to investigate the effect of mountain uplift in the context of the atmosphere–ocean system, and a few studies have proposed that the uplift of the Andes (Sepulchre et al., 2009) and Rocky Mountains (Seager et al., 2002) is closely linked to the evolution of oceanic circulations, including the Gulf Stream and Humboldt Current, and the El Niño–Southern Oscillation system (Feng and Poulsen, 2014). Although it has been indicated that TP uplift affects sea surface temperatures, sea surface salinity, precipitation, and trade winds for both the Pacific and equatorial Indian Ocean (Abe et al., 2003; Kitoh, 2004; Okajima and Xie, 2007), the influence of TP uplift on high-latitude ocean circulations, particularly in the North Atlantic, has

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rarely been explored.

The potential importance of mountain uplift in modifying the oceanic thermohaline circulation has previously been investigated. Ruddiman and Kutzbach (1989) indicated that mountain uplift-induced changes in North Atlantic surface circulation are expected to increase North Atlantic Deep Water formation. In addition, Rind et al. (1997) performed coupled model simulations with and without TP and proposed that the TP may have a considerable impact on the large-scale meridional overturning circulation (MOC). However, the integration time used in this pioneering simulations was too short to fully evaluate the deep oceanic circulation response, and thus no previous study has yet quantified the possible role of the TP on the MOC.

On a geological timescale, remarkable reorganization and evolution of large-scale oceanic overturning circulation, from the Southern Ocean deep water dominating mode to the modern-like North Atlantic deep water mode, have been evidenced through the Late Eocene to the Early Oligocene (Wright and Miller, 1993; Davies et al., 2001; Via and Thomas, 2006). This dramatic shift is associated with major rearrangements in ocean seaways and other tectonic changes, although the ultimate trigger is still being debated (Zhang et al., 2011). Given the timing of TP uplift (Wang et al., 2008; Molnar et al., 2010), it is important to quantify the contribution of TP uplift on meridional ocean circulation of the Northern Hemisphere. In this study, therefore, two coupled atmosphere–ocean numerical integrations, with and without TP, are designed to investigate the role of the TP on the Atlantic MOC (AMOC) and Pacific MOC (PMOC). Due to the length of these coupled simulations, here we restrict our analysis to the sensitivity of the TP uplift without modifying other parameters.

2. Model, experimental design, and density flux analysis

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2.1. Model and experiments

The Community Earth System Model (CESM) version 1.0.5 of the National Center for Atmospheric Research is a widely used, well-validated coupled model with dynamic atmosphere, land, ocean, and sea-ice components (Gent et al., 2011). It is applied to this study at a low-resolution configuration that is computationally efficient and well-described (Shields et al., 2012) and employs an atmospheric horizontal grid of roughly 3.75° × 3.75° (T31) with 26 vertical levels. The ocean model adopts a finer oceanic horizontal grid, with a nominal 3° resolution increasing to 1° near the equator (116 × 100 grid points, latitude by longitude) and 60 unevenly spaced layers in the vertical. The sea-ice and land models share the same horizontal grids as the ocean and atmosphere models, respectively, where the sea-ice component is a dynamic–thermodynamic model that includes a subgrid-scale ice thickness distribution and energy-conserving thermodynamics (Holland et al., 2012).

Two experiments are conducted; firstly, a control run with modern topography (MTP, Figure 1a), and secondly a run where topography within the region of 20°~60°N and 60°~140°E at altitudes higher than 200 m is set to 200 m (NTP, Figure 1b), which enables examination of the climate effect in relation to TP topography. This TP uplift configuration has been referred to in the majority of previous simulation works (e.g., Liu and Yin, 2002; Jiang et al., 2008). This greatly simplified topographic setting is not intended to represent a realistic scenario constrained by geological evidence and instead represents two end-members of the potential growth histories of the TP. So, it is important to note that these experiments only aim to investigate the TP uplift occurring in "a cold world" with an atmospheric CO_2 corresponding to pre-industrial values (284.0 ppm).With the exception of topography, all the other boundaries, such as continent–ocean distributions and orbital parameters, are prescribed to pre-industrial conditions. The MTP is continually integrated for

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1100 years, and the NTP is additionally integrated for another 1840 years starting from the year 1100 of the MTP. Global mean surface air temperature and sea temperature at a depth of 1000 m are shown in Figure 1c. Both simulations reach an equilibrium state after more than 1000 model years of integration time, and the final 200 years of both cases are applied for our climate state analysis.

