Roles of the Tibetan Plateau vortices in the record Meiyu rainfall in 2020

Lun Li1 | Congwen Zhu1 | Renhe Zhang2,3 | Boqi Liu1

1State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China
2Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences, Fudan University, Shanghai, China
3CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China

Correspondence
Lun Li, Chinese Academy of Meteorological Sciences, #46, Zhong-Guan-Cun South Avenue, Beijing 100081, China.
Email: lilun@cma.gov.cn

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Abstract
Meiyu rainfall in June–July of 2020 hit the Yangtze-Huaihe River basin, and the precipitation at lots of observational stations broke the records, inducing severe disasters there. Tibetan Plateau vortices (TPVs) generated over the Tibetan Plateau are local major rainfall triggers. In previous knowledge, TPVs can affect the rainfall in eastern China, only after emigrating from the Tibetan Plateau. In this work, roles of TPVs in the record Meiyu are revealed, implying that the effects of TPVs may be underestimated previously. Firstly, TPVs dying out over the Tibetan Plateau may be transformed into troughs and continue to move eastward, influencing the rainfall in Yangtze-Huaihe River basin. Secondly, southwest vortices, the important rainfall producers in China, tend to be generated and maintained when TPVs are located over eastern plateau. The results give extended knowledge on the effects of TPVs, which are beneficial for the rainfall prediction in eastern China.

KEYWORDS
Meiyu, Tibetan Plateau vortices, trough, southwest vortices

INTRODUCTION
Meiyu is the major rainfall season in East Asia (Ninomiya and Murakami, 1987; Tao and Chen, 1987). Generally, Meiyu starts from early June and ends in mid-July, with the zonally elongated rain band covering the mid-lower reaches of Yangtze River, Japan and Korea (Tao and Chen, 1987; Tanaka, 1992; Sampe and Xie, 2010). Record Meiyu happened in June–July of 2020, hitting wide areas in Yangtze-Huaihe River basin in China. The accumulated precipitation in Meiyu period has broken the historic record since 1961, with lots of observational stations breaking their own records. Consequently, severe disasters in Yangtze-Huaihe River basin are induced (e.g., floods, landslides), bringing huge economic and lives losses, and substantial damage to normal production and life.

[Correction added on 10 December 2020, after first online publication: The fourth sentence in paragraph 2 of section 3.2 has been corrected in this version.]
Tibetan Plateau vortices (TPVs) are generated at 500 hPa mainly during May–August over the Tibetan Plateau, which are local major rainfall triggers (Ye and Gao, 1979; Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981). The TPVs can move eastward and emigrate from the Tibetan Plateau under certain conditions, which act as very important rainfall producers in southwestern and eastern China (Wang et al., 2009; Huang et al., 2015; Yu et al., 2015; Li et al., 2019). Lots of heavy rainfalls and floods in southwestern and eastern China have been proved to be linked to the TPVs emigrating from the Tibetan Plateau (Yang et al., 2001; Zhang et al., 2001; Yu, 2008). Formally, a TPV is defined as a low, which forms over the Tibetan Plateau with closed contour lines or cyclonic winds at three observation stations at 500 hPa (Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981). The evolution of TPVs is thought to be greatly affected by both the large-scale circulations and the thermodynamic conditions (e.g., condensational latent heat, sensible heat) over the Tibetan Plateau (Liu and Fu, 1985; Dell’Osso and Chen, 1986; Shen et al., 1986a, 1986b; Wang, 1987; Li and Zhao, 2002; Li et al., 2014a, 2014b), with the latter being proved to be closely related to the time-lagged effect of the spring sensible heat over the Tibetan Plateau (Wang et al., 2014). TPVs are shallow cyclonic systems when they are on the Tibetan Plateau, with the horizontal and vertical scales being 400–800 and 2–3 km, respectively (Ye and Gao, 1979; Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981; Luo, 1992; Luo et al., 1994; Feng et al., 2014). After they move off the Tibetan Plateau, the structure becomes deeper, but the intensity is much weaker, compared with those before moving off the plateau (Li et al., 2020).

