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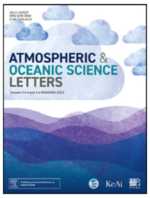

Investigating the effect of the Tibetan Plateau on the ITCZ using a coupled Earth system model

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ABSTRACT

The effect of the Tibetan Plateau (TP) on the Intertropical Convergence Zone (ITCZ) was investigated using a coupled Earth system model. The location of the ITCZ (in this work represented by the center of the tropical precipitation maximum) over the tropical Atlantic was found to be sensitive to the existence of the TP. Removing the TP led to a remarkable sea surface temperature (SST) cooling (warming) in the Northern (Southern) Hemisphere, which manifested clearly in the Atlantic rather than the Pacific. The locations of maximum precipitation and SST moved southwards clearly in the tropical Atlantic, forcing a southward shift of the atmospheric convection center, and thus the ITCZ. The shift in the ITCZ was also supported by the latitudinal change in the ascending branch of the tropical Hadley Cell, which moved southwards by about 2° in the boreal summer in response to the TP's removal. From the viewpoint of the energy balance between the two hemispheres, the cooling (warming) in the Northern (Southern) Hemisphere requires an enhanced northward atmospheric heat transport across the equator, which can be realized by the southward displacement of the ITCZ. This study suggests that the presence of the TP may have played an important role in the climatology of the ITCZ, particularly its location over the tropical Atlantic.

摘要

本文利用耦合地球气候系统模式研究了青藏高原对热带辐合带 (ITCZ) 的影响. 我们研究发现热带大西洋ITCZ的位置对青藏高原存在与否有明显的敏感性. 与目前真实情况相比, 移除青藏高原会导致北半球海面降温, 南半球海面升温. 这种海面温度变化在大西洋表现得尤为明显, 导致热带大西洋最大海温中心向南移动, 从而迫使大气对流中心向南移动, 即表现为ITCZ的南移. 相应地, 夏季热带大气Hadley环流的上升支也发生明显南移. 北 (南) 半球海洋变冷 (变暖) 这种态势要求增强跨赤道向北的大气经向热量输送, 从而维持各个半球的能量平衡, 而这需要ITCZ位置的南移才能实现. 本文研究表明, 青藏高原的存在在现今ITCZ气候态的形成中可能扮演了重要角色.

1. Introduction

As the highest highland region in the world, the Tibetan Plateau (TP) plays a crucial role in the formation of the climate pattern in the Northern Hemisphere (NH) (e.g., Yeh et al., 1957; Ye and Gao, 1979; Yanai et al., 1992; Meehl, 1994; , Wu, 2004, 2007; Wu et al., 2012; Yao et al., 2006, 2012; Cheng and Wu, 2007; Duan and Wu, 2008). It has substantial effects on Asian weather and climate, controlling the Asian summer monsoon system by providing thermal forcing (e.g., Yanai et al., 1992; Wang, 2006; Wu and Liu, 2012). Quantifying the TP effects on some key climate elements with Earth system models is an active area of research. Understanding its global effect will help us make a reasonable prediction of future climate change.

The Intertropical Convergence Zone (ITCZ) is a zonally elongated narrow band of deep convective cloud convergence. The ITCZ can be identified as the position of the maximum rainfall in the tropical ocean, and it has clear seasonal variations, typically with its location changing from 10°S in the boreal winter to 10°N in the boreal summer. What controls the ITCZ location has been studied comprehensively. Generally, there are two classes of opinions on the determining factor of the ITCZ position. One emphasizes the local effects on the ITCZ. Earlier studies emphasized that under the present continental distribution and local tropical coastlines, local feedbacks are the primary causes of the northern ITCZ location. These local feedbacks include sea surface temperature (SST)–stratus cloud positive feedback in the eastern Pacific and Atlantic (Xie and Philander, 1994; Philander et al., 1996), and

