Enhanced Latent Heating over the Tibetan Plateau as a Key to the Enhanced East Asian Summer Monsoon Circulation under a Warming Climate[Ⓢ]

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(Manuscript received 1 July 2018, in final form 21 February 2019)

ABSTRACT

Coupled climate system models consistently show that the low-level southerly wind associated with the East Asian summer monsoon (EASM) is enhanced under anthropogenic greenhouse gas forcing, and the enhanced EASM was attributed to the enhanced land–sea thermal contrast by previous studies. Based on a comparison of the global warming scenarios with the present-day climate in an ensemble of 30 coupled models from phase 5 of the Coupled Model Intercomparison Project (CMIP5), we show evidence that changes in land–sea thermal contrast cannot explain the enhanced EASM circulation in terms of the seasonality. Indeed, the enhanced low-level southerly wind over East Asia is associated with a large-scale anomalous cyclone around the Tibetan Plateau (TP), and numerical simulation by the Linear Baroclinic Model suggests that the enhanced latent heating over the TP associated with enhanced precipitation is responsible for this low-level cyclone anomaly and the enhanced EASM circulation projected by the coupled models. Moisture budget analysis shows that enhanced hydrological recycling and enhanced vertical moisture advection due to increased specific humidity have the largest contribution to the increased precipitation over the TP, and more than half of the intermodel uncertainty in the projected change of EASM circulation is associated with the uncertainty in the changes of precipitation over the TP. Therefore, the TP plays an essential role in enhancing the EASM circulation under global warming through enhanced latent heating over the TP.

1. Introduction

East Asia features by a monsoon climate, with a seasonal reversal of low-level prevailing wind from southerly wind in summer to northerly wind in winter (Figs. 1a,b). In summer, abundant water vapor is transported from tropical ocean to East Asia by the monsoon southerly wind in the lower troposphere (Fig. 1a), which is responsible for the major rainy season over East Asia

[Ⓢ] Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-18-0427.s1>.

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FIG. 1. The climatology in the 20C simulation and the projected change by the MMM of the CMIP5 models. (a),(b) The wind vector and meridional wind (shading; m s^{-1}) at 850 hPa in the 20C simulation. (c),(d) The MMM-projected change in the wind vector and meridional wind (shading; m s^{-1}) at 850 hPa per 1 K of tropical mean surface warming under RCP8.5. Areas where the projected changes in the meridional wind agreed by more than 70% of the models are stippled. Results are shown for (a),(c) summer and (b),(d) winter.

(Zhou and Yu 2005; Sun et al. 2011; Li et al. 2014). The summer monsoon in East Asia is subject to substantial variability, and it is crucial for agriculture production in East Asia and can induce severe meteorological disasters (Ding 2007; Zhou et al. 2009a; Li et al. 2016). The strength of the East Asian summer monsoon (EASM) is usually measured by the low-level southerly wind or the associated zonal gradient of sea level pressure (e.g., Guo 1983; Wang et al. 2001; Wang et al. 2008a). When the low-level southerly wind over East Asia is stronger (weaker) than normal, the major rain belt over East Asia is shifted northward (southward). Therefore, a stronger EASM circulation is responsible for excessive rainfall over the northern part of East Asia and deficient rainfall along the Yangtze

River in the southern part of East Asia (Wang et al. 2008a; Yang et al. 2015).

Given the great societal impact of monsoons on East Asia, the response of the EASM to climate change has attracted wide interest from the monsoon community. Although a decadal weakening of EASM after the late 1970s was reported based on the observational record (e.g., Yu et al. 2004; Yu and Zhou 2007; Ding 2007; Zhou et al. 2009b), growing evidence suggests that this decadal change was dominated by the internal variability of the climate system (such as the Pacific decadal oscillation) or aerosol forcing (Li et al. 2010; Lei et al. 2014; Song et al. 2014; Yu et al. 2016; Zhu et al. 2016; Yang et al. 2017), and the strength of EASM has recovered recently (Zhu et al. 2011; Liu et al. 2012; Xu et al. 2013, 2015).

Paleoclimate records suggest a stronger EASM circulation and a northwestward shift of East Asian rain belt during warmer epochs (Man et al. 2012; Yang et al. 2015).

Coupled climate models are a useful tool to understand the response of the EASM to the ongoing global warming. Forced by the increased greenhouse gas (GHG) concentration, the enhanced summer monsoon southerly wind over East Asia is a robust feature projected by the coupled climate system models from CMIP3 to CMIP5 (Sun and Ding 2010; Chen et al. 2012; Ding et al. 2013; Jiang and Tian 2013; Kamae et al. 2014; Kitoh 2017) and by other individual models (Bueh and Lin 2003; Ham et al. 2016). The enhancement of EASM circulation in response to global warming simulated by the coupled models is supported by paleoclimate evidence, and it also suggests that the observed decadal change in recent decades is dominated by the internal variability rather than global warming (Zhou et al. 2009a; Li et al. 2010; Deser et al. 2012; Xu et al. 2013; Song and Zhou 2015).