Because TPVs emigrating from the Tibetan Plateau are thought to play an important role in the rainfall east of the Tibetan Plateau, TPVs that emigrate from the Tibetan Plateau are mainly concerned previously when investigating the Meiyu rainfall, and the ones dying out over the Tibetan Plateau are always neglected. In the present work, the TPVs dying out over the plateau are taken into the investigation, to explore if there are some other ways for them to affect the rainfall in Yangtze-Huaihe River basin. The results give extended knowledge on the effects of TPVs, which are beneficial for the rainfall prediction in eastern China.

2 | DATA AND METHOD

Final (FNL) operational global analysis data from NCEP (http://rda.ucar.edu/datasets/ds083.2, ds083.2) [DOI: 10.5065/D6M043C6] in June–July of 2020 is adopted to identify the TPVs and analyze the circulations. The FNL data are at a 6-hr interval and covers globally with a 1° × 1° horizontal resolution. Actually, the reliability of FNL in analyzing the circulations associated with the TPVs has been verified previously (Li et al., 2014a, 2020). Because the FNL data starts from July 1999, the climatic means are taken as the averages between 2000 and 2019. Accordingly, anomalies of the variables (e.g., geopotential height, zonal and meridional winds, and vertical velocity) are calculated as differences between the original data and the climatic means. In addition, daily and 6-hourly precipitation with approximately 2,400 stations, obtained from National Meteorological Information Center of China Meteorological Administration (CMA) is utilized. Daily precipitation averaged between 2000 and 2019 is removed from the original data to calculate the daily precipitation anomalies. Because the Meiyu in 2020 mainly persisted during June to July of 2020, the research period is 1 June–July 31, 2020 in the present work.

To diagnose the effect of TPVs on the ascending motion, adiabatic quasi-geostrophic \( \omega \) equation (Equation 1) (Tam and Li, 2006; Kosaka et al., 2011) is diagnosed, in which the variables are decomposed into zonal means (denoted by over bars) and their perturbations (denoted by primes). All operators and variables in Equation 1 are of conventional usage in meteorology.

\[
\left( \sigma \nabla^2 + f_0 \frac{\partial \zeta}{\partial p} \right) \omega = f_0 \frac{\partial}{\partial p} \left( u_k \frac{\partial \zeta'}{\partial x} + u_k' \frac{\partial \zeta}{\partial x} + v_k \frac{\partial \zeta}{\partial y} + v_k' \frac{\partial \zeta'}{\partial y} + v_k \frac{\partial x}{\partial y} + v_k' \frac{x}{\partial y} \right) \\
+ \nabla^2 \left[ \frac{R}{P} \left( u_k \frac{\partial T'}{\partial x} + u_k' \frac{\partial T}{\partial x} + v_k \frac{\partial T}{\partial y} + v_k' \frac{\partial T'}{\partial y} + v_k \frac{T}{\partial y} + v_k' \frac{T'}{\partial y} \right) \right].
\]

In Equation (1), the terms in \( f_0 \frac{\partial}{\partial p} \left( u_k \frac{\partial \zeta}{\partial x} + u_k' \frac{\partial \zeta'}{\partial x} + v_k \frac{\partial \zeta}{\partial y} + v_k' \frac{\partial \zeta'}{\partial y} + v_k \frac{\partial x}{\partial y} + v_k' \frac{x}{\partial y} \right) \) represent terms 1 to 6 respectively; and the terms in \( \nabla^2 \left[ \frac{R}{P} \left( u_k \frac{\partial T'}{\partial x} + u_k' \frac{\partial T}{\partial x} + v_k \frac{\partial T}{\partial y} + v_k' \frac{\partial T'}{\partial y} + v_k \frac{T}{\partial y} + v_k' \frac{T'}{\partial y} \right) \right] \) represent terms 7 to 11, respectively.

3 | RESULTS

3.1 | Troughs transformed from the TPVs

TPVs generated during 1 June to July 31, 2020 and the 6-hourly precipitation averaged in the meridional range of Yangtze-Huaihe River basin (approximately between
Meiyu rainfall, the defined TPVs-related rainfall episodes should satisfy three conditions: both the positive vorticity at 500 hPa and the precipitation continuously stretch eastward from the Tibetan Plateau to Yangtze-Huaihe River basin (approximately east of 110°E); TPVs are observed on the eastward extending positive vorticity bands. In these TPVs-related rainfall episodes, the periods in which the rainfall falls east of the Tibetan Plateau are defined as TRO periods (marked with short red lines in Figure 1).

