Replies to Reviewer #1:

Thank you very much for these constructive comments. We have revised the manuscript carefully based on these suggestions. The following are our point-by-point replies.

Using numerical simulations with a low-resolution Earth System Model (CESM1.0 at ~ 3°), the authors investigate how the absence/presence of major mountain ranges (the Tibetan Plateau/Himalaya, the Antarctic topography, the Andes, the Rockies and the Greenland topography) alters the global meridional overturning circulation. They show that in a "flat" Earth, the AMOC shuts down in favour of the PMOC, and that adding new reliefs to this flat Earth may spectacularly reorganize the global MOC. In particular they show that the presence of the Tibetan Plateau is both a sufficient condition to suppress the PMOC and a necessary (but not sufficient) condition to the existence of the AMOC. They show that the Andes and Antarctic Mountains are reinforcing drivers of, respectively, the PMOC (but not the AMOC) and both the AMOC or PMOC (depending on the presence or not of the Tibetan Plateau). On the contrary, the Rockies and the Greenland topography only exhibit weak impacts on the MOC in the simulations presented here. Finally, an interesting aspect is that the authors perform what can be seen as a more realistic scenario of the Cenozoic mountain evolution (Flat2Real), in which they sequentially add the aforementioned mountain ranges to a flat Earth and tentatively suggest that the main phases of uplift during the Cenozoic (Since 65 Ma) may have at least partly driven the Cenozoic MOC evolution, though it must be noted that the authors state the limitations of their approach to the "real" history of the MOC.

I must say I really enjoyed reading this manuscript. The experiments are nicely designed and the results are robustly demonstrated. The manuscript is also clear and well-written. I would quite straightforwardly recommend this manuscript for publication from a physics (mechanistic) perspective. However, and in particular in the context of a broadly oriented journal like Nature Communications, I feel like the rationale behind the experiments and the contribution of the findings to the understanding of long-term Cenozoic evolution should be better discussed and/or articulated (see below) and I therefore recommend to return the manuscript to the authors with minor revisions. I hope this can help strengthen the manuscript for broader impact and I would be happy to read a revised version.

Responses: Thank you very much for your valuable comments, which help us improve the manuscript tremendously. Considering the comments from all the reviewers, we revised the manuscript primarily in these following aspects:

1) Introduction to research background is much improved. We rewrote statements and make it clear to readers that there are many controversies regarding the on/off state of the AMOC/PMOC, as well as the timing of mountain uplift.

2) Mechanisms for global climate changes in response to mountain uplift are explained with more details;

3) Some relevant references are added; and most of figures are replotted.

Specific comments:

1. *First, while I think the authors nicely show how the Tibetan Plateau and Antarctic Mountains make the system switch from the PMOC to the AMOC, the chronology of MOC changes and uplift events described in l. 7-14 and 24-33 overlooks the (very) large uncertainties associated with these. For instance, some studies argue that parts of the Tibetan Plateau were already high in the late Eocene (37.9-33.7 Ma) (e.g., Xiong et al. 2020, Su et al. 2019). The Transantarctic and Gamburtsev Mountains over Antarctica were likely already present at the start of the Cenozoic (65 Ma) (Elliot 2014, Ferraccioli 2011), except if the Antarctic uplift considered here is in fact the Eocene-Oligocene (56-23 Ma) glaciation of Antarctica? In this case, it should be more explicit. The history of the AMOC/PMOC is also quite debated and not really agreed upon. l. 7-14 and 24-33 instead convey another impression upon reading. I agree that it is not at all the job of this manuscript to provide a comprehensive review of these changes but these sections should be re-written with more caveats to reflect these uncertainties.*

Responses: Thank you very much for raising these important questions. We rewrote this part and made it clear to readers that there are many controversies on the on/off state of the AMOC/PMOC in the history in Lines 7-15: "*Geological evidence reveals that the primary deep-water formation region in the Northern Hemisphere (NH) might have undergone a shift from the Pacific to the Atlantic in the past. Some studies suggest that North Pacific deep-water (NPDW) formation was strong during the Paleocene period (about 65-55 Ma, million years ago), while North Atlantic deep-water (NADW) formation was weak and likely begun to develop during the early Oligocene period (about 35-33 Ma). Consequently, the modern AMOC might initially develop in the late Miocene (about 12-9 Ma) and be fully established until the late Pliocene to early Pleistocene period (about 4-3 Ma). Nonetheless, the actual evolutionary history of the AMOC and PMOC remains a topic of considerable debate.*"

As far as the uplift timings of different mountains are concerned, we rewrote the statement in Lines 27-40 as follows: "… *Although the transantarctic and Gamburtsev Mountains over Antarctica were likely already present at the start of the Cenozoic (65 Ma) (Elliot 2014, Ferraccioli 2011), the glaciation of Antarctica was thought to occur during the Eocene-Oligocene (56-23 Ma), predating the uplift of the Andes Mountains (AM) that rose around 24 Ma…*" "*… Although some studies argue that parts of the TP were already formed in the late Eocene (38-33 Ma) (e.g., Xiong et al. 2020, Su et al. 2019), the rapid and main uplift of TP was established about 10 Ma. This timing coincided with the onset of NADW formation, suggesting a potential connection between these two mountains uplifts and the development of NADW. Still, it's important to note that the timing of the uplift of major global mountain ranges remains a highly debated topic.*"

Please refer to Lines 27-40 in the revised manuscript. Due to the article length limited by the journal, we apology that we are unable to include detailed description on the uncertainties in the manuscript.

2. *Second, though this is touched upon on l. 18-19 and 235-236, the impacts of oceanic gateways cannot simply be neglected because these have the potential to counterbalance the effects of mountain uplift by providing pathways to efficiently mix water masses. I think that mentioning some relevant work relative to the Cenozoic evolution of a few major gateways, e.g., Drake Passage/Tasman Seaway, Panama, Arctic gateways, and how they may have modulated the ocean circulation would be worthwhile. For instance, before the deep opening of Drake Passage / Tasman Seaway in the late Eocene (e.g., Sauermilch et al. 2021), it is likely that the Ekman pumping due to the Westerlies may have been much weaker. This is especially relevant as some simulation findings contradict the history of MOC changes as written l. 7-14 and could be used to provide alternative hypothesis: still using the Drake/Tasman example, Fig. 2 shows that adding the Antarctic Mountains substantially increase the PMOC intensity (by the way this is not seen on Flat2Real because the simulation is only run for 400 years after the AT addition and before the AM addition, which is not enough in particular because the AM drives a similar increase in PMOC intensity and obscures the AT effect). However, chronologically, the PMOC is expected to decrease during the Cenozoic (l. 10 of the manuscript, see also Ferreira et al. 2018) although this is quite uncertain. In this case, a counterbalancing effect of the Southern Ocean gateways could provide a hypothesis to limit the impact of AT on the MOC.*

Responses: Thank you very much for your insightful comments. You proposed a very interesting question that deserves an in-depth investigation. Following your comments, we are going to design experiments to study individual contributions of open/closed Drake Passage/Tasman seaway and the AT/AM topography height, and their combined effect on the global MOCs.

Since the manuscript is limited by words, we only briefly mention that "…*ocean basin geometry, ocean gateways and continental topography may contribute to different overturning modes. ... The opening of the Drake Passage/Tasman seaway in the late Eocene may have promoted the NADW formation and AMOC formation...*" in lines 19-23.

3. *Now I am well aware of how delicate it is to speculate about such changes and I am not asking the authors to overly expand on these kinds of hypothesis but I think the authors should still use a couple of judiciously-chosen example to make clear that repeating these experiments with another land-sea mask (e.g. narrow Drake/Tasman and wide Panama gateways) could give a completely different story, including a possibly much weaker role for the Tibetan Plateau.*

Responses: Thank you very much for these insightful comments. This work is just a beginning; and we are actually starting to do lots of other experiments to enhance our understanding of the topography, the ocean and land gateway's roles in the ocean circulation. There are so much to do. We would like to show you our future work, if possible, based on your suggestion of the experiments.

The purpose of this work is to assess the roles of different mountains in the GMOC under present-day situation. We try to focus on comparing the roles of different mountains, not on comparing mountains' roles with the roles of other factors (such like ocean gateway, land gateway, etc.). We totally agree with you that there would be many possibilities and the outcomes could be completely different if we try to mimic "real" evolution of paleoclimate.

Minor points.

1. *l. 113 Why is the salt flux virtual?*

Responses: It actually is "freshwater flux" across the ocean surface, not really salt flux; so, it is called "virtual salt flux."

