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6-7 pages including table and figures that will fill in *Nature*

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This paper presents a novel and quantitative evaluation of the role played by different continental mountains in shaping the global ocean meridional overturning circulation (MOC). Our findings suggest that the uplift of the Tibetan Plateau is a major determinant of the present-day pattern of the global MOC, while the contributions of other large mountains are limited. This finding has broad implications for our understanding of Earth's climate system, and will be of interest to the readership of *Nature*.

Which Mountains Matter Most to Global Meridional Overturning Circulation?

Key points:

1. In contrast to the existing view suggesting that a narrow basin is more conducive to the deep overturning circulation than a wider basin (Ferreira et al., 2010; Nilsson et al., 2013; Jones and Cessi, 2017), we show that with global flat continental topography, the thermohaline circulation actually occurs in the wider basin of the Pacific, instead of the narrower one of the Atlantic.
2. The Tibetan Plateau (TP) changes the global hydrological cycle in a fundamental way, disrupting the Pacific meridional overturning circulation (PMOC) by diverting fresh water toward the North Pacific instead of the North Atlantic. However, the TP alone cannot fully establish the Atlantic MOC (AMOC); its effects can be complemented by the Antarctic (AT).
3. The AT contributes significantly to strong southward mass transport in the intermediate-deep ocean of the Southern Hemisphere via Ekman pumping in the Southern Ocean, as previously suggested (Delworth and Zeng, 2008; Marshall and Speer, 2012; Nikurashin and Vallis, 2012). However, the location of this strong transport depends on the basin where the deep-water formation occurs in the Northern Hemisphere.
4. Contrary to the claim that the Rocky Mountains (RMs) modulate water vapor transport between the North Pacific and North Atlantic (Schmittner et al., 2011), leading to a see-saw change between the PMOC and AMOC, we show that the RMs have no significant effect on either the PMOC or the AMOC.
5. The Andes Mountains (AMs) intensifies the wind-driven subtropical cell in the South Pacific, which in turn results in a more robust thermohaline structure of the PMOC in the South Pacific, i.e., a more pronounced inter-hemispheric PMOC.
6. The topography of Greenland has negligible impact on the global thermohaline circulation.

Abstract: The meridional overturning circulation (MOC) in the ocean is a key player in the global climate system, while continental topography provides an essential backdrop to the system. In this study, we design a series of coupled model experiments to investigate the influence of various mountain ranges on the global thermohaline circulation. The results highlight the paramount influence of the Tibetan Plateau (TP) on the global thermohaline circulation. It emerges as a requisite for establishing the Atlantic MOC (AMOC) and a determining factor for the cessation of the Pacific MOC (PMOC). Additionally, the Antarctic continent plays a vital role in facilitating the TP to form the AMOC. While the formation of the AMOC cannot be attributed to any single mountain range, the TP alone can inhibit the PMOC's development. By modifying the global hydrological cycle, the TP is likely to have been crucial in molding the global thermohaline circulation.

1 The meridional overturning circulation (MOC) in the ocean plays a pivotal role in both
2 regional and global climate, via large-scale heat and freshwater transports. In the current climate,
3 the MOC exists mainly in the Atlantic, referred to as the Atlantic MOC (AMOC), which is
4 characterized by deep convection and deep-water formation in the Labrador Sea and Greenland-
5 Iceland-Nordic (GIN) seas of the subpolar Atlantic^{1,2}. The observed strength of the AMOC is
6 approximately 18 Sv³. There is no equivalent Pacific MOC (PMOC) in the North Pacific.

7 Geological evidence reveals that the primary deep-water formation region in the Northern
8 Hemisphere (NH) might have undergone a shift from the Pacific to the Atlantic in the past. Some
9 studies suggested that North Pacific deep-water (NPDW) formation was strong during the
10 Paleocene period (about 65-55 million years ago, or about 65-55 Ma)^{4,5}, while the North Atlantic
11 deep-water (NADW) formation was weak and likely began to develop during the early Oligocene
12 period (about 35-33 Ma)^{6,7}. Consequently, the modern AMOC might initially develop in the late
13 Miocene (about 12-9 Ma) and not be fully established until the late Pliocene to early Pleistocene
14 (about 4-3 Ma)⁸. Nonetheless, the actual evolutionary history of the AMOC and PMOC remains a
15 topic of considerable debate.

16 The asymmetry of net surface freshwater flux is often cited as the cause of different
17 overturning modes between the Atlantic and Pacific. The North Atlantic has higher sea-surface
18 salinity (SSS) than the North Pacific because the former has a net evaporation, while the latter is
19 nearly neutral⁹. Moreover, ocean basin geometry and ocean gateways may contribute to the
20 different overturning modes. Research indicated that narrow basins are more conducive to deep
21 overturning circulation than wide basins^{2,10,11}. The opening of the Drake Passage/Tasman Seaway
22 in the late Eocene is believed to have promoted the NADW formation and thus the AMOC
23 formation¹².

24 Geological evidence also suggests that the uplift of large continental mountains has had a
25 significant impact on the climate¹³. The evolution of continental terrain can precipitate
26 contrasting shifts in the global MOC (GMOC)¹⁴⁻¹⁶. The Rocky Mountains (RMs) rose from the
27 sea level about 80 Ma¹⁷, and reached its current elevation about 45 Ma⁸. Although the
28 transantarctic and Gamburtsev Mountains over the Antarctica were likely already present at the
29 start of the Cenozoic (65 Ma)^{18,19}, the glaciation of the Antarctica is believed to have occurred
30 during the Eocene-Oligocene (56-23 Ma), predating the uplift of the Andes Mountains (AMs),
31 which rose around 24 Ma²⁰ and matured around 15-10 Ma²¹. The uplift of these mountains
32 significantly predated the onset of the NADW formation. The Greenland (GL) underwent its
33 initial phase of uplift in the late Miocene (11-10 Ma)²². Although some studies argued that parts
34 of the Tibetan Plateau (TP) were already formed in the late Eocene (38-33 Ma)^{23,24}, the rapid and
35 main uplift of the TP was realized between 10 and 8 Ma²⁵⁻²⁹. This timeline aligns with the onset
36 of the NADW formation, hinting at a potential connection between the uplift of these two
37 mountain ranges and the development of the NADW. Recent research indicated that the TP acts
38 as a pivotal element influencing changes in the GMOC^{30,31}. Still, it is pivotal to acknowledge that
39 the chronology of the uplift of major mountain ranges continues to be a subject of intense
40 discussion and investigation.

41 In this study, our focus is to determine the specific impact of some major mountain ranges
42 on the GMOC, considering the modern-day basin geometry, rather than tracing the historical
43 evolution of ocean circulation. To achieve this, we conducted several series of experiments using
44 a coupled climate model (see [Methods](#) and [Table 1](#)). These results reveal that the TP is the
45 primary contributor to the formation of the AMOC and the breakdown of the PMOC.

46

47 **MOC states under different mountains**

48 Adding mountains sequentially to flat continents in the model can ultimately lead to the
49 establishment of the AMOC and the collapse of the PMOC (Fig. 1). However, this dramatic
50 change occurs only after the TP is added. In the Flat scenario, the MOC features a modest PMOC
51 of about 9 Sv and a negligible AMOC of less than 1 Sv, consistent with previous findings¹⁴⁻
52 ^{16,31,32}. Following the TP uplift in model year 4001 (red curve), the AMOC recovers rapidly,
53 overshoots its realistic value in about 800 years, and reaches an equilibrium state in about 1000
54 years, which matches the normal state in Real of about 18 Sv (grey line). Overshooting during
55 AMOC recovery is common in freshwater hosing experiments³³, CO₂ forcing experiments³⁴, and
56 other paleoclimate simulations³⁵, although their mechanisms may differ. Simultaneously, the
57 PMOC collapses quickly (blue curve), and reaches an "off" state in Real of about 4 Sv in about
58 200 years. It suggests that the AMOC would be difficult to establish in the absence of the TP,
59 while the PMOC would not exist in the presence of the TP.

60 None of the individual topography uplift from the Flat terrain is capable of initiating the
61 AMOC. However, the TP uplift alone can cause the collapse of the PMOC (Fig. 2a). The
62 presence of individual AT and AM, on the other hand, can result in a stronger PMOC than that in
63 Flat. As demonstrated by Jiang and Yang³⁶, the presence of the RM alone has negligible effects
64 on both AMOC and PMOC. Although the presence of the TP alone leads to a slight increase in
65 the AMOC strength (approximately 2 Sv), it is inadequate for its complete establishment.
66 Conversely, the PMOC is practically abolished in the presence of the TP alone.

67 Studies have demonstrated that the removal of the TP can result in the collapse of the
68 AMOC^{30,31,37}. This implies that the combination of the RM, AM, AT, and GL is insufficient to
69 sustain the AMOC. Indeed, this is precisely the situation before the TP is added, as illustrated in
70 Fig. 1. Moreover, we investigated the impacts of various combinations of RM, AM, AT, and GL;
71 and none of these arrangements can establish the AMOC, irrespective of the order in which they

72 were introduced to Flat. As the TP alone cannot support the establishment of the AMOC, we are
73 left with the question: what is the minimum topographic requirement, in addition to the presence
74 of the TP, for the establishment of the AMOC?