Understanding the mechanism for the response of the EASM to global warming requires knowledge about the formation mechanism of the EASM. Zonal land–sea thermal contrast is regarded as the primary driver for the low-level southerly wind of the EASM (Zhou et al. 2009b; Zhou and Zou 2010; Li et al. 2016; Kitoh 2017). As the thermal inertia of ocean is much greater than that of land, a warmer East Asian land area than western North Pacific in summer drives a zonal pressure gradient and a low-level southerly wind over East Asia. The land–sea thermal contrast is evident not only at the surface but also in the middle to upper troposphere, with an upper tropospheric warm center over the Tibetan Plateau (Li and Yanai 1996; Dai et al. 2013; Wu et al. 2015). The upper-tropospheric land–sea thermal contrast well explains the variability of EASM and South Asian summer monsoon at interannual, decadal, and millennial time scales (Ueda et al. 2006; Man et al. 2012; Dai et al. 2013; Kamae et al. 2017; Endo et al. 2018).

Besides the land–sea thermal contrast, the Tibetan Plateau (TP) also plays a key role in the formation of EASM via its dynamic and thermodynamic effects. The relative location of the westerly jet to TP is essential to the seasonal march of the East Asian rain belt. The mei-yu (called baiu in Japanese and changma in Korean) onset occurs when the westerly jet marches from the TP to the northern slope of the TP, and the rainy season over northern China starts when the westerly jet is located well to the north of the TP (Molnar et al. 2010; Chiang et al. 2015; Chiang et al. 2017). The northward shift of the westerly jet in the upper troposphere is associated with enhanced low-level southerly wind over

East Asia and excessive (deficient) precipitation over northern (southern) China (Liang and Wang 1998; Li et al. 2010; Xuan et al. 2011; Chiang et al. 2017). Besides the above dynamic effect, elevated heating over the TP attracts a low-level mass convergence toward the TP, which induces a low-level cyclonic wind around the TP (Ding and Chan 2005; Wu et al. 2007; Wu and Liu 2016; Wang et al. 2019). Sensible heating near the surface and latent heating associated with condensation over the TP are both effective in strengthening the Asian monsoon (Wu et al. 2007, 2016; Wang et al. 2008b; Xu et al. 2013; Hu and Duan 2015; Wu and Liu 2016).

Almost all of the previous studies attributed the enhanced EASM circulation under global warming to the enhanced land–sea temperature contrast at the surface or in the free troposphere (e.g., Bueh and Lin 2003; Ding et al. 2013; Jiang and Tian 2013; Kamae et al. 2014; Endo et al. 2018). It is a global phenomenon that the amplitude of land surface warming is stronger than the ocean throughout the year (Byrne and O’Gorman 2013; Kamae et al. 2014), but the overall weakening of global monsoon circulation under global warming cannot be explained by the overall increase of global land–sea thermal contrast (Kitoh et al. 2013; Kitoh 2017; Biasutti et al. 2018). As shown in Fig. 1c and in Jiang and Tian (2013), the enhanced low-level southerly wind over East Asia is associated with a cyclone anomaly around the TP. However, the role of the TP on the response of EASM circulation to global warming was not clear up to now. Therefore, this study aims at answering the following questions: Is the enhanced EASM circulation under global warming driven by the land–sea thermal contrast or the thermal forcing from the TP? How does the TP modulate the response of EASM circulation to global warming?

The remainder of this paper is organized as follows. The model and analysis methods are introduced in section 2. The projected change in East Asian monsoon in association with the land–sea thermal contrast is examined in section 3, and the possible role played by the TP is investigated in section 4. Finally, the conclusions are summarized in section 5.

2. Model, data, and methods

a. CMIP5 models

To extract the GHG-forced response, 30 available models from CMIP5 are adopted for analysis in this study (the names and institutions for the models are listed in Table S1 in the online supplemental information), and the historical and representative concentration pathway (RCP) 8.5 and RCP4.5 experiments are

analyzed. The historical experiment is performed under observed historical external forcing (e.g., GHG and aerosols) (Taylor et al. 2012), and the 1950–99 period in the historical experiment is used to represent the baseline climate, referred to as 20C. The RCP8.5 and RCP4.5 experiments are forced by future global warming scenarios with a radiative forcing of 8.5 and 4.5 W m^{−2} in the year of 2100 (van Vuuren et al. 2011). The 2050–99 periods in the RCP8.5 and RCP4.5 experiments (referred to as 21C) are adopted and compared with 20C in the historical experiment. Instead of the 20-yr average recommended by the IPCC, the 50-yr average is adopted, following many previous studies (Xie et al. 2010; Long and Xie. 2015; He et al. 2017), to obtain the forced response by more efficiently suppressing internal variability of the climate system. Only one realization for each model is used to equally weight the models.