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positive feedback between deep convection and boundary-layer convergence over the warm pool of the western Pacific (Charney, 1971; Waliser and Somerville, 1994). The other focuses on the remote effects on the ITCZ. Recent studies have emphasized that nonlocal processes, such as hemispheric differences in extratropical and polar cloud cover (e.g., Hwang et al., 2013), and the extratropical ocean circulation (Frierson et al., 2013; Fuckar et al., 2013; Marshall et al., 2014), are important to determine the ITCZ location. From the viewpoint of global energy balance, Marshall et al. (2014) suggested that the mean ITCZ location is ultimately controlled by the meridional ocean heat transport (OHT) in the Atlantic, through mediating the cross-equatorial atmosphere heat transport (AHT). Donohoe et al. (2013) quantified that, from seasonal to glacial timescales, the change in cross-equatorial AHT (ΔAHT_{EQ}) correlates with the shift in the ITCZ location with a regression coefficient of about 3° of latitude per pegawatt (1 PW = 10^{15} Watts). That is, for a change of 1 PW AHT across the equator, the ITCZ responds with a 3° shift in the meridional direction. These studies highlight that a shift in the ITCZ is an indicator of readjustment in the energy balance between the two hemispheres and provides a quantitative benchmark to assess ITCZ displacement in response to a certain forcing.

This paper investigates a simple but important question: How does the TP affect the mean location of the ITCZ? The ITCZ can be thought of as a pivot point of the energy balance in the Earth climate system, which might be remarkably different with or without the TP. The role of the TP in this energy pivot point needs to be clarified.

2. Model and experiments

The Community Earth System Model (CESM), version 1.0, developed by the National Center for Atmospheric Research, was used to study the effect of the TP on the ITCZ via three topography experiments (Fig. 1). CESM is a fully coupled global climate model that provides simulations of the Earth's past, present, and future climate states. CESM1.0 has been widely used and validated by the community. The model grid employed in this study was T31_gx3v7. The atmospheric model used grid T31 with a horizontal resolution of approximately 3.75° × 3.75° and 26 vertical levels. The ocean model used grid gx3v7. It had 60 vertical levels and a uniform 3.6° spacing in the zonal direction. In the meridional direction, the grid was nonuniformly spaced: it was 0.6° near the equator, gradually increased to a maximum of 3.4° at 35°N/°S, and then decreased polewards. A detailed description can be found in Yang et al. (2015).

The "Real" experiment was a 2400-year control run with realistic topography (Fig. 1(a)), whose climatology was described in detail in Yang et al. (2015). "NoTibet" and "Flat" were two parallel simulations with the land elevation set at 50 m around the TP and globally, respectively (Fig. 1(b, c)). These two simulations started from the year 2000 of Real and were integrated for 400 years with modified continents. All other conditions were the same as in Real, complying with the standard configuration and a preindustrial CO_2 level of 285 ppm. The averages of the last 100 years of outputs were used for analysis unless stated otherwise. Student's *t*-test was used to examine the statistical significance of the results. It was found that most changes were significant at the 95% confidence level, which was expected because altering the TP topography induces strong mechanical forcing and strong responses around the globe.

3. Changes in the ITCZ, precipitation, and SST

The experiments showed that the TP does affect the location of the ITCZ over the tropical Atlantic, but seems to have little effect on the ITCZ over the tropical Pacific. In this study, we defined the mean ITCZ location using the tropical precipitation center. This definition also coincided with the convergence center of surface winds. Fig. 2 shows the annual mean and seasonal mean locations of the ITCZ in the Real, NoTibet and Flat experiments. In terms of the annual mean, the tropical precipitation pattern was almost unchanged without the TP (Fig. 2(a)). The precipitation pattern in Flat became slightly more symmetric about the equator, with respect to Real (Fig. 2(d)). From the annual mean viewpoint, changes in both the location and intensity of the ITCZ were not clear in both cases.