2.2. Density flux analysis

Because one of the major aims of this paper is to analyze the changes in meridional ocean circulation, we decided to focus on the density flux parameter, which is appropriate to diagnose these ocean circulation changes. The dense deep water masses are formed in the area with relatively high surface density achieved by cooling or increasing salinity. To better understand which processes dominated the MOC changes in simulations, it is instructive to further analyze the time evolution of density fluxes budget. Therefore, a density flux analysis method, in which the total density flux decomposes into haline contribution due to freshwater flux and thermal contribution due to heat flux (Schmitt et al., 1989), is adopted in our study. The total density flux is calculated from a linearized state equation of seawater, as

$$\boldsymbol{F_\rho = -\alpha \cdot \frac{Q}{C_p} + \rho(0,T) \cdot \beta \cdot \frac{(E-P-R-I)\cdot S}{1-S}}$$

$\boldsymbol{F_\rho}$ is the total density flux, $\boldsymbol{-\alpha \cdot \frac{Q}{C_p}}$ is thermal density flux, and $\boldsymbol{\rho(0,T) \cdot \beta \cdot \frac{(E-P-R-I)\cdot S}{1-S}}$ is haline density term. $\boldsymbol{C_p}$, $\boldsymbol{T}$ and $\boldsymbol{S}$ are the specific heat capacity, surface temperature and salinity of seawater, respectively. $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the thermal expansion and haline contraction coefficients, respectively. $\boldsymbol{\rho(0,T)}$ is the density of freshwater with salinity of 0 psu and temperature of $\boldsymbol{T}$. $\boldsymbol{Q}$ represents the net surface heat flux. $\boldsymbol{E}$, $\boldsymbol{P}$, $\boldsymbol{R}$, and $\boldsymbol{I}$ denote the freshwater fluxes due to evaporation, precipitation, river runoff, and sea-ice melting (or brine rejection), respectively.

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3. Results

3.1. Changes in AMOC and PMOC

There are evident changes in the AMOC and PMOC indices in response to TP uplift (Figure 1d). With MTP, the AMOC stabilizes at around 17 Sv (Sv = 10^6 m^3 s^{-1}) for more than 1000 years (Figure 1d, 1–1100 years, red line), which agrees with observations (Cunningham et al., 2007), but with NTP there is a continual weakening of AMOC until the point of quasi-collapse (ca. 2 Sv, Figure 1d). In contrast, the PMOC of NTP begins at a sluggish level from MTP (Figure 1d, 1–1100 years, purple line) and takes as long as 1200 years to reach an equilibrium state that is comparable to the level of AMOC in MTP (ca. 18 Sv, Figure 1d, 1101–2940 years, purple line). In agreement with the dramatic responses of AMOC and PMOC, sea surface salinity increases in the North Pacific but decreases in a broad area of the North Atlantic (Figure 2b). To fully understand the different behaviors between AMOC and PMOC in NTP, in the following sections we further analyze the changes in atmospheric and oceanic circulations and atmosphere–ocean feedbacks.

3.2. Atmospheric responses

The modified AMOC and PMOC are linked to large-scale atmospheric circulation changes. In terms of model results of the NTP relative to the MTP, the surface air temperature over and around the TP and in the North Pacific increased but decreased over the North Atlantic (Figure 2a), which agrees with previous simulations (Broccoli and Manabe, 1992; Kutzbach et al., 1993). In addition, there are intensified westerlies over the North Atlantic and weakened subtropical anticyclones and trade winds over the Pacific (Figure 2c); the former results from a significant increase in the meridional pressure gradient driven by a large-scale equatorward shift of air mass occupying the current position of the TP (Figure 2c) and from a reduced drag of the orographically induced gravity

waves associated with the absence of the TP (Palmer et al., 1986; Sinha et al., 2012), whereas the latter is derived from the weakening of zonal Eurasia–Pacific thermal contrast, especially in boreal summertime, in relation to removal of the mountains (Ruddiman and Kutzbach, 1989; Rodwell and Hoskins, 2001; Kitoh, 2004).

When the TP is removed, the atmospheric moisture transport between the Pacific and Atlantic Oceans undergoes a basin-basin asymmetric redistribution as a response to large-scale circulation anomalies (Figure 2c). In comparison with MTP results, the NTP simulation show large amounts of anomalous westerly moisture flux transported through the lowlands of Central America to the North Atlantic, causing weak moisture convergence therein (Figure 2d). In addition, removal of the TP leads to a significant divergence of moisture over East Asia and the western North Pacific marginal seas (Figure 2d), which is linked to a weakened monsoon circulation and is consistent with previous simulations (Liu and Yin, 2002; Kitoh, 2004; Molnar et al., 2010). More importantly, this Asia monsoon collapse associated with TP removal was shown to more aggravated in the context of coupled models as compared to that in atmosphere alone models due to enhanced ocean–atmosphere feedback (Kitoh, 2004). Meanwhile, the freshwater discharge around the western North Pacific marginal seas from the Asian rivers was previously found to be substantially reduced in response to monsoon collapse (Kitoh et al., 2010).

3.3. Oceanic responses and atmosphere–ocean feedbacks

3.3.1. Changes in freshwater and sea-ice

The above changes in large-scale atmospheric circulation markedly decrease the total ocean density flux in the North Atlantic (Figure 3a, brown), supporting the trend of the AMOC (Figure 1d). Both the increases of net freshwater and wind-driven sea-ice expansion are responsible for the

