Optimal Meridional Positions of the Tibetan Plateau for Intensifying the Asian Summer Monsoon

JUNBIN WANG,a,b SONG YANG,a,b,c ZHENNING LI,d MENGMENG LU,b,e ZIQIAN WANG,a,b,c AND GUOXIONG WU f

a School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China
b Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China
c Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, China
d Division of Environment and Sustainability, Hong Kong University of Science and Technology, Hong Kong, China
e State Key Laboratory of Severe Weather and Institute of Climate System, Chinese Academy of Meteorological Sciences, Beijing, China
f State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 22 August 2021, in final form 9 February 2022)

ABSTRACT: The Tibetan Plateau (TP) exerts significant influences on Earth’s climate, and it is commonly accepted that the plateau enhances the intensity of the Asian summer monsoon (ASM). However, since the TP is located in the subtropics and its climate responses consist of both tropical and extratropical characteristics, a natural question to ask is how the TP would affect the ASM if it were shifted to different latitudes. A series of experiments with a state-of-the-art Earth system model demonstrates that the current location of the TP is not optimal for intensifying the ASM. When the TP is moved southward, the tropical South Asian monsoon (SAM) intensifies, associated with strengthened thermally driven atmospheric circulation, while the South Asian monsoon weakens. When the TP is located in higher-than-current latitudes, on the other hand, the SAM weakens and the EAM intensifies. In particular, when the TP shifts northward by 8° of latitude, the Asian continent witnesses the heaviest summer monsoon rainfall. Changes in the meridional location of the plateau cause substantial differences in atmospheric circulation and water vapor transport, and thus in monsoon rainfall.

SIGNIFICANCE STATEMENT: The existence of the Tibetan Plateau (TP) enhances the Asian summer monsoon; however, the optimal positions of the TP for affecting the monsoon and its various components are unknown. This study shows that the different TP locations exert different influences on the monsoon. When the TP is shifted southward, the South Asian monsoon intensifies while the East and Southeast Asian monsoons weaken. When the TP is shifted northward, the South Asian monsoon weakens constantly while the East and Southeast Asian monsoons strengthen before they become weaker when the plateau is shifted by 12° of latitude. Much of the Asian continent would witness the heaviest monsoon rainfall when the TP is shifted northward by 8° of latitude.

KEYWORDS: Monsoons; Climate models; Climate variability

1. Introduction

Located in the subtropical central-eastern Eurasian continent, the Tibetan Plateau (TP) is the highest plateau of the world with an average elevation above 4000 m. Since the temperature lapse rate on the mountain surface is much lower than that in the air above, the temperature difference between the mountain surface and the free atmosphere widens with the increasing altitude. Meanwhile, combined with the large amount of solar radiation, the sensible heat over the TP increases rapidly in summertime, enabling the plateau to become a huge heat source (Flohn 1957; Yeh et al. 1957; Ye and Wu 1998). According to the theory of the “TP sensible-heat-driven air pump” (TP-SHAP) (Wu et al. 2007), the sensible heat over the TP surface acts as a heat pump to uplift water vapor from the lower troposphere to the upper atmosphere to form clouds and rainfall of the Asian summer monsoon (ASM). In addition, based on the theory of potential vorticity conservation (Gill 1980; Hoskins 1991; Yanai et al. 1992), the thermal effect of the TP generates a large-scale cyclonic vortex, through which water vapor is transported to Northeast Asia, causing torrential rainfall associated with the East Asian summer monsoon. Thus, the TP is also recognized as a key component of the ASM system (e.g., Chen and Bordoni 2014; He et al. 2015; Hu and Duan 2015; Liu et al. 2007; Lu et al. 2021; Ma et al. 2017; Wang et al. 2016; Wu et al. 2009, 2012a).