75 We find that only the combination of the TP and AT can lead to the establishment of the
76 AMOC from Flat, whereas the combination of the TP with any other mountains is ineffective
77 (Fig. 2b). With TP+AT, the AMOC gradually increases within the first 800 years, followed by a
78 sharp increase to a very high level in a short time, ultimately reaching quasi-equilibrium in
79 approximately 2000 years, with the magnitude equivalent to that in Real. However, in the other
80 combinations, even after an integration of 2200 years, the AMOC does not increase significantly.
81 These experiments suggest that only the AT effectively assists the TP in the formation of the
82 AMOC. Conversely, the PMOC quickly disappears in any experiment where the TP is present.

83 Figure 3 shows the patterns of the AMOC, PMOC, and GMOC in each experiment. In Flat
84 (Figs. 3a1, a2), only the shallow wind-driven subtropical cells (STCs) are present in the Atlantic;
85 while the PMOC is strong, it has a weak inter-hemispheric structure (Figs. 3b1, b2), consisting of
86 the wind-driven STCs and subpolar thermohaline circulations. In the Pacific, the wind-driven
87 STCs are strong and hemispherically symmetric, occupying the upper 500-m ocean between 30°S
88 and 30°N. The thermohaline circulation originates in the North Pacific north of 30°N, and its
89 lower branch occupies the deep ocean beneath 1000 m, extending to the Southern Ocean. The
90 PMOC in the South Pacific (Fig. 3b2) is much weaker than the AMOC in the South Atlantic in
91 Real (Fig. 3a8). The structure of strong PMOC and weak AMOC is maintained in Flat2Real
92 before the TP uplift, and in the experiments without the TP.

93 The uplift of the TP appears to have fundamentally changed the GMOC. Based on the
94 experiments we conducted, we conclude that the TP is a necessary condition for the "on" state of
95 the AMOC and a sufficient condition for the "off" state of the PMOC. The AT is also critical to

96 the establishment of the AMOC. Among the various topographic features, the TP stands the most
97 significant factor influencing the GMOC.

98

99 **Mechanism: freshwater flux, Ekman pumping, and sea ice**

100 Compared to Real, the MOC in Flat results from three key factors: 1) higher net
101 evaporation in the North Pacific and greater precipitation in the North Atlantic, 2) stronger
102 Ekman downwelling in the North Pacific, and 3) weaker Ekman pumping in the Southern Ocean
103 and associated weaker southward water mass transport in the intermediate-to-deep South Pacific.
104 The first two factors contribute to the formation of the NPDW and the shutdown of the NADW,
105 while the third factor weakens the thermohaline component of the PMOC. The impacts of net
106 evaporation in the North Atlantic and Ekman pumping in the Southern Ocean on the AMOC have
107 been well recognized³⁸⁻⁴³. Here, we quantify their roles using topography experiments.

108 In Real, the sea-surface density (SSD) in the subpolar Atlantic is over $27.5 \sigma_0$, which is
109 sufficient for the NADW formation, even with Ekman upwelling (Fig. 4a2). However, in Flat the
110 SSD in the North Atlantic is reduced to $25.5 \sigma_0$ (Fig. 4a1); and this reduction ($\Delta\sigma \sim 2.0 \text{ kg/m}^3$)
111 (Fig. 4b1) is significant enough to halt the NADW formation. In Real, the North Pacific SSD is
112 $25.5\text{-}26 \sigma_0$; and in Flat, it is increased to $26.5 \sigma_0$ in the Northeast Pacific (Fig. 4a1). This increase
113 ($\Delta\sigma \sim 0.5 \text{ kg/m}^3$) is sufficient for shallow surface-water subduction, but is insufficient for deep-
114 water formation, which requires the assistance from enhanced Ekman downwelling (Fig. 4b1)³².
115 Note that the physical processes involved in NADW formation in Real and NPDW formation in
116 Flat are not the same. The former primarily involves thermohaline dynamics, while the latter
117 involves both thermohaline and wind-driven dynamics³².

118 The change in SSD from Real to Flat can be attributed to the change in SSS (Fig. 4c1), in
119 which the virtual salt flux resulting from net evaporation (i.e., evaporation minus precipitation, or

120 EMP) and sea-ice melting (Extended Data Fig. 2b1) playing crucial roles. The contribution of
121 sea-surface temperature change to SSD change is limited³¹. For a steady state, EMP across the
122 ocean surface is almost equivalent to the vertically integrated water vapor transport divergence
123 ($\nabla \cdot \vec{v}q$) throughout the entire atmosphere column, when freshwater flux from land surface and
124 river runoff are disregarded.

125 In the transition from Real to Flat, aided by anomalous lows over the North Atlantic and
126 North American continent (Extended Data Fig. 3b1), more atmospheric moisture is transported
127 eastward from the North Pacific and north-eastward from the central tropical Pacific to the North
128 Atlantic (Extended Data Fig. 3a1), leading to increased moisture convergence over the North
129 Atlantic. Later, the southward expansion of sea ice in the subpolar Atlantic results in sea-ice
130 melting at the same time, providing a substantial amount of fresh water into the ocean (Extended
131 Data Fig. 2b1), eventually leading to the shutdown of the AMOC. Meanwhile, aided by
132 anomalous highs over the North Pacific and southern China (Extended Data Fig. 3b1), less
133 atmospheric water vapor converges over the western tropical and subtropical Pacific (Extended
134 Data Fig. 3a1), causing an increase in SSS there (Fig. 4c1). The resulting high-salinity surface
135 water is transported northward by the Kuroshio Current and further eastward by the Kuroshio
136 Extension, thereby triggering the NPDW formation. The anomalous high over the North Pacific
137 also leads to Ekman downwelling (Fig. 4b1), which further aids the NPDW formation. These two
138 processes collectively lead to the establishment of the PMOC in Flat.

139 In Flat, the thermohaline component of the PMOC in the South Indo-Pacific is weaker than
140 that of the AMOC in Real (Figs. 3b2 vs 3a8). This can be attributed to the weaker Ekman
141 pumping in the Southern Ocean in Flat in comparison to that in Real (Fig. 5a1). The absence of
142 the Antarctic topography induces a high-pressure anomaly over the Antarctic, which produces an
143 anomalous northward pressure gradient, and thus an anomalous easterlies based on the

144 geostrophic balance. This eventually results in an 80% reduction in wind stress and Ekman
145 pumping along the Antarctic continent (Fig. 5a1). The impact of this reduction on the MOC is
146 evident in Figs. 3c1-c3, with the Deacon cell being weakened by 50% in Flat. As a result, the
147 southward water mass transport in the intermediate-to-deep ocean across 30°S is about 30%
148 weaker in Flat when compared to that in Real (Extended Data Fig. 4).

149 Once we recognize the changes in the MOC from Real to Flat, it becomes easy to
150 understand the MOC changes in TP. From Flat to TP, the changes in the NH atmospheric
151 circulation and moisture transport (Extended Data Figs. 3a4, b4) are similar to those from Flat to
152 Real (Extended Data Figs. 3a2, b2). Consequently, we see similar changes in SSD, SSS, and
153 Ekman pumping in TP as those in Real (Figs. 4a2-c2, a3-c3). Specifically, the TP uplift leads to
154 more net precipitation (Extended Data Fig. 2b3) and thus smaller SSD in the North Pacific, and a
155 stronger Ekman upwelling in the North Pacific (Fig. 4b3), which jointly shut down the PMOC.
156 Moreover, the TP uplift causes less atmospheric moisture transport from the central tropical
157 Pacific to the North Atlantic (Extended Data Fig. 3a4), resulting in accumulation of more saline
158 surface water in the North Atlantic. However, the SSD in the North Atlantic (Fig. 4b3) is still
159 smaller than in Real (Fig. 4b2) at this stage. The AMOC shows only a slight increase (Fig. 2a).
160 Furthermore, the Ekman pumping in the Southern Ocean in TP is much weaker than that in Real
161 (Fig. 5a2), which limits further development of the AMOC.

162 The presence of the AT alone does not alter the surface buoyancy in the NH (figure not
163 shown). Similar to Flat, the NPDW formation occurs instead of the NADW formation. However,
164 the Ekman pumping in the Southern Ocean in AT is as robust as that in Real (Fig. 5a3), resulting
165 in a more potent Deacon cell (Fig. 3f1) and a more forceful thermohaline component of the

166 PMOC (Fig. 3e1) than those in Flat. Similar to Flat, the strong southward water mass transport
167 occurs in the South Indo-Pacific, but not in the South Atlantic (Fig. 5b3, Extended Data Fig. 4).

168 With the assistance of the AT, the establishment of the AMOC in TP+AT becomes possible
169 (Fig. 3d8). The presence of the TP shuts down the PMOC, shifting the deep-water formation
170 from the North Pacific to the North Atlantic. Simultaneously, the presence of the AT leads to
171 strong Ekman pumping in the Southern Ocean, which enhances the NADW formation remotely
172 (Fig. 4c4). The MOC patterns in TP+AT are almost identical to those in Real (Fig. 3d8 vs Fig.
173 3a8) since both the surface buoyancy in the North Atlantic and the Ekman pumping in the
174 Southern Ocean are almost identical to those in Real (Figs. 4a4, 5a4). Note that in TP+AT, there
175 is strong southward water mass transport in the South Atlantic, instead of in the South Indo-
176 Pacific as in AT (Figs. 5b3, b4, Extended Data Fig. 4), because the presence of the TP alters the
177 deep-water formation in the NH, which allows only the NADW to reach the Southern Ocean.