initial reduction of total ocean density flux and further induce a gradual weakening of the AMOC. In more details, on the one hand, the anomalous atmospheric circulation associated with the removal of the TP drives more vapor transportation northward (Figure 2d) over the North Atlantic Ocean, causing more precipitation at the beginning of NTP simulation (Figure 3b, ca. 1101–1200 years, red line). Correspondingly, the net freshwater flux (precipitation plus runoff minus evaporation) convergence into the North Atlantic basin at 40°–70°N increases by 0.005 Sv (~3%) and 0.025 Sv (~16%) at the initial and final states of NTP simulations (Figure 3b, green), respectively. On the other hand, there is a significant increase in area-averaged sea-ice coverage over the North Atlantic through wind-driven processes (Figure 3c, green). With the TP, the annual mean sea-ice forms mainly in the northern and western region of the sub-polar North Atlantic, and it shifts southward and eastward when driven by cyclonic wind stress associated with the Icelandic Low, and melts in the Labrador Sea (sub-polar gyre) caused by warm condition (Figure 4a). By comparison, after removal of the TP, anomalously intensified cyclonic winds induce an anomalous eastward sea-ice velocity (Figure 4c), and cause a rapid eastward shift of sea-ice margin (Figure 4c). Meanwhile, the local melted sea-ice due to thermodynamics processes reduces in the southeast of Greenland (red shading, Fig. 4c), but increases in the south of Greenland (blue shading, Fig. 4c). It suggests that there is much more sea-ice transporting from high latitudes into the sub-polar gyre region, and the anomalous expansion of sea-ice margin in this region primarily originates from wind-driven eastward transportation (dynamics processes), but not local formation (thermodynamic processes). Because of this increased sea-ice through thermodynamically insulating the sea water from the freezing air, the release of sensible and latent heat into the atmosphere decreases and the density of sea water finally reduces, which processes have also been previously elucidated by Zhu et al. (2014).

Moreover, the total ocean density flux increases in the North Pacific in response to the removal of the TP. Due to the weakened Asian monsoon circulation and associated decrease in rainfall and runoff after lowering the topography, the net freshwater flux received by the North Pacific decreases by 0.08 Sv (~26%) and 0.12 Sv (~40%) during the initial and end stages of the NTP simulation, respectively (Figure 6b, green). This continuous negative freshwater flux forcing tends to increase density and initially leads to the formation of North Pacific dense water, which is verified from changes in the haline density flux (Figure 6a). Specifically, during the first 200 years of the NTP run, the haline density flux constantly produces a net positive contribution to the total density relative to the MTP haline term (Figure 6a, blue line). Meanwhile, the thermal density flux remains at a lower level (Figure 6a, ca. 1101–1300 years, red line) relative to the MTP. Thus, it indicates that the initially increased density of North Pacific is largely attributed to the haline density term, but not thermal density term.

3.3.2. Roles of atmosphere–ocean feedbacks

The aforementioned weakening of the AMOC due to atmospheric processes further triggers a positive atmosphere–ocean feedback loop through reducing northward heat transport, and subsequent decreasing sea surface temperatures, then allowing sea-ice to expand, suppressing the releasing of evaporating latent and sensible, and reducing the sea water density, and further weakening the AMOC, as previously shown in Jayne and Marotzke (1999) and Zhu et al. (2014). Note that the negative effect of net freshwater becomes increasingly unimportant compared to the heat flux feedback associated with latent/sensible heat changes (Figure 3a). Finally, the thermal density flux decreases by 49% relative to the MTP run, which substantially dominates total density flux changes (Figure 3a). To be specific, the annual mean total density flux and mixed layer depth

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over the North Atlantic, especially around the Iceland where the collapse of deep water formation occurs, is dramatically decreased in NTP (Figure 5d, the maximum mixed layer depth is about 100 m) in comparison to that in MTP (Figure 5a, the maximum mixed layer depth is approximately 900 m). Moreover, this reduced total density flux over North Atlantic is more attributed to the decreased thermal density flux associated with less latent and sensible released (Figure 5e) than the changed haline density flux (Figure 5f).

Atmosphere–ocean feedbacks also strengthen the PMOC. Due to the initial development of the PMOC mentioned in section 3.1, a positive feedback (as pointed out in Warren (1983)) is initiated by the intensifying meridional oceanic circulation; this transports warmer subtropical water northward and leads to buoyancy loss and evaporation increase (Figure 6b). This feedback is also able to re-trigger PMOC enhancement. By comparison to the changes in North Atlantic, both the regionally averaged sea-ice coverage (Figure 6c) and February sea-ice margin (Figure 4f) over North Pacific experience a slightly northward retreat and have a relatively smaller effect on the simulated strengthening of PMOC. Over a longer time, the thermal density flux, which is due to the loss of total heat, contributes more to the total density flux than the haline flux in relation to a reduction in net freshwater discharge (Figure 6b). Spatially, both increased total density flux and mixed layer depth in North Pacific Ocean show opposite change characteristics with the North Atlantic (Figure 7d). Correspondingly, in comparison to the MTP, there is a widespread increase of thermally induced density flux in the sub-polar North Pacific in NTP (Figure 7f), but with little spatially changed in haline density flux (Figure 7f). Thus, in contrast to the results shown in the North Atlantic, the increased total heat exchange between the atmosphere and ocean due to the processes of sensible and latent heat releases (Figure 6b) ultimately becomes a dominant factor in maintaining a vigorous PMOC by controlling the increased total density flux (Figure 6a).

