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# Causation of the heavy rainfall in Kyushu in early July 2020: A perspective of the depression that originated over the Tibetan Plateau

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Heavy rain fell in Kyushu, Japan, in early July 2020, which caused huge life and economic losses. The present work reports that a Tibetan Plateau vortex (TPV) generated over the Tibetan Plateau transformed into a trough at the eastern edge of the Tibetan Plateau, and the trough continued to move eastward and was responsible for the heavy rainfall in Kyushu. Accordingly, the maintenance and eastward movement of the trough and the influencing mechanism of the trough on the rainfall in Kyushu are explored based on the final analysis data (FNL) from NCEP and the JRA-55 reanalysis from JMA. Diagnoses of the potential vorticity (PV) tendency equation indicate that the horizontal PV flux convergence east of the trough is the primary contributor to the eastward movement and maintenance of the trough. Furthermore, the trough is proved to have important effects on the moisture condition and the ascending motion around Kyushu. That is, the trough increases the moisture in Kyushu by intensifying the eastward moisture transportation to Kyushu; the positive vorticity and warm center, as well as the wind perturbation related to the trough, are in favor of stronger ascending motion in Kyushu. The findings in this work provide extended knowledge on the causation of rainfall in Japan, which is beneficial for further precipitation prediction.

## KEYWORDS

Tibetan Plateau vortex, trough, eastward movement, moisture, ascending motion

## 1 Introduction

Heavy rainfall hit south Japan in early July 2020, with the precipitation in Kyushu breaking the historic record. The heavy rainfall caused severe floods and resulted in huge life and economic losses. Previous studies have revealed some crucial factors contributing to the heavy rainfall in Japan (shown as follows). Baiu fronts always appear in the Baiu season, and the mesoscale disturbances are frequently observed on Baiu fronts, which are responsible for the heavy rainfall in Japan (Mohri, 1956; Matsumoto et al., 1971; Nguyen-Le et al., 2017). The moisture transported by southerlies is important in triggering rainfall in Japan (Ogura et al., 1985; Kato, 2005; Sekizawa et al., 2019; Shimpo et al., 2019), which can be enhanced by the warm sea surface (Tsuguti and Kato, 2014; Sekizawa et al., 2019). Some rainfall events are related to depressions/tropical cyclone/extratropical cyclone activities (Krishnan and Sugi, 2001; Nguyen-Le et al., 2017), and typhoons in West Pacific always cause heavy rainfall in Japan (Misumi, 1996; Wang et al., 2009; Yoshida and Itoh, 2012; Kanada et al., 2017). In addition, upper-tropospheric troughs and jets are also important rainfall contributors (Shimpo et al., 2019; Tsuji et al., 2020; Yokoyama et al., 2020). In this work, a trough that transformed from a Tibetan Plateau vortex (TPV) at 500 hPa was found to be responsible for the heavy rainfall in

Kyushu on 3–4 July 2020. Because both the TPV and trough are low-pressure systems, they are collectively called depression here.

TPVs are generated over the Tibetan Plateau at 500 hPa mainly during May to August, which are local major rainfall producers. Most of them die out *in situ*, but some can emigrate from the Tibetan Plateau under certain conditions and impose significant effects on the rainfall in east China. Formally, a TPV is defined as a low-pressure system 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). TPVs are shallow when located on the Tibetan Plateau, with the horizontal and vertical scales being 400–800 km 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 the TPVs emigrate from the Tibetan Plateau, the structures become deeper than those before moving off (Li et al., 2020a). Lots of heavy rainfalls in Southwest and East China are linked to the TPVs emigrating from the Tibetan Plateau (Yang et al., 2001; Zhang et al., 2001; Yu, 2008). Particularly, some eastward-moving TPVs can persist for several days and reach the West Pacific, which affects the rainfall in Japan (Yu and Gao, 2006).

Although our previous work revealed that the mid-upper level trough near Japan is responsible for the heavy rainfall there, the origination and evolution of the trough are not clear yet. In addition, previous studies pointed out that the TPVs emigrating from the Tibetan Plateau can affect the rainfall in Japan, but the ones not emigrating from the Tibetan Plateau are always not concerned. In the present work, a trough at the eastern edge of the Tibetan Plateau was found to be transformed from a TPV, which greatly affected the rainfall in Kyushu on 3–4 July 2020. Accordingly, the maintenance and eastward movement of the trough and its influencing mechanism on the rainfall are investigated. This work attempts to provide extended information about the causation of heavy rainfall in Kyushu, which is helpful for future precipitation prediction.

Data and methods utilized in this work are provided in Section 2. In Section 3, the rainfall which occurred in early July 2020 in Kyushu is introduced, and the maintenance and eastward movement mechanism of the trough transformed from the TPV are explored. In Section 4, the effects of the trough on the rainfall in Kyushu are investigated. Conclusions and discussions are given in Section 5.