The response of a variable X to global warming is evaluated as the multimodel median (MMM) of the difference between 21C and 20C scaled by the amplitude of tropical mean surface warming, denoted as X' . The MMM of the tropical mean surface warming in 21C relative to 20C is 2.83 K for RCP8.5 and 1.72 K for RCP4.5. The MMM is adopted instead of the multimodel mean to suppress the impact from outlier models (Gleckler et al. 2008), and the MMM-projected change is considered as significant if the sign of change is agreed upon by more than 70% of the individual models, approximately equivalent to 95% confidence level according to the Student's t test (Power et al. 2012). For brevity, the RCP8.5 scenario is adopted throughout this study, whereas the RCP4.5 scenario is adopted to examine the dependence of the results on the scenario.

b. Moisture budget analysis

Moisture budget analysis is adopted to understand the change in precipitation over the TP. Following Chou et al. (2009), the moisture budget equation is written as

$$P' = E' - \bar{\omega} \frac{\partial q'}{\partial p} - \omega' \frac{\partial \bar{q}}{\partial p} - \langle \bar{\mathbf{V}} \cdot \nabla q' \rangle - \langle \mathbf{V}' \cdot \nabla \bar{q} \rangle + R, \quad (1)$$

where P , E , ω , q , p , $\mathbf{V}$, and R stand for precipitation, evaporation, vertical velocity, specific humidity, pressure, the horizontal wind vector, and the residual, respectively. The symbol $\langle \cdot \rangle$ indicates the vertical integration from surface to 200 hPa. The variable with an overbar indicates the mean state in 20C, and the variable with a prime indicates the difference between 21C and 20C scaled by tropical mean surface warming. According to Eq. (1), the change of precipitation is composed of evaporation change E' , thermodynamic and dynamic changes of vertical moisture advection

($-\langle \bar{\omega} \partial q' / \partial p \rangle$ and $-\langle \omega' \partial \bar{q} / \partial p \rangle$), thermodynamic and dynamic changes of horizontal moisture advection ($-\langle \bar{\mathbf{V}} \cdot \nabla q' \rangle$ and $-\langle \mathbf{V}' \cdot \nabla \bar{q} \rangle$), and the residual R . The moisture budget analysis is confirmed to be valid over the TP and on its northern and southern slopes (Peng and Zhou 2017; Wang et al. 2017, 2018).

c. Linear Baroclinic Model

The Linear Baroclinic Model (LBM) is adopted in this study to investigate the response of anomalous atmospheric circulation to anomalous diabatic heating. The LBM is a primary equation model developed by Watanabe and Kimoto (2000), and it was widely used to investigate the response of atmospheric circulation to anomalous heat source over the TP (Wang et al. 2008b; Harada et al. 2014; Qu and Huang 2016; Cao et al. 2017). In this study, the LBM is run at a resolution of triangular truncation of T42, with 20 sigma levels in the vertical. The model is forced by steady diabatic heat source and integrated for 50 days, and the average for the last 20 days is taken as the equilibrium response.

3. Projected changes in the East Asian monsoon circulation and land–sea thermal contrast

Under a warming climate forced by increased concentration of anthropogenic GHG, the most prominent feature of the response of the low-level atmospheric circulation over East Asia and the west Pacific is the enhanced southerly wind associated with EASM circulation. As shown in the MMM-projected change in wind at 850 hPa, the enhancement of the low-level southerly wind from the eastern part of China to Mongolia is agreed upon by more than 70% of the individual models (Fig. 1c). Similar change is also obtained under RCP4.5 (figure not shown) and reported by many previous studies (e.g., Sun and Ding 2010; Chen et al. 2012; Jiang and Tian 2013). This phenomenon cannot be explained by the change in the western North Pacific subtropical high (WNPSH), as the projected change of atmospheric circulation over subtropical western Pacific is weak and uncertain among the models (Fig. 1c). In fact, the WNPSH at the lower troposphere remains generally unchanged (He and Zhou 2015) or slightly weakened (Huang et al. 2016) under a warmer climate, which cannot explain the enhanced southerly wind over East Asian land region. The projected southerly wind anomaly is absent in winter (Fig. 1d).