2. Throughout. How is computed Ekman pumping/downwelling?

Responses: The Ekman pumping is calculated using the wind stress at the ocean surface. $\omega_E = curl(\frac{\tau}{\rho f})$, where τ is the surface wind stress with the units of N/m^2, ρ is the density of sea water ($\rho = 1024\ kg/m^3$), and f is Coriolis parameter with the units of 1/s. So, the units of

$$\omega_E \sim \frac{1}{m}\left(\frac{\frac{N}{m^2}}{\frac{kg}{m^3}\cdot s^{-1}}\right) \sim \frac{1}{m}\left(\frac{\frac{kgm/s^2}{m^2}}{\frac{kg}{m^3}\cdot s^{-1}}\right) = m/s \rightarrow cm/day$$

In the caption of Fig. 4, we added how the Ekman pumping is calculated.

3. l. 165-166. Not only surface buoyancy in North Atlantic but also Ekman pumping in the Southern Ocean.

Responses: Thank you very much for point out this detail. In the revised manuscript, we changed this statement to "s*ince both the surface buoyancy in the North Atlantic and the Ekman pumping in the Southern Ocean are almost identical to those in Real (Figs. 4a4, 5a4).*"

4. l. 176-177. This sentence reads a bit weirdly because the AM does not alter the moisture pattern either but still affect the MOC intensity via alteration of the atmosphere dynamics.

Responses: Thank you very much for pointing out this problem. We should say that the presences of RM and GL do not significantly alter the global atmospheric moisture pattern and the tropical atmospheric circulation, so that they have very limited effects on the AMOC and PMOC.

If we agree that the AMOC or PMOC consists of the thermohaline component (mainly determined by the buoyancy flux in the mid-to-high latitudes) and the wind-driven component (mainly determined by the wind stress and Ekman pumping in the tropics), it should be easy to understand that the RM and GL's minimal roles in the AMOC and PMOC. However, the AM affects the wind-driven component of the PMOC via altering the tropical wind system although it does not alter the moisture pattern in the mid-to-high latitudes either.

In the revised manuscript, we state that "*The presence of other large topographies, such as AM, RM, and GL, would not switch the MOC from the Pacific to the Atlantic.*" (in lines 178-180); and "*On the other hand, both RM and GL have minimal effects on the PMOC (Figs. 3a3-f3) because their presences do not significantly alter the global atmospheric moisture pattern and the* *atmospheric circulation in the tropics* (Extended Data Fig. 6)." (in lines 183-186). Extended Data Fig. 6 is added to this revision. It is also added here as Fig. R1 for reference.

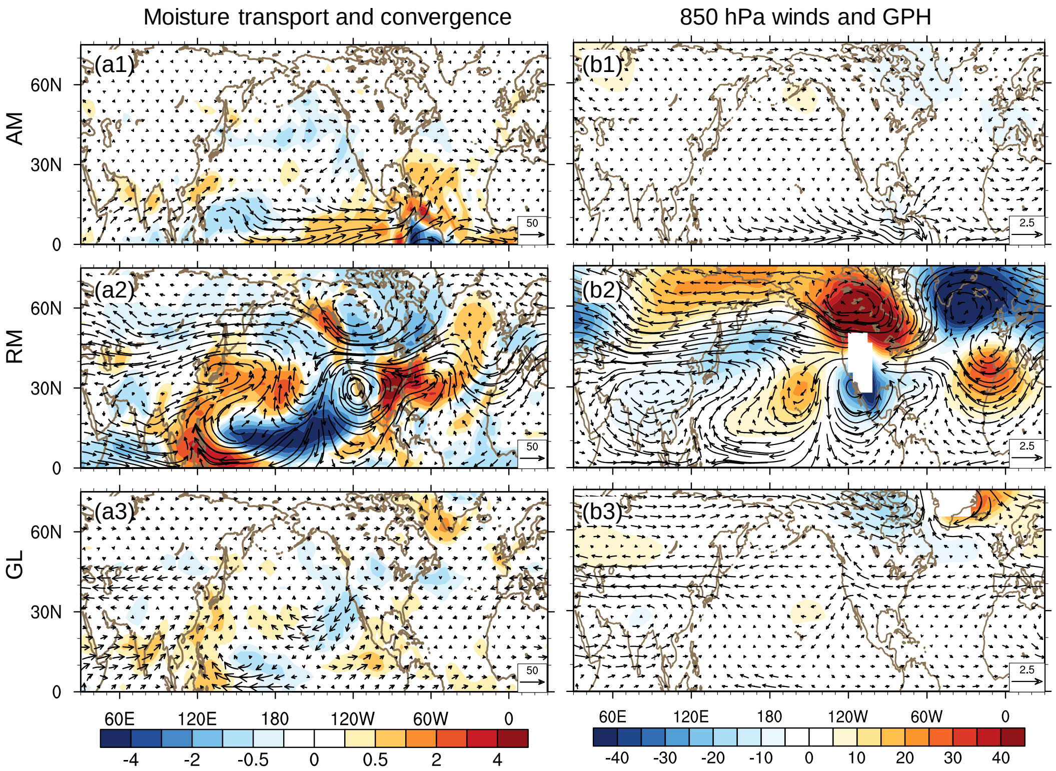

Fig. R1 Equilibrium changes in atmospheric circulation and moisture transport. (a1)-(a3) changes in vertically integrated moisture transport (vector; units: kg·m^{-1}s^{-1}) and its convergence (shading; units: 10^{-5} kg·m^{-2}s^{-1}), (b1)-(b3) geopotential height (shading; units: 10 m) and winds (vector; units: m/s) at 850 hPa. (a1)-(a3) and (b1)-(b3) are changes in AM, RM and GL, respectively, with respect to Flat. The atmospheric moisture convergence (divergence) is plotted as positive (i.e., $-\nabla \cdot \vec{v}q > 0$) (negative, $-\nabla \cdot \vec{v}q < 0$), representing a gain (EMP<0) (loss, EMP>0) of ocean freshwater from (to) the atmosphere.

5. *Methods. Are changes in runoff consequent in the simulations? What would happen if the runoff was adequately re-routed?*

Responses: Thank you very much for these questions. The runoff is calculated in Common Land Model (CLM) of CESM1.0. It includes the liquid water runoff (R) and ice runoff (I). The changes of runoff in the simulations are adjusted according to the River Transport Model (RTM). The RTM uses a linear transport scheme at 0.5° resolution to route water from each grid cell to its downstream neighboring grid cell. The ocean freshwater liquid and ice fluxes are passed to the flux coupler that distributes the fluxes to the appropriate ocean grid cells.

In all experiments, the ice_runoff is set to "*False*" and the ice runoff is zero. In response to the topographic change, the direction and discharge of river runoff will be changed. In CESM1.0, the drainage or sub-surface runoff is based on the SIMTOP scheme (Niu et al., 2005). Due to the limited geological data, it is difficult to get the exact distributions of river runoff during the period of mountain uplift. There is no artificial modification to the river runoff. The results of runoff changes are based on the model simulations.

Figure R2 show the runoff flux (units: mSv) anomalies in several experiments relative to Flat. Positive value means that the ocean gains fresh water. In general, the effect of river runoff change on the ocean circulation can be neglected.

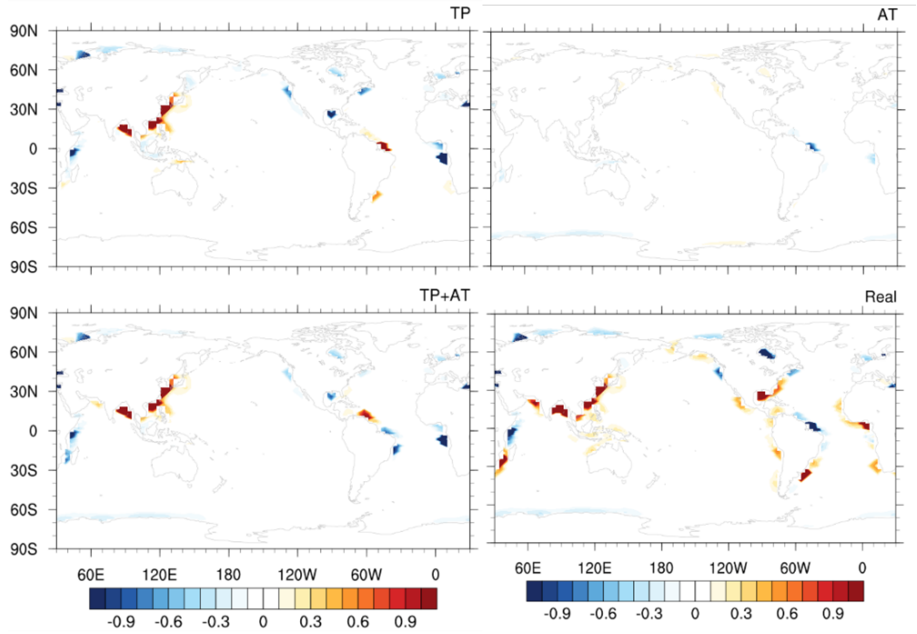

Fig. R2 River runoff flux (units: mSv) anomalies in experiments TP, AT, TP+AT, and Real, with respect to Flat. Positive value means freshwater gain by the ocean.