The mountain uplift effect of the TP plays an important role in transporting dust aerosols from the surrounding area. Specifically, the dust from the Taklimakan Desert can be lifted to the northern slope of the TP by strong upslope winds and indirectly lead to further developed clouds over the TP. Associated with the eastward movement of the clouds polluted by the Taklimakan dust, rainfall over the downstream regions (e.g., northern China) would intensify significantly (Liu et al. 2020a; Tan et al. 2021). In addition, the variation of the downstream climate over East Asia can be attributed to the interaction of the TP with the westerlies. Chiang et al. (2020) demonstrated that the seasonal migration of the westerlies could lead to seasonally varying downstream circulation and result in the seasonality of the East

Denotes content that is immediately available upon publication as open access.
Asian summer monsoon. Kong and Chiang (2019) found that the timing and duration of the mei-yu were mainly controlled by the meridional position of the westerlies relative to the TP. In addition, Liu et al. (2020b) showed that meridional shift of the midlatitude subtropical westerly jet stream could trigger flooding or droughts over northern China.

Because of the TP’s complex topography and surface conditions, sufficient observational records can hardly be obtained over the TP (Duan et al. 2014), and numerical modeling is an effective method to improve our understanding of the climate effect of the plateau. Based on the results from an atmospheric general circulation model, Hahn and Manabe (1975) demonstrated that the TP was essential for maintaining the South Asian low pressure system and the southwesterly monsoon flow by comparing the model simulations with and without mountains. Kitoh (2004) showed that the baiu rainfall intensified with increasing mountain uplift in a global ocean–atmosphere coupled model. Also using an ocean–atmosphere coupled model, Abe et al. (2013) demonstrated the importance of the TP for the onset of South Asian monsoon. Furthermore, Lu et al. (2017, 2018) recently suggested that the thermal condition of the TP can influence the “upstream” climate over West Asia, North Africa, southern Europe, and even the North Atlantic Ocean based on experiments with a fully coupled model.

Most previous studies have been focused on the climate effects of the TP’s primary position, and much less effort has been devoted to understanding the impacts of the specific positions of the TP. In the tropics, the Coriolis effect is small, and thus the divergent part of atmospheric circulation is relatively more dominant. Under this regime, a large terrain mainly produces thermally driven atmospheric circulations. In the higher latitudes, the Coriolis effect increases and the rotational part of atmospheric motion becomes more important, and thus a large terrain mainly induces Rossby wave trains. Since the TP is located in the subtropics, it exerts the combined effects of both divergent and rotational parts and produces very complicated patterns of climate response. Experiments with meridionally repositioned TP achieved by a state-of-the-art Earth system model are conducted to broaden our horizons on the different portions of atmospheric motion to the changes in the TP’s meridional positions. We also explore the optimal positions of the TP that exert the strongest impacts on the Asian monsoon.

The paper is organized as follows. Section 2 provides a description of the model and experiment design. In section 3, the effects of meridionally relocated TP on the various regional summer monsoon systems, as well as the related physical processes, are discussed. Conclusions and a further discussion are given in section 4.

2. Data, model experiments, and analysis methods

a. Data and model

The ERA5, the most updated dataset created by the European Centre for Medium-Range Weather Forecasts (ECMWF), is used in this study. Specifically, the temperature, precipitation, and wind fields for the period of 1979–2020 are analyzed.

The model applied is the Community Earth System Model version 1.2.2 (CESM 1.2.2) from the National Center for Atmospheric Research (NCAR), which is a fully coupled global climate model that can provide state-of-the-art simulations of climate states. The atmospheric resolution of the CESM CAM4 is $1.9^\circ \times 2.5^\circ$ in longitude and latitude with 26 vertical levels, and oceanic resolution of the CESM POP2 is about 1°. The values of solar forcing, aerosol, carbon dioxide, and ozone concentration are all fixed at the levels of year 2000 in all experiments.