Additionally, daily precipitation anomalies averaged during the entire Meiyu period and in the TRO periods are presented in Figure 2. The spatial distribution of the precipitation in TRO periods coincides well with that in the Meiyu period, and the intensity in the former is obviously larger than that in the latter, indicating that the precipitation in the former scenario greatly contributes to the Meiyu rainfall in 2020 and decides its pattern to a great extent. Thus, it is inferred that the TPVs-related cyclonic circulations continue to move eastward and affect the Meiyu rainfall, following the disappearance of TPVs.

In order to obtain the common features of circulations linked to the TPVs after the TPVs die out, storm-centered composites are adopted. The last times that TPVs are observed are taken as \( t = 0 \), and four times afterwards are marked as \( t = 1 \), \( t = 2 \), \( t = 3 \), and \( t = 4 \), respectively. The intervals between the five times are 6 hr. Locations of the TPVs’ centers at \( t = 0 \) are considered as the origin of the coordinates. And then, the anomalous geopotential height at 500 hPa at each time is composed separately, and the results are shown in Figure 3. The coordinates on the x-axis (y-axis) are the relative coordinates from the center of TPVs at \( t = 0 \) in the zonal (meridional) direction, and only the composites at four times after \( t = 0 \) are shown in this work. In Figure 3, at \( t = 0 \), negative geopotential height anomalies center is located at the origin of the coordinate, corresponding to the low-pressure center of TPVs; an anomalous low is observed north of the TPVs. At the following times, the lows north of the TPVs become stronger, favoring more intensive westerly wind north of TPVs. The intensified westerlies north of the TPVs are not beneficial for the maintenance of the closed cyclonic circulation of TPVs, prompting the transformation of TPVs to troughs. After the TPVs disappear, from \( t = 1 \) to \( t = 4 \), troughs related to the TPVs continue to move eastward, corresponding to the eastward propagation of positive vorticity at 500 hPa shown in Figure 1.

To investigate the influence of the TPVs-related troughs, composites of anomalous geopotential height and wind at 500 hPa, as well as the anomalous vertical velocity at 500 hPa in TRO periods are presented in Figure 4. In Figure 4a, negative geopotential height anomalies...
passing significance test are mainly found east of the Tibetan Plateau between 30°N and 42°N, reflecting the activities of TPVs and the TPVs-related troughs in this region. Meanwhile, positive geopotential height anomalies are found north of northeastern China and south of 30°N. Accordingly, anomalous northerlies associated with the anomalous low between 30°N and 42°N are observed north of the Yangtze River, and anomalous southerlies linked to the anomalous high south of 30°N are found south of the Yangtze River. Actually, the anomalous high south of 30°N indicates the western Pacific subtropical high. The anomalous northerlies north of the Yangtze River and southerlies south converge in Yangtze-Huaihe River basin, which is in favor of the ascending motion there. Given the ascending motion is the crucial factor in triggering rainfall, the vertical velocity anomalies at 500 hPa is provided in Figure 4b. To clearly display the spatial distribution of vertical motion in Yangtze-Huaihe River basin, the region enclosed in the red rectangle frame is focused on. In Figure 4b, remarkable anomalous ascending motion appears in Yangtze-Huaihe River basin, with the centers located at approximately 109°E, 30°N, 117°E, 33°N, and 119°E, 30°N. The three ascending motion centers not only match the rainfall centers in TRO periods (Figure 2b), but also coincides well with those in the entire Meiyu period (Figure 2a), implying the significant impact of the troughs transformed from the TPVs on the Meiyu rainfall.

Briefly, TPVs dying out over the Tibetan Plateau also have great effect on the Meiyu rainfall in 2020, in the form of eastward-moving troughs.