178 The presence of other large topographies, such as AM, RM, and GL, would not switch the
179 MOC from the Pacific to the Atlantic. However, the PMOC in Exp AM is noticeably stronger
180 than that in Flat (Fig. 2a). The presence of the AM reduces the equatorial trade wind, but
181 amplifies the off-equatorial Ekman pumping (Extended Data Fig. 5a), thereby boosting the wind-
182 driven STC in the South Indo-Pacific (Extended Data Fig. 5b) and augmenting the thermohaline
183 component of the PMOC there, leading to a stronger PMOC (Fig. 3e2). On the other hand, both
184 the RM and GL have minimal effects on the PMOC (Figs. 3a3-f3) because their presences do not
185 significantly alter the global atmospheric moisture pattern³⁰ and the atmospheric circulation in the
186 tropics (Extended Data Fig. 6).

187 The AMOC gradually increases in the first few hundred years after the addition of the TP in
188 both Flat2Real and TP+AT, followed by an acceleration and eventual return to a normal state in
189 Real (Figs. 1, 2b). The latter process is accompanied by a swift sea-ice loss in the subpolar

190 Atlantic. The evolution of sea ice in Flat2Real is shown in Fig. 6. The northward retreat of sea ice
191 in the subpolar Atlantic leads to additional freshwater loss in the NADW formation region
192 (Extended Data Figs. 2b2, b5), which increases SSD and thus consequently enhances the AMOC.
193 This implies a positive feedback between AMOC enhancement and sea-ice retreat. In the first
194 few hundred years after adding the TP, the sea-ice margin in the subpolar Atlantic retreats
195 slightly northward (Fig. 6b), and the March mixed layer depth (MLD) deepens slightly (Fig. 6a),
196 corresponding to a weak NADW formation. About 500 years after the TP uplift, the sea-ice
197 margin retreats rapidly northward (Fig. 6b, dashed red curve), indicating a large amount of
198 freshwater flux loss in the North Atlantic, a rapid deepening of the MLD (Fig. 6a), and a swift
199 enhancement of the AMOC (Figs. 1, 2b). The sea-ice margin reaches its quasi-equilibrium
200 roughly 1000 years after the TP uplift (Fig. 6b), accompanied by significant sea-ice melting in
201 the GIN seas. The sea-ice evolution in TP+AT (Extended Data Figs. 7a-b) displays a similar
202 pattern to that in Flat2Real, while changes in sea ice and MLD in TP are minimal (Extended Data
203 Figs. 7c-d).

204

205 **Summary and discussion**

206 Continental topography plays a vital role in shaping Earth's climate. By conducting
207 topography perturbation experiments, we can observe the dynamic processes by which
208 atmospheric freshwater converges over the Pacific and diverges over the Atlantic in response to
209 the TP uplift. These processes shut down the PMOC and enhance the NADW formation. The
210 latter process then starts a positive feedback loop between the AMOC and sea ice in the subpolar
211 Atlantic, pushing the final establishment of the AMOC. The TP acts as a giant attractor of fresh
212 water in the NH, while the Antarctic continent acts as a giant draught-fan engine that forces
213 Ekman pumping in the Southern Ocean, contributing to the establishment of the global ocean

214 conveyor belt. Although no single mountain range can lead to the full establishment of the
215 AMOC, the TP alone can shut down the PMOC. The presence of the TP can modulate the global
216 hydrological cycle in a fundamental way, which may have shaped the modern-day thermohaline
217 circulation.

218 Our experiments illustrate the dynamic contribution of Ekman pumping in the Southern
219 Ocean to the GMOC, which is consistent with previous finding^{40,41,44}. However, this Ekman
220 pumping can pump water from either the North Pacific or the North Atlantic, depending on in
221 which basin the NH deep-water formation occurs. Only after the TP uplift, the change in global
222 hydrological cycle leads to more saline water accumulated in the North Atlantic, initializing the
223 NADW formation. Assisted by strong Ekman pumping due to the AT, the AMOC can be
224 established. In addition, our topography experiments show a clear planetary wave train in the NH
225 mid-to-high latitudes ([Extended Data Fig. 3](#)) connecting the Eurasian continent, the North
226 Pacific, the North American continent, and the North Atlantic as the atmospheric circulation
227 changes with the addition of the TP. This wave train structure is similar to that observed from
228 Flat to Real, highlighting TP's global effects. No other topography can force this kind of wave
229 train structure in the NH.

230 Rather than mimicking past climate evolution, the mountain uplift experiments in this study
231 allow us to explore the linkages between uplift regions and climate changes in remote areas of the
232 modern world. The results not only shed light on current climate patterns, but also provide insight
233 into specific periods of paleoclimate, such as the climate development in the late Cenozoic.
234 Previous studies suggested that the TP uplift played a key role in shaping Cenozoic climate
235 through circulation changes and weathering^{13,45,46}: over the past 40 million years, this uplift led to
236 substantial deflection of the atmospheric jet stream, intensified monsoonal circulation, increased
237 rainfall on the front slopes of the Himalayas, and favorable conditions for the formation of deep

238 and intermediate waters in the North Atlantic. By using experiment Flat as a starting point and
239 tracing the changes due to various uplifts, we can quantify the linkages between uplifts and
240 climate changes. Particularly, this study establishes the direction of MOC change as a function of
241 increasing uplift over time.

242 It should be noted that the conclusions of this study may have some limitations due to the
243 model employed. Indeed, we should always be careful when assessing the credibility of model's
244 results. For instance, the model resolution may not be optimal for analyzing the impact of
245 topography on the global climate, as models with coarse resolution [may not adequately reproduce](#)
246 [the effects of mountain ranges with complex topography](#), particularly those [with an elongated](#)
247 [shape such as the Andes or the Rockies](#). Additionally, we did not consider the effects of
248 continental drift and oceanic gateway switches, nor did we treat Greenland and Antarctic
249 glaciation dynamically. Furthermore, the background climate in the experiments uses the
250 preindustrial conditions with constant CO₂, and the effect of chemical erosion in rapidly uplifted
251 areas on atmospheric CO₂ is not accounted for. Typically, atmospheric CO₂ levels cannot remain
252 in a steady state during the time of intense tectonism, which can last for millions of years, due to
253 the temperature-weathering feedback mechanism⁴⁵. To better understand the uplift effect on the
254 global climate, it is essential to gain a quantitative understanding of the long-term carbon cycle.
255 Overall, there are many factors at play in long-term climate change, and their effects remain
256 poorly constrained.

257 We want to emphasize that our model results capture the basic direction of climate change.
258 The uplift of giant mountains undoubtedly played a significant role in the evolution of global
259 thermohaline circulation; and our results align with those of other orography experiments
260 conducted using different models^{14-16,37}. However, the impact of giant mountains on the AMOC
261 remains a topic of debate. Maroon⁴⁷ discovered that the RM can have a significant effect on the

262 GMOC through its impact on hydrology. Davini et al.⁴⁸ found that removing the Greenland ice
263 sheet can cause the AMOC to weaken by more than 10%, even without considering the impact of
264 freshwater input from the melting ice. Singh et al.⁴⁹ flattened the orography of the Antarctic ice
265 sheet, and discovered that the upper cell of the MOC weakens while the deep cell strengthens.
266 Understanding which mountains exert control over the MOC is critical for comprehending
267 oceans' roles in past and future climate transitions. We hope that this study will help clarify this
268 issue and reduce the controversy surrounding it.

269

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Methods

We use the National Center for Atmospheric Research Community Earth System Model version 1.0 (NCAR CESM 1.0) in this study. The CESM1.0 employed here has the grid of T31_gx3v7, which consists of the atmospheric component (CAM4) with 26 vertical levels and T31 horizontal resolution ($3.75^\circ \times 3.75^\circ$); the ocean component (POP2) with 60 vertical levels and gx3v7 horizontal resolution (approximate 3° near the poles to 0.6° at the equator); the land component (CLM4) and the sea-ice component (CICE) with the same horizontal resolution as the CAM4 and POP2, respectively. More details about these model components can be found in Gent et al.⁵⁰ and Shields et al.⁵¹.

To compare the impacts of various mountain ranges on the global MOC, we conduct a few sets of topography experiments ([Table 1](#), [Extended Data Fig. 1](#)). These experiments are designed in relation to the “Flat” experiment, [Exp Flat] which features a globally flat topography at 50 m above the sea level ([Extended Data Fig. 1a](#)). Although not precisely representative of any specific Earth epoch, Flat serves as a reference point for the other experiments. Flat is integrated for 1600 years under the preindustrial conditions, starting from a control run with realistic modern topography (Real) that was completed previously⁵². We examine the effects of five prominent topographies in this study: the Rocky Mountains, the Antarctic continent, the Andes Mountains, Greenland, and the Tibetan Plateau. Except for topography height, all other boundary conditions remain the same as in Flat or Real. The ocean-land configuration is set to modern-day conditions without correction for plate tectonic motion. Atmospheric CO₂ 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 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.