b. Experiment design

To explore the effects of the meridionally relocated TP, we conduct a series of coupled numerical experiments. Figure 1 shows the topography height among the control run (CON) and six sensitivity experiments. In experiment TP_S4, we move the main part of the TP (with altitude above 1500 m) to the south by increments of 4° of latitude; in TP_N4, TP_N8, TP_N12, and TP_N16, the main portion of the TP is shifted to the north by 4°, 8°, 12°, and 16° of latitude, respectively. Due to the high topography around the TP, replacing the original position of the TP with a 0-m plain would create a lot of cliffs and cause simulation errors in these complex terrains. To ensure the model to function properly, we replace the primary position of the TP with a flat land of 1000 m. Both the control run and the sensitivity runs are integrated for 230 years, and the output from the first 200 years is considered as the model spinup and the results of years 201–230 are analyzed. The configuration of the model experiments is also summarized in Table 1.

c. Analysis methods

Four commonly applied, physics-based dynamical indices of the ASM are used to grasp the main monsoon circulation patterns among the various experiments. The Webster and Yang (WY) index (Webster and Yang 1992) measures the variation of large-scale ASM circulation, while the South Asian monsoon (SAM) index by Goswami et al. (1999), the East Asian monsoon (EAM) index by Lau et al. (2000), and
the Southeast Asian monsoon (SEAM) index by Wang and Fan (1999) evaluate the variations of summer monsoon circulations over South Asia, East Asia, and Southeast Asia, respectively. That is, these monsoon indices, whose definitions are provided in Table 2, are applied to depict the changes in the various components of the ASM.

When considering the overall impact of the meridionally relocated TP on the total monsoon rainfall over the whole Asian region, simply adding up the monsoon rainfall in South Asia and East Asia (the main regions of Asian summer monsoon rainfall) seems to be an easy way. However, as the magnitude of monsoon rainfall in South Asia is much larger than that in East Asia, a simple summation would result in a poor representation of the rainfall variability in East Asia. A more reasonable approach is to first calculate the change rates of the rainfall in South Asia and East Asia in each experiment relative to the same regions in the CON separately, and then add them up to obtain the total relative change rate. Taking the TP_S4 experiment as an example, the total relative change rate of monsoon rainfall is calculated as follows:

**TABLE 1. Configuration of model experiments.**

<table>
<thead>
<tr>
<th>Experiment abbreviation</th>
<th>Experiment design</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>External forcing at the level of year 2000, 230-yr integrated, output from years 201 to 230 for analysis</td>
</tr>
<tr>
<td>TP_S4</td>
<td>As in CON, but the topography of the TP with altitude above 1500 m is moved to the south by 4° of latitude</td>
</tr>
<tr>
<td>TP_N4</td>
<td>As in CON, but the topography of the TP with altitude above 1500 m is moved to the north by 4° of latitude</td>
</tr>
<tr>
<td>TP_N8</td>
<td>As in CON, but the topography of the TP with altitude above 1500 m is moved to the north by 8° of latitude</td>
</tr>
<tr>
<td>TP_N12</td>
<td>As in CON, but the topography of the TP with altitude above 1500 m is moved to the north by 12° of latitude</td>
</tr>
<tr>
<td>TP_N16</td>
<td>As in CON, but the topography of the TP with altitude above 1500 m is moved to the north by 16° of latitude</td>
</tr>
</tbody>
</table>

