Heating status of the Tibetan Plateau from April to June and rainfall and atmospheric circulation anomaly over East Asia in midsummer

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Abstract Based on the 1958—1999 monthly averaged reanalysis data of the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and the rainfall data of 160 Chinese surface stations, the relationship between rainfall and the atmospheric circulation anomaly over East Asia (EA) in July and the sensible heating (SH) over the Tibetan Plateau (TP) from April to June (AMJ) is investigated by using the rotational experimental orthogonal function (REOF) method. The results show that the TP is an isolated heating source in this period. The lagged correlation analysis between the first rotational principal component (RPC) of SH over the TP in May and rainfall of EA in July demonstrates that strong SH over the TP before July leads to a positive rainfall anomaly over the TP, the valley between the Yangtze River and Huaihe River, and the regions south and southeast of the TP, and the Sichuan Basin and Yunnan-Guizhou Plateau, but less rainfall anomaly over the regions north, northeast, and west of the TP. Such rainfall anomaly patterns are shown to be well coordinated with those of the circulation and vapor flux fields, and are explained by using the thermal adaptation theory and quasi-stationary large-scale vorticity equation. Therefore, the status of SH over the TP during AMJ can be used as a predictor for the rainfall anomaly over EA, especially in the valley between the Yangtze River and Huaihe River.

Keywords: Tibetan Plateau, sensible heating, East Asia, rainfall, circulation.

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It is well known that the mechanical and thermal forcing of the TP influences the atmospheric circulation, weather, and climate of the Northern Hemisphere remarkably. As early as in the 1950s, Yeh[1] found that the seasonal transition over EA happens abruptly and is associated with the existence of the TP. Later, Yeh et al.[2] and Flohn[3] found that the air column over the TP is a heat source in summer. By analyzing the variation characteristics of the South Asia High, Flohn[4] brought forward a viewpoint that the South Asia High is a consequence of the thermal forcing of the TP. Furthermore, the results of numerical experiments by Broccoli and Manabe[5] showed that large-scale orography such as the TP and Rocky Mountains can result in the drought climate in the middle latitude belt over the Northern Hemisphere. Wu and Zhang[6] analyzed the relation of the persistent land SH over the TP to the Asia summer monsoon onset and pointed out that due to the strong advection in spring, such a persistent SH leads to warmer air temperatures over the eastern TP, to the development of the lower layer southerly to the area, and convergence there. This then provides a favorable background for the earliest Asia summer monsoon onset over the north of the Bay of Bengal.

In recent years, there have been many studies on the influence of the TP heating on the circulation and rainfall in the summer season over China. Luo and Chen[7] revealed that when the TP heating source strengthens, the rainfall in the upper reaches of the Yangtze River and over the valley of the Huaihe River will be more than normal, whilst the rainfall in the area of South China will be less than normal. Liu et al.[8] found that stronger TP heating causes the subtropical anticyclone over the Western Pacific (SAWP) move southward, airflow convergence in the valley between the Yangtze and Huaihe Rivers, and results in more rainfall over there. By using observational data, Zhao and Chen[9] showed that when the heating source over the TP is stronger (weaker) than normal, there is abnormal cyclonic (anticyclonic) circulation in the lower troposphere over the TP and surrounding areas, and abnormal southwest (northeast) winds in the lower layer over the Yangtze River valley, corresponding to the strong (weak) EA summer monsoon.

Most of these studies focused on the simultaneous relationship between the atmospheric circulation or rainfall over EA and the heating over the TP in summertime, and cannot be used for prediction. Zhao and Chen[10] recently implied that the heating status over the TP in April can give a clue to predict the forthcoming weather over regions such as the reaches between the Yangtze River and Huaihe River, and South China and North China. However, the data they used for the study were from the 148 surface stations, and most of them were located in the eastern part of China. Hence the effects of TP heating on the rainfall anomalies over the TP and surrounding areas became unclear. The aim of this study is to reveal the influence of the heating status over the TP before the EA summer monsoon onset upon the atmospheric circulation and rainfall in the forthcoming monsoon season. Firstly, the spatial patterns and temporal coefficients of the SH over the TP region in each month during AMJ are obtained by using the REOF analysis. Then the influence of the SH in May upon the rainfall, streamfunction, and vapor flux fields in July are revealed by calculating the lagged correlation. The mechanism linking the heating over the TP and the circulation and rainfall over EA is also explored by employing the thermal adaptation theory and the large-scale quasi-steady vorticity equation.