3.2 | Effects on the southwest vortices

Southwest vortices (SWVs) are mesoscale cyclonic circulations identified at 700 hPa, which occur in southwestern China, such as in the eastern and southeastern flanks
of the Tibetan Plateau (Tao, 1980; Lu, 1986; Wang and Orlanski, 1987). SWVs are not only important summer rainfall-producers in southwest China, but also can affect the rainfall in wider areas in eastern China when moving eastward (Tao, 1980; Lu, 1986). In the Meiyu rainfall in 2020, SWVs are generated frequently in the area of 104°–109°E, 28°–34°N, with the total occurrence frequency being 25 (Figure 5). Most of the SWVs disappear west of 110°E, and 4 SWVs move to eastern China. Previous work (Chen et al., 2004; Xiao et al., 2009; Zhou et al., 2009) suggested that the TPVs located over the eastern Tibetan Plateau can influence the genesis of SWVs, based on only one case. However, whether the results are applicable in the other cases are not clear yet, which needs to be further explored based on lots of cases. Thus, in addition to the effect of troughs transformed from TPVs, the influence of TPVs located over the eastern Tibetan Plateau on the SWVs is further investigated. All of the TPVs observed over the eastern Tibetan Plateau in the entire Meiyu period are involved. Because ascending motion is crucial for the rainfall and the related condensational latent heat release, which is the important factor in the genesis and maintenance of SWVs (Kuo et al., 1988; Pan et al., 2008; Fu et al., 2011; Li et al., 2017), the vertical motion east of the Tibetan Plateau in the genesis area of SWVs (104°–109°E, 28°–34°N) is analyzed. The scenarios that TPVs exist over eastern plateau between 98°E and 104°E and that no TPVs exist are compared, and the differences of the vertical velocity averaged between 28°N and 34°N are shown in Figure 6a. It is found that when there are TPVs over the eastern Tibetan Plateau, the ascending motion in the genesis area of SWVs is apparently stronger than in the scenario that no TPVs exist, implying the important effect of TPVs on the vertical motion east of the Tibetan Plateau.

The adiabatic quasi-geostrophic \( \omega \) equation (Equation 1) is employed to reveal the mechanism that the TPVs influence the vertical motion east of the Tibetan Plateau. The times when the TPVs are observed over the eastern Tibetan Plateau between 98°E and 104°E are
selected, and the budgets of vertical velocity perturbation at 500 hPa in the genesis area of SWVs (104°–109°E, 28°–34°N) are calculated (Figure 6b). 500 hPa is the non-divergence level, which is stable for analyzing the vertical motion. Terms 1, 4, 8, and 11 contribute to ascending motion east of the Tibetan Plateau, among which term 4 is the largest contributor, followed by term 1. Thus, only terms 1 and 4 are discussed in detail here. Term 1 indicates the vertical differential of vorticity perturbation advection by the mean zonal flow, which is closely related to the vertical vorticity over the eastern Tibetan Plateau. TPVs are lows with positive vertical vorticity, accordingly, the mean westerlies transport the positive vorticity eastward to the genesis area of SWVs. Meanwhile, the vorticity perturbation advection by the mean zonal flow reaches the maximum at about 400 hPa (figure not shown), leading to $\frac{\partial}{\partial p} \left( \bar{u} \frac{\partial \zeta}{\partial x} \right) > 0$, which benefits the ascending motion east of the plateau. Term 4 is the vertical differential of vorticity perturbation advection by meridional flow perturbation. The structure of TPVs shows that there is southerly perturbation on the east of TPVs (Li et al., 2020), and the vertical vorticity perturbation at 500 hPa decreases northward in the genesis area of SWVs (figure not shown), producing positive vorticity perturbation advection by the southerly perturbation. In addition, the vorticity perturbation advection by meridional flow perturbation increases with the height (figure not shown), contributing to the ascending motion there ($\frac{\partial}{\partial p} \left( \bar{v} \frac{\partial \zeta}{\partial y} \right) > 0$). According to the analyses above, the positive zonal gradient of vorticity ($-\frac{\partial \zeta}{\partial x} > 0$) and southerly perturbation ($\bar{v}$) associated with the TPVs are important for the vertical motion east of the Tibetan Plateau.