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4. Conclusions and Discussion

This study investigates the effect of TP uplift on large-scale oceanic circulation using a low-resolution version of CESM. Results show that the removal of the TP initially changes the wind-driven atmospheric moisture transport process and the wind-driven sea-ice coverage expansion process, which are responsible for the initial weakening of AMOC. Meanwhile, the suppressed monsoonal circulation in East Asia and western Pacific marginal seas induces the decrease of rainfall and runoff and further causes the initially increased PMOC. Moreover, the positive feedback further changes AMOC and PMOC. In particular, the AMOC weakening can further decrease North Atlantic sea surface temperatures, ocean–atmosphere temperature contrast, evaporation, and precipitation, and subsequently increase sea-ice coverage. These processes together cause the final changes of AMOC and PMOC (Figure 8).

A previous study demonstrated the role of Rocky Mountain uplift on heat transport and Gulf Stream patterns in the North Atlantic (Seager et al., 2002). In this study, we focus on the most prominent long-term orogenesis occurring since the Eocene: the TP and Himalayan uplift and associated impacts on the MOC. Our results can be compared with those derived from earlier simulations, although experimental configurations differ somewhat. It has been indicated that removal of global mountains triggers the collapse of deep water in the North Atlantic but enables formation in the North Pacific in two different coupled models (Schmittner et al., 2011; Sinha et al., 2012; Maffre et al., 2017). The simulated weakening of the AMOC is also qualitatively consistent with recent experiments using a decreased elevation of the TP and Central Asia (Fallah et al., 2016). However, only TP topography is reduced in our study, but our results are comparable with those of past studies, therefore highlighting the key role that TP has played in forming the current large-scale deep oceanic circulation pattern. Nevertheless, given that all existing simulations (including ours)

have used a rather coarse resolution of coupled model configuration, it is considered that a finer resolution model may provide a better representation of western boundary currents and allow for a more accurate and realistic resolving of ocean eddies, which are believed to be critically important oceanic processes that should be taken in realistic simulations of the AMOC (Spence et al., 2008). It is thus considered that investigating the response of the PMOC and AMOC to TP uplift using an atmosphere–ocean general circulation model with a higher spatial resolution would be useful. Besides, the robust changes in AMOC and PMOC, and associated mechanisms due to the TP uplift can be achieved through multi-model comparison.

Based on a comprehensive analysis of modern climatological data, Warren (1983) and Emile-Geay et al. (2003) hypothesized that the present MOC (mainly occurring in the Atlantic but not in the Pacific) is determined by large mountains, namely the Himalayas and Rockies, which induce an asymmetric distribution of wind stress and moisture transport features between the Atlantic and Pacific basins. However, previous studies have also demonstrated that the asymmetric continental extents and basin widths (basin geometries) between the two basins (Weaver et al., 1999; Nilsson et al., 2013) also play a possible key role in maintaining the present day AMOC. Our simulations support this hypothesis and highlight the significant role of the TP alone in supporting the modern AMOC. Similar PMOC–AMOC seesaw dynamics have also been determined in simulations (Saenko et al., 2004; Chikamoto et al., 2012; Hu et al., 2012) as well as in observations (Okazaki et al., 2010; Menviel et al., 2014; Freeman et al., 2015) based on the last deglaciation. Such studies have also suggested that large PMOC–AMOC seesaw modulations can be triggered by slight changes in freshwater/salinity redistributions between the Pacific and Atlantic. Furthermore, we provide an insight that the maintenance mechanism of PMOC in without TP, to some extent, is the same as the AMOC in the present day. Specially, for the current North Atlantic, there is a

persistently northward movement of warm and salty water mass from tropical-subtropical Gulf Stream region into North Atlantic and farther poleward into the Norwegian and Greenland Seas, where it is exposed to very cold atmospheric temperatures and followed by a gradual cooling and in turn a higher density due to release substantial sensible and latent heat into the overlying cold atmosphere, which is the same as PMOC, before eventually forming North Atlantic Deep Water.

Our simulations have potential implications for understanding paleotemperature reconstructions and paleoceanographic circulation reorganization. The Earth has experienced a long-term cooling trend throughout the Cenozoic on the basis of many proxies and stacked records (Zachos et al., 2001, 2008), in association with a reduced equator to pole thermal gradient. A very important contribution to understanding the large cooling during the Cenozoic has been determined as the drastic decrease in atmospheric CO_2 since the Eocene (DeConto and Pollard, 2003; DeConto et al., 2008). On the other hand, a study with new data base further indicated that this thermal evolution has been different among ocean basins during the Cenozoic (Cramer et al., 2009), and this differing evolutionary pattern between basins is largely related to large-scale ocean dynamics and tectonic events (Zhang et al., 2011). Moreover, epsilon-Neodymium (eps-Nd) isotopes in the deep Pacific suggest that the North Pacific was characterized by vigorous deep water formation during ca. 65–40 Ma (Thomas, 2004). Other new eps-Nd records also confirm that the overturning circulation was already established in the high-latitude North Pacific prior to 40 Ma (Hague et al., 2012; Thomas et al., 2014). In comparison, a modern-like bipolar oceanic circulation, characterized by two branches of deep water formation in the southern ocean and North Atlantic, began in the late Eocene (~38.5 Ma) in relation to the effect of southern ocean gateway openings (Borrelli et al., 2014). Several records also support that the onset of the present AMOC state began at the Eocene–Oligocene transition (~34 Ma) in association with the tectonic deepening of the Greenland–Norwegian Sea

(Wright and Miller, 1993; Davies et al., 2001; Via and Thomas, 2006). However, it is likely that the intermittent Cenozoic uplift of the TP reached a certain height by the Early Oligocene, as shown in geologic evidences (Dupont-Nivet et al., 2008; Wang et al., 2008). Our own contribution demonstrates that major uplift occurring during this period was also an important player in climate changes via hydrologic and ocean dynamics changes. Indeed, we pinpoint the drastic effect of TP uplift alone on the distribution of the northern hemispheric MOCs and potentially provide clues for proxy record interpretation.