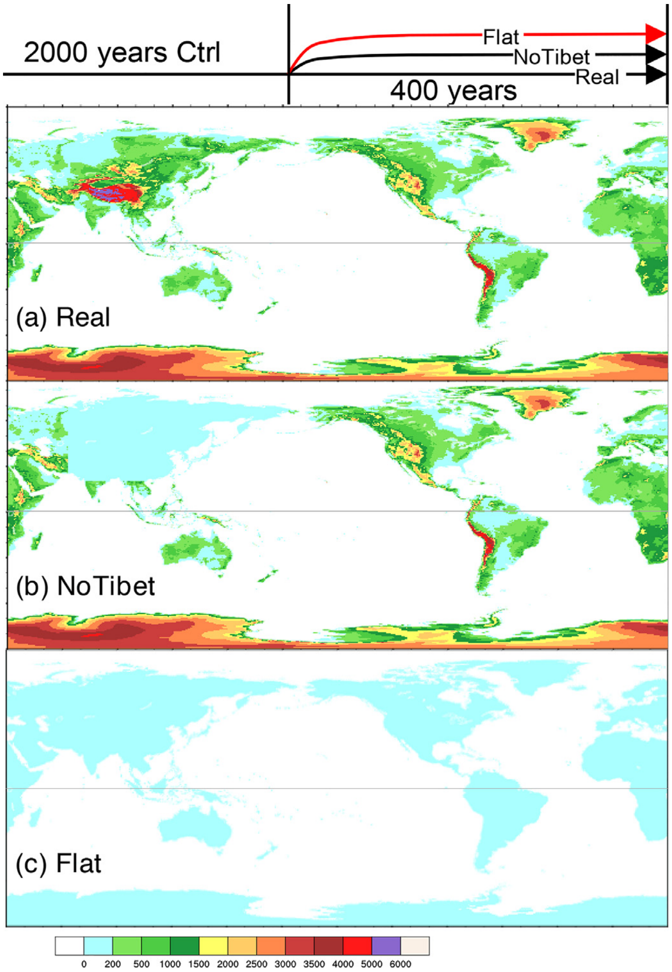

Fig. 1. Configuration of the topography in the coupled model experiments: (a) control experiment with realistic topography (Real); (b) experiment without the Tibetan Plateau (NoTibet); (c) experiment with flat topography globally (Flat). The uppermost panel shows the integration lengths of the experiments.

The seasonal location and intensity of the ITCZ are shown in Fig. 2(b, c) and Fig. 2(e, f). It is clear that the precipitation change over the TP region was the most remarkable. The summer precipitation north of the equator was reduced (Fig. 2(b) and Fig. 3(a)) because removing the heat pump of the TP shut down the ascending motion over the TP, while the winter precipitation over the TP remained almost unchanged (Fig. 2(c)). The TP, however, had remote effects on the summer precipitation over the far eastern Pacific near the coast of central America and the tropical Atlantic. A dipole-like change occurred over these regions when removing the TP, reducing the precipitation to the north of the equator and enhancing it to the south (Fig. 3(a)). However, the effect of the TP on remote regions appeared to be insignificant in terms of winter precipitation (Fig. 2(c)). The cross-equatorial surface winds (figure not shown) were also changed accordingly in these seasons without the TP. Of course, the global topography was critical for the precipitation pattern and surface winds in the tropics in summer (Fig. 2(e) and Fig. 3(b)), which were very similar to those in NoTibet, suggesting the most important role among the world's continental mountain regions is that played by the TP.

The changes in the summer precipitation pattern in NoTibet and Flat can be well explained by the changes in the summer SST pattern (Fig. 3),