As the strength of the East Asian meridional wind in the lower troposphere was claimed to be associated with the zonal land–sea thermal contrast (Wang et al. 2008a; Dai et al. 2013), the projected changes in the temperature of the surface air and the upper troposphere (vertically averaged within 200–500 hPa) are shown in

Figs. 2a and 2b. The increase of surface air temperature is stronger over the land area than at the ocean, especially in the arid land regions (**Fig. 2a**), due to the lower heat capacity and the limited capacity for evaporation over land (**Sutton et al. 2007; Byrne and O’Gorman 2013**). At the upper troposphere, the amplitude of warming is dominated by a meridional contrast, with an enhanced warming in the tropics than the extratropics (**Fig. 2b**), consistent with previous studies (**Ueda et al. 2006; Harada et al. 2014; Endo et al. 2018**), possibly due to the strong moist adiabatic adjustment in the tropics (**Knutson and Manabe 1995; Schneider et al. 2010**). The 25°–50°N averaged amplitude of warming, as shown in **Fig. 2c**, is characterized by an enhanced warming over the land area at the surface and in the lower troposphere, but stronger warming over the western North Pacific than East Asian land area in the upper troposphere. Therefore, the change in the zonal land–sea thermal contrast in the upper troposphere cannot explain the enhanced low-level southerly wind over East Asia under global warming scenarios, although it did a good job for the reanalysis data (**Dai et al. 2013**) and in the last millennium simulation (**Man et al. 2012**).

Under the GHG forcing, air temperature near the surface shows a greater warming over most of the global land area than the ocean throughout the year, which is confirmed by both coupled models and observation (**Byrne and O’Gorman 2013; Jiang and Tian 2013; Kamae et al. 2014**). If the stronger warming of East Asian land area relative to the western North Pacific is responsible for the enhanced southerly wind over East Asia, anomalous southerly wind in response to global warming may be seen over East Asia throughout the year when the amplitude of warming over East Asia is stronger than western Pacific throughout the year. To test this hypothesis, **Fig. 3a** shows the projected change in the 850-hPa meridional wind averaged over 25°–50°N, 110°–120°E, and **Fig. 3b** shows the projected change in the difference of the averaged surface air temperature between the land grid points and the oceanic grid points within 25°–50°N, 100°E–180°, for all the 12 months under both RCP8.5 and RCP4.5 scenarios.

Based on the response of meridional wind under both RCP8.5 and RCP4.5 scenarios, a significant anomalous southerly wind over East Asia can be identified only in June–September (JJAS), with an amplitude of 0.1–0.2 m s^{−1} per 1 K of tropical surface warming, but the southerly wind anomaly is absent in the other months (**Fig. 3a**). However, the amplitude of surface air warming is stronger over land than over the ocean throughout the year, regardless of the scenario (**Fig. 3b**). The magnitude of the warming over land than the ocean is even stronger in winter than in summer (**Fig. 3b**), which is

FIG. 2. Projected changes in temperature per 1 K of tropical surface warming (color shading): (a) surface air temperature and (b) 200–500-hPa-averaged temperature. (c) The vertical profile of the average temperature for 25°–50°N. The black contours indicate the temperature in the 20C simulation.

inconsistent with the seasonality in the response of low-level meridional wind over East Asia. The present evidence suggests that the enhanced southerly wind in East Asia in summer and early autumn (JJAS) cannot be simply attributed the change in the zonal land–sea temperature contrast, and some other factor must be accounted for.

A close inspection of **Fig. 1c** shows that the projected changes in the low-level wind in summer is characterized by an anomalous cyclonic circulation around the TP, that is, a westerly wind anomaly along 20°N on the southern slope of the TP, a southerly wind anomaly on the eastern side of the TP from eastern China to

FIG. 3. The MMM-projected change of certain indices per 1 K of warming based on RCP8.5 (red bar) and RCP4.5 (orange bar) scenarios: (a) the East Asian meridional wind index, defined as the regional-averaged meridional wind at 850 hPa (m s^{-1}) within 25° – 50°N , 110° – 120°E (box in Fig. 1c); (b) the land–sea thermal contrast index between East Asia and the west Pacific, defined as the difference of averaged surface air temperature between the land grid points and the oceanic grid points within 25° – 50°N , 100°E – 180° (K); and (c) the TP precipitation index, defined as the regional-averaged precipitation within 25° – 40°N , 70° – 100°E (mm day^{-1}). The black error bar indicates the intermodel spread in terms of the 30th and 70th percentiles among the individual models.

Mongolia, and an easterly wind anomaly at 50° – 60°N on the northern flank of the TP. This anomalous cyclone is also evident in Fig. 6b in Jiang and Tian (2013), and it may suggest a possible modulation of the TP on the response of EASM circulation to global warming, which will be investigated in detail in the next section.

4. The role of the TP on the response of EASM to global warming

a. Connection of the enhanced EASM to the diabatic heating over the TP

Although the enhanced southerly wind over East Asia is evident in JJAS, we still focus on the seasonal mean

from June to August (JJA), which is the major summer monsoon period over East Asia. The thermodynamic impact of the TP on East Asian climate is associated with the surface sensible heating (Wu et al. 2007; Wu and Liu 2016) and the latent heating associated with precipitation over the TP (Hsu and Liu 2003; Wang et al. 2008b). Therefore, the MMM-projected changes in surface sensible heating and column latent heating in JJA under RCP8.5 are shown in Fig. 4, where the column latent heating is calculated as precipitation multiplied by a constant $L = 2.5 \times 10^6 \text{ J kg}^{-1}$ (Li et al. 2012).