Reference:

Niu, G.-Y., Yang, Z.-L., Dickinson, R.E., and Gulden, L.E. 2005. A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. 110: D21106. DOI: 10.1029/2005JD006111.

6. *Fig. 4. I get what dots and crosses represent on Fig. 4a1-a4 but not on Fig. 4b1-b4 (the difference figures). Do crosses (dots) represent increased downwelling (upwelling)?*

Responses: Black dots represent Ekman pumping, and crosses, Ekman downwelling (units: cm/day). In Fig. 4b1, black dots and crosses denote anomalous Ekman pumping and downwelling, respectively, in Flat, with respect to Real. In Figs. 4b2-b4, black dots and crosses denote Ekman pumping changes in Flat2Real, TP, and TP+AT, respectively, with respect to Flat. Figure 4's caption was rewritten, and made clearer in the revised manuscript.

7. *Also what do you mean by "mean Ekman pumping/downwelling"? I do not understand how dots and crosses can have units of cm/day.*

Responses: The mean Ekman pumping/downwelling represents the Ekman pumping averaged over the last 100 years of each experiment. Sorry for the mistake in our previous manuscript. The dots and crosses do not have units, representing just the region where the upper ocean have positive (upward) and negative (downward) movements. The caption of Fig. 4 was rewritten, and made clearer in the revised manuscript.

8. *Fig. 5. Mass transport on Fig. 5b1-b4 should be in Sv to be consistent with the other figures.*

Responses: Thank you very much for this suggestion.

In the previous Figs. 5b1-b4, the mass transport across 30°S was obtained by zonal integration of meridional velocity, V(z)*Lx, which has the units of m^2/s.

Figures 5b1-b4 are replotted in the revised manuscript, in which the mass transport is calculated as V(z)*Lx*dz(z), where dz(z) is the layer depth of V(z), so that the units are m^3/s (Sv). Now, the mass transport throughout the manuscript has consistent units.

9. *Fig. 6. What month or season is reflected in the sea-ice margin/velocity? It should be clearly written in the legend.*

Responses: Thank you very much for pointing out this problem. In Fig. 6a, the sea-ice coverage is the annual averaged, and the MLD is for March. In Fig. 6b, all changes are annual averaged. In the revised manuscript, these are clearly stated in figure captions.

10. *Extended data Fig. 1 should be plotted at model resolution because this is what matters in the results.*

Responses: Thank you for this suggestion. In the revised manuscript, Extended Data Fig. 1 is replotted with data at model resolution. Please refer to Fig. R3.

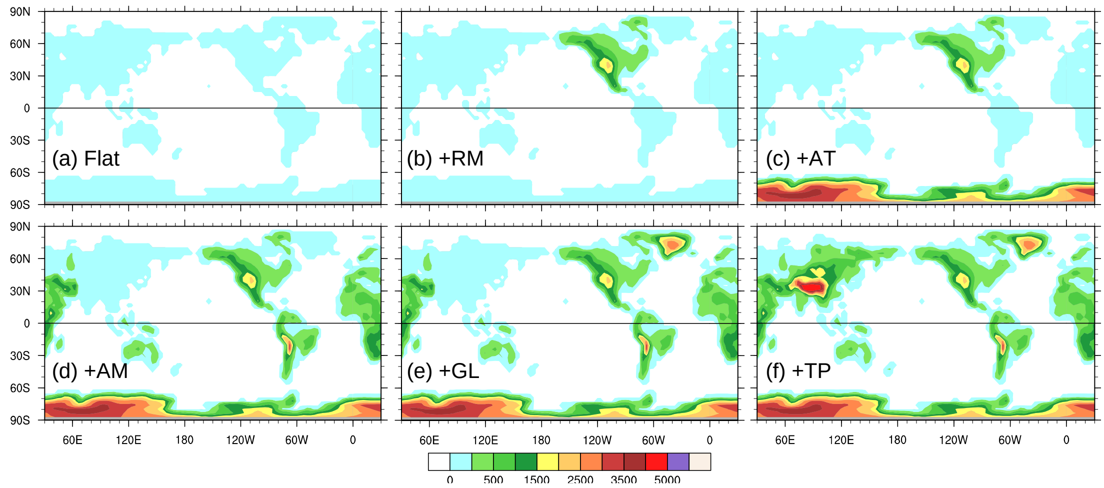

Fig. R3 Topography configurations in coupled model experiments.

References:

1. Elliot, D. H. (2013). The geological and tectonic evolution of the Transantarctic Mountains: a review. Geological Society, London, Special Publications, 381(1), 7-35.

2. Ferraccioli, F., et al. (2011). East Antarctic rifting triggers uplift of the Gamburtsev Mountains. Nature, 479(7373), 388-392.

3. Ferreira, D., et al. (2018). Atlantic-Pacific asymmetry in deep water formation. Annual Review of Earth and Planetary Sciences, 46, 327-352.

4. Sauermilch, I., et al. (2021). Gateway-driven weakening of ocean gyres leads to Southern Ocean cooling. Nature communications, 12(1), 6465.

5. Su, T., et al. (2019). Uplift, climate and biotic changes at the Eocene-Oligocene transition in south-eastern Tibet. National Science Review, 6(3), 495-504.

6. Xiong, Z., et al. (2020). The early Eocene rise of the Gonjo Basin, SE Tibet: From low desert to high forest. Earth and Planetary Science Letters, 543, 116312.

Response: These references are added in the revised manuscript.

Replies to Reviewer #2:

Thank you very much for these constructive comments. We have revised the manuscript carefully based on these suggestions. The following are our point-by-point replies.

The manuscript by Haijun Yang et al. presents an investigation into the influence of orography on the Meridional Overturning Circulation (MOC) using the low-resolution coupled model CESM. Previous studies, including Fallah et al. (2016), Su et al. (2018), and Yang and Wen (2020), have examined the effects of the Tibetan plateau on oceanic circulation. Maffre et al. (2017) conducted an analysis on the impact of global orography on oceanic circulation by comparing two simulations: one incorporating present-day geography and another using a flat Earth representation. In this regard, Haijun Yang et al.'s work combines these two approaches by investigating the effects of a flat Earth representation and various combinations of present-day orography on oceanic circulation. While this study is interesting, I have a few concerns regarding this approach.

Responses: Thank you very much for your valuable comments, which help us improve the manuscript tremendously. Considering the comments from all the reviewers, we revised the manuscript primarily in these following aspects:

1) Introduction to research background is much improved. We rewrote statements and make it clear to readers that there are many controversies regarding the on/off state of the AMOC/PMOC, as well as the timing of mountain uplift.
2) Mechanisms for global climate changes in response to mountain uplift are explained with more details;
3) Some relevant references are added; and most of figures are replotted.

Specific comments:

1. *(L24-L39) One concern with the sensitivity experiments conducted in this study is that they include the entire topography of the continent, rather than focusing solely on specific features like the Tibetan plateau or the Rocky Mountains. Previous research has demonstrated that the uplift of the Tibetan plateau influences the Atlantic Meridional Overturning Circulation (AMOC). However, by incorporating the entire topography of a continent, it becomes challenging to isolate the effects of individual landforms and determine whether minor features play a role in the establishment or disruption of the AMOC/PMOC.*

Responses: Thank you very much for this question.

In previous studies, we also conducted an experiment with only TP removed (Fig. R4a), while the Mongolian Plateau was unchanged. This experiment is called No_RegionalTP. The AMOC change in No_RegionalTP is almost identical to that in NoTibet (Fig. R4b), suggesting that the TP is important to the AMOC, while the Mongolian Plateau is not. However, for the PMOC, although the TP is the most important, the Mongolian Plateau also plays a role. This is qualitatively consistent with the finding of White et al. (2017), which disclosed an important role of the Mongolian Plateau in the Pacific wintertime atmospheric circulation. Since both the wind-driven and thermohaline dynamics are important to the PMOC establishment, the Mongolian Plateau can affect the wind-driven part of the PMOC through its role in the Pacific atmospheric circulation.