Finally, this simulation is performed with constant atmospheric CO_2 concentrations at the pre-industrial, whereas it was higher during the uplift phase in the real world. In the context of past warm world, such as Late Eocene, the climate conditions are accompanied with high atmospheric CO_2 concentration, limited sea ice extent, and significantly modified land–sea distribution. Under these warmer boundary conditions, the responses of AMOC to the TP induced freshwater forcing may be very different from the modern conditions. Therefore, it will be necessary to perform further numerical experiments with more realistic boundary conditions to accurately investigate the contribution of the TP uplift on ocean circulation and therefore to be able to compare with data reconstructions.

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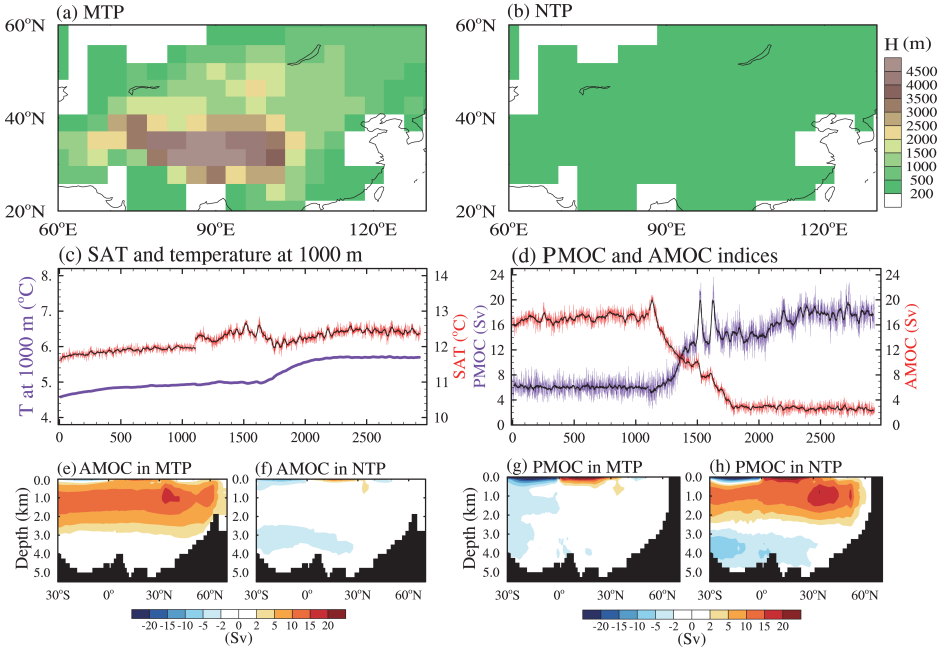

Figure 1. Two topographic height configurations used in experiments: (a) MTP and (b) NTP. (c) Time series of global mean annual 2-m surface air temperature (SAT) and sea temperature at 1000 m depth in MTP (1–1100 years) and NTP (1101–2940 years) simulations; bold black lines show 21-year running mean. (d) Same as (c) but for PMOC and AMOC indices, respectively. AMOC and PMOC indices are defined as the annual maximum of the meridional stream function value north of 28 °N and below depth of 500 m, respectively. (e–h) Climatological annual mean Atlantic and Indian–Pacific meridional overturning stream function in MTP (e and g) and NTP (f and h); positive (negative) shading represents clockwise (counterclockwise) circulations.

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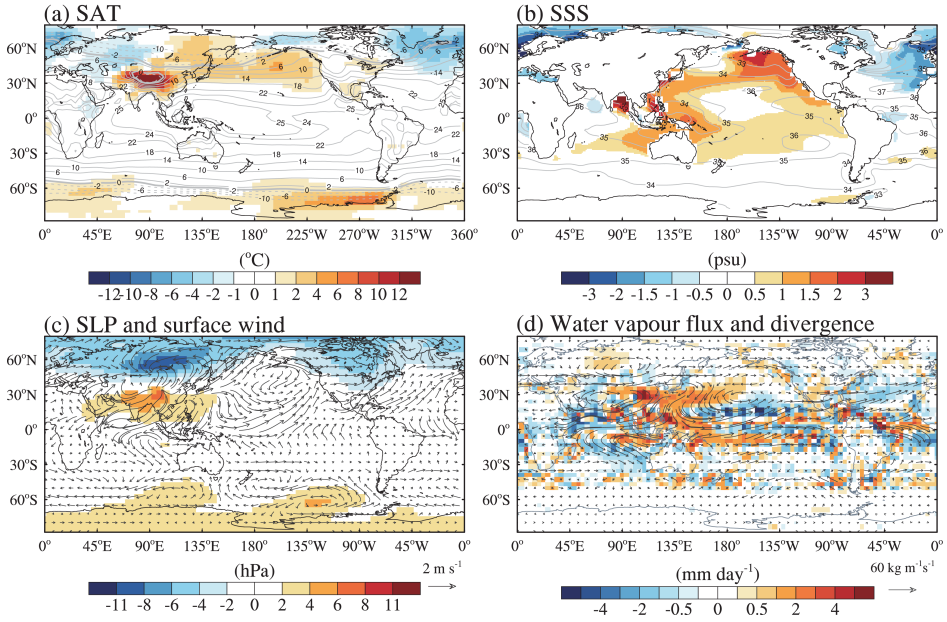