1 Data and methods

The heating rate, wind speed, vapor flux, and precipitation rate fields used in this work are the monthly averaged NCEP/NCAR reanalysis data[11] from 1958 to 1999. The heating rate is provided at 28 σ layers in the vertical. The horizontal resolutions are 1.875°×1.875° for heating and precipitation rate, and 2.5°×2.5° for the other variables. SH comes from the integral of vertical diffusive heating that equals the land surface sensible heat flux. The total atmospheric diabatic heating is the sum of the integrals of vertical diffusion, large-scale condensation, deep convection, shallow convection, longwave radiation, and shortwave radiation heating. In view of the orographic complexity in EA, all p-coordinate data are interpolated to σ-coordinates. To ensure the credibility of NCEP/NCAR data, the distributions of its precipitation rate are compared with those of observations obtained from 160 stations over China.

The REOF method[12—14] is to rotate the output of EOF analysis orthogonally by using the varmax method. This procedure conserves the sum of the variance of the rotated principal components before and after rotating, and thereby keeps the advantage of the EOF analysis in compressing the complicated variability of the original data into a relatively few temporally uncorrelated components. On the other hand, it overcomes the shortcoming in the traditional EOF analysis in which each spatial pattern depicts the variation structure of the whole field with almost equal weights. In this study we first get the main spatial patterns of the monthly SH during AMJ in an area including the TP and its surrounding regions by the traditional EOF analysis. To identify the local characteristics of the SH distribution, the leading 18 spatial patterns (accumulative variances in every month are more than 90%) are rotated by the varmax method. Then, the patterns of correlation between spring SH and the July climate fields such as precipitation, zonal and meridional wind speed (U and V), and zonal and meridional vapor flux (UQ and VQ) are obtained by calculating lagged correlation coefficients between the RPC1 in May and these fields. Finally, the correlation coefficients between RPC1 in May and U, V in July are used to compose a streamfunction field that expresses the anomalous atmospheric circulation pattern associated with the spring TP heating. Following a similar approach, the summertime anomalous transfer of water vapor and its divergence in association with the TP heating in May are constructed by using those correlation coefficients between RPC1 and UQ, VQ.

2 The REOF analysis of the SH over the TP during AMJ

Figure 1 shows the four leading spatial patterns of SH in May over the TP area (23.809° — 40.952° N, 75° —100° E) with 150 grid points altogether. The value at every grid point is the correlation coefficient between the *in situ* SH time series and the corresponding RPC, and the square of every value is the variance contribution to the data series of this grid point. Because the data used have been normalized, the variance at each grid point equals 1. Therefore, the square of the grid point's value is also the variance contribution rate to the corresponding grid point and only grid points with large values provide us with useful information. For instance, grid points with absolute values larger than 0.8 denote that at least 64% (square of 0.8) of the local variance is represented by this pattern. In fig. 1(a), the interpretational variance of REOF1 to the data series reaches 23.8%, indicating this pattern can represent the significant characteristics to a large degree of the SH distribution in May. Since most of the grid points over the TP possess local variance of more than one third (value larger than 0.6), whereas those outside the TP are remarkably smaller, the SH over the TP in May is distinguished from the surrounding regions, and such a REOF1 can therefore be considered as an isolated heating pattern. In this pattern, two maximum centers of more than 0.9 are respectively located over the southwest and southeast TP. Figs. 1(b), (c), and (d) represent the spatial patterns in which the heating centers are, respectively, located over the Indian Desert southwest to the TP, the valley of the Brahmaputra southeast to the TP, and the Qilian Mountain northeast to the TP. The accumulative variance contribution of these four leading patterns approaches half of the total, indicating that they depict the main characteristics of SH spatial distribution over there in May. As a matter of fact, if data are not normalized before REOF analysis, the reconstructed field by these four leading spatial patterns and the corresponding temporal coefficients agrees fairly well with the original data field (figure not shown here).