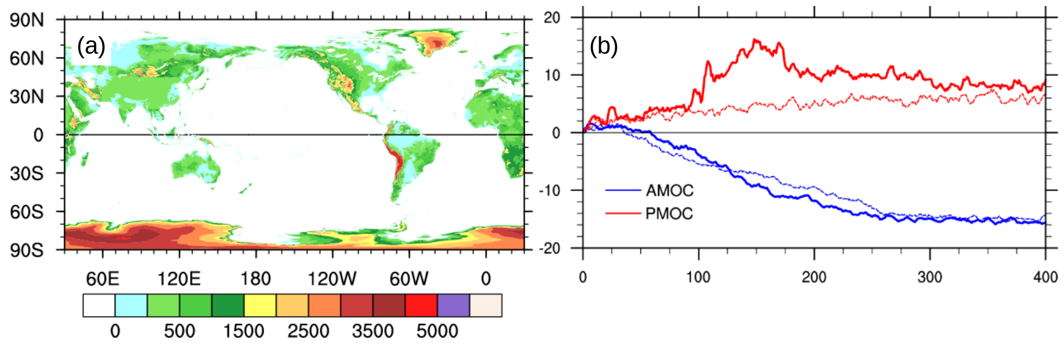

Fig. R4 (a) Topography configuration without Tibetan Plateau (60°-130°E, 20°-45°N) (No_RegionalTP). (b) Temporal evolutions of the PMOC (red) and AMOC (blue) in NoTibet (solid curves) and No_RegionalTP (dashed curves).

We also answered this question in our previous work on the TP's effect on the ENSO (Wen et al., 2020) (Fig. R5). The results from No_RegionalTP are nearly unchanged from those in NoTibet. σ(SST) in No_RegionalTP is roughly of the same magnitude as that in NoTibet (Fig. R6). The tropical SST anomaly shows much bigger oscillation after the TP removal (Fig. R6). Also, the mean ocean climate changes are very close to each other in No_RegionalTP and NoTibet: weakened trade winds, SST warming in the central-eastern Pacific, and SST cooling in the western Pacific, more freshwater gain in the central tropical Pacific, shallower MLD in the central tropical Pacific, and flattened thermocline (Fig. R7). In addition, we examined the atmospheric circulation change in No_RegionalTP (Fig. R8). We found that the atmospheric circulation changes over the tropical oceans are nearly identical in NoTibet and No_RegionalTP. Difference exists only in high latitudes. Our work also confirmed that the landform around the TP is much more important than that around the Mongolian Plateau in tropical climate change.

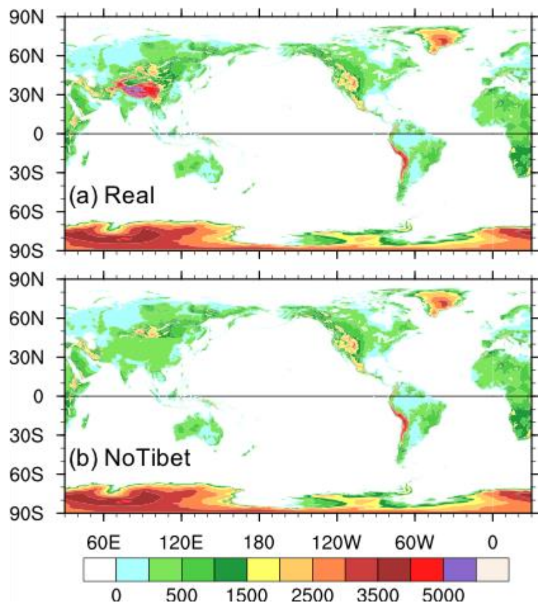

Fig. R5 Topography configuration in coupled model experiments. (a) is for the control simulation with realistic topography (Real), and (b) is for the experiment without the regional Tibetan Plateau (No_RegionalTP; 60°-140°E, 20°-45°N) . Units: m.

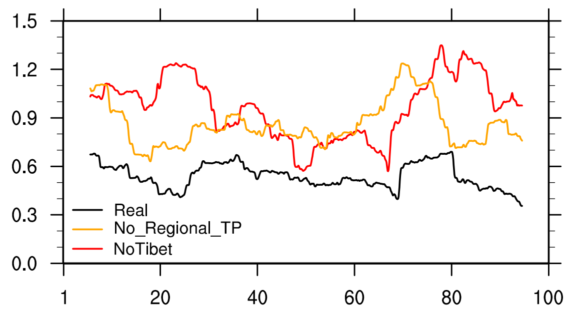

Fig. R6 Time series of standard deviation of SST anomalies (σ(SST); °C) averaged in the Niño-3 region (150°-90°W, 5°S-5°N). The σ(SST) field is smoothed with a sliding window of 11 years. Black line is for Real, red is for NoTibet, and orange is for No_RegionalTP.

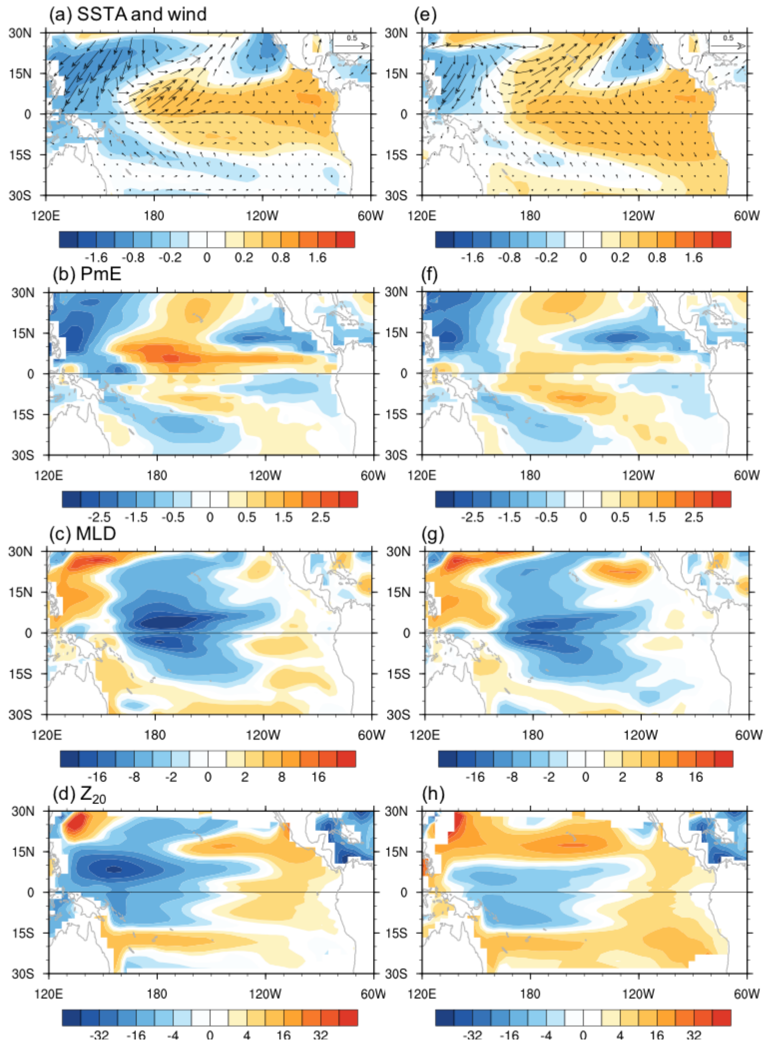

Fig. R7 Quasi-equilibrium changes in mean tropical climate, including (a): SST (°C) and surface wind stress (dyn/cm^2), (b): precipitation minus evaporation (PmE; 10^{-5} kg/m^2/s), (c): MLD (m), and (d): thermocline depth (m) in NoTibet. (e-h) are the same as (a-d), except for No_RegionalTP.