Figure 2. (a) Climatological SAT in MTP (contour) and anomalies (shaded) for NTP minus MTP; (b) same as Figure 2a, but for sea surface salinity (SSS); (c) changes in sea-level pressure (SLP, shading) and surface wind (vectors); and (d) vertically integrated (surface to 300 hPa pressure layer) water vapor flux (vectors) and its convergence (shading) in NTP relative to MTP. Unit of convergence is converted to mm day^{-1} assuming the density of liquid water as 1 g cm^{-3}.

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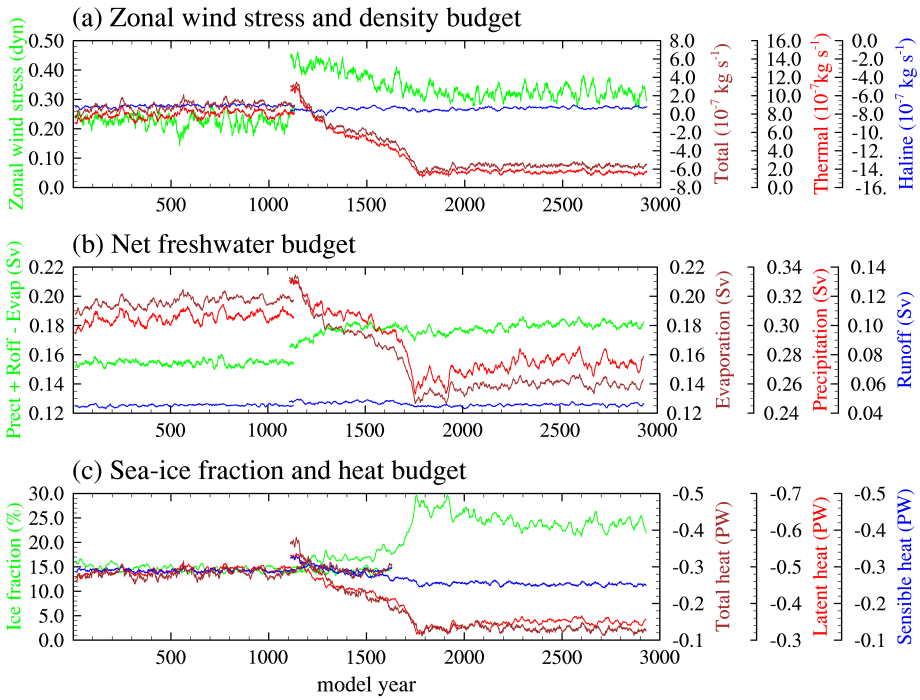

Figure 3. Regional annual mean across North Atlantic basin at 40°–70°N for MTP (1–1100 years) and NTP (1101–2940 years) of (a) zonal surface wind-stress, total density flux, haline density flux, and thermal density flux (total density flux is decomposed into haline contribution due to freshwater flux and thermal contribution due to heat flux (*Schmitt et al.*, 1989); (b) net freshwater, precipitation, runoff, and evaporation fluxes; (c) sea-ice fraction, total heat, sensible heat, and latent heat fluxes, (units: PW, 1 PW = 10^{15} W). For comparison purposes, all lines with common units use identical vertical scale spacing.

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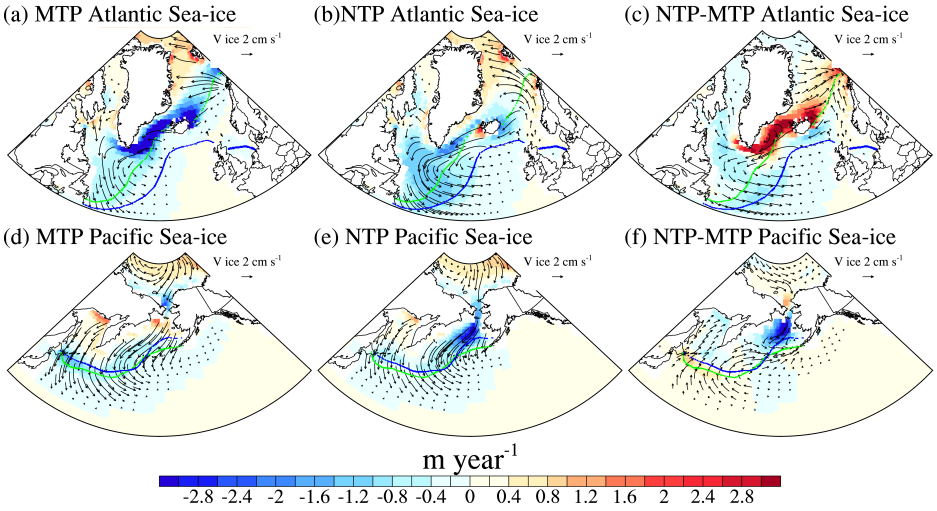