The first set of experiments includes adding each of the five different topography individually to the Flat. These experiments are named RM (Rocky Mountains), AT (Antarctic), AM (Andes Mountains), GL (Greenland), and TP (Tibetan Plateau), respectively. [Exps. Xxx] Each topography is added to Flat starting from year 801; and each experiment is then integrated for at least 800 years. The second set of experiments, named Flat2Real, includes adding the five topography sequentially according to their uplift times. The RM is added to Flat in year 801; and the model is integrated for 1200 years. The AT is added after the RM in year 2001; and the model is integrated for 400 years. The AM is added in year 2401; and the model is integrated for 1000 years. The GL is added in year 3401; and the model is integrated for 600 years. The TP is added in year 4001; and the model is integrated for 2000 years. The third set of experiments combines topography differently, such as TP+RM, TP+AT, TP+AM, and TP+GL, plus Real with all five mountains. All these experiments start from year 801 of Flat, and are integrated for at least 800 years. More detailed information can be found in [Table 1](#).

The changes due to the presence of unique topography are obtained by subtracting the results of Flat from each topography experiment. Some experiments show an initial jump when adding the topography suddenly, but that jump has little effect on the equilibrium state. These experiments indicate that uplift causes a wide array of changes in the global climate. We use student-*t* test 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 visual clarity, significance test is not included in any figures.

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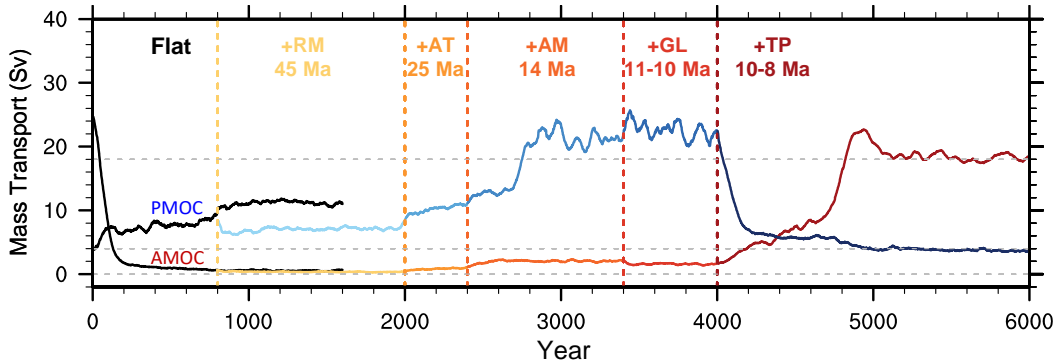
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Tables

Table 1 Description and annotation of experiments. “RM, AT, AM, GL, and TP” represent the Rocky Mountains, the Antarctic, the Andes Mountains, Greenland, and the Tibetan Plateau, respectively. “All” represents the global topography. “Year” represents the integration length of the experiment. The AMOC and PMOC strengths (units: Sv) are obtained by averaging results over the last 100 years of the integration. Strong AMOC and PMOC are marked by bold face.

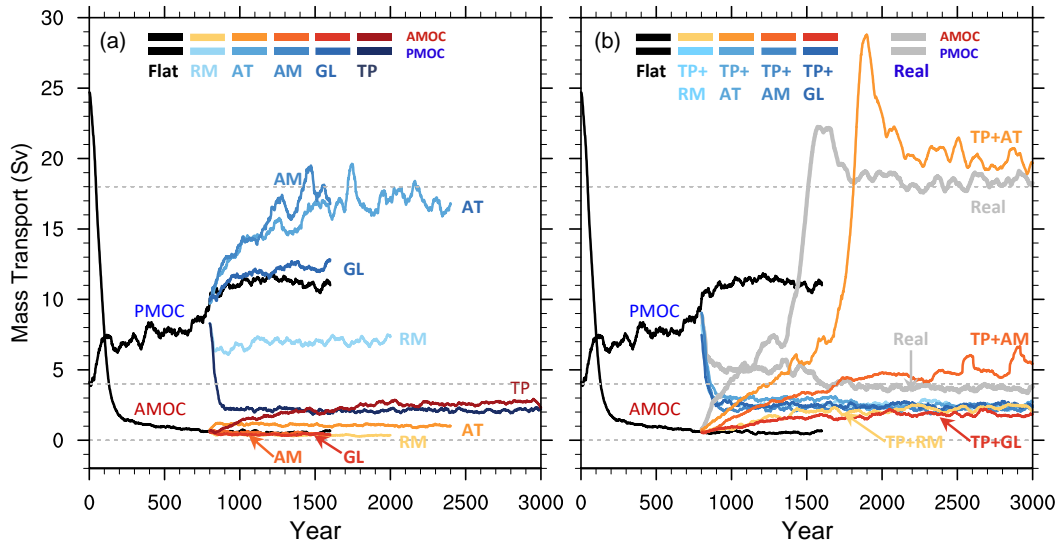
Experiment	Year	AMOC	PMOC	Description
Flat	0001-1600	0.7	12.0	Flat global topography (50 m)
AM	0801-1600	0.5	15.8	Add AM to Flat
AT	0801-2400	1.1	16.6	Add AT to Flat
GL	0801-1600	0.4	12.5	Add GL to Flat
RM	0801-2000	0.4	7.1	Add RM to Flat
TP	0801-3000	2.4	2.0	Add TP to Flat
RM+AT	2001-2400	0.9	10.6	Add AT to the previous stage
RM+AT+AM	2401-3400	2.1	21.2	Add AM to the previous stage
RM+AT+AM+GL	3401-4000	1.5	21.9	Add GL to the previous stage
RM+AT+AM+GL+TP	4001-6000	18.1	3.5	Add TP to the previous stage
TP+AM	0801-3000	5.0	2.0	Add TP and AM to Flat
TP+GL	0801-3000	1.7	2.4	Add TP and GL to Flat
TP+AT	0801-3000	19.4	2.5	Add TP and AT to Flat
TP+RM	0801-3000	2.4	2.4	Add TP and RM to Flat
Real	0801-3000	18.2	3.6	Add all topography simultaneously to Flat

1 **Figures with legends**



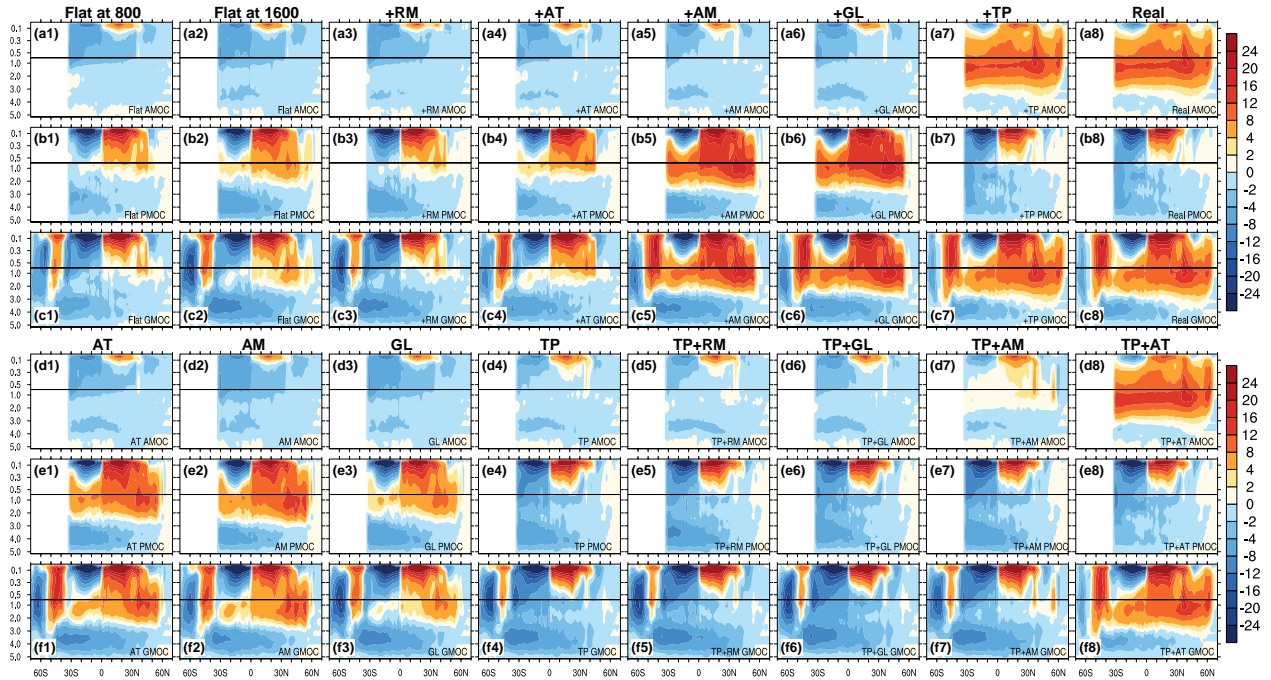
2
 3 **Figure 1 Temporal evolutions of the AMOC and PMOC with the sequential uplift of**
 4 **different mountains in Flat2Real.** The AMOC is represented by a red-scale colored curve, and
 5 the PMOC, by a blue-scale colored curve. Each segment corresponds to one mountain uplift.
 6 The "+" sign is used to indicate that a topography is added to the previous stage. The AMOC
 7 and PMOC indexes are defined as the maximum meridional overturning streamfunction (units:
 8 Sv, 1 Sv=10⁶ m³/s) between 20° and 70°N and below 500-m depth in the North Atlantic and
 9 North Pacific, respectively. Each time series is smoothed using a 51-year running mean. The
 10 mountain uplifts here are the Rocky Mountains (RM), Antarctic (AT), Andes Mountains (AM),
 11 Greenland (GL), and Tibetan Plateau (TP).