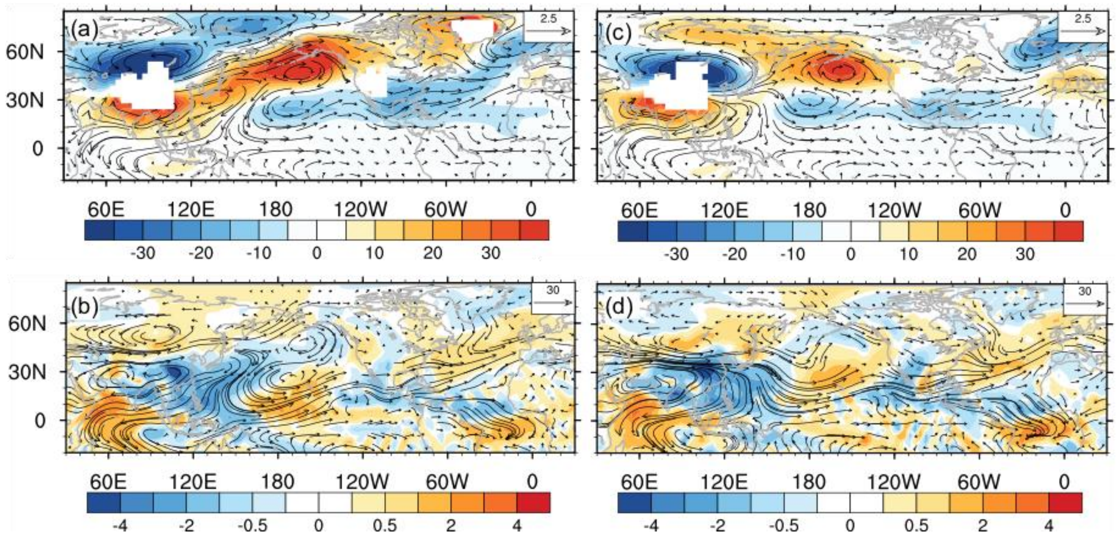

Fig. R8 Quasi-equilibrium changes in (a) geopotential height (shading; m) and wind (vector; m/s) at 850 hPa and (b) vertically integrated water vapor transport ($\rho_a \vec{v} q$; vectors; kg/m/s) and its convergence ($-\rho_a \nabla \cdot (\vec{v} q)$; shading; 10^{-5} kg/m^2/s) in NoTibet. (c-d) are the same as (a-b), except for No_RegionalTP.

References:

Wen, Q., K. Doos, Z. Lu, Z. Han, and H. Yang, 2020: Investigating the role of the Tibetan Plateau in ENSO variability. *J. Climate*, 33, doi: 10.1175/JCLI-D-19-0422.1.

Sha, Y., Z. Shi, X. Liu, and Z. An, 2015: Distinct impacts of the Mongolian and Tibetan Plateaus on the evolution of the East Asian monsoon. *J. Geophys. Res.*, **120**, 4764–4782, doi:10.1002/2014JD022880.

Shi, Z., X. Liu, Y. Liu, Y. Sha, and T. Xu, 2015: Impact of Mongolian Plateau versus 759 Tibetan Plateau on the westerly jet over North Pacific Ocean. *Climate Dyn.*, **44**, 3067–3076, doi:10.1007/s00382-014-2217-2.

White, R. H., D. S., Battisti, and G. H. Roe, 2017: Mongolian mountains matter most: impacts of the latitude and height of Asian orography on Pacific wintertime atmosphere circulation. *J. Clim.*, **30**, 4065-4082.

2. *Additionally, the study includes the Andes Mountains and the entire South American, African, Middle Eastern regions up to the Zagros Mountains and Anatolian plateau under the scenario "AM". Regarding the ice sheet (Antarctica and Greenland), the study tests the sensitivity to changes in elevation, but it is not specified whether the authors maintained the albedo of ice when removing the Antarctica / Greenland topography (the term ice sheet is never employed in the manuscript). This information is crucial as altering the albedo would affect the energy balance and potentially influence the circulation patterns and precipitation.*

Responses: Thank you very much for pointing out these problems.

In Flat2Real, it's true that when adding AM after AT, we actually add the whole South American topography, the African topography, the Australian topography, and most of the European topography (Extended data Fig. 1d). However, in single topography experiment AM (Fig. R9a) and combined-topography experiment TP+AM (Fig. R9b), the AM only includes the South American topography.

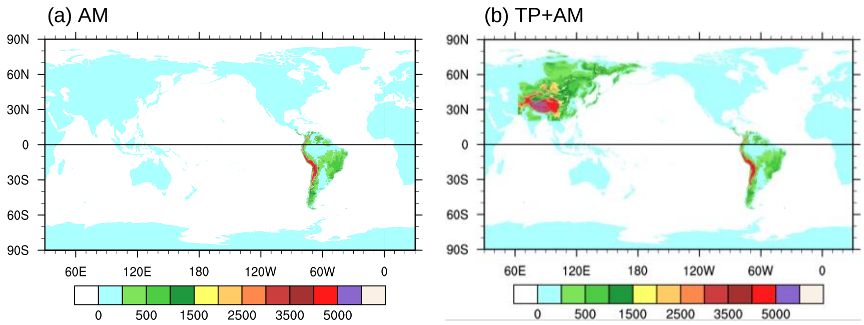

Fig. R9 Topography configuration in coupled model experiments. (a) is for single AM experiment, and (b) is for the combined experiment TP+AM. Units: m.

As far as the AMOC and PMOC are concerned, the combined effect of the South American topography (without the AM), the African topography, the Middle Eastern regions up to the Zagros Mountains, and the Anatolian Plateau are insignificant, which can be deduced from Fig. 1 and Fig. 2a. In Fig. 1, the PMOC after adding AM (from year 2400 to year 3400) is about 20 Sv, which includes the combined effect of those topographies. In Fig. 2a, the PMOC after adding AM to Flat is about 18 Sv, which does not include the combined effect of those topographies. The AMOC during years 2400-3400 of Fig. 1 is about 2 Sv, while it is about 1 Sv in only-AM experiment in Fig. 2a. Due to the limitation of computer resources, we did not design experiments to explicitly investigate the effects of the South American topography (without the AM), the African topography, the Middle Eastern regions up to the Zagros Mountains, and the Anatolian Plateau on the PMOC and AMOC.

Since this work only focuses on the topography effect, in all experiments we only modify the height of topography, keeping the albedo at the same value of Flat. The albedo can be freely adjusted with the integration of simulations. The dynamic ice sheet component in our experiments is closed. In the model setting, the land ice component is set to SGLC (stub glacier model), which means no dynamic ice sheets. The glacier areas and elevations are taken entirely from CLM's surface dataset; and no downscaling is done over non-glacier land units. The ice sheets are treated as big bright rocks. The bare ice albedo is prescribed to be 0.50 by default. The albedo of glacier is 0.80 for visible radiation.

In the revised manuscript, we explicitly state how the ice sheet is treated in the experiments. We agree that altering the albedo would affect the energy balance and potentially influence circulation patterns and precipitation patterns. However, in such a short manuscript, we cannot investigate albedo effect in detail. We would like to emphasize that the initial value of albedo over topography region is kept the same as that in FLAT, and it will self-adjusted according to thermal conditions during model integration. For example, with the uplift of a mountain, the albedo will increase.

In the 2nd paragraph of Methods section of the revised manuscript, we rewrote the related sentence as follows: "*Except for topography height, all other boundary conditions remain the same as in Flat and Real. The ocean-land configuration is set to modern-day conditions without correction for plate tectonic motion. Atmospheric CO_2 concentration is maintained at the preindustrial level (285 ppm). Changes in river routing and vegetation type are not considered. Continental ice sheets are treated as bright rocks in the model. The planetary albedo can adjust by itself according to thermal conditions. These experiments are conducted as single-variable (orography) sensitivity tests, rather than paleoclimate simulations involving multiple prescribed geologic boundary conditions*."

3. *Moreover, when orography is removed, the drainage basin system is expected to undergo changes. The authors indicate that river routing is kept unchanged. Understanding the modifications in the drainage basin system is relevant to comprehending the overall impact of orography removal on oceanic circulation.*

Responses: Thank you very much for raising this question.

In the actual process of topographic uplift, the direction and discharge of river runoff will be changed. In CESM1.0, drainage or sub-surface runoff is based on the SIMTOP scheme (Niu et al., 2005). Due to limited geological data, it is difficult to get the exact distributions of river runoff during the period of mountains uplift. There is no artificial modification of river runoff. The results of runoff changes are based on model simulations.

Figure R10 shows the runoff flux (units: mSv) anomaly in several experiments (TP, AT, TP+AT, Real) relative to Flat. We can conclude that the anomalous freshwater flux due to the changes in the drainage basin system has a very limited impact on the global-scale ocean circulation.