Figure 4. The North Atlantic and Pacific region features of annual mean sea-ice formation rate (shading; positive stands for formation, and negative stands for melting), sea-ice velocity (vectors, cm s^{-1}), and for (a, d) MTP, (b, e) NTP, and (c, f) difference between NTP and MTP. The February sea-ice margin is indicated with dashed lines (defined as the 15% sea-ice coverage, green line for MTP, blue line for NTP)

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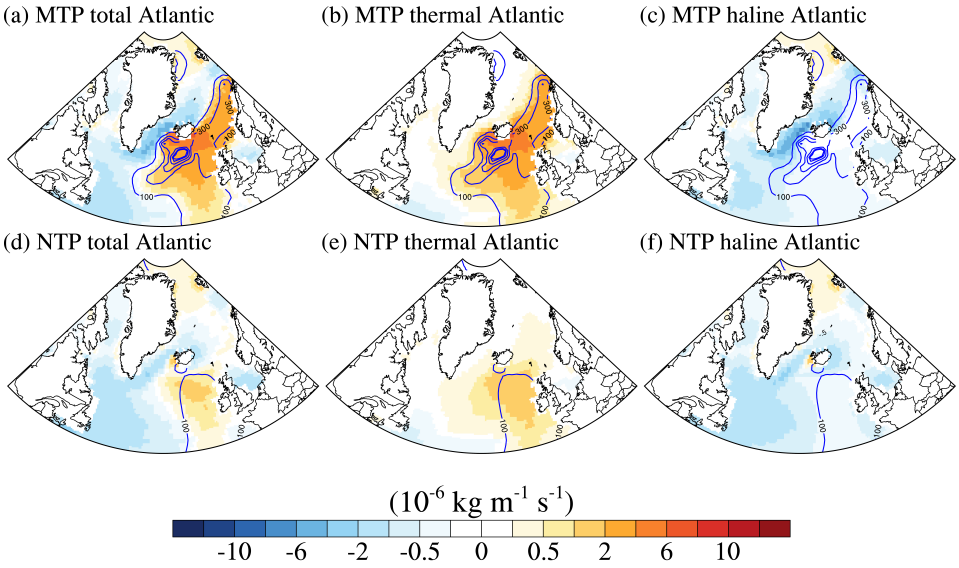

Figure 5. The annual mean (a, d) total density flux (shading; positive means flux makes water denser), (b, e) the thermal density flux, (c, f) the haline density flux, and the winter mixed layer depth (blue contour, contour interval: 200 m) in the MTP (upper pane) and NTP (lower pane).

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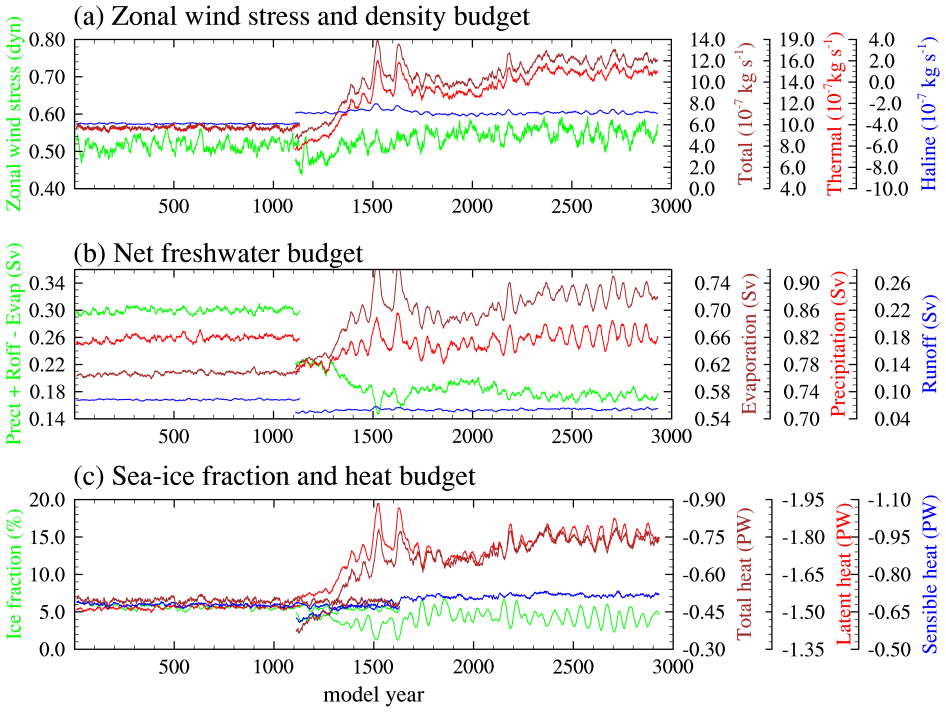

Figure 6. As in Figure 3, but for North Pacific basin at 30°–70°N.