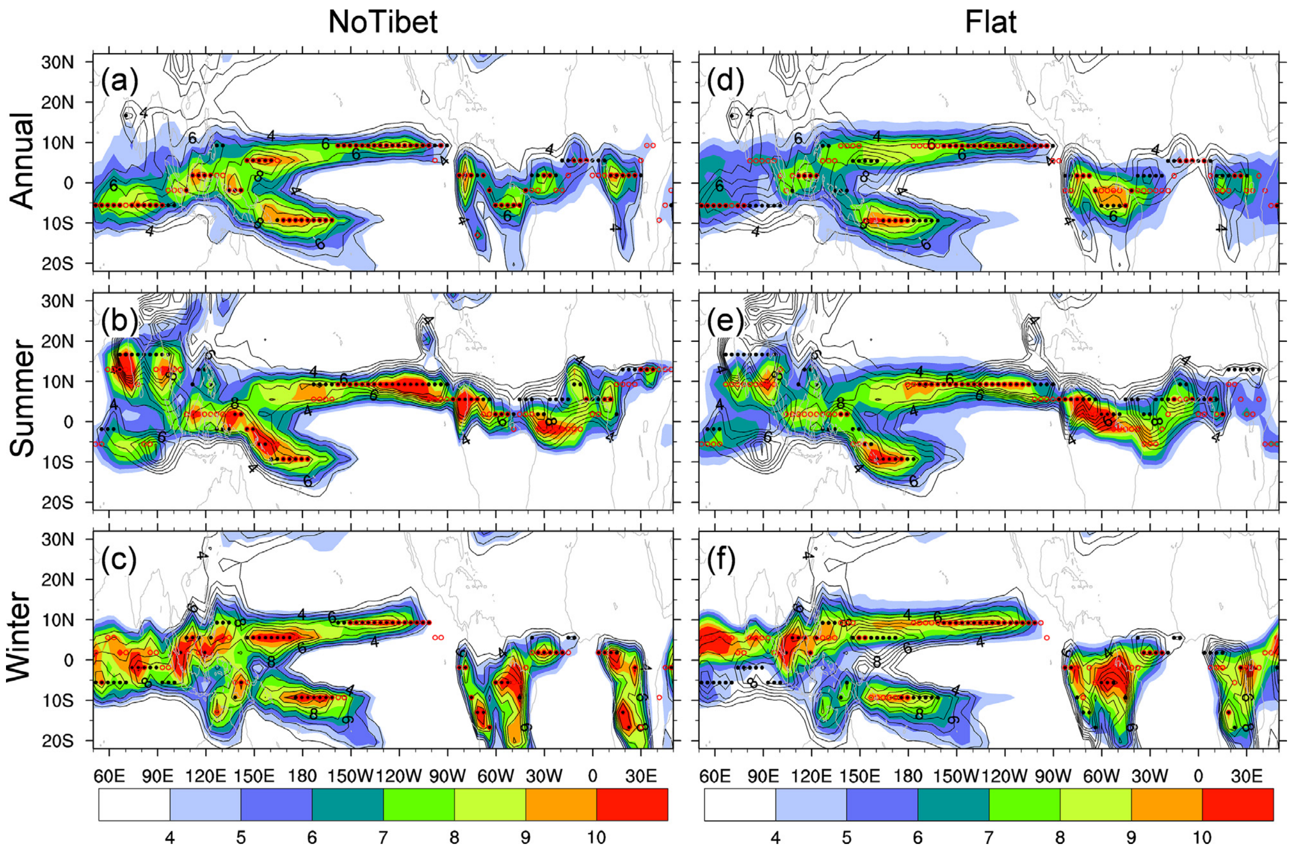

Fig. 2. Precipitation (units: mm yr^{-1}) and the location of the ITCZ (defined by the maximum precipitation in the tropics): (a) annual mean precipitation in Real (contours) and NoTibet (shading), in which the black dots and red circles mark the ITCZ in Real and NoTibet, respectively; (b, c) similar to (a) except for boreal summer (June–July–August) and boreal winter (December–January–February), respectively, in which contours (shading) denote(s) the summer mean precipitation in Real (NoTibet); (d–f) similar to (a–c) except for Real (contours) and Flat (shading).