## 2 Data and methods

### 2.1 Data

The final operational global analysis (FNL) data are used to investigate the large-scale circulations and the evolution of depression originating over the Tibetan Plateau, which is derived from the Global Forecasting System of the National Centers for Environment Prediction (NCEP) (<http://rda.ucar.edu/datasets/ds083.2>, ds083.2 [DOI: 10.5065/D6M043C6]). The FNL data are at a 6 h interval and cover globally with a  $1^\circ \times 1^\circ$  horizontal resolution. The reliability of the FNL data in researching the circulations related to the depressions over the Tibetan Plateau has been verified in our previous work (Li et al., 2014a; Li et al., 2020b). Because the FNL data start 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, moisture flux, etc.) are calculated as differences between the original data and the climatic means. The 6-hourly JRA-55 precipitation data provided by Japan Meteorological Agency (<https://jra.kishou.go.jp/JRA-55/>) are used in this work, which performs well in displaying extreme rainfall events in East Asia (Kim et al., 2019).

### 2.2 Trough-centered composites

Because the trough transformed from the TPV is a moving system, composites of the variables at different times in geographic coordinates will be greatly smoothed. To exhibit the features of the trough, the trough-centered composites are conducted. That is, at a specific time, the center of the trough (maximum of the positive vertical vorticity at 500 hPa in the trough area) is taken as the origin of the coordinates, and then, the variables at different times are composed. Thus, the composed center of the trough is the origin of the coordinates, and the coordinates on the  $x$ -axis ( $y$ -axis) are the relative coordinates from the composed center of the trough in the zonal (meridional) direction.

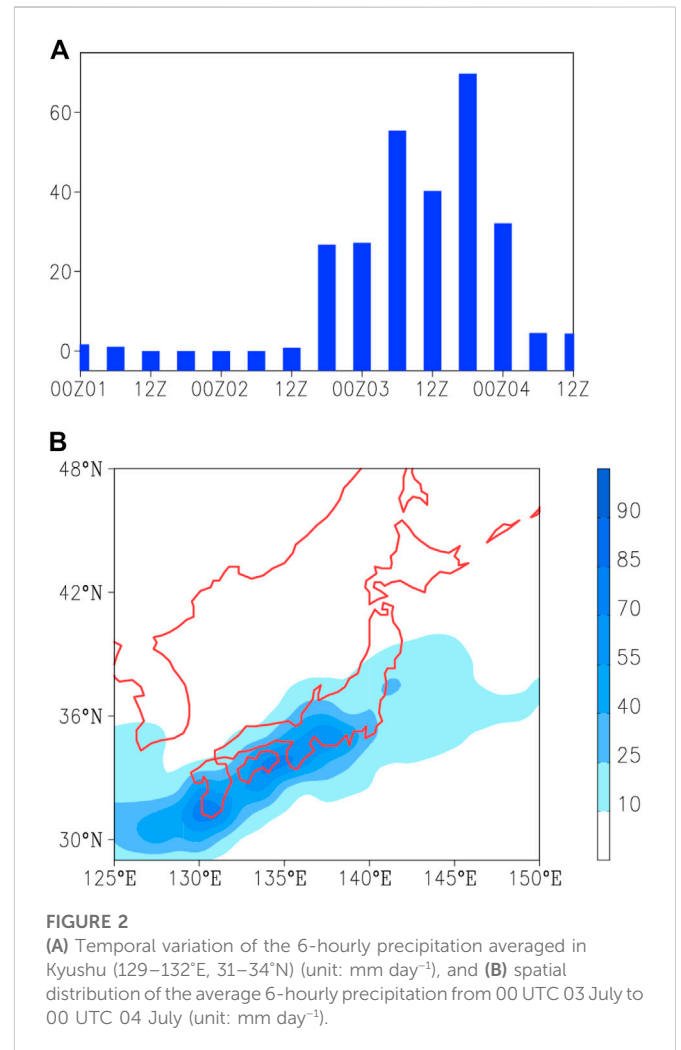
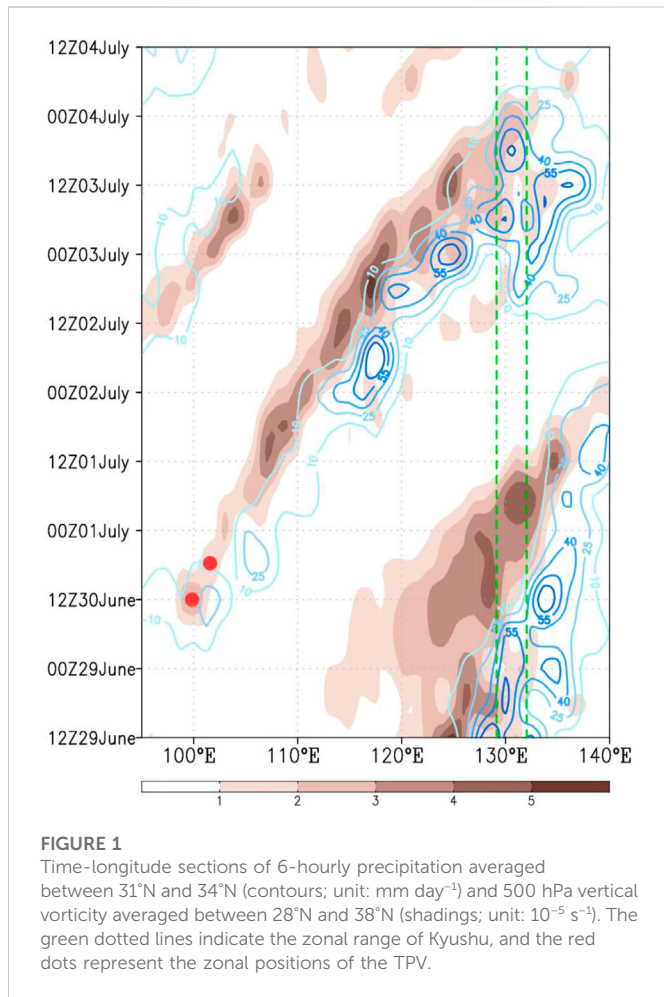
### 2.3 Potential vorticity (PV) tendency equation and quasi-geostrophic $\omega$ equation