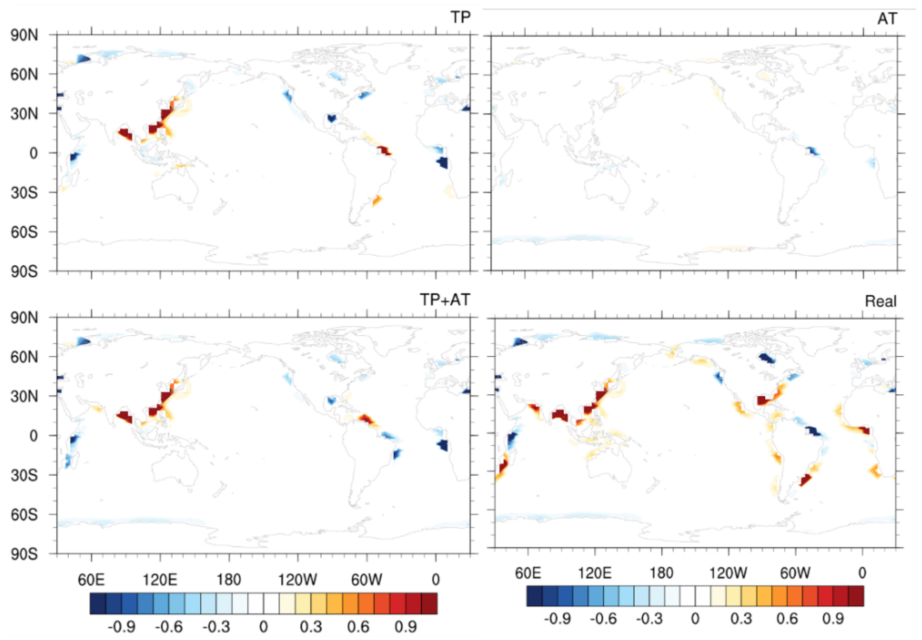

Fig. R10 River runoff flux (units: mSv) anomaly in experiments TP, AT, TP+AT, and Real, with respect to Flat. Positive value means the ocean gain fresh water.

Reference:

Niu, G.-Y., Yang, Z.-L., Dickinson, R.E., and Gulden, L.E. 2005. A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. 110: D21106. DOI: 10.1029/2005JD006111.

4. *These concerns regarding the specificity of landforms, albedo adjustments, and drainage basin modifications should be addressed in the manuscript to provide a comprehensive analysis of the study's findings.*

Responses: Thank you very much for this suggestion. In the revised manuscript, we added some detail on how we treat the changes in landforms, albedo, drainage basin, and river runoff flux in Method. Please refer to the replies to Q.2 above.

Due to space limited by the journal, a comprehensive analysis of these factors on ocean circulations is not feasible. We are working on a longer manuscript, in which comprehensive analysis will be conducted.

5. *Despite the fact that the authors exclude to explain the evolution of AMOC during the Cenozoic and restrain this explanation to the role of Tibetan plateau in the present-day geography, the Figure 1 exhibits the impact of a sequential uplift of mountains with a "geological" chronology. The sequence is supposed to mimic the main phase of uplift (or growth of ice sheet). Although the authors do not try to provide a detailed explanation of the evolution of the AMOC/PMOC during the Cenozoic era and instead focus on the role of the topography in present-day geography, Figure 1 demonstrates the impact of sequential mountain uplift with a geological chronology. The sequence is intended to simulate the impact on ocean circulation of the primary phase of uplift or the growth of an ice sheet.*

Responses: Thank you very much for this comment. To some extent, we can learn from experiment Flat2Real about how the AMOC/PMOC could be established in the past. However, the actual evolution processes of the AMOC/PMOC during the Cenozoic era were much more complicated, because they involved so many boundary conditions. In a short manuscript like this one, we can only focus on a narrow topic, namely, the role of some giant topography in the AMOC in present-day climate.

6. *The length of the simulation is a matter of debate. Following the addition of Antarctic, the simulation is integrated for 400 years. However, this duration may be considered relatively short to ensure that the deep ocean layers have fully reached equilibrium with the boundary conditions.*

Responses: Thank you very much for pointing out this problem.

We should have run +AT of Flat2Real for a much longer time (at least 1000 years). In the very early stage of this work, we did not realize this problem and just kept running the model, since the AMOC does not increase at this stage. We were just eager to see when the AMOC can get up.

To make up this problem, in the later stage of this project we ran the experiment OnlyAT from Flat for 1600 years (Fig. 2a) and found that the PMOC in OnlyAT could reach 18 Sv and the AMOC was still not established. Therefore, we can say that during years 2000-4000 of Flat2Real, the AT did contribute to the strong PMOC in the later stage; and at the same time, it did not lead to the AMOC formation in the later stage.

7. *(L69) The authors do not provide an explanation regarding whether the albedo was modified when removing the topography of Antarctica. It would be beneficial to clarify whether any adjustments were made to account for changes in albedo resulting from the modification of Antarctic topography.*

Responses: Thank you very much for raising this question. Please also refer to our replies to Q.2.

In all experiments, we only modify the height of topography, keeping the albedo at the same value of Flat. The albedo can freely adjust during the integration of the simulation. The dynamic ice sheet component in our experiments is turned off, which means no dynamic ice sheets. The ice sheets are treated as big bright rocks. The bare ice albedo is prescribed to be 0.50 by default. The albedo of glacier is 0.80 for visible radiation.

Figure R11 shows albedo in different experiments. The small difference over the Antarctic continental is from model's adjustments. It's not caused by changes in ice sheets. Albedo is calculated using (FSDS-FSNS)/FSDS, where FSDS represents downwelling solar flux at the surface, and FSNS represents net solar flux at the surface.

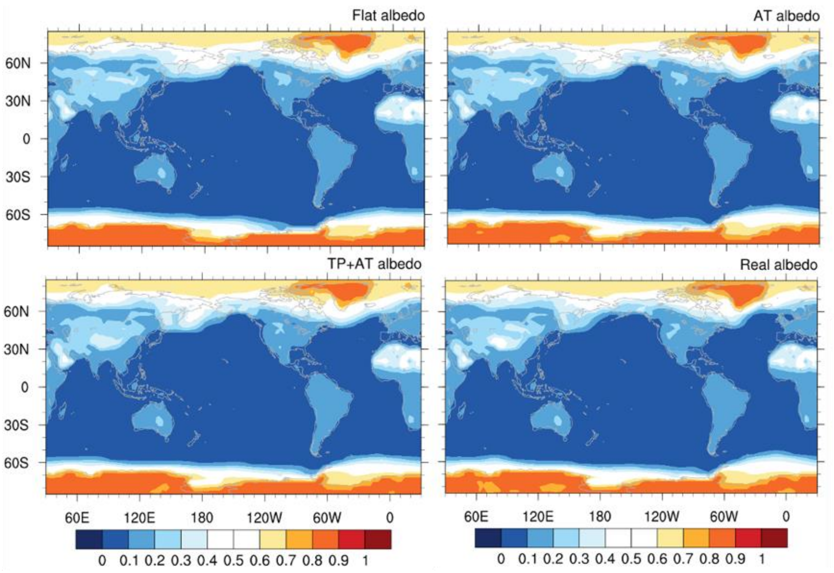

Fig. R11 Surface albedo in different experiments

In our previous study (Wen et al., 2021), we conducted a detailed study of albedo effects and found that changes in albedo over the TP (thermal effect) have a much smaller impact on the ocean circulation, when compared with TP's dynamic effect.

Reference:

Wen Q, Yang H, Yang K, et al. Possible thermal effect of Tibetan Plateau on the Atlantic meridional overturning circulation[J]. Geophysical Research Letters, 2022, 49(4): e2021GL095771.

8. *(L93-⋯) The authors primarily focus on describing the oceanic changes in their study, driven by atmospheric modifications resulting from the addition or removal of topography. However, they do not provide a detailed explanation of the underlying mechanisms involved. It would indeed be valuable to include a few sentences elucidating the specific mechanisms by which the evaporation or precipitation patterns are altered when modifying the topography.*

Responses: Thank you very much for this suggestion.

The underlying mechanisms are detailed in the following paragraph (Lines 108-148). In our previous studies (Fig. 4 in Wen and Yang, 2020; Fig. 12 in Yang and Wen, 2020), we discussed the mechanisms thoroughly. Removing the TP leads to enhanced atmospheric water vapor transport from the Pacific to the Atlantic, resulting in decreased freshwater flux over the western Pacific and increased freshwater flux over the North Atlantic, which lead to the PMOC formation and AMOC decline.