**TABLE 2. Definitions of four commonly applied dynamical monsoon indices for various summer monsoon components.**

<table>
<thead>
<tr>
<th>Index</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>WY</td>
<td>Vertical shear of zonal winds at 850 and 200 hPa over tropical southern Asia: $U_{850}(5^o-20^oN, 40^o-110^oE) - U_{200}(5^o-20^oN, 40^o-110^oE)$</td>
</tr>
<tr>
<td>SAM</td>
<td>Vertical shear of meridional winds at 850 and 200 hPa over South Asia: $V_{850}(10^o-30^oN, 70^o-110^oE) - V_{200}(10^o-30^oN, 70^o-110^oE)$</td>
</tr>
<tr>
<td>SEAM</td>
<td>Horizontal shear of 850-hPa zonal wind over Southeast Asia: $U_{850}(5^o-15^oN, 90^o-130^oE) - U_{850}(22.5^o-32.5^oN, 110^o-140^oE)$</td>
</tr>
<tr>
<td>EAM</td>
<td>Horizontal shear of 200-hPa zonal wind over East Asia: $U_{200}(40^o-50^oN, 110^o-150^oE) - U_{200}(25^o-35^oN, 110^o-150^oE)$</td>
</tr>
</tbody>
</table>
Total relative change rate = \frac{\text{Pre}_{\text{SA}}(\text{TP}_{\text{S4}}) - \text{Pre}_{\text{SA}}(\text{CON})}{\text{Pre}_{\text{SA}}(\text{CON})} + \frac{\text{Pre}_{\text{EA}}(\text{TP}_{\text{S4}}) - \text{Pre}_{\text{EA}}(\text{CON})}{\text{Pre}_{\text{EA}}(\text{CON})}.

Here, \text{Pre}_{\text{SA}}(\text{TP}_{\text{S4}}) and \text{Pre}_{\text{SA}}(\text{CON}) represent the South Asian (5°–30°N, 60°–105°E) monsoon rainfall in TP_{S4} and CON, while \text{Pre}_{\text{EA}}(\text{TP}_{\text{S4}}) and \text{Pre}_{\text{EA}}(\text{CON}) represent the East Asian (20°–50°N, 105°–135°E) monsoon rainfall in TP_{S4} and CON.

3. Results

a. Validation of results from the model’s control experiment

The JJA climatological patterns of precipitation, 850-hPa winds, 200-hPa temperature, and 200-hPa winds in observations and the CON run are shown in Fig. 2 to evaluate the model simulation. Overall, the model can well capture the distributions of precipitation obtained from the ERA5, although the magnitude of precipitation over the northeastern Arabian Sea and eastern TP is slightly overestimated (Figs. 2a,b). Moreover, compared to observations, the model is able to simulate the warm center over the western TP, although the modeled center is somehow too strong (Figs. 2c,d). Significantly, the model shows excellent

FIG. 2. Observed climatology of (a) JJA rainfall (shading; mm day⁻¹) and 850-hPa winds (vectors; m s⁻¹), as well as (c) JJA 200-hPa temperature (shading; K) and 200-hPa winds (vectors; m s⁻¹), for the period of 1979–2020. (b),(d) As in (a) and (c), but for the period of 201–230 in CON run. The topography of TP above 1500 m is marked with black contours.

FIG. 3. Normalized curves of the monsoon indices in various experiments. The black, red, blue, and green lines respectively represent the WY, SAM, SEAM, and EAM indices.
performance in simulating the circulation patterns in both the lower troposphere (850 hPa) and the upper troposphere (200 hPa), which is advantageous for our subsequent analysis of the ASM based on dynamical indices. In summary, the NCAR CESM provides reasonably realistic pictures of the thermal center of the TP, the ASM circulation, and the monsoon rainfall, and is therefore suitable for our investigations of the climate effect of the TP on the Asian summer monsoon.

b. Changes in summer monsoon indices and rainfall patterns

Figure 3 shows the features of the four monsoon indices in various experiments. It is interesting to note that the SAM index exhibits a linear decreasing trend from TP_S4 to TP_N16, meaning that the South Asian summer monsoon become stronger (weaker) when the TP is relocated southward (northward) in the tropics (extratropics). The large-scale tropical Asian monsoon measured by the WY index changes little when the TP is moved southward from the current position to TP_S4; however, it weakens when the TP is relocated northward especially from CON (the current “real” position) to TP_N4, and from TP_N4 to TP_N8. On the other hand, the EAM weakens when the TP is placed southward to the tropics; however, it strengthens when the plateau is moved northward from the CON position and obtains its largest intensity when the TP is relocated northward by 8° of latitude as in TP_N8. Nevertheless, the EAM weakens when the TP is moved farther toward the extratropics, from TP_N8 to TP_N16. Figure 3 also shows that the change in the SEAM as a response to the TP shift is similar to that in the EAM.