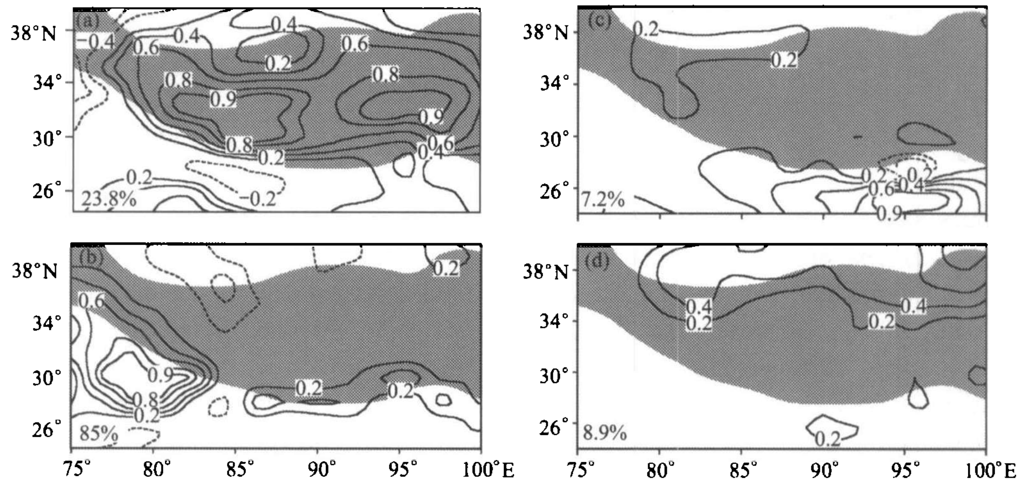

Fig. 1. The leading four REOFs of SH over the TP and adjacent regions in May (from top to bottom are REOF1, REOF2, REOF3, and REOF4 respectively. The value of contours is the correlation coefficient between SH and the corresponding temporal coefficient, variance contribution percent is indicated in the lower left-hand corner of each panel, and shaded areas are the 3000-m high topography.

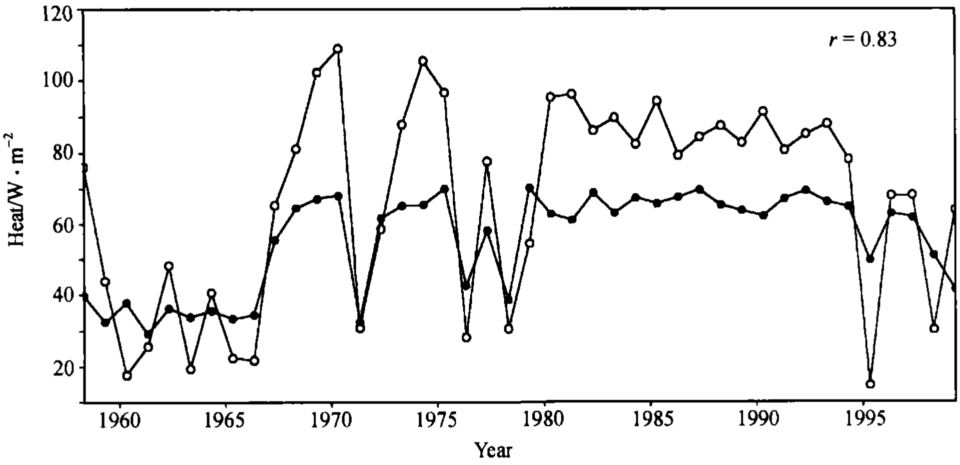

Fig. 2. Temporal variation of the area-averaged atmospheric heating source (open circles) and SH (closed circles) over the TP in May. The number in the upper right-hand corner is the correlation coefficient between them.

Figure 2 shows the temporal variations of the area—averaged atmospheric total diabatic heating as well as SH over the TP. Some analogies between these two curves are prominent, and their correlation coefficient is 0.83, which is above the 0.001 significance level. This implies that in AMJ, the temporal variation of SH reflects the characteristics of the total diabatic heating. Actually, if the REOF analysis is applied to the total diabatic heating of May, its REOF1 and even RPC1 are analogous to those of SH (figure not shown here). Furthermore, the correlation coefficient between the RPC1 of SH and the area-averaged SH index over the TP in May shown in fig. 2 is 0.89. These facts give further evidence to illuminate the comparability of the temporal variation tendency between the REOF1 and the SH index.

A similar REOF analysis has been applied to the SH variations over TP in April and June, and the results (figures omitted here) demonstrate that their first REOFs are very similar to those of May, and the variance of each REOF1 of these three months exceeds 20%. Moreover, the variation tendency of each RPC1 is also like the others. All these indicate that the remarkable persistency is the basic characteristic of the SH variation over the TP during AMJ. For this reason, we choose the RPC1 of SH in May as a representative to explore the influence of SH over the TP during the presummer season on the rainfall and atmospheric circulation over EA in midsummer.