9. *In this work, the authors do not explicitly mention conducting statistical significance tests to evaluate the differences between two variables.*

Responses: Thank you very much for pointing out this problem.

We have done statistical tests for all variables, but did not mention them in this manuscript explicitly due to the limitation of word count.

Most changes seen in the experiment results are statistically significant. We did Mann-Kendall test for all figures related to the differences between two variables. For the clarity of visual effect, we decided not to show the significance test in the figures.

In the last paragraph of Methods section of the revised manuscript, we state that "*The student-t test is used to examine the statistical significance of our results. Most changes are significant at the 95% confidence level, which is expected because altering large topography induces strong mechanical forcing and obvious responses around the globe. For clarity, significance test is not provided in any figures.*"

Figure R12 shows the SSS change in TP, AT, TP+AT, and Real, with respect to FLAT, in which the crosses represent the area that exceeds the 95% significance level.

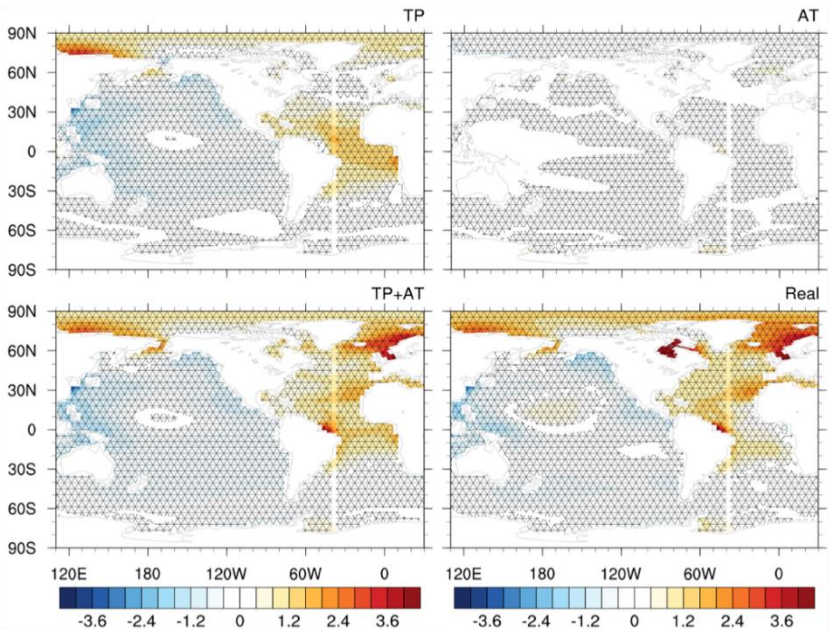

Fig. R12 Changes in annual mean SSS in TP, AT, TP+AT, and Real, with respect to FLAT. Stippling indicates changes exceeding the 95% significance level according to the Mann-Kendall trend test.

10. *(L112-122) The mechanism causing a change in precipitation or evaporation (or both) are discussed. The changes in atmospheric circulation and moisture transport are associated to changes in GPH. The authors do not explicitly delve into the topic of temperature changes in relation to GPH variations, nor do they discuss the potential role of Sea Surface Temperature (SST) changes in the North Atlantic affecting the North Atlantic Deep Water (NADW) circulation. To provide a more comprehensive analysis, it would be beneficial for the authors to address the possible temperature changes resulting from GPH modifications and discuss the influence of SST changes on NADW formation explicitly. Incorporating these aspects would further elucidate the connections between atmospheric circulation, temperature, and oceanic processes, enhancing the overall understanding of the research findings.*

Responses: Thank you very much for raising this question.

In this work, we state that "*The change in SSD from Real to Flat can be primarily attributed to the change in SSS*" and did not discuss the SST change in the North Atlantic, because we had a thorough discussion on this topic in our previous papers (e.g., Yang and Wen, 2020). Due to the limitation of paper length, in the revised manuscript we added a brief statement that the temperature effect on the AMOC is not important.

Figure R13 (i.e., Fig. 2 of Yang and Wen, 2020) shows that after 50 years of the TP removal, the AMOC exhibits a roughly linear decline for about 200 years. The AMOC is finally weakened by more than 80% and practically shut down in about 300 years.

As the first step to understand the AMOC change, the temporal evolution of surface buoyancy change averaged in the NADW region is examined in Fig. R13b. The sea-surface density (SSD) increases during the first 50 years and then decreases linearly (black curve), consistent with the change of the AMOC index (Fig. R13a). The SSD change consists of SST-induced change (dashed red) and sea-surface salinity (SSS)-induced change (dashed blue). Note that the surface ocean keeps cooling in the whole 400 years (red curve), which always increases the SSD (dashed red). In contrast, the SSS increases first and then decreases (blue curve), followed closely by the SSD change (dashed blue and black curves). Based on Fig. R13b, we quantify that the increase of SSD during stage I is contributed by surface cooling (30%) and surface salinization (70%), while the SSD decrease later on is totally contributed by surface freshening. It clearly illustrates that the weakening of the AMOC should be attributed to the freshwater increase in the NADW region

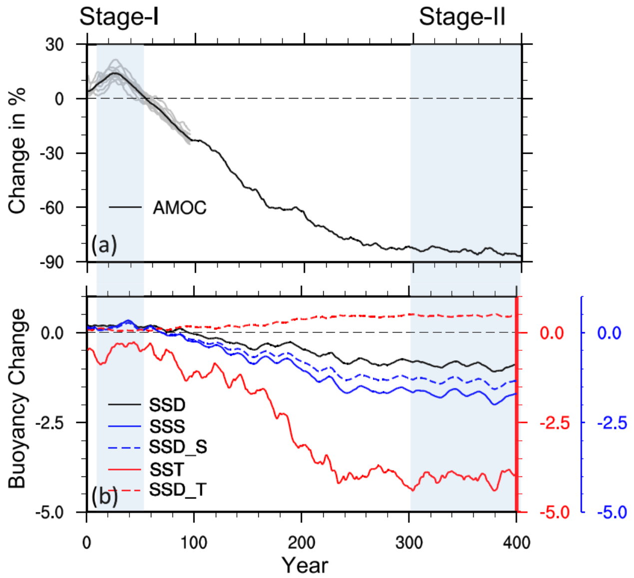

Fig. R13 (a) Temporal evolution of percentage change in Atlantic meridional overturning circulation (AMOC), with gray curves representing results from 10 ensemble runs. The AMOC index is defined as the maximum streamfunction in the range of 0°-10°C over 20°–70°N in the Atlantic. (b) Temporal changes in sea-surface salinity (SSS; psu; blue), sea-surface temperature (SST; °C; red), and sea-surface density (SSD; kg m^{-3}; black). SSD changes due to SSS and SST are plotted as dashed blue and dashed red curves, respectively. The y-axis on the left is for density change. The red and blue y-axes on the right side are for SST and SSS changes, respectively. All variables are averaged over the NADW formation region.

Figure R14 (i.e., Fig. 4 in Yang and Wen, 2020) shows the horizontal patterns of buoyancy change in the North Atlantic in both stages. In stage I, the SST change has a tripolar structure (Fig. R14a): a significant cooling (more than 2°C) occurs in the midlatitudes between 40° and 60°N, saddled by two warming regions located in the GIN seas and tropics, respectively. The SSS change has an east-west dipole structure (Fig. R14b), with significant salinization in the Labrador Sea and south of the Greenland Sea and a weak freshening in the eastern North Atlantic. The combined effect of changes in SST and SSS results in SSD increase (Fig. R14c), particularly in the NADW region; this increases the MLD and thus the deep-water formation, leading to a stronger AMOC in stage I. In stage II, the quasi-equilibrium changes in SST, SSS, and SSD show rather simple structures (Figs. R14d-f), that is, significant cooling, freshening, and thus a lighter surface ocean in the entire North Atlantic, consistent with the ‘‘off’’ state of the AMOC. It is clear that the SSD changes in the North Atlantic in both stages are mostly determined by SSS change.