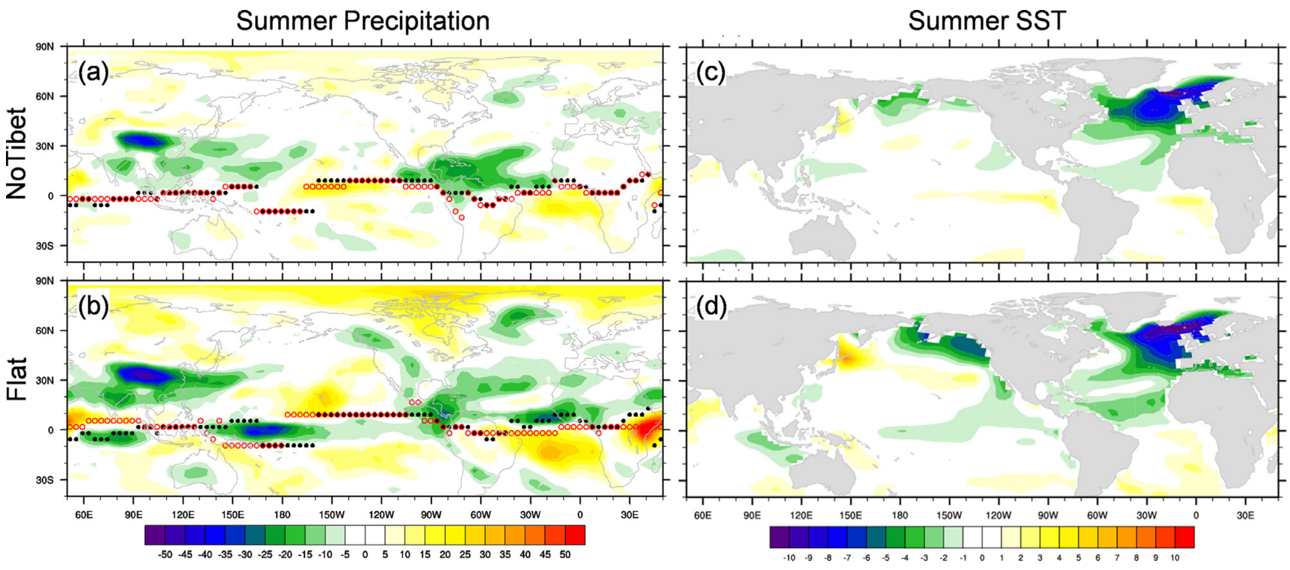

Fig. 3. Changes in precipitation (units: mm yr^{-1}) and SST (units: °C): (a, b) summer precipitation change in NoTibet and Flat, respectively, with respect to Real; (c, d) summer SST change in NoTibet and Flat, respectively, with respect to Real. In (a, b), black dots represent the ITCZ in Real, and red circles mark the ITCZ in NoTibet and Flat, respectively.

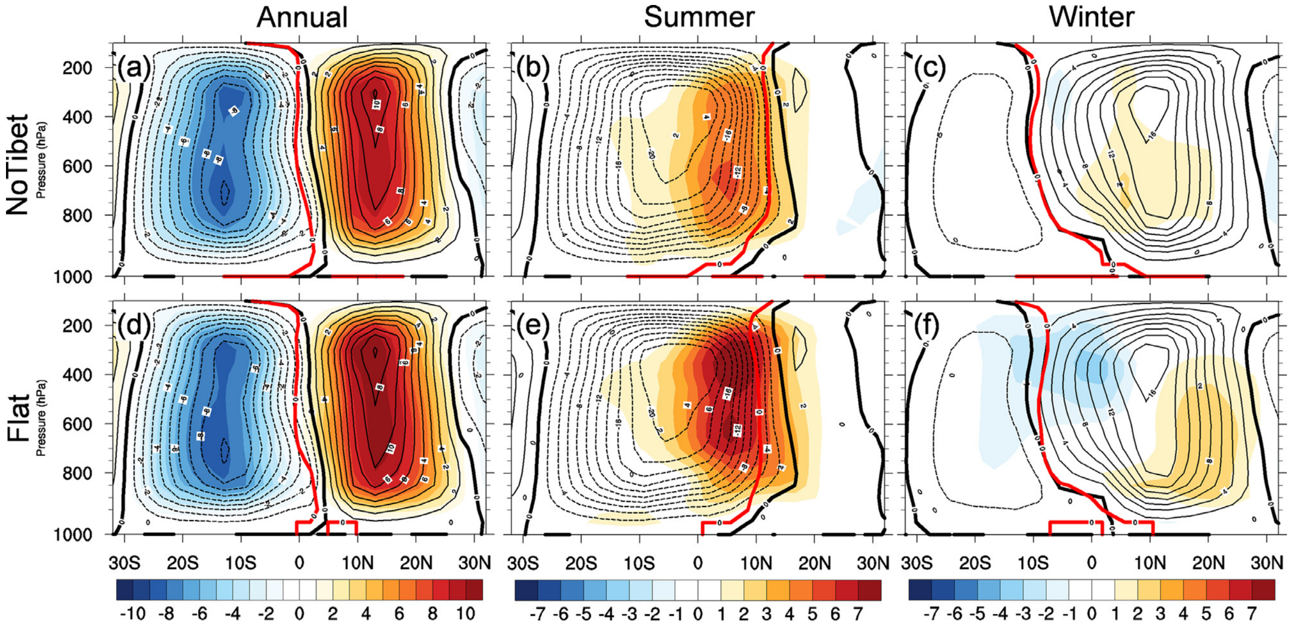

Fig. 4. The HC (units: 10^{10} kg s^{-1}) and its change: (a) annual mean HC in Real (contours) and NoTibet (shading), in which the thick black and red curves mark the zero streamfunction in Real and NoTibet, respectively; (b) summer mean HC in Real (contours) and its change in NoTibet (shading), in which the thick black and red curves mark the zero streamfunction in summer in Real and NoTibet, respectively; (c) similar to (b) except for winter; (d–f) similar to (a–c) except for Flat.