3 Correlation between the SH over the TP in May and rainfall over EA in summer

Figure 3(a) demonstrates the spatial distribution of lagged correlation between the RPC1 of SH over the TP in May and the precipitation rate over EA in July. It is seen that when the SH over the TP is anomalously strong, there will be less rainfall in the following summer regions: north of the TP, from the northeastern TP to North China, Kashmir, the southern part of South China, and the Northern Japan Sea. In contrast, much more rainfall will appear over the western and southeastern TP, to the north of the Bay of Bengal, the Yunnan—Guizhou Plateau located southeast of the TP, and the valley between the Yangtze River and Huaihe River. Fig. 3(b) shows the distribution of the lower troposphere (σ =0.811, equivalent to 800 hPa of a plain area) streamfunction that is constructed by the correlation coefficients between the RPC1 of SH in May and U, V fields in July. There is abnormal cyclonic circulation over the TP with a center located on its southwest flank and convergence over the southeastern part. These are in coordination with the two rainfall centers shown in fig. 3(a). Conversely, abnormal anticyclonic circulation with its center situated over Mongolia controls the whole mid and higher latitude domains over EA, resulting in divergent circulation to the west of the TP. These are in coordination with the negative rainfall regions shown in fig. 3(a). In fig. 3(b), besides strong abnormal cyclonic circulation that is observed over the western Pacific, over the area between two abnormal cyclonic circulations and the anticyclonic circulation over Mongolia, abnormal southward air flows from Northeast China to North and South China.

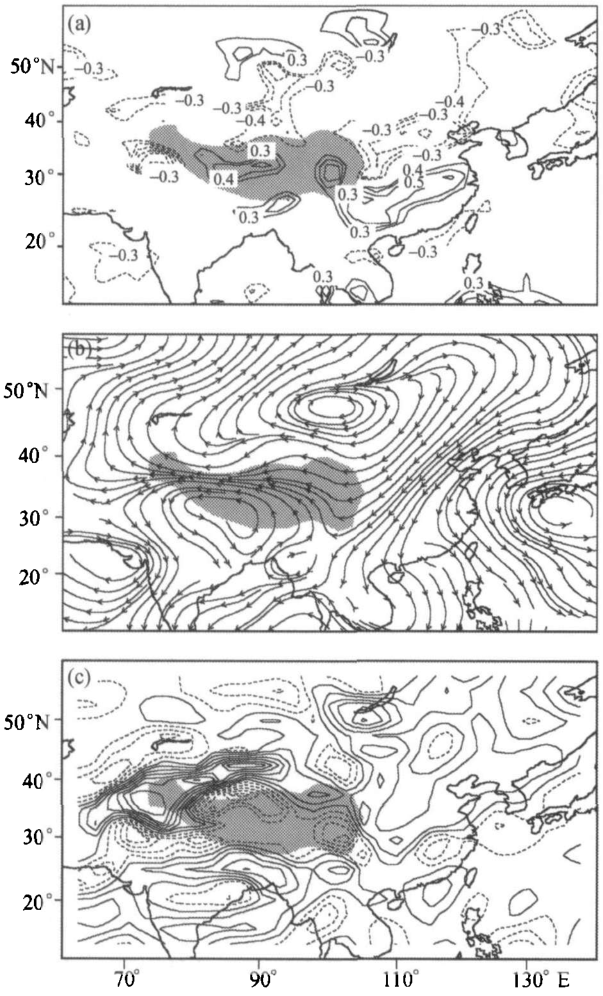

Fig. 3. (a) Precipitation rate field, (b) streamline field, and (c) divergence of water vapor flux field over EA in July related to the REOF1 of SH over the TP area in May. Contours with absolute value of 0.3 and 0.4 in panel (a) denote reaching a confidence level of 95% and 99% respectively, contours with positive (negative) values in panel (c) denote divergence (convergence), and shaded areas are the 3000-m high topography.