PV budgets analyses can well-interpret the evolution of TPVs (Li et al., 2011; Zheng et al., 2013; Li et al., 2014b), which is conducted in this work to investigate the maintenance and eastward movement mechanism of the trough influencing the rainfall in Kyushu. PV tendency equation without frictional effects is shown in Eq. 1 (Li et al., 2017). Because the trough is accompanied by rainfall during its eastward movement,  $Q$  in Eq. 1 is calculated as the condensational latent heating. The formula of the condensational latent heating rate and the meanings of variables and each term can be found in the study by Li et al. (2017).

$$\frac{\partial P_E}{\partial t} = -\frac{\partial u P_E}{\partial x} - \frac{\partial v P_E}{\partial y} - \frac{\partial \omega P_E}{\partial p} + g \frac{\partial v}{\partial p} \frac{\partial Q}{\partial x} - g \frac{\partial u}{\partial p} \frac{\partial Q}{\partial y} - g(f + \zeta p) \frac{\partial Q}{\partial p}. \quad (1)$$

Additionally, given that the ascending motion is a key factor in triggering the rainfall, the adiabatic quasi-geostrophic  $\omega$  equation (Tam and Li, 2006; Kosaka et al., 2011) is calculated to explore the effect of the trough that originated from the Tibetan Plateau on the vertical motion around Kyushu. Variables in the adiabatic quasi-geostrophic  $\omega$  equation are decomposed into zonal means (denoted by over bars) and their perturbations (denoted by primes), and the processed equation is shown in Equation 2. All operators and variables are of conventional usage in meteorology. In general on the right hand side of Eq. 2, terms 1–6 represent the vertical differentials of vorticity advection, and terms 7–11 denote temperature advection. The specific meanings of the crucial terms in this rainfall event are introduced in detail in Section 4.

$$\left( \sigma \nabla^2 + f_0^2 \frac{\partial^2}{\partial p^2} \right) \omega' = f_0 \frac{\partial}{\partial p} \left( \bar{u}_g \frac{\partial \zeta_g'}{\partial x} + u_g' \frac{\partial \zeta_g'}{\partial x} + \bar{v}_g \frac{\partial \zeta_g'}{\partial y} + v_g' \frac{\partial \zeta_g'}{\partial y} + \bar{v}_g \frac{\partial \bar{\zeta}_g}{\partial y} + v_g' \frac{\partial \bar{\zeta}_g}{\partial y} \right) \\ \nabla^2 \left[ \frac{R}{P} \left( \bar{u}_g \frac{\partial T'}{\partial x} + u_g' \frac{\partial T'}{\partial x} + \bar{v}_g \frac{\partial T'}{\partial y} + v_g' \frac{\partial T'}{\partial y} + \bar{v}_g \frac{\partial \bar{T}'}{\partial y} + v_g' \frac{\partial \bar{T}'}{\partial y} \right) \right]. \quad (2)$$