We further evaluate the effect of the TP’s meridional relocation on the summer monsoon rainfall over South Asia and East Asia. As presented in Fig. 4b, compared to CON, the experiment of southward-shifting TP (TP_S4) presents enhanced monsoon rainfall but all experiments of northward-shifting TP (from TP_N4 to TP_N16) show reduced rainfall in South Asia. However, a noted feature is that the regional monsoon rainfall increases slightly from TP_N4 to TP_N16, opposite to the gradual decrease in the dynamical SAM index shown in Fig. 3, implying that the northward shift of the TP exerts complex influences on South Asian monsoon rainfall (see discussion in the next section). On the contrary, the rainfall over East Asia (Fig. 4c) shows similar changes as the EAM index and the SEAM index in Fig. 3. Specifically, the northward movement of the TP (from TP_N4 to TP_N16) brings more summer monsoon rainfall to East Asia compared with that in TP_S4 and CON. It should be pointed out that the above conclusions remain mainly unchanged when the EAM domain is extended eastward from 135° to 150°E as in the area where the EAM index is defined and when the SAM domain is zonally widened from 60°–105°E to 50°–120°E.

To analyze the change in the combined rainfall of tropical South Asia and subtropical/extratropical East Asia, we calculate the total relative change rate of rainfall in each TP-shifting
experiment (Fig. 4d). Overall, the rainfall over the broad-scale Asian monsoon region increases when the TP is shifted southward (TP_S4), which significantly enhances the rainfall over South Asia at the cost of rainfall reduction over East Asia. When the TP is shifted northward, the broad-scale monsoon rainfall increases most significantly in TP_N8, and then in TP_N12, at the cost of rainfall reduction over South Asia. Interestingly, the relative change rate in each TP-shifting experiment is positive, indicating that the current TP position is not optimal for intensifying the ASM rainfall. The optimal TP position is to the north of its current location by 8° of latitude as shown in experiment TP_N8.

![Fig. 5. JJA climatology of 200-hPa geopotential height (shading; m) and 200-hPa winds (vectors; m s⁻¹) in (a) the CON run and (b)–(e) various TP-shifting experiments. In the plots, geopotential height is multiplied by 0.1.](image-url)
c. Effects on the South Asian summer monsoon

Previous studies have revealed that the thermal effect of the TP is essential for the formation and intensification of the SAM, primarily through the pumping effect driven by surface sensible heat (Wu et al. 2012b). Furthermore, the heating effect of the TP can reverse the meridional temperature gradient and intensify the meridional monsoon circulation, which is crucial for water vapor transport and the formation of summer monsoon rainfall over South Asia (Wang et al. 2018; Wu et al. 2015).

We further analyze the South Asian high (SAH) and the meridional–vertical cross section of atmospheric circulation to better understand the relationship between the TP meridional position and the South Asian summer monsoon (Figs. 5 and 6). Specifically, when the TP approaches the south, the SAH is closer to the region of dominant divergent effect and becomes stronger (Fig. 5b) south of its normal position in the CON run (Figs. 5a,b), further causing a stronger thermally driven meridional circulation to the southern TP (Fig. 6b). This intensified meridional monsoon circulation induces significant water vapor transport from the Indian Ocean to the southern TP and leads to strengthened ascent over the southern slope of the TP and descent over northern India, favorable for a dipole pattern of rainfall around 20°N (Fig. 7b). Oppositely, when the TP is gradually migrated to the north (from CON to TP_N16), its divergent effect progressively decreases and the SAH becomes weaker (e.g., south of 30°N; Figs. 5c–e). The TP thus can hardly empower the thermally driven meridional circulation to the south. The anomalous meridional monsoon cell is reversed from that in CON (comparing Figs. 6c–e with Fig. 6a), which contributes to the apparent weakening of the Somali jet and the decreased rainfall over the northern Arabian Sea and the southern TP (Figs. 7c–e). Therefore, with the weakening of the