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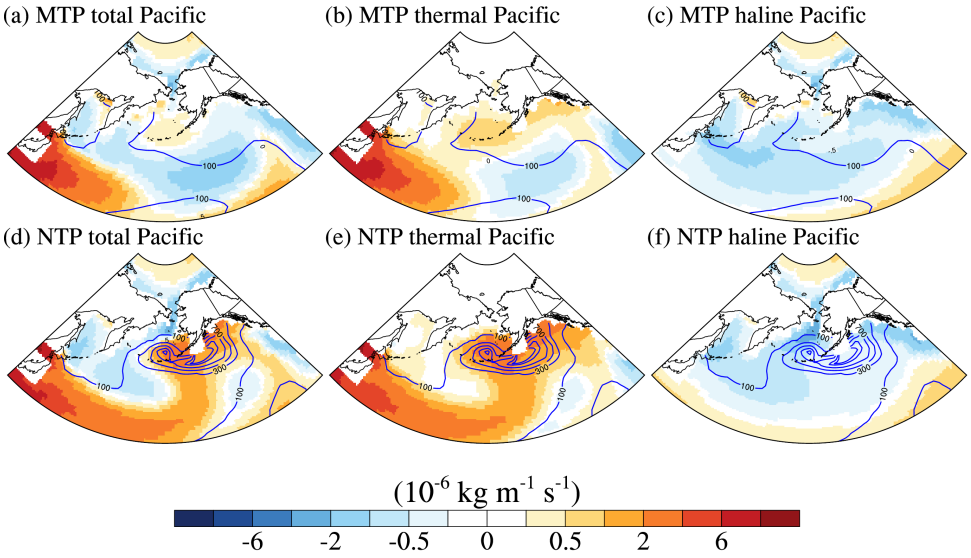

Figure 7. The same as Figure 5, but for the North Pacific (30–80 °N).

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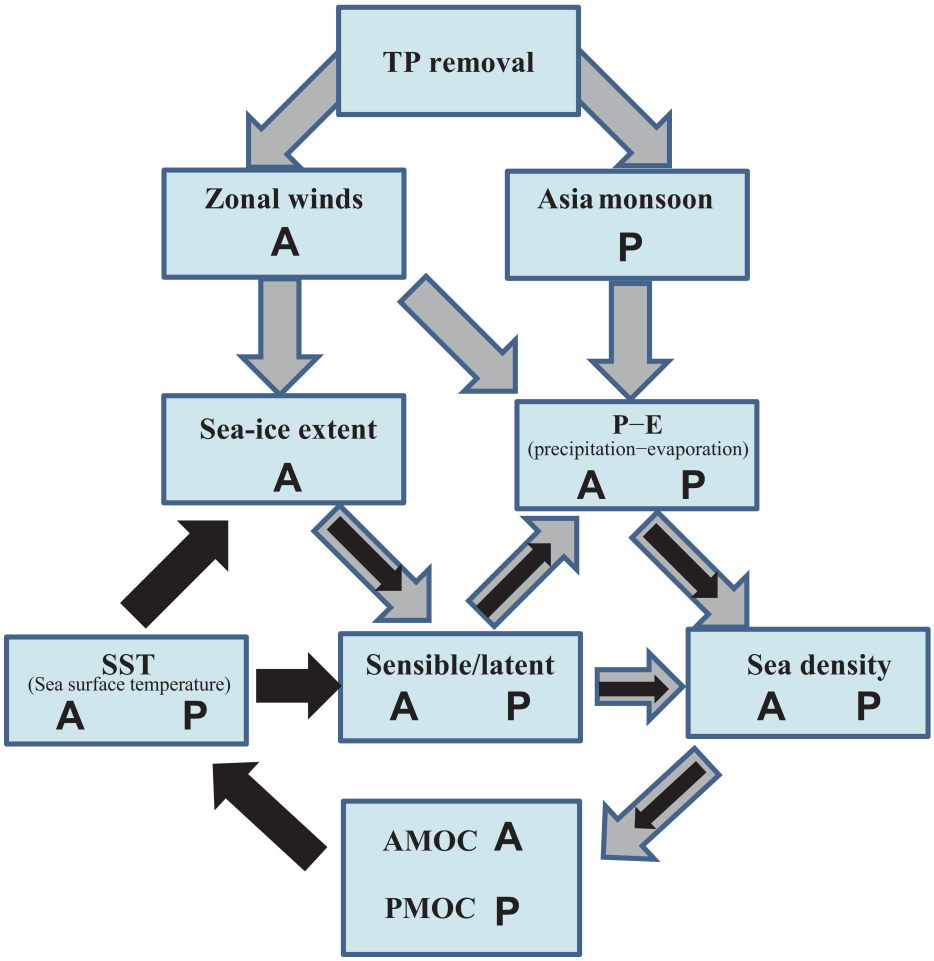

Figure 8. Schematic diagram about the influence of the removal of TP on the AMOC and PMOC. Vectors in gray denote the climate responses in relation to the increased in wind-induced and decreased monsoonal-driven net precipitation-evaporation and wind-driven sea-ice processes. The black color vectors denote the feedback processes related to the AMOC weakening. The bold characters A and P stand for the physical processes occurring over the North Atlantic and Pacific, respectively.