12



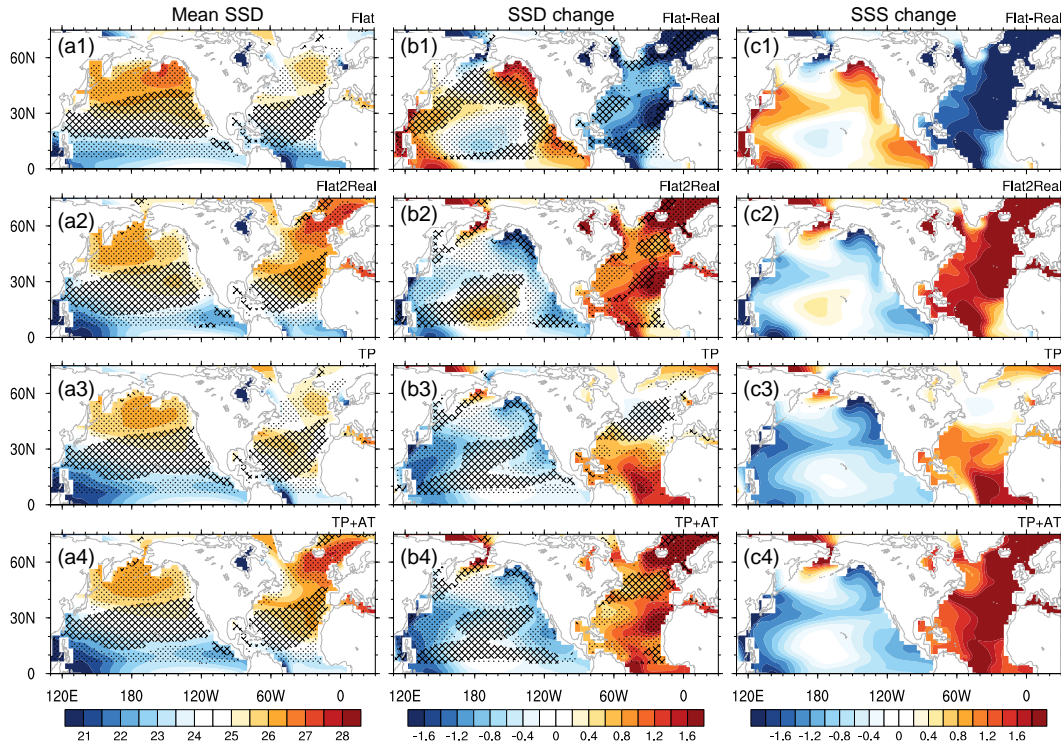
1
 2 **Figure 2 Temporal evolution of the AMOC and PMOC in different topography**
 3 **experiments.** Details of these experiments are given in Table 1. The AMOC and PMOC are
 4 represented by red-scale and blue-scale colored curves, respectively. **a**, Results of individual
 5 topography experiments. **b**, Results of TP plus another topography. All curves are smoothed
 6 using a 51-year running mean. Dashed grey reference lines in **(a-b)** indicate the mean strengths
 7 of the AMOC and PMOC in Real, which are 18 and 4 Sv, respectively.

8



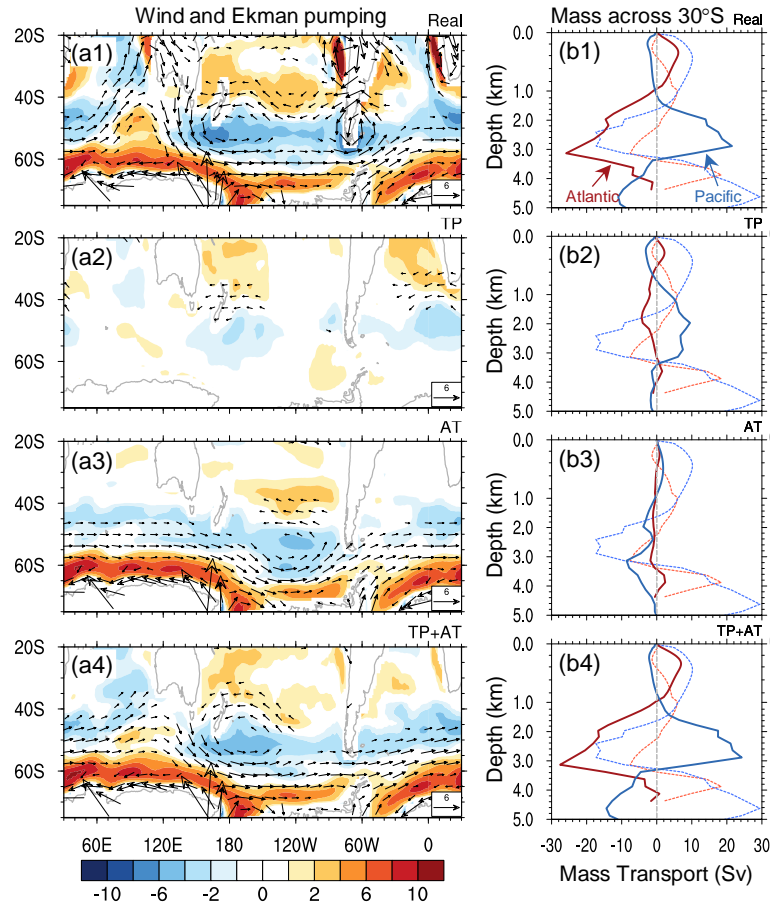
1
 2 **Figure 3** Patterns of the MOC in different experiments. (a-c), The AMOC, PMOC, and
 3 GMOC in Flat2Real, respectively. The first (second) column shows the MOC patterns averaged
 4 over years 701-800 (years 1501-1600) of Flat. The third to seventh columns show the MOC
 5 patterns averaged over years 1801-2000, 2201-2400, 3201-3400, 3801-4000, and 5601-6000 of
 6 Flat2Real, respectively, corresponding to the sequential uplift of different mountains. The last
 7 column shows the MOC pattern averaged over years 2501-3000 of Real. (d-f), The MOC
 8 patterns for the last 200 years of each experiment (from left to right): AT, AM, GL, TP, TP+RM,
 9 TP+GL, TP+AM, and TP+AT. The vertical coordinate is depth (units: km).

10



1
 2 **Figure 4 Mean SSD, Ekman pumping, and their changes. (a1-a4)**, Mean SSD (units: kg/m^3)
 3 in Flat, Flat2Real, TP, and TP+AT, respectively, with black dots (crosses) denoting mean Ekman
 4 upwelling (downwelling) in each experiment. The Ekman pumping is calculated as $\omega_E =$
 5 $\text{curl}\left(\frac{\tau}{\rho f}\right)$, where τ is the surface wind stress with units of dyn/cm^2 , ρ is the density of sea water
 6 ($1024 \text{ kg}/\text{m}^3$), and f is Coriolis parameter with units of $1/\text{s}$. **b1** shows the equilibrium changes in
 7 SSD and Ekman pumping in Flat with respect to Real, while **b2-b4** show their equilibrium
 8 changes in Flat2Real, TP, and TP+AT, respectively, with respect to Flat. Black dots (crosses)
 9 denoting region with anomalous Ekman upwelling (downwelling). **c1** shows the equilibrium SSS
 10 changes (units: psu) in Flat with respect to Real, while **c2-c4** show the equilibrium SSS changes
 11 in Flat2Real, TP, and TP+AT, respectively, with respect to Flat. Note that the patterns of **b1** and
 12 **b2** and those of **c1** and **c2** are nearly identical but with opposite signs. **b1** and **c1** are included
 13 for convenience of analysis. The mean SSD in experiments AT and AM is similar to that in Flat,
 14 and thus is not shown here.

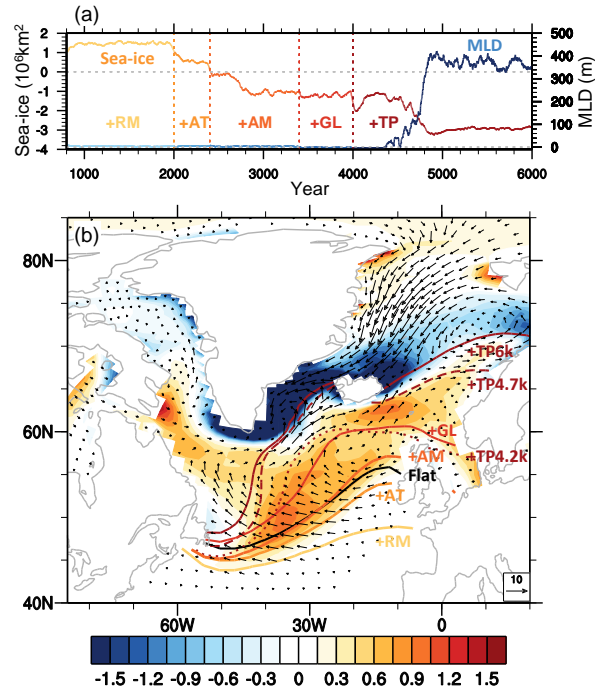
Mountains' role in the global meridional overturning circulation



1
 2 **Figure 5 Changes in wind, Ekman pumping, and mass transport. (a1-a4)**, Equilibrium
 3 changes of wind stress at 850 hPa (vector; units: m/s) and Ekman pumping (shading; units:
 4 cm/day) in Flat2Real, TP, AT, and TP+AT, respectively, with respect to Flat. Positive (negative)
 5 value indicates Ekman upwelling (downwelling). Ekman pumping is calculated using the surface
 6 wind stress as described in Fig. 4. **(b1-b4)**, Equilibrium changes of zonally integrated net
 7 meridional water mass transport (units: Sv) across 30°S in Flat2Real, TP, AT, and TP+AT,
 8 respectively, with respect to Flat. The mean net meridional mass transport in Flat is plotted as a
 9 dotted curve, with the red and blue curves indicating the Atlantic and Pacific, respectively.
 10 Positive value represents northward transport. The vertical coordinate in **(b1-b4)** is depth (units:
 11 km).