Under GHG forcing, the surface sensible heating is slightly weakened over the TP but it is significant only at the northeastern part of the TP (Fig. 4a), consistent with the observed weakening of sensible heating over the TP in recent decades (Duan and Wu 2008; Yang et al. 2014). The slightly weakened surface sensible heating cannot explain the anomalous cyclone around the TP and the enhanced southerly wind over East Asia (Wu et al. 2007; Wu and Liu 2016). In contrast, the column latent heating is projected to be significantly enhanced over almost the entire TP, consistent with the observed trend of precipitation over the TP (X. Li et al. 2017). The enhancement of condensational latent heating is much greater than the change in surface sensible heating over most area of the TP, especially over the southern slope of the TP (Fig. 4b), which may exert a forcing on the atmospheric circulation over East Asia (Hsu and Liu 2003; Wang et al. 2008b; Xu et al. 2013).

To quantify the seasonality of the change in the column latent heating over the TP and its possible dependence on the scenario, Fig. 3c shows the projected changes in regional averaged precipitation over the TP (averaged within 25° – 40°N , 70° – 100°E ; i.e., see the box in Fig. 4b) based on both the RCP8.5 and RCP4.5 scenarios. It is clear that the magnitude of increase in precipitation is greater in summer and early autumn than the other seasons. The strongest increase of precipitation over the TP is seen in July and August, both of which amount to about 0.3 mm day^{-1} per 1 K of tropical surface warming. As the TP and South Asia receive the most abundant precipitation during the monsoon season from June to September (Duan et al. 2013; Wu 2017), the change in precipitation over the TP follows the “wet-season-get-wetter” pattern (Huang et al. 2013). The seasonality of the increase in precipitation over the TP is consistent with the enhancement of the southerly wind over East Asia in JJAS, regardless of the emission scenario, further suggesting the possible impact of enhanced latent heating over the TP on the change of atmospheric circulation in East Asia.

To examine whether the magnitude of change in precipitation over the TP explains the intermodel uncertainty

FIG. 4. The MMM-projected changes in (a) the JJA-mean surface sensible heating and (b) the column latent heating associated with precipitation per 1 K of tropical surface warming under the RCP8.5 scenario (W m^{-2}). The range of the TP with a surface pressure lower than 850 hPa is indicated by the white line. The MMM-projected changes agreed on by more than 70% of the individual models are stippled.

in the change of EASM circulation, scatter diagrams for the intermodel spread of the changes in these two quantities are shown in Fig. 5. It is clear that the models with a stronger increase of precipitation over the TP are evidenced by stronger enhancement of low-level southerly wind over East Asia in summer. The intermodel correlation between these two quantities is 0.76 under the RCP8.5 scenario and 0.75 under the RCP4.5 scenario, both of which are significant and explain more than half of the intermodel variance. This suggests that the

intermodel spread in the projected changes of the EASM circulation is largely dependent on the intermodel uncertainty of the changes in the latent heating associated with precipitation over the TP.

The above results show that the significantly increased latent heating over the TP is closely associated with the seasonality of the change in EASM and the intermodel uncertainty among the CMIP5 models. Previous studies suggested that a positive latent heating anomaly over the TP or on the southern slope of the TP favors an

FIG. 5. The scatter diagram among the individual models for the projected changes in meridional wind over East Asia in JJA (y axis; m s^{-1} ; averaged within 25° – 50°N , 110° – 120°E) as a function of the changes in the precipitation over the TP (x axis; mm day^{-1} ; averaged within 25° – 40°N , 70° – 100°E) per 1 K of warming under the (a) RCP8.5 and (b) RCP4.5 scenarios. The intermodel correlation is marked on the upper-right corner of each panel.

FIG. 6. (a) Longitude–height profile and (b) latitude–height profile of the MMM-projected change in the diabatic heating (K day^{-1}) over the TP in JJA per 1 K of warming based on the RCP8.5 scenario. The longitude–height profile is averaged within 25° – 40°N , and the latitude–height profile is averaged within 70° – 100°E .

enhanced EASM circulation and northward shift of East Asian summer rainfall at interannual and decadal time scales (Wang et al. 2008b; Xu et al. 2013; Wu 2017; Wu and Jiao 2017), but it is not clear whether the TP has a substantial impact on EASM circulation under the global warming scenario. In the following subsection, the possible impact of enhanced latent heating over the TP on EASM circulation will be investigated.

b. Atmospheric circulation anomaly stimulated by enhanced heating over the TP

The Linear Baroclinic Model (LBM), linearized at the mean state of the MMM-simulated 20C climatology of the CMIP5 models, is adopted to investigate the response of the atmospheric circulation to the three-dimensional changes in the diabatic heating over the TP. The three-dimensional diabatic heating over the TP (25° – 40°N , 70° – 100°E) is calculated for each model following Yanai and Tomita (1998), and the vertical profile of the MMM-projected change of the diabatic heating adopted to force the LBM is shown in Fig. 6. It is clear that the increased diabatic heating has a maximum at about 300–400 hPa in the mid- to upper troposphere (Fig. 6), consistent with the substantial increase of latent heating associated with precipitation (Fig. 4b), and it suggests the dominant contribution of latent heating to the changes in the total diabatic heating.