Water vapor transportation in the mid and lower troposphere can be judged by using the integrals of UQ and VQ from $\sigma=0.99$ to $\sigma=0.5$. The correlation coefficients between the RPC1 and the vertically integrated UQ as well as VQ can be used to construct a vector field $\vec{V}q$. Its divergence implies the relationship between the TP heating and water vapor convergence (divergence). As shown in fig. 3(c), the regions over the TP, the Yunnan-Guizhou Plateau, as well as the valley between the Yangtze River and Huaihe River, are water vapor convergence regions, whereas the regions over the northwestern TP, north of the TP, and from the northeastern TP to North China are water vapor divergence regions. Therefore, we see a general consistency in fig. 3, i.e., regions with positive (negative) rainfall correlation coefficient correspond to the abnormal cyclonic (anticyclonic) circulation or lower level convergence (divergence), as well as water vapor convergence (divergence) in the mid and lower troposphere.

To verify these conclusions obtained from the reanalysis data, the observed rainfall data of the 160 surface stations over China are employed to conduct the following composites. Because the years with the strongest REOF1 of SH over the TP in May are 1977, 1969, 1982, 1986, and 1999 in turn, and the years with the weakest REOF1 are 1966, 1960, 1959, 1965, and 1971, the composites are made for these two extremes respectively. Since most of the 160 stations are located in eastern China, only the rainfall data from the stations east of the TP are used for the composites. Fig. 4(a) and (b) show the 5-year averaged rainfall anomaly in July for the strongest and weakest 5 years respectively. It is prominent that the rainfall patterns in East China in July are completely reversed in the two composites. Strong (weak) heating over the TP corresponds to more (less) rainfall in the regions of the valley of the Yangtze River and Huaihe River, the middle reaches of the Yangtze River, and the Yunnan-Guizhou Plateau, etc., and less (more) rainfall in North and South China. These results are in good agreement with those obtained from the NCEP/NCAR reanalysis data.

It is noteworthy that all the strong SH years over the TP are El Niño years, whereas there is no obvious relationship between the weak SH years and La Niña events. This implies that stronger heating over the TP may be related to the warm phase of the ENSO cycle, and the SH over the TP during AMJ can be considered as a stronger signal than ENSO events for the

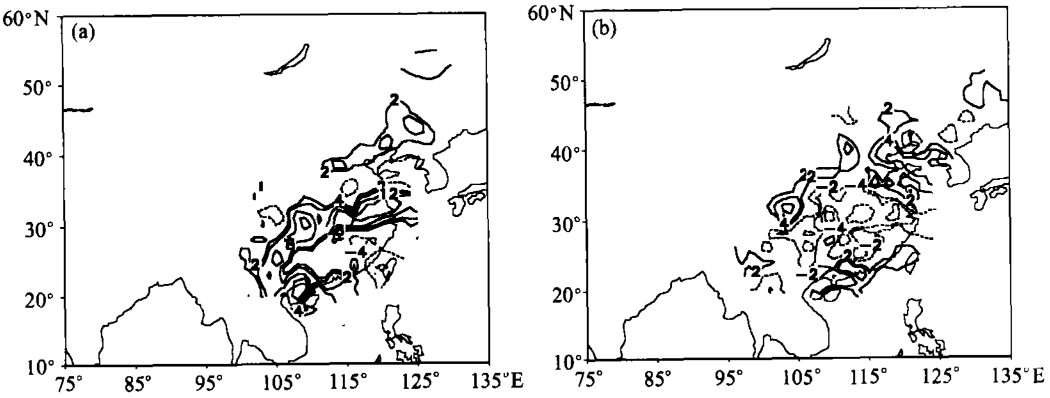

Fig. 4. Mean rainfall anomaly (mm/day) of 160 stations of China in July in the (a) strongest and (b) weakest five years of the REOF1 of SH over the TP in May.

prediction of the rainfall over EA, especially over the valley of the Yangtze River and Huaihe River.

4 Mechanism linking the TP heating during AMJ to the rainfall anomaly over EA in summer

The anomalous rainfall in summer over the TP can be partly explained by the thermal adaptation theory[15]. The SH anomaly over the TP in spring not only persists during AMJ, but is also positively correlated with the *in situ* total heating. The significance level of the lagged correlation between the area-averaged SH in May over the TP and its total diabatic heating in July exceeds 0.05. That means the stronger the SH in AMJ, the stronger the atmospheric heating source in the forthcoming summer. Based upon the thermal adaptation theory, heating leads to the abnormal cyclonic circulation and airflow convergence in the lower layers over the heating, and abnormal anticyclonic circulation and airflow divergence in the upper layers. Therefore, over the heating region, strong ascending motion will develop and suck abundant water vapor from the south, resulting in abnormal rainfall in the heating region.