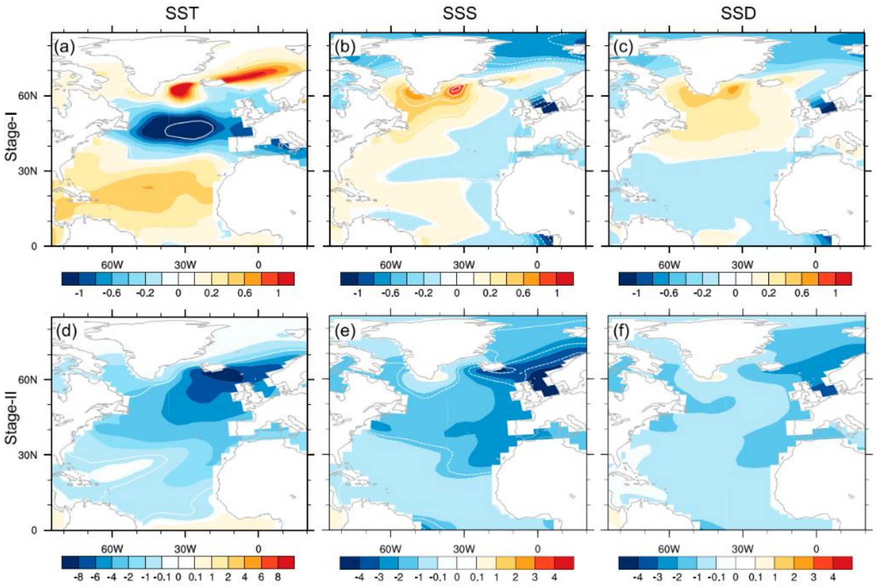

Fig. R14 Changes in (a) SST (°C), (b) SSS (psu), and (c) SSD (kg m^{-3}) averaged over stage I. (d)-(f) As in (a)-(c), but for stage II. The white contours in (a) and (d) denote the SSD change induced by SST change, while those in (b) and (e) denote the SSD change induced by SSS change. Dashed contours are for negative change, and solid contours are for positive change.

Reference:

Yang, H., and Q. Wen, 2020: Investigating the role of the Tibetan Plateau in the formation of Atlantic meridional overturning circulation. *J. Climate*, 33(9), 3585-3601, doi: 10.1175/JCLI-D-19-0205.1.

11. (L122-L123) "The expansion of sea ice (…) carries a substantial amount of freshwater" : the sentence is not clear to me.

Responses: Thank you very much for this question.

During the southward expansion of sea ice, there is a remarkable amount of sea-ice melting at the same time, which provides fresh water to the ocean, leading to the AMOC shutdown. In the revised manuscript, we revised this sentence and made it clearer in lines 129-131.

12. (L135) "The absence of the Antarctic topography leads to an 80% decrease in wind stress": is it due to temperature gradient?

Responses: Thank you very much for this question.

This is mainly due to the change of meridional pressure gradient. Absence of the Antarctic topography causes an anomalous high pressure over the Antarctic, which produces an anomalous northward pressure gradient, and thus an anomalous easterlies based on the geostrophic balance. In the revised manuscript, we made this point clearer in lines 141-144.

13. *Figure 5: the Ekman pumping/downwelling is discussed with the 850hPa wind stress. This is not clear. Why don't the authors show the wind stress at the sea surface?*

Responses: Thank you very much for raising this question.

In Fig. 5, the Ekman pumping/downwelling is calculated by using surface wind stress: $\omega_E = curl(\frac{\tau}{\rho f})$, where τ is surface wind stress. The wind field we used is at 850 hPa, because at this level the geostrophic balance is satisfied, so that the wind field can also represent the pressure field.

Figure R15 shows Ekman pumping and wind stress at sea-surface level. We can see that the ageostrophic component of the wind is strong, compared to that in Fig. 5. For the Ekman pumping, both geostrophic and ageostrophic components of the wind are important to produce vertical movement in the upper ocean.

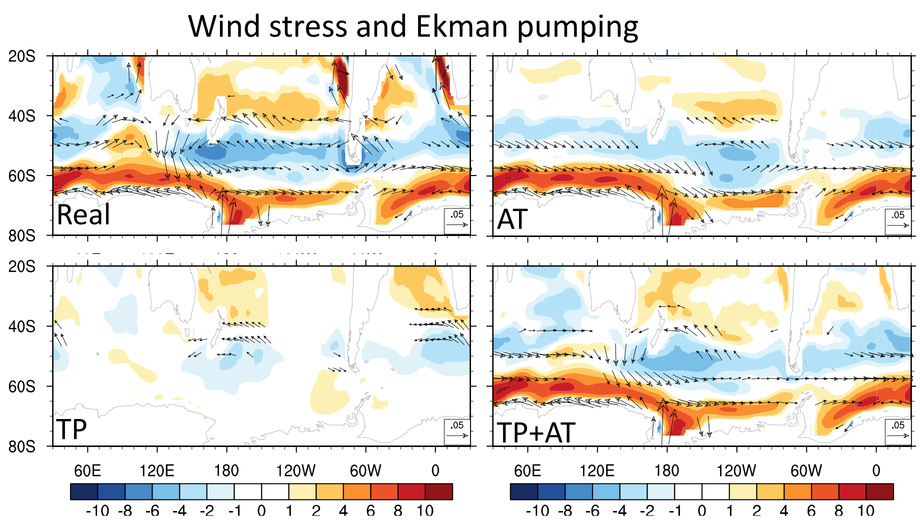

Fig. R15 Surface wind stress (units: dyn/cm^2) and Ekman pumping (units: cm/day). The values less than 0.015 dyn/cm^2 are not shown.

14. *Positive mass transport across 30°S is counted positively northwards. This is not mentioned in the figure caption.*

Responses: Thank you very much for this suggestion. We revised it in Fig. 5.

15. *(L202+Extended Data Figure 3a1-4) The authors' conclusion that the Tibetan plateau acts as a significant attractor of freshwater in the Northern Hemisphere (NH) is potentially accurate if the boundary conditions used in their scenario are limited to the Tibetan plateau alone. However, it is important to consider that changes in the North Pacific region can also be influenced by the westerlies blowing from Eastern Asia, which may be impacted by the presence or absence of landforms located to the north of the Tibetan plateau.*

Responses: Thank you very much for raising this question.

Please refer to our reply to Q.1 and Figs. R4, R5 and R8. It is true that changes in the North Pacific can also be influenced by the westerlies from East Asia, which can be impacted by the presence or absence of landforms (such like the Mongolian Plateau) to the north of the TP. However, the TP's impact dominates; so we did not separately consider the impact from the Mongolian Plateau.

16. *(L224) I think that the authors could quote a more recent paper than the Ruddiman's 1989 paper*

Responses: Thank you very much for this suggestion. We added a recent review paper published in *Nature* as reference #46 in the revised manuscript.

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).

17. *(L232-243) I agree with the observation regarding the limitations of the study, particularly with respect to the spatial resolution of the atmospheric model. I wonder whether the low resolution of the model might not be a potential factor contributing to the lack of impact observed for certain mountain ranges, particularly those with an elongated shape such as the Andes or the Rockies. Mountain ranges with complex topography may not be adequately captured or represented in the model due to the coarse resolution. In contrast, the Antarctic ice cap and the Tibetan plateau may be better resolved within the model. This could explain why their impacts are more apparent in the simulations.*

Responses: Thank you very much for these insightful thoughts.

We are going to repeat some experiments using high-resolution version of CESM2.0. This will be very resource-consuming and take a long time. We hope to have some new fascinating findings.

Other comments:

1. *(L24-33) The timing of uplift is also debatable. A part of the Tibetan plateau is largely uplifted before the Late Miocene.*

Responses: Thank you very much for this comment. We mentioned this problem in the revised manuscript in lines 38-40.

2. *Antarctic (ice sheet?): the authors explains that "Antarctic rapidly expanded in the Oligocene and persisted until the Late Oligocene". This is not clear to me what the authors mean by "persisted until the Late Oligocene". Does it mean that the ice sheet melts after the Late Oligocene ? No reference is provided.*

Responses: Thank you very much for raising this question. Here, we mean the glaciation of the Antarctic persists from the early Oligocene to the late Oligocene (34-26 Ma). In the revised manuscript, we rewrote this sentence as follows: "…*Although the transantarctic and Gamburtsev Mountains over the Antarctica were likely already present at the start of the Cenozoic (65 Ma) (Ferraccioli 2011; Elliot 2014), the glaciation of the Antarctica was thought to occur during the Eocene-Oligocene (56-23 Ma)*…"

3. *Andes uplift => reference 19 : Zachos et al. 2001 ?* Revised
4. *Figure 5: continent contours are too thin to be seen when printed* Replotted.
5. *Extended Data Figure 3: continent contours are hard to see* Replotted.