The equilibrium response of the wind and meridional wind at 850 hPa to the change of diabatic heating is

shown in Fig. 7a. Forced by the positive diabatic heating (mainly latent heating) anomaly over the TP, the low-level atmospheric circulation is characterized by a cyclone anomaly around the TP, including the westerly wind anomaly along 20°N on the southern slope of the TP, the southerly wind anomaly over the eastern part of China on the eastern side of the TP, and the easterly wind anomaly within 50° – 60°N on the northern side of the TP. The averaged southerly wind anomaly within 25° – 50°N , 110° – 120°E is 0.14 m s^{-1} in the LBM simulation, quantitatively consistent with the projected change by the CMIP5 models (see Fig. 3a). The pattern and the magnitude of the wind anomaly simulated by LBM in Fig. 7a resemble the projection by the CMIP5 models, suggesting that the enhanced latent heating over the TP is indeed responsible for the enhanced southerly wind of EASM. If the LBM is linearized at the mean state of NCEP–NCAR reanalysis data (Kalnay et al. 1996) or the 21C climatology in the RCP8.5 experiment, the response of the atmospheric circulation is similar in terms of the spatial pattern and magnitude (Fig. S1).

In addition to changed diabatic heating, the enhanced static stability of troposphere (Schneider et al. 2010) induces a mean advection of stratification change (MASC), which generally acts to weaken atmospheric circulation (Ma et al. 2012; Harada et al. 2014; Qu and Huang 2016; He et al. 2017). MASC is defined as the product of mean-state vertical velocity and the change in static stability $S'\bar{\omega}$, where S' is the change of static stability under global

FIG. 7. (a) The LBM-simulated response of the wind vector and meridional wind (shading; m s^{-1}) at 850 hPa to the MMM-projected increase of diabatic heating over the TP (25° – 40°N , 70° – 100°E), where the LBM is linearized at the mean state of 20C of the CMIP5 models. (b) As in (a), but forced by the sum of the increase of diabatic heating over the TP (25° – 40°N , 70° – 100°E) and the MASC from the TP to East Asia (25° – 40°N , 70° – 140°E).

warming and $\bar{w}$ is vertical velocity in the 20C simulation (Ma et al. 2012; He et al. 2017). In summer, MASC is negative over climatological ascending regions including most parts of the TP and East Asia almost throughout the troposphere (Fig. S2), which acts like a negative heating (Ma et al. 2012). Nevertheless, the magnitude of MASC is smaller than the enhancement of latent heating over the TP, and the sum of MASC and the change in diabatic heating still resembles the vertical profile of enhanced latent heating over the TP (Fig. S3). Forced by the sum of the enhanced latent heating over the TP (25° – 40°N , 70° – 100°E) and MASC from the TP to East Asia (25° – 40°N , 70° – 140°E), an enhanced southerly wind over East Asia is still simulated by the LBM (Fig. 7b), suggesting the dominant role of enhanced latent heating over the TP. Previous studies have already confirmed the positive impact of heat source over the TP on the strength of the EASM based on observation at interannual and interdecadal time scales (Wang et al. 2008b; Xu et al. 2013; Hu and Duan 2015), and our results further show that the enhanced latent heating over the TP plays a key role for the enhanced EASM circulation under global warming projections and the intermodel uncertainty.

c. Moisture budget on the enhanced precipitation over the Tibetan Plateau in summer

To understand the dominant contributor to the enhanced precipitation over the TP in JJA, the projected changes in precipitation and the first five terms on the right-hand side of Eq. (1) are shown in Fig. 8. It is obvious that enhanced evaporation and the thermodynamic change of vertical moisture advection are the largest contributors

to the increased precipitation over the TP, which are significant at almost all of the grid points over the TP (Figs. 8b,c). The substantial contribution of enhanced evaporation to the increased precipitation over the TP suggests an enhanced local hydrological recycling, consistent with the observed intensification of hydrological cycle over the TP (Yang et al. 2014; C. Zhang et al. 2017; G. Zhang et al. 2017). Meanwhile, the enhanced vertical moisture advection due to increased atmospheric water vapor content makes a much larger contribution than any other terms on the southern part of the TP and South Asia, consistent with Wang et al. (2017), but the dynamic change of vertical moisture advection is weak (Fig. 8d). The thermodynamic and dynamic changes in horizontal moisture advection are both small and uncertain over the TP (Figs. 8e,f), consistent with previous studies that the horizontal moisture advection is usually less important than vertical moisture advection to precipitation (Chou et al. 2009; Lin et al. 2014; W. Zhang et al. 2017; He and Li 2019).