The large-scale frictionless atmospheric motion in the subtropical regions can be regarded as barotropic and quasi-horizontal in summer. Under this condition, the vertical vorticity equation can be written as

$$\frac{d\zeta}{dt}+\beta v+(f+\zeta)\nabla\cdot\vec{V}=0, \qquad (1)$$

where the variables are conventional in meteorology. Because in July the ridgeline of the subtropical anticyclone in the free atmosphere (i.e., 850—200 hPa) over EA is located between 25°N and 30°N[16], the vorticity advection term $\vec{V}\cdot\nabla\zeta$ is relatively small and formula (1) can be simplified as[17—19]

$$\beta v+(f+\zeta)\nabla\cdot\vec{V}=0. \qquad (2)$$

Since the TP heating can induce cyclonic circulation in the lower layers and ancticyclonic circulation in the upper layers, it generates the lower-layer southerly and upper-layer northerly winds to its east just over eastern China. According to (2), lower-layer convergence and upper-layer divergence should occur, leading to the development of strong ascending motion. This is in cooperation with the development of the southerly, resulting in the abundant rainfall over eastern China. In contrast, the prevailing southward dry and cold airflows in the west part of the heating source over the TP and the associated divergence and descending air will result in less rainfall. Such coordination among streamfunction, water vapor flux, and rainfall fields is well demonstrated in fig. 3(a), (b), and (c).

In a simultaneous correlation analysis, Liu et al.[8] found that the strong July heating over the south and southeast TP can produce Rossby waves, and make the SAWP move southward. Airflows then converge between the Yangtze and Huaihe Rivers resulting in more rainfall there. In our time-lagged correlation analysis, the stronger heating over the TP will lead to stronger anticyclonic circulation in the mid and high latitudes of EA, while abnormal cyclonic circulation over the western Pacifics will lead to the anomalous southward flows from Northeast China to South China in fig. 3(b). Such an anomalous northerly interacts with the prevailing summer monsoon southerly in the lower layers over East China. The cold and dry anomalous air from higher latitudes and the warm and humid basic air from the tropics converge over the valley between the Yangtze and Huaihe Rivers (fig. 3(c)), resulting in much more rainfall there. The rainfall anomalies over North China and South China are negative because the water vapor flux over the regions is divergent. From these, we can draw the conclusion that the summertime abnormal rainfall pattern over East China, i.e., more rainfall along the reaches of the Yangtze and Huaihe Rivers and less rainfall in North China and South China, is closely related with the abnormal strong heating over the TP before the summer monsoon onset.

5 Conclusions and discussions

The TP is a huge heating source upheaved in the mid-troposphere in summer. Besides the mechanism forcing, its thermal forcing can also obviously affect the atmospheric circulation. During the period of AMJ, the temporal variation of SH over the TP is representative of the total diabatic heating, and the SH over the TP is persistent. The monthly REOF1s of SH from April to June over the TP are similar and demonstrate it as an isolated heating source throughout this period. The persistency of the TP heating may be related to the land surface process. The modeling of Yeh et al.[20] showed that the land surface process possesses several months 'memory'. The numerical simulation results of Wu et al.[21] revealed the change in the land surface process in spring can change and affect the climate in early summer, and we may infer that stronger (weaker) SH corresponds to higher (lower) soil temperature as well as less (more) soil moisture content. Such a land surface condition is propitious to the persistently stronger (weaker) heating over the TP in the early summer.

When the SH over the TP is abnormally strong during AMJ, there will be more rainfall in July over the Yunnan-Guizhou Plateau and the middle reaches of the Yangtze River and Huaihe River. Correspondingly, there is lower-layer convergence of water vapor flux in these regions. In contrast, there will be less rainfall in the regions north, northeast, and west of the TP in coordination with the lower-layer divergence of water vapor flux. All these can be well explained in terms of the thermal adaptation theory and large-scale quasi-stationary barotropic vorticity equation. Therefore, the heating status over the TP during AMJ can be used as a useful signifier for predicting the early summer rainfall and atmospheric circulation over EA, especially over the valley between the Yangtze and Huaihe Rivers.

The circulation and rainfall distributions in summer over China are influenced by many factors. Besides the mechanical and thermal forcing of the TP, the activities of cold air in the mid and higher latitudes and typhoons in the subtropics, the variations of the SAWP and the southwest jet in the lower layers, the ENSO cycle, and the land-air interaction, etc. can also affect the summer climate anomaly over China. These deserve further studies in the future.

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