![Fig. 6](image-url)
thermally driven circulation, the SAM declines continually from TP_S4 to TP_N16 as shown in Fig. 3. However, when the TP is shifted farther north (from TP_N8 to TP_N16), an anomalous low-level cyclonic circulation is induced in the Indian subcontinent (Figs. 7c–e). As the TP is gradually moved away, its thermal effect is no longer sufficient to bring water vapor from the Indian Ocean to the north. Consequently, the rainfall that originally occurs on the southern slopes of the TP is transported eastward by the Indian subcontinent cyclonic circulation, causing enhanced rainfall over the Bay of Bengal, the Indo-China peninsula, and southern China. A portion of the water vapor can still be transported to the “new” TP location in TP_N4 and TP_N8, reaching the northern regions that are far from South Asia. From TP_N12 to TP_N16, however, water vapor stays mainly in the south and contributes to the summer rainfall over South Asia. Hence, the rainfall in the South Asian region presents a rising tendency from TP_N4 to TP_N16 (Fig. 4b) and the WY index shows a slight increase from TP_N8 to TP_N16 (Fig. 3), consistent with the continuing enhancement of the anomalous cyclonic circulation (Figs. 7c–e).

FIG. 7. (a) JJA climatology of rainfall (shading; mm day$^{-1}$) and vertically integrated water vapor flux (vectors; kg m$^{-1}$ s$^{-1}$) in CON run, and (b)–(e) corresponding differences between various TP-shifting experiments and CON. Dots indicate the values that are significantly above the 95% confidence level, and blue arrows denote that the wind anomalies are statistically significant ($p < 0.05$) based on the Student’s $t$ test.
Effects on the East Asian summer monsoon

The TP heating can generate anomalous potential vorticity forcing, and especially produce a strong anticyclone near the tropopause (Wu et al. 2016). Under the background of the midlatitude westerly flow, this strong anticyclone produces an eastward-propagating Rossby wave train, which deforms the western Pacific subtropical high and enhances moisture convergence toward East Asia (Wang et al. 2008). These results can be seen clearly from Fig. 8 when the TP is relocated in different latitude positions. In TP_S4, since the rotational effect of the TP decreases, a warm cyclonic circulation anomaly appears only over the north of the TP (of its primary position), triggering a downward-propagating Rossby wave train with a cyclonic anomaly over 30°–40°N. Oppositely, the northern movement of the TP (from CON to TP_N16) with a stronger rotational impact not only results in a warm cyclonic circulation anomaly in its primary position but also forms a cold anticyclonic anomaly in its new position. According to the great circle theory (Hoskins and Karoly 1981; Longuet-Higgins 1964), the warm cyclonic anomaly can trigger a Rossby wave train quite similar to that in the TP_S4, while the cold anticyclonic anomaly also produces a distinct Rossby wave train and forms an anticyclonic circulation anomaly over the western North Pacific. As noted, this anticyclone anomaly produced by the northward movement of the TP exhibits a northeastward shift (Figs. 8c,d).

As presented in Fig. 9, the downward-propagating Rossby wave trains create a series of barotropic zonal wind anomalies over East Asia. The cyclonic anomaly over around 30°N in TP_S4 contributes to anomalous easterly jet stream at around 40°N and westerly jet stream over 20°N, signaling a southward shift of the subtropical high over East Asia. In contrast, from TP_N4 to TP_N16, the northward shift of the TP is always accompanied by consistently northward migration of westerly jet stream anomaly to the north of the TP and easterly jet stream anomaly to the south of the plateau, implying a northward shift of the subtropical high.