**FIGURE 6** Differences between the elements in the scenario that TPVs exist over the eastern Tibetan Plateau and those in that no TPVs exist: (a) vertical velocity averaged between 28°N and 34°N (contours; unit: Pa s$^{-1}$), (c) zonal gradient of the vorticity perturbation (contours; unit: 10$^{-10}$ m$^{-1}$ s$^{-1}$), (d) meridional wind perturbation (contours; unit: m s$^{-1}$). Composites of terms 1–11 in Equation 1 averaged in the genesis area of SWVs (bars; unit: 10$^{-18}$ m s$^{-1}$ kg$^{-1}$) are shown in (b). In (c) and (d), the gray shadings indicate the eastern Tibetan Plateau, whose easternmost boundary is taken as 104°E; the genesis area of SWVs (104°–109°E, 28°–34°N) are enclosed with blue rectangles. Areas in which statistical significance exceeding 90% confidence level are indicated by gray shadings in (a), and yellow shadings in (c) and (d).
Furthermore, the zonal gradients of vorticity (southerly perturbations) in the scenarios that TPVs exist over eastern plateau and that no TPVs exist are compared, and the differences are shown in Figure 6c (Figure 6d). Generally, both the positive zonal gradient of vorticity and the southerly perturbation east of the Tibetan Plateau are stronger when TPVs are observed over eastern plateau, particularly around 106°E, 33°N, implying that these TPVs are responsible for vertical motion east of the plateau. Thus, the TPVs located over the eastern Tibetan Plateau not only affect the rainfall in southwestern China, but also are beneficial for the activities of SWVs, which contributes to the record Meiyu rainfall in 2020.

In a word, the TPVs not emigrating from the Tibetan Plateau also have great effects on the Meiyu rainfall in 2020. Firstly, troughs transformed from the TPVs continue to move eastward and affect the Meiyu rainfall. Secondly, the TPVs over the eastern Tibetan Plateau enhance the ascending motion east of the plateau, which prompts the rainfall there and favors the genesis and maintenance of SWVs.

4 CONCLUSIONS AND DISCUSSION

Meiyu rainfall in June–July 2020 is extremely heavy, causing severe floods and geologic hazards in Yangtze-Huaihe River basin. TPVs are previously considered as important rainfall triggers in southwestern and eastern China, after they emigrate from the Tibetan Plateau. In the present work, the roles of TPVs in the record Meiyu in 2020 are investigated, which suggests that the effects of TPVs may be underestimated in previous knowledge. The results are summarized as follows.

1. Although the TPVs die out, the troughs transformed from the TPVs continue to move eastward and affect the Meiyu rainfall.

Previous knowledge suggested that the TPVs have important effect on the Meiyu rainfall when they emigrate from the Tibetan Plateau. Actually, in the Meiyu rainfall in 2020, because of the intensification of westerlies north of the TPVs, the closed circulations of TPVs are destroyed and transformed into troughs. The troughs continue to move eastward after the TPVs disappear and affect the Meiyu rainfall. The anomalous northerlies associated with the troughs converge with the anomalous southerlies related to the western Pacific subtropical high, leading to ascending motion in Yangtze-Huaihe River basin and thereby contributing to the Meiyu rainfall there. As a result, the spatial distribution of the average daily precipitation anomalies related to the TPVs coincides well with that during the entire Meiyu period, with the intensity in the former remarkably larger than that in the latter. Thus, troughs transformed from the TPVs are responsible for the record Meiyu rainfall in 2020.

2. TPVs that do not emigrate from the plateau can influence the SWVs, through affecting the ascending motion east of the Tibetan Plateau.

SWVs are important rainfall triggers in China. In the Meiyu period in 2020, all of the TPVs observed over the eastern Tibetan Plateau are selected, and the adiabatic quasi-geostrophic \( \omega \) equation is calculated in the genesis area of the SWVs. It is found that the positive vertical vorticity and the southerlies associated with the TPVs are responsible for the ascending motion east of the Tibetan Plateau. Generally, the ascending motion east of the Tibetan Plateau is much stronger when the TPVs exist over the eastern plateau, compared with that in the scenario that no TPVs are observed. Ascending motion is crucial factor in triggering rainfall and the related condensational latent heat release, which is the important factor in the genesis and maintenance of SWVs. Therefore, TPVs located over the Tibetan Plateau benefit the genesis and maintenance of the SWVs.

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ORCID

Lun Li https://orcid.org/0000-0002-1736-1123
Boqi Liu https://orcid.org/0000-0001-7606-8747
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