12

Mountains' role in the global meridional overturning circulation



1

2 **Figure 6 Changes in sea ice and MLD with the sequential uplift of different mountains in**

3 **Flat2Real. a**, Temporal evolution of the changes in sea-ice cover in the Arctic (units: 10^6 km^2 ,

4 left ordinate) and MLD (units: m, right ordinate) in the subpolar Atlantic, with respect to Flat. The

5 sea-ice cover is annual averaged. The MLD is for March and is calculated using the method of

6 Large et al. (1997), which represents the site of the deepest vertical mixing and convection, and

7 thus deep-water formation. **b**, Sea-ice margin (curve) at different stages of Flat2Real, and

8 equilibrium change in virtual salt flux (VSF) due to sea-ice formation or melting (units: psu/year ;

9 shading), and sea-ice velocity (units: cm/s ; vector), with respect to Flat. These changes are

10 annual averaged. The sea-ice margin is defined by the 15% sea-ice fraction; and different colors

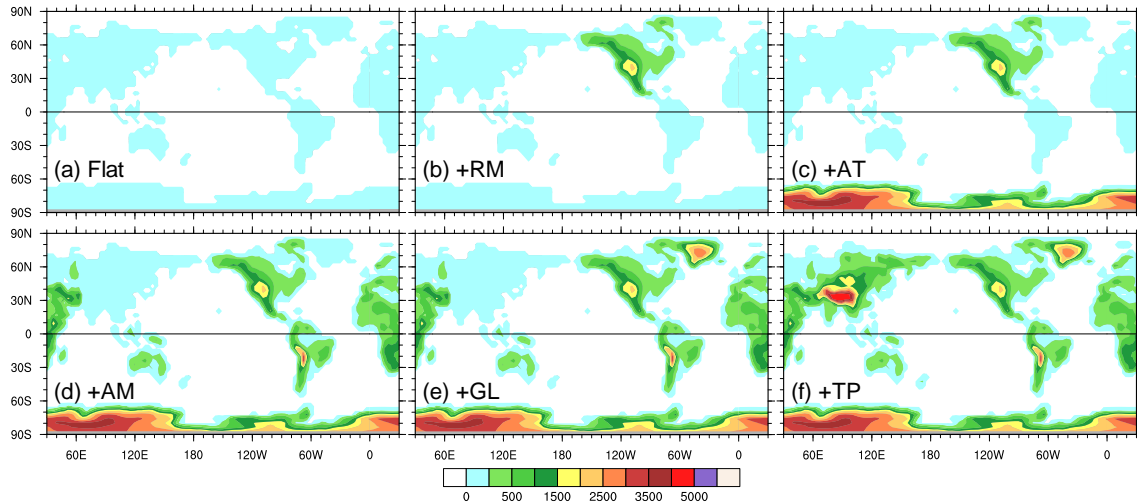
11 show sea-ice margins at different stages of the uplift. Changes in sea-ice velocity and VSF are

12 obtained by subtracting Flat from the last 200-year-averaged values of Flat2Real. Positive

13 (negative) VSF indicates loss (gain) of fresh water in the ocean.

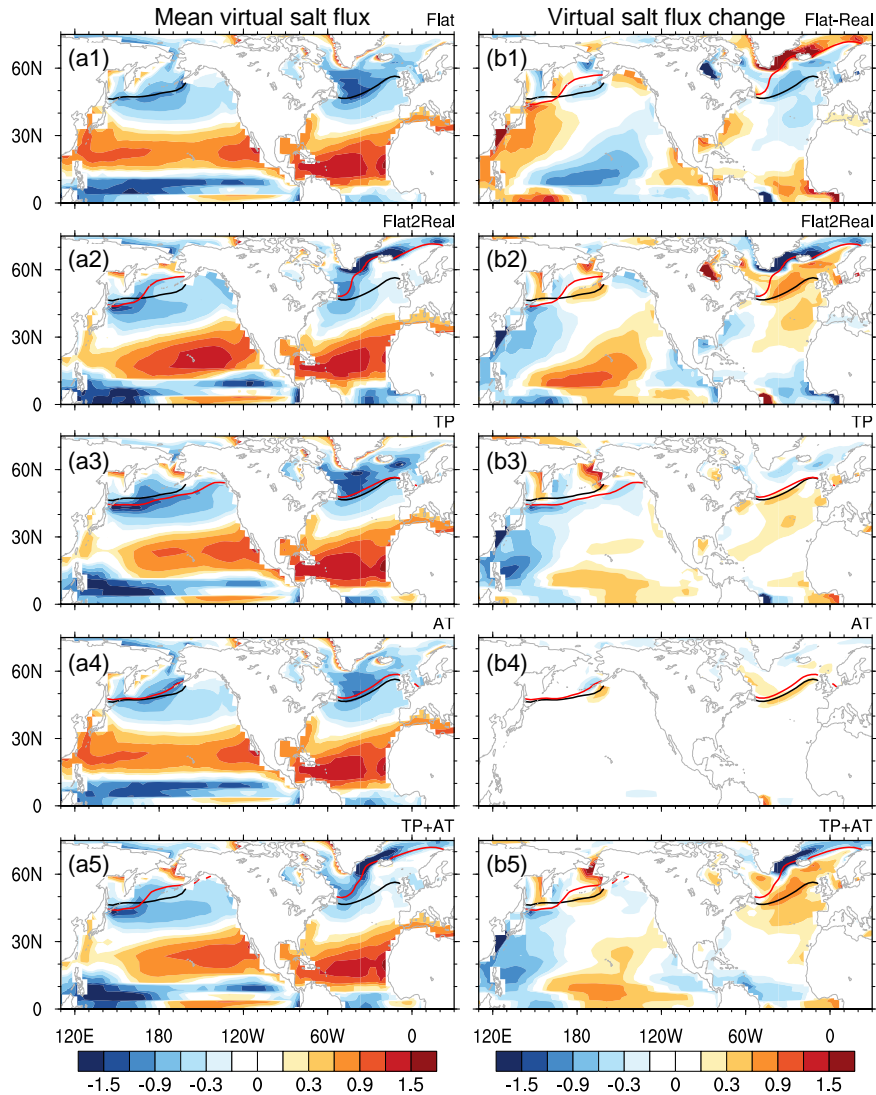
Mountains' role in the global meridional overturning circulation

1 **Extended Data Figures**



2
 3 **Extended Data Figure 1 Topography configurations in coupled model experiments. a,**
 4 **Modified topography with global flat topography (Flat); b, Modified topography after adding the**
 5 **Rocky Mountains (RM) to Flat; c, after adding the Antarctic (AT); d, after adding the Andes**
 6 **Mountains; e, after adding Greenland (GL); and f, after adding the Tibetan Plateau (TP). The “+”**
 7 **sign indicates that topography is added to the previous stage. Units: m.**