particularly those over the tropical Atlantic. There was strong SST cooling in the North Atlantic and northeastern Pacific (Fig. 3(c, d)), while south of the equator there was weak SST warming. The SST changes were significant at the 95% confidence level. For visual clarity, we do not show the significance test results in Fig. 3 or in other figures in this paper. The SST cooling (warming) in the north (south) was most remarkable in the Atlantic. Therefore, the atmospheric convection belt and thus the precipitation center in the tropical Atlantic had to move southwards, following the southward displacement of the ocean heating maximum. These changes in SST, surface ocean heat flux, as well as other important climate quantities in NoTibet and Flat have been deliberated in Yang et al. (2020) and Yang and Wen (2020). Removing the TP can eventually shut down the Atlantic meridional overturning circulation (AMOC) in the Atlantic, reducing the northward OHT and leading to a strong cooling in the North Atlantic and a weak warming in the Southern Hemisphere (SH) (Yang and Wen, 2020), as seen in Fig. 3(c, d). The ITCZ over the tropical Atlantic has to move southward so that more AHT can be transported northwards to compensate for the cooling in the NH.

4. Hadley cell and AHT changes

The location and intensity of the ITCZ are collocated with the ascending branch of the Hadley cell (HC). A shift in the ITCZ corresponds to a shift in the zero streamfunction line of the HC (Donohoe et al., 2013). Fig. 4 shows the HC and its change in different seasons in our experiments. The zero streamfunction line in the deep tropics (Fig. 4) can roughly designate the vertical structure of the ITCZ. Due to the lack of topography-induced ascending motion, the summer HC was weakened by ~10% in NoTibet (Fig. 4(b)) and by ~20% in Flat (Fig. 4(e)), mainly to the north of the equator, in agreement with reduced precipitation there. Accordingly, the zero streamfunction line at 500 hPa was shifted southwards by ~3° in NoTibet and by ~5° in Flat. However, the winter HC did not change much, in both intensity and zero streamfunction location (Fig. 4(c, f)). The presence or absence of the TP had little effect on the winter HC (Fig. 4(c)). The change in the annual mean HC mainly reflected the change in the summer HC, with a slightly weaker (stronger) HC in the south (north) branch and a southward shift of the zero streamfunction line by about 3° at 500 hPa in both NoTibet and Flat (Fig. 4(a, d)).

The shift in the zero streamfunction line is significant in summer. It can reflect the shift in the ITCZ but the two are not equivalent. In fact, the ITCZ occurs substantially equatorward of the location of the zero streamfunction (Lindzen and Hou, 1988; Donohoe et al., 2013). The maximum convective precipitation occurs where the meridional gradient of the overturning streamfunction is the greatest according to the continuity equation. We can clearly see that the latter was located southwards of the zero streamfunction line in summer, where the maximum change in the HC occurred (Fig. 4(b, e)). In fact, Donohoe et al. (2013) obtained a simple scaling among the shift in the ITCZ, ΔAHT_{EQ}, and the shift in the zero streamfunction line at 500 hPa. For 1 PW ΔAHT_{EQ}, the ITCZ shifts about 2.4°–3.0° and the zero streamfunction line shifts about 9° at 500 hPa. We used these scalings to judge the significance of the ITCZ shift in our experiments.