Previous studies claimed that the change in tropical precipitation is largely dominated by the offsetting effect between the thermodynamic change and the dynamic changes in vertical moisture advection (Held and Soden 2006; Huang et al. 2013). But the dynamic change in vertical moisture advection is small and insignificant over the entire TP and most part of South Asia (Fig. 8d), consistent with the overall weak change of the South Asian monsoon circulation (Christensen et al. 2013; Kitoh et al. 2013; Chen and Zhou 2015). According to Ma and Yu (2014), the increased atmospheric static stability acts to weaken the South Asian monsoon

FIG. 8. Projected changes of the terms in Eq. (1) based on the MMM (mm day^{-1}): (a) precipitation change, (b) evaporation change, (c) thermodynamic change of vertical moisture advection, (d) dynamic change of vertical moisture advection, (e) thermodynamic change of horizontal moisture advection, and (f) dynamic component of horizontal moisture advection. The projected changes agreed on by more than 70% of the individual models are stippled. The elevated topography with a surface pressure lower than 850 hPa is marked with the thick white contour.

FIG. 9. Projected changes in the zonal wind, including (a) the vertical profile for the 70°–100°E average over the TP, (b) the vertical profile for the zonal average across 180°W–180°E, and (c) the zonal wind at 200 hPa. In (a) and (b), the black and white contours are the mean-state zonal wind for 20C and 21C, respectively (contour interval: 5 m s^{-1}). In (c), the black contours are the mean-state zonal wind for 20C, and the white contour stands for the high topography where the surface pressure is lower than 850 hPa.

circulation, whereas the enhanced meridional land–sea thermal contrast acts to enhance it at the lower troposphere. Given the overall weak change of South Asian monsoon circulation (Endo and Kitoh 2014), the precipitation over the TP is not much affected by the dynamic change of vertical moisture advection, but it is dominated by the effects of increased atmospheric water vapor content and the intensified water vapor recycling over the TP.

d. Changes in the westerly jet

The TP may also exert its forcing on the EASM through dynamic processes (i.e., the mechanical forcing of the topography on the westerly jet; Molnar et al. 2010;

Chiang et al. 2015, 2017), and the East Asian summer monsoon is anomalously strong when the westerly jet is displaced northward at interannual time scale (Liang and Wang 1998; Zhou and Yu 2005; Li et al. 2010; Xuan et al. 2011; Chiang et al. 2017). As shown in Fig. 9a, the averaged change of zonal wind within 70°–100°E is characterized by two features. First, the westerly wind is enhanced in the upper troposphere but weakened in the middle to lower troposphere over the TP and the northern side of the TP, suggesting an upward shift of the westerly jet. Second, the westerly wind gets enhanced on the southern flank of the jet at 400–200 hPa but is weakened on the northern flank of the jet, and the amplitude of the enhanced westerly wind is

stronger on the southern flank than on the northern flank of the jet at 200–100 hPa, suggesting a southward shift of the westerly jet in the upper troposphere over the TP. A comparison between the white contours for 21C and the black contours for 20C also suggests the upward and southward shift of the westerly jet over the TP (Fig. 9a). The southward shift of the westerly jet over the TP does not favor an enhanced EASM circulation (Liang and Wang 1998; Li et al. 2010; Xuan et al. 2011; Chiang et al. 2017).

To examine whether the change of westerly jet over the TP is distinct from the zonal-averaged change, Fig. 9b shows the zonal-averaged change in zonal wind. It is clear that the zonal-averaged jet shifts upward and northward (Fig. 9b), consistent with previous studies (Lorenz and DeWeaver 2007; Singh and O’Gorman 2012; Harada et al. 2014; Voigt and Shaw 2016). Therefore, the southward shift of westerly jet over the TP is a localized phenomenon. As shown in Fig. 9c, the southward shift of the westerly jet is a robust phenomenon across the entire TP and is also evident over the western North Pacific. This is consistent with the southward shift of South Asian high (Qu and Huang 2016) and the slight southward shift of the western North Pacific subtropical high (He and Zhou 2015).

East Asian summer monsoon circulation is claimed to be controlled by the land–sea thermal contrast and the forcing by TP. Based on our results for the projected changes under global warming scenarios, the zonal land–sea thermal contrast at the upper troposphere is decreased and it cannot explain the enhanced EASM circulation. The amplitude of the surface air warming over the East Asian land area is greater than over the surrounding ocean throughout the year, which cannot explain the seasonality in the change of the monsoon circulation. The projected change in the low-level circulation is characterized by an anomalous cyclone around the TP, suggesting that the TP may play a key role in the enhanced EASM circulation. As the southward shift of the westerly jet on the northern side of the TP is unfavorable for an enhanced EASM, the TP may not modulate the EASM circulation through its dynamic effect under the global warming scenario. In contrast, the enhanced latent heating over the TP well explains the enhanced low-level southerly wind, its seasonality, and the intermodel spread. Therefore, the thermodynamic effect of the TP is most probably responsible for the enhanced low-level southerly wind of EASM circulation.