8



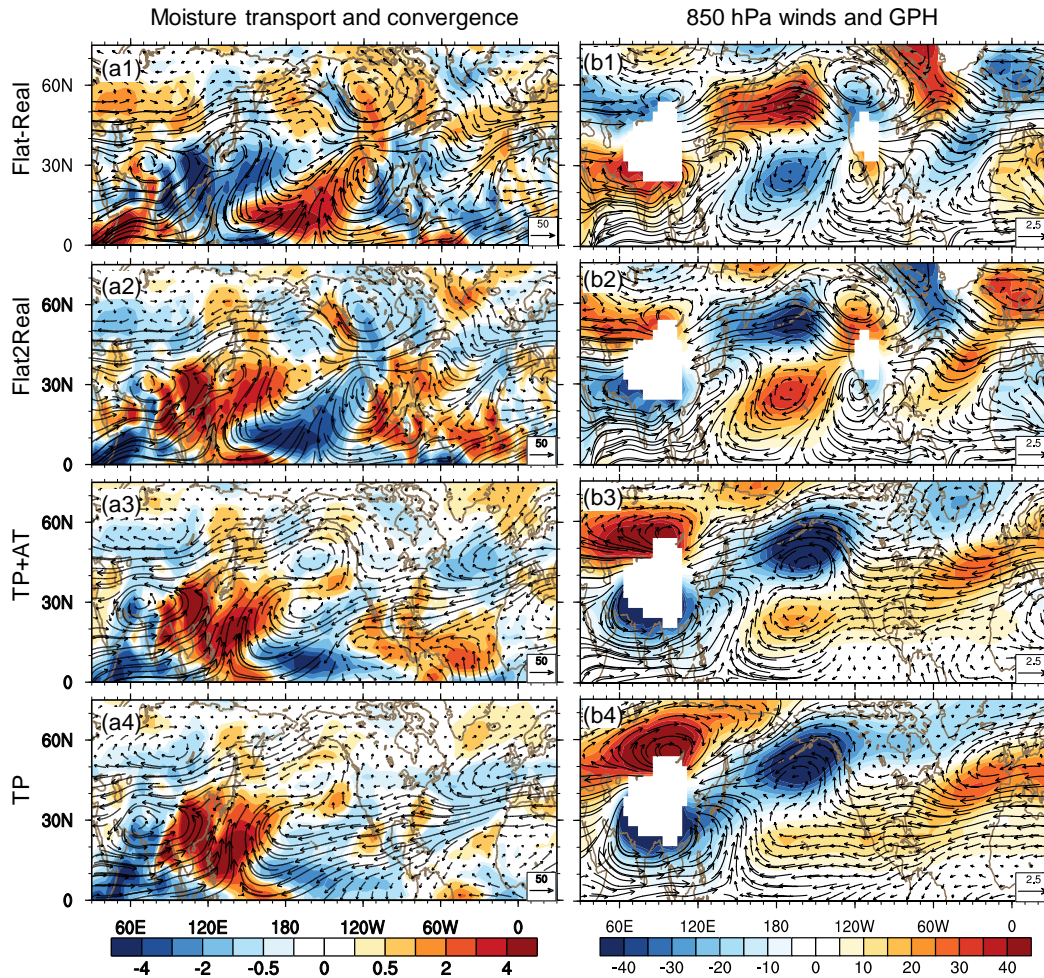
1
 2 **Extended Data Figure 2 Mean VSF and its change. (a1-a5)**, Mean VSF (units: psu/year) in
 3 Flat, Flat2Real, TP, AT, and TP+AT, respectively. Black curve represents sea-ice margin in Flat,
 4 and red curve is for respective experiment. **b1**, Equilibrium change of VSF in Flat with respect to
 5 Real. **(b2-b5)**, Equilibrium changes of VSF in Flat2Real, TP, AT, TP+AT, and AM, respectively,
 6 with respect to Flat. Sea-ice margin is defined by 15% sea-ice fraction. Positive value denotes
 7 that the ocean becomes more saline due to VSF. Note that patterns of **b1** and **b2** are nearly
 8 identical, but have opposite signs. **b1** is included here for the convenience of analyses
 9 presented in the paper.

1 From Flat to TP, the pattern of VSF change (**b3**) is similar to that of Flat2Real (**b2**). However, the
2 magnitude of this change in the North Atlantic is much weaker than that in Flat2Real. This
3 suggests the TP uplift is sufficient to shut down the PMOC, but it can only cause marginal
4 NADW formation, which is insufficient for the AMOC establishment.

5 From Flat to AT, the VSF change in the Northern Hemisphere (NH) is negligible (**b4**). This
6 suggests the AT uplift has a minimal effect on the NH hydrological cycle, which would not alter
7 the GMOC in Flat.

8 From Flat to TP+AT, the VSF change (**b5**) is nearly identical to that in Flat2Real (**b2**), in terms of
9 both pattern and magnitude. This suggests that these two giant structures can roughly fulfill the
10 duties of global mountains in shaping the GMOC.

11

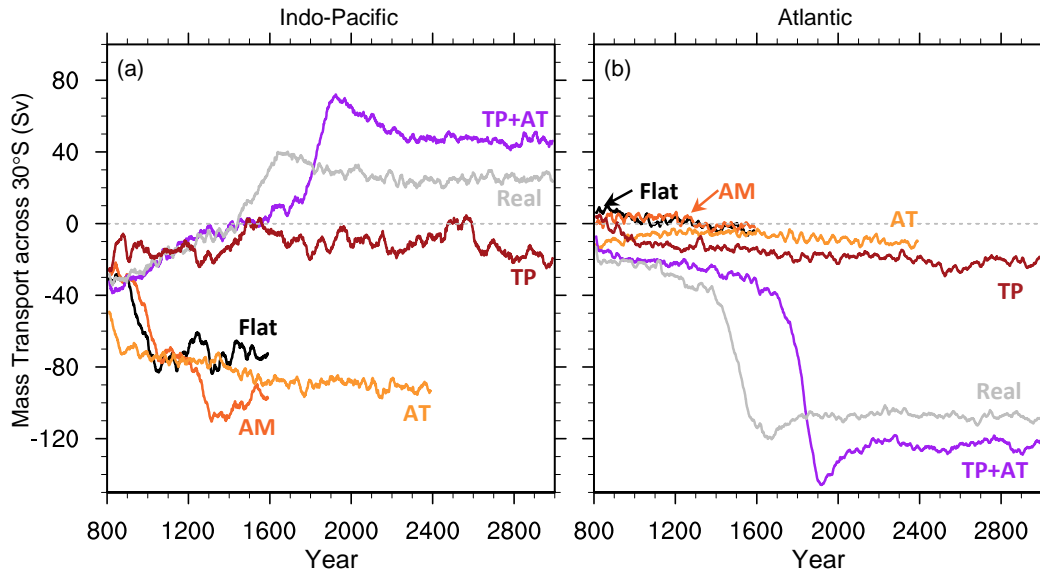


1
 2 **Extended Data Figure 3** Equilibrium changes in atmospheric circulation and water vapor
 3 **transport.** (a1-a4), Changes in vertically integrated water vapor transport (vector; units: $\text{kg}\cdot\text{m}^{-1}\text{s}^{-1}$)
 4 and its convergence (shading; units: $10^{-5} \text{ kg}\cdot\text{m}^{-2}\text{s}^{-1}$); (b1-b4), Geopotential height (shading;
 5 units: 10 m) and wind (vector; units: m/s) at 850 hPa. a1 and b1 are changes in Flat, with
 6 respect to Real. (a2-a4) and (b2-b4) are changes in Flat2Real, TP+AT and TP, respectively,
 7 with respect to Flat. Atmospheric water vapor convergence (divergence) is plotted as positive
 8 (i.e., $-\nabla \cdot \vec{v}q > 0$) (negative, i.e., $-\nabla \cdot \vec{v}q < 0$), representing a gain (EMP<0) (loss, EMP>0) of
 9 ocean fresh water from (to) the atmosphere. Note that patterns of a1 and a2 and those of b1
 10 and b2 are nearly identical, but have opposite signs. a1 and b1 are included here for the
 11 convenience of analyses presented in the paper.

Mountains' role in the global meridional overturning circulation

1 From Flat to TP and From Flat to TP+AT, the patterns of atmospheric changes (**a4**, **b4** and **a3**,
2 **b3**) are similar to those of Flat2Real (**a2**, **b2**), particularly regarding moisture changes and wave
3 structures over the Euro-Asian continent and the North Pacific. There are some differences
4 between them over the eastern North Pacific, North American continent, and North Atlantic,
5 which can be attributed to the effect of the RM. The presence of the RM does substantially affect
6 the atmospheric circulation and moisture situation over the North American continent and North
7 Atlantic. However, as revealed previously (Jiang and Yang, 2021), the net effect of all factors
8 related to the RM on the VSF in the North Atlantic is small.

9



1
 2 **Extended Data Figure 4 Evolution of meridional mass transport across 30°S in the**
 3 **intermediate-deep ocean. a, b**, Mass transports across 30°S (units: Sv) in the South Indo-
 4 Pacific and South Atlantic, respectively. The mass transport is obtained by integrating the
 5 meridional velocity over the depth of 2000-3000 m along 30°S. Positive (negative) value denotes
 6 northward (southward) transport.

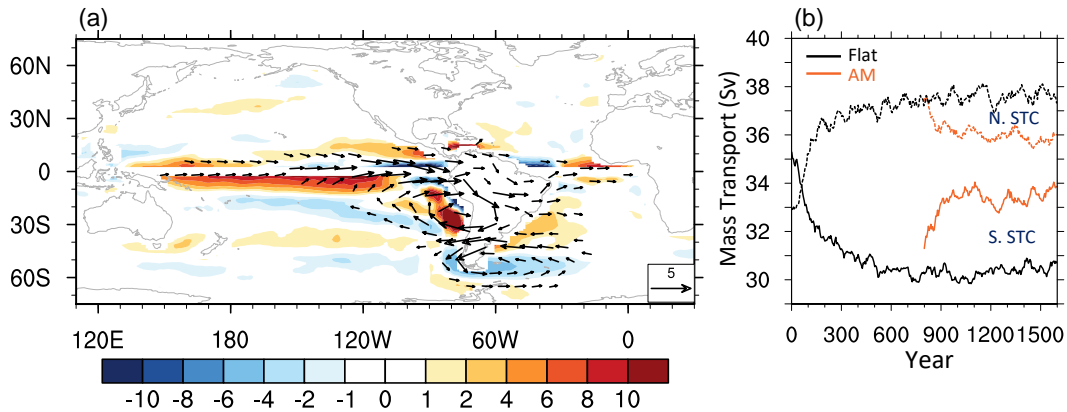
7 In the present climate (Real), the strong thermohaline circulation in the Atlantic corresponds to a
 8 strong southward mass transport in the intermediate-deep ocean of the South Atlantic, while the
 9 strong wind-driven circulation in the Indo-Pacific corresponds to a moderate northward mass
 10 transport in the South Indo-Pacific, as depicted by the grey curve in **b** and **a**, respectively.