Fig. 5 shows the mean meridional heat transport (MHT) and changes in AHT. The annual mean MHT showed a near antisymmetric structure about the equator (Fig. 5(a)), consistent with previous studies (Trenberth and Caron, 2001). In both NoTibet and Flat, the Atlantic OHT was weakened substantially, due to reduced AMOC (Yang and Wen, 2020). Strong cooling occurred in the North Atlantic and mild warming occurred in the SH (Fig. 3(c, d)). The atmosphere responded to ocean changes with strong warming in the SH and cooling in the NH. The AHT was enhanced towards the NH, compensating for the weakened northward OHT (Yang and Wen, 2020). This was particularly clear in summer. Since the shift in the ITCZ is explicitly related to cross-equatorial AHT, here, we focused on the AHT in the tropics (Fig. 5(b–f)). The AHT consists of latent energy (LE; blue curves in Fig. 5(b, c)) and dry static energy (DSE; red curves). These two components were out of phase in the tropics, and the net AHT at the equator was dominated by the DSE. The seasonal variation in AHT at the equator (Fig. 5(b)) was closely correlated with the seasonal shift in the ITCZ (Fig. 2(b, e)) and HC (Fig. 4(b, e)).

Without the TP, the ΔAHT_{EQ} was 0.3 PW in summer (Fig. 5(e)) and almost zero in winter (Fig. 5(f)). This mild AHT change in summer can shift the ITCZ southwards by ~0.8°, based on the scale of 2.4° per PW given by Donohoe et al. (2013). The northward LE transport was weakened owing to the lack of ascending motion in the TP region (Fig. 5(e);

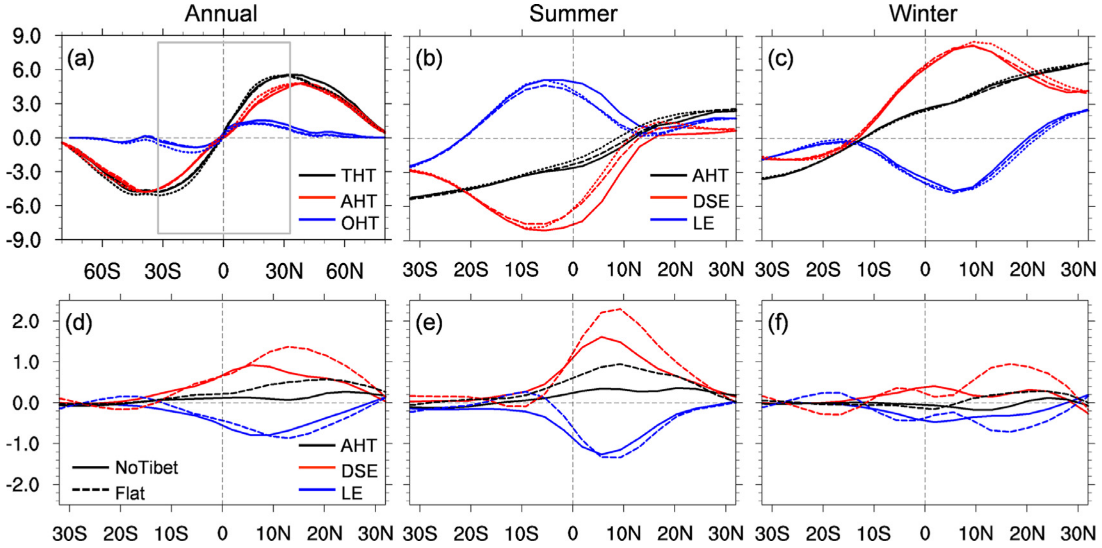

Fig. 5. (a) Annual mean MHT, in which the black, red, and blue lines denote the total heat transport (THT), AHT, and OHT, respectively; and the solid, dashed, and dotted lines refer to the Real, NoTibet, and Flat experiments, respectively. (b) Summer mean AHT (black), with the red and blue lines denoting the atmospheric dry static energy (DSE) and latent energy (LE) transport, respectively. (c) Similar to (b) except for winter. In (b, c), the solid, dashed, and dotted lines refer to the Real, NoTibet, and Flat experiments, respectively. (d) Annual mean AHT changes in the NoTibet (solid line) and Flat (dashed line) experiments, with the black, red, and blue lines denoting the changes in net AHT, DSE, and LE, respectively. (e, f) Similar to (d) except for summer and winter, respectively.

solid blue curve). However, the northward DSE transport was enhanced because of the lack of blocking of the summer monsoon (Fig. 5(e); solid red curve). These two components compensated largely each other in both summer and winter, leaving a weak $\Delta\mathrm{AHT}_{\mathrm{EQ}}$ (the annual mean change was only 0.05 PW; Fig. 5(d)). Therefore, the energy balance pivot point, i.e., the ITCZ, shifted slightly in boreal summer. The TP appears to play a role in the global energy balance.