With the shifts of the westerly jet stream and the subtropical high, the rainfall pattern over East Asia shows a band-drift distribution (Fig. 10, in which the patterns of water vapor flux are similar to those of the low-level winds). In TP_S4 (Fig. 10b), the anomalous easterly flow around 40°N is associated with local sinking motions while the returning westerly flow is linked to the rising motions near 20°N, which leads to a positive–negative rainfall pattern in East Asia and...
indicates a weakened East Asian summer monsoon. On the contrary, in TP_N4 (Fig. 10c) and TP_N8 (Fig. 10d), the positions of the anomalous easterly and westerly flows are completely reversed, associated with the descending motions on the south and the ascending motion on the north. The enhanced rainfall around 40°N and the reduced rainfall over 30°N correspond to strengthened East Asian summer monsoon. However, it should be pointed out that when the TP is located farther north (TP_N16; Fig. 10e), rainfall decreases over northern China because of the eastward shift of the subtropical high and the inflow of easterly water vapor transport. It is only when the TP is fully located in the subtropics (when the TP shifts northward by 4°–8° of latitude) that the subtropical high is in its optimal position to bring a great amount of rainfall to East Asia, meaning a strong EAM.

**e. Effects on the Southeast Asian summer monsoon**

According to Wang and Fan (1999), the SEAM index was defined with respect to the convective latent heat release around the Philippines (10°–20°N, 115°–140°E). Yoo et al. (2006) further showed that the SEAM index was linked with the features of atmospheric circulation and rainfall not only over the Philippine Sea but also in the entire Southeast Asia. Specifically, the SEAM index was characterized by intensified westerlies over tropical Asia and a cyclonic pattern over the western Pacific, which lead to increasing rainfall over 10°–20°N in the western Pacific.

Indeed, the value of the SEAM index as defined can be interpreted as the intensity of the cyclonic vorticity over the Southeast Asian region. A large SEAM index value means large positive vorticity, corresponding with substantial water vapor convergence and rainfall over the Philippine Sea and entire Southeast Asia. As presented in Fig. 11, the eastward-propagating Rossby wave train produced by the relocated TP brings significant meridional vorticity transport over the western North Pacific. In TP_S4, a negative vorticity band over 10°–20°N leads to an anomalous anticyclonic circulation over the Philippines (Fig. 10b), resulting in reduction of rainfall over equatorial Southeast Asia especially around the South China Sea. In contrast, the northward shifted TP (from TP_N4 to TP_N8) brings a positive vorticity band around 20°N (Figs. 11b,c) and results in the continuing enhancement of the anomalous cyclonic circulation over 10°–20°N in the western Pacific (Figs. 10c,d). Correspondingly, both the rainfall over Southeast Asia and the SEAM index are enhanced from TP_N4 to TP_N8. However, the negative vorticity band at 10°N strengthens and extends to the northwest from TP_N8 to TP_N16, decreasing the cyclonic pattern and the rainfall over the equatorial Philippine Sea (Fig. 10e).

In addition to the rotational effect, the divergent effect of the TP also exerts an impact on the SEAM. As seen in the vertical cells from 30°N, 100°E to 10°N, 120°E in Fig. 12, the thermal uplift of the TP can modulate the vertical motions over Southeast Asia. In TP_S4, the increase in divergent effect results in a strong upward motion over the TP, along with a significant descending motion over the South China Sea and the Philippines. Besides, such a circulation structure leads to reduced rainfall over the South China Sea. Oppositely, from CON to TP_N16, the gradual shift of the TP reduces the thermally driven upward motion, accompanied by an increase in rising motion over Southeast Asia. Correspondingly, the

---

**Fig. 9.** 110°–150°E averaged JJA zonal winds in CON (contours; m s⁻¹) and the differences between the various TP-shifting experiments and the CON (shading; m s⁻¹). Dots indicate the values that are significantly above the 95% confidence level.
summer monsoon rainfall over the South China Sea gradually increases from TP_N4 to TP_N16.