5. Conclusions and discussion

The low-level southerly wind is a key component of EASM circulation. Coupled models consistently show

an enhanced low-level southerly wind over East Asia in summer. Such an atmospheric circulation response to GHG forcing was attributed to the enhanced land–sea thermal contrast by previous studies, but the possible role played by TP was overlooked. In this study, we provide evidence to show that the enhanced EASM circulation cannot be fully explained by the enhanced land–sea thermal contrast. Based on the output of 30 models from CMIP5, we provide further evidence that the enhanced EASM circulation may be related to the enhanced latent heating due to substantially increased precipitation over the TP. The response of the atmospheric circulation over East Asia to the enhanced heating over the TP was investigated by the LBM, and the mechanism for the enhanced precipitation over the TP was diagnosed via the moisture budget equation. The major findings in this study are summarized as follows.

- 1) The projected enhancement of low-level southerly wind over East Asia in coupled models under global warming scenario is associated with a low-level cyclone anomaly around the TP. At the upper troposphere, the zonal land–sea thermal contrast between East Asia and western North Pacific is weakened in summer. At the surface, the amplitude of warming over the East Asian land area is stronger than over the western North Pacific throughout the year and even stronger in winter, which cannot explain the fact that the low-level southerly wind response over East Asia only appears in summer and early autumn (JJAS). Therefore, the enhanced EASM circulation cannot be simply attributed to the enhanced land–sea thermal contrast, and the role played by the TP should be considered.
- 2) Under GHG forcing, the precipitation over the TP is substantially enhanced, and the increase of precipitation over the TP is the strongest during the local rainy season in summer and early autumn, well corresponding to the seasonality of the enhanced low-level southerly wind in East Asia. As suggested by the moisture budget analysis, two processes contribute the most to the increased precipitation over the TP: one is the enhanced vertical moisture advection associated with increased atmospheric water vapor content, and the other is the enhanced local hydrological recycling associated with enhanced evaporation over the TP. A diagnosis of the intermodel spread among the CMIP5 models also suggests that the magnitude of change in precipitation over the TP explains more than half of the intermodel variance in the changes of low-level EASM circulation. Individual models with a greater increase of precipitation over the TP tend to project a stronger enhancement of EASM circulation, and vice versa.

- 3) The TP plays a key role in the response of EASM to global warming via its thermodynamic effect. Based on the LBM simulation, the enhanced latent heating over the TP associated with increased precipitation in summer stimulates a low-level cyclone wind anomaly around the TP, with southerly wind anomaly over East Asia, which well explains the pattern and magnitude of the enhanced EASM circulation in the coupled model projections. However, the westerly jet on the northern side of the TP shifts southward under global warming, which is different from the zonal averaged response of westerly jet, and the dynamic impact of the TP on the westerly jet cannot explain the enhanced EASM circulation.

The mean-state precipitation over the TP may be overestimated by CMIP5 models (Su et al. 2013). However, there is large observational uncertainty about the mean-state precipitation over the TP in summer (Feng and Zhou 2012), which ranges from 3.03 mm day^{-1} in the CMAP dataset (Xie and Arkin 1997) to 4.00 mm day^{-1} in the GPCP dataset (Adler et al. 2003), averaged over 1979–99. According to the MMM of the 30 models, the mean-state precipitation over the TP in summer is 4.26 mm day^{-1} over the same period, which indeed seems to be overestimated compared to the observation. Based on the intermodel relationship between mean-state precipitation over the TP and the projected change in precipitation over the TP (Fig. S4), there is only a weak relationship between these two quantities with a linear correlation coefficient of 0.26, which is insignificant at the 90% confidence level. Therefore, the mean-state precipitation over the TP does not exert a simple linear impact on the change of precipitation over the TP. Besides narrowing the observational uncertainty on the mean-state precipitation over the TP, more effort is needed to know how the bias in the simulation of mean-state precipitation impacts the projected change in precipitation, before applying observational constraint (Gao et al. 2016; G. Li et al. 2017) to the changes of precipitation over the TP and monsoon circulation over East Asia.

Acknowledgments. The authors wish to acknowledge Prof. Masahiro Watanabe for offering the code of LBM, and the three anonymous reviewers for their constructive comments. Chao He wishes to thank Prof. Xiangde Xu and Dr. Boqi Liu in CMA, Dr. Bo Wu in IAP and Dr. Pengfei Zhang in UCSD for useful discussions. This work was supported by National Key Research and Development Program of China (Grant 2017YFA0604601), the National Natural Science Foundation of China (Grants 41875081, 91637208, and 41605038), and the

Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20060102). Ziqian Wang was also supported by the Pearl River S&T Nova Program of Guangzhou.

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