More remarkable change in Flat led to a bigger change in AHT than in NoTibet (Fig. 5(e, f); dashed curves). The $\Delta\mathrm{AHT}_{\mathrm{EQ}}$ was approximately 0.5 PW in summer (Fig. 5(e)) and −0.1 PW in winter (Fig. 5(f)). Here, it is noticeable that the meridional structures of AHT change were similar in NoTibet and Flat, except that the modification in Flat caused stronger responses in the energy balance. For example, the net peak ΔAHT in Flat was about twice that in NoTibet (Fig. 5(e)). The topography does affect the ITCZ climatology in summer, under the situation of constant land–ocean contrast in the two hemispheres.

In summer, a large amount of cross-equatorial AHT can be attributed to the strong Somali jet associated with the Asian summer monsoon (Heaviside and Czaja, 2012), which is in turn related to the summer ITCZ location. Air with relatively low moist static energy is transported northwards at low levels by the Somali jet, while air with higher moist static energy is returned at high levels, which accounts for a southward AHT of ~0.6 PW across the equator in summer. Therefore, the Somali jet contributes greatly to the summer northerly ITCZ. In our topography experiments, the Somali jet was only slightly changed in NoTibet and weakened by 50% in Flat (figures not shown).

In our experiments, the enhanced northward AHT resulted from the weakened northward OHT, due to the weakened AMOC (Yang and Wen, 2020). This is qualitatively consistent with previous studies (Broccoli et al., 2006; Frierson et al., 2013; Fuckar et al., 2013; Marshall et al., 2014). The $\Delta\mathrm{AHT}_{\mathrm{EQ}}$ was strong enough to displace the ITCZ over the tropical Atlantic because of the weakening of the AMOC, although it was not strong enough to displace the ITCZ over the tropical Pacific. The enhanced northward AHT across the equator has to compensate for the southward OHT change, because of the constraint of the global energy balance (Yang et al., 2016). On decadal and longer timescales, this compensation is excellent when neglecting the changes in climate feedbacks (Shaffrey and Sutton, 2006; Vellinga and Wu, 2008; Yang et al., 2016). The $\Delta\mathrm{AHT}_{\mathrm{EQ}}$ reflects the shift in the ITCZ very well. The location of the ITCZ can be viewed as a pivot point of an energy balance between the two hemispheres, and should play a critical role in the global-scale energy compensation between the AHT and OHT.

5. Conclusion and discussion

In this study, we investigated the effect of TP uplift on the location of the ITCZ. We conclude that the vast continental topography of the TP can affect the energy balance between the two hemispheres. Specifically, the uplift of the TP mainly affects the summertime location of the ITCZ over the Atlantic basin, but has little effect over the Pacific basin. The TP is one of key factors in determining the climatology of the ITCZ. Of course, this conclusion is tentative and contingent on the model resolution employed. In a high-resolution coupled model, we may see a clearer shift in the ITCZ in both summer and winter, and in both the tropical Pacific and Atlantic, in accordance with the scale assessment of Donohoe et al. (2013).

The ITCZ acts like a pivot point of an energy balance in the Earth system. This pivot point appears to be mainly determined by the land–ocean contrast in the two hemispheres at present, which is supported by the results of the Flat experiment (Fig. 2(d–f)). With the uplift of topography in the NH, more moisture will converge towards high mountains, particularly over the TP region (Fig. 2(b)). The Asian summer monsoon will be greatly enhanced in the presence of the TP (Wu and Liu, 2012). In our experiments, we did not consider the changes in surface albedo and vegetation (Zhao et al., 2015), which may cause significant changes in local climate feedback and radiative balance at the top of the atmosphere, and ultimately affect the energy balance between the two hemispheres. In addition, the ITCZ variability was not examined in this study. The internal coupled modes of the Earth system may be different with or without the TP, which could potentially affect the location of the ITCZ. Detailed investigation into these questions through experiments with high-resolution atmospheric models is urgently needed.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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