4. Conclusions and discussion

In this study, we have depicted the effect of meridionally relocated TP on the ASM based on a series of idealized experiments, encouraging a better understanding of the role of the TP in the dynamics of Asian monsoon system. The current TP is located in the transitional subtropical zone between the tropics and the higher latitudes, and thus exerts both divergent and rotational effects on the ASM, accompanied by complicated monsoon features. It is hoped that relocating the TP southward and northward (from TP_S4 to TP_N16) would enhance our understanding of the monsoon features through the changes in the divergent and rotational responses of monsoon circulation to the meridional shift of the plateau.
Our results show that a southward-relocated TP (TP\textsubscript{S4}) would exert a stronger divergent effect and drive an intensified meridional circulation in the tropics, leading to a stronger SAM. Specifically, enhanced southwesterly water vapor transport induces more rainfall over the Indian subcontinent and the southern slope of the TP. However, a weaker Rossby wave is excited from the original TP position, accompanied by a southward shift of the subtropical high and the jet system, causing a pattern of positive–negative rainfall anomalies over East Asia. Additionally, the descending motion over Southeast Asia caused by the stronger uplift of the TP suppresses the rainfall over the South China Sea.

In contrast, when the TP is shifted to the north (from CON to TP\textsubscript{N16}), the decreased divergent effect results in weaker meridional monsoon circulation. Both zonal and meridional SAM circulations weaken, leading to rainfall reduction over the northern Arabian Sea and the southern TP. A gradually enhanced Rossby wave train reflecting the intensifying rotational effect of the TP is found, accompanied by northward shift of the zonal jet system and northeastern move of the subtropical high. Correspondingly, the EAM circulation and the monsoon rainfall over East Asia are reinforced from CON to TP\textsubscript{N8}, while weakened from TP\textsubscript{N8} to TP\textsubscript{N16} when the TP is relocated to higher latitudes where the direct impacts by tropical and subtropical monsoons weaken.

It is interesting to note that when the TP is shifted northward by 8° of latitude (TP\textsubscript{N8}), the Asian continent witnesses the strongest summer monsoon rainfall. Compared with the current TP position in CON, the new TP position in TP\textsubscript{N8} may yield a more reasonable configuration for the strong divergent and rotational combined effects of the TP on the overall Asian monsoon rainfall, although a thorough explanation about the maximum effectiveness of about 8° shift is still needed. Indeed, it has been demonstrated that the EAM and the SEAM maximize their intensities at the cost of the weakening of the SAM.

Finally, it should be pointed out that we have just conducted one experiment of southward shift of the TP due to the restriction of real land–sea distribution, and thus the divergent effect of the TP cannot be fully embodied. Further analysis with more model settings such as moving the TP farther southward after extending the land–sea boundary southward and near the equator is being conducted to gain a better understanding of the divergent effect of the TP.

Acknowledgments. We appreciate the effective discussions with Prof. John C. H. Chiang of the University of California, Berkeley, and Prof. Bin Wang of the University of Hawaii, and
the constructive comments by two anonymous reviewers, which are helpful for improving the overall quality of the paper. We also thank the National Center for Atmospheric Research for providing the CESM coupled general circulation model. J. Wang thanks the China Scholarship Council joint Ph.D. training program for providing support for his stay at the University of Gothenburg. This work is funded by the National Natural Science Foundation of China (Grant 42088101), National Natural Science Foundation of China (Grant 42175023), Guangdong Major Project of Basic and Applied Basic Research (Grant 2020B0301030004), and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies (Grant 2020B1212060025).

Data availability statement. The ERA5 monthly data were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) at the Climate Data Store (CDS; https://cds.climate.copernicus.eu/cdsapp#!dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form).

REFERENCES


FIG. 12. Differences in JJA vertical velocity (shading; m s\(^{-1}\)) and vertical cells (vectors; m s\(^{-1}\)) from the point 30°N, 100°E to the point 10°N, 120°E among various experiments. In the plots, vertical velocity is multiplied by 1000. Only the values of differences in vertical cells that are significantly above the 95% confidence level are plotted.