11 In Flat, the strong southward mass transport occurs in the South Indo-Pacific due to the PMOC,
 12 while the corresponding mass transport in the South Atlantic is very weak due to weak wind-
 13 driven circulation, as depicted by the black curve in **a** and **b**.

14 In Exp TP, the PMOC is shut down and the AMOC is not fully established, resulting in weak
 15 meridional mass transports in both the South Indo-Pacific and Atlantic, as depicted by the dark-
 16 red curve in **a** and **b**.

Mountains' role in the global meridional overturning circulation

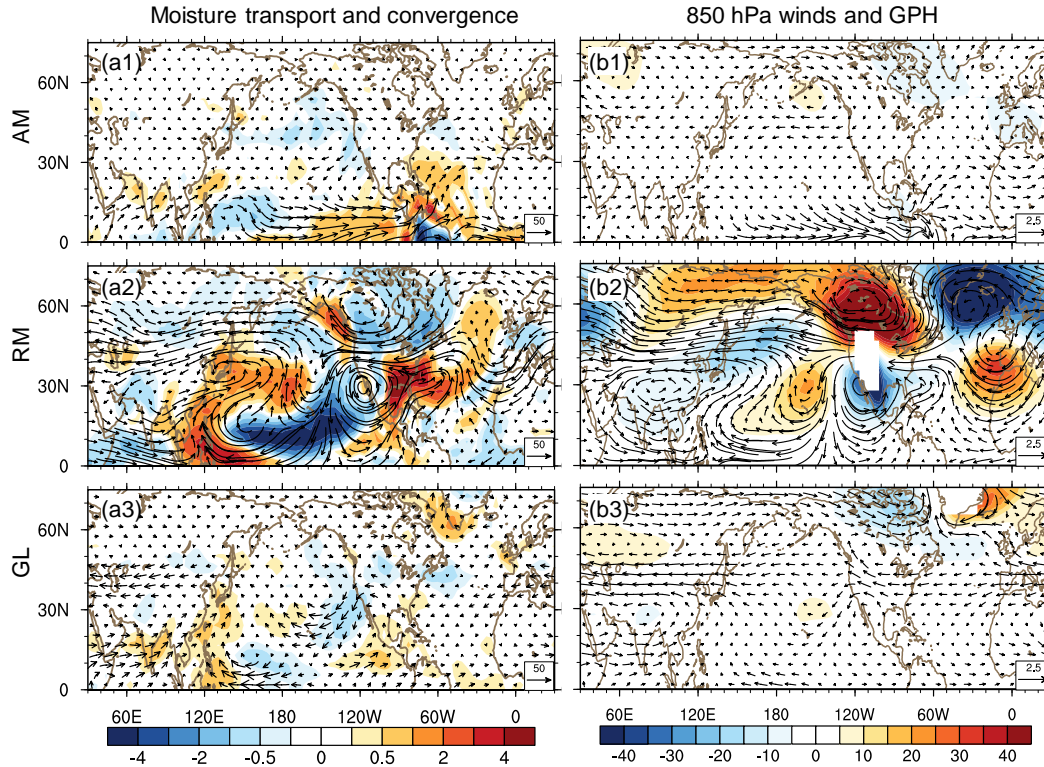
- 1 In TP+AT, the AMOC is fully established and the PMOC disappears completely. The situation of
- 2 meridional mass transport is similar to that in Real, as depicted by the purple curve in **a** and **b**.
- 3 In Exps AT and AM, the situations are similar to those in Flat.
- 4



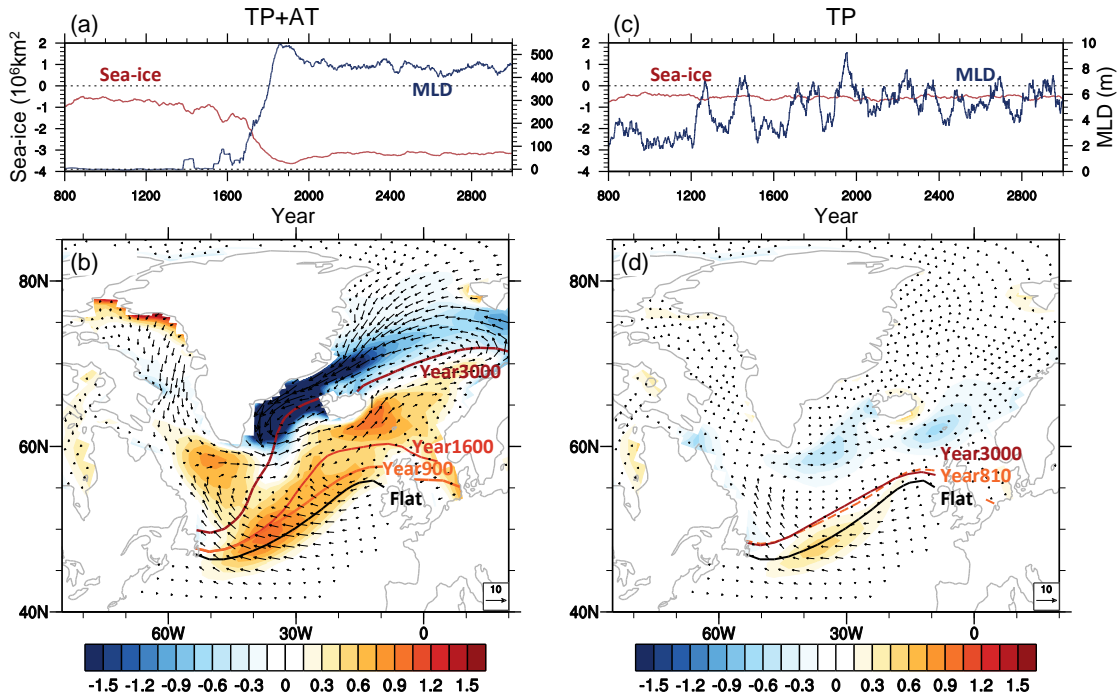
1
 2 **Extended Data Figure 5 Equilibrium changes in wind and Ekman pumping, and temporal**
 3 **evolution of the STCs in AM with respect to Flat. a,** Changes in surface wind (vector; units:
 4 m/s) and Ekman Pumping (shading; units: cm/day) with positive (negative) value for upwelling
 5 (downwelling). **b,** Evolution of STC (units: Sv) in Flat (black curve) and Exp AM (red curve) in the
 6 North Pacific and South Pacific, respectively. The dashed (solid) curves represent the northern
 7 (southern) STC, whose index is defined as the absolute maximum value of the STC in the upper
 8 500 m between 0° and 30°N (30°S and 0°).

9 Compared to Flat, the stronger southern STC in Exp AM (solid orange curve in **b**) is a result of
 10 stronger Ekman pumping in the tropical Pacific south of the equator (as depicted in **a**), which
 11 reinforces the southern branch of the PMOC in the South Pacific. The weaker northern STC in
 12 the North Pacific is due to the counteraction between the lower branch of the northern STC
 13 (southward) and the upper branch of the PMOC (northward).

14



1
 2 **Extended Data Figure 6 Equilibrium changes in atmospheric circulation and moisture**
 3 **transport. (a1-a3)** changes in vertically integrated moisture transport (vector; units: $\text{kg}\cdot\text{m}^{-1}\text{s}^{-1}$)
 4 and its convergence (shading; units: $10^{-5} \text{ kg}\cdot\text{m}^{-2}\text{s}^{-1}$), **(b1-b3)** geopotential height (shading; units:
 5 10 m) and wind (vector; units: m/s) at 850 hPa. **(a1-a3)** and **(b1-b3)** are changes in Exps AM,
 6 RM, and GL, respectively, with respect to Flat. The atmospheric moisture convergence
 7 (divergence) is plotted as positive (i.e., $-\nabla \cdot \vec{v}q > 0$) (negative, i.e., $-\nabla \cdot \vec{v}q < 0$), representing a
 8 gain (EMP<0) (loss, EMP>0) of ocean fresh water from (to) the atmosphere.
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 2 **Extended Data Figure 7 Changes in sea ice and MLD. (a, b)** are for TP+AT; and **(c, d)** for
 3 Exp TP. **a, c**, Evolutions of changes in sea-ice cover in the Arctic (units: 10^6 km^2 , left ordinate)
 4 and MLD in the subpolar Atlantic (units: m, right ordinate), with respect to Flat. The sea-ice cover
 5 is annual averaged. The MLD is for March and is calculated using the method of Large et al.
 6 (1997), which represents the site of the deepest vertical mixing and convection, and thus deep-
 7 water formation. **b, d**, Sea-ice margins (curve) at different stages, and equilibrium changes in
 8 VSF due to sea-ice formation or melting (shading; units: psu/year) and sea-ice velocity (vector;
 9 units: cm/s), with respect to Flat. Sea-ice margin is defined by 15% sea-ice fraction; and different
 10 colors show sea-ice margins in different stages of the uplift. Positive (negative) VSF means the
 11 ocean loses (gains) fresh water.

12 In TP+AT, the sea-ice retreat and MLD deepening in the subpolar Atlantic are similar to those in
 13 Flat2Real. However, in Exp TP, the sea ice retreats only slightly, and the MLD remains nearly
 14 unchanged.

Mountains' role in the global meridional overturning circulation