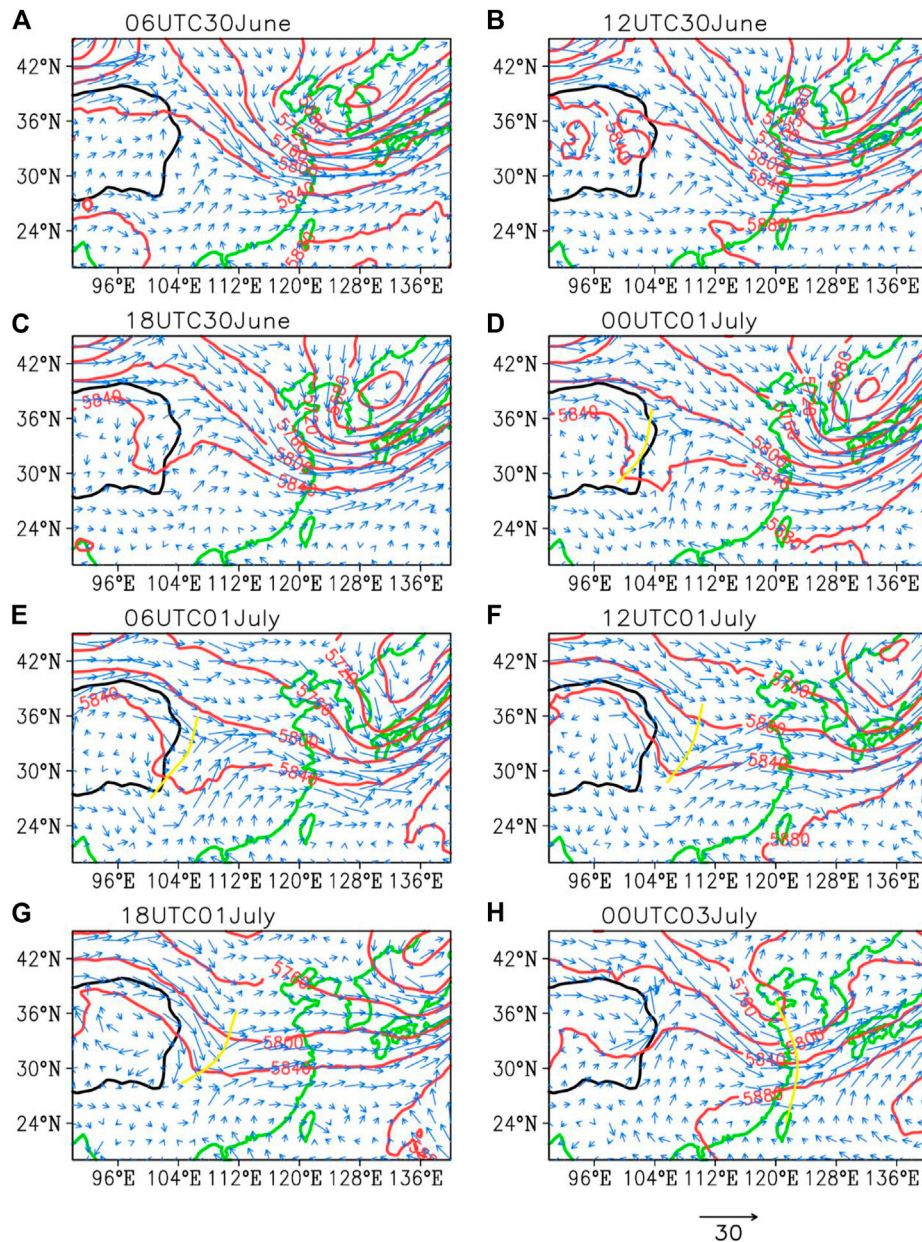
### 3 Introduction of the rainfall event in Kyushu in early July 2020

#### 3.1 Rainfall

The 6-hourly precipitation averaged between 31°N and 34°N, covering the meridional range of Kyushu, is displayed by the contours in [Figure 1](#). The rainfall centers are observed to propagate eastward between late June and early July, from 100°E to 135°E. The precipitation was weak when falling on and near the Tibetan Plateau and became stronger in central and east China. The rainfall in Kyushu persisted from 12 UTC 02 July to 00 UTC 04 July; however, only the rainfall episode between 00 UTC 03 July and 00 UTC 04 July is related to the rainband stretching from the Tibetan Plateau. Because this work aims to reveal the effect of the eastward-moving depression that originated over the Tibetan Plateau, the rainfall episode from 00 UTC 03 July to 00 UTC 04 July is of primary concern. To further demonstrate the relationship between the rainfall in Kyushu and the depression originating over the Tibetan Plateau, the vertical vorticity at 500 hPa averaged between 28°N and 38°N, which covers the meridional range of the Tibetan Plateau, is represented by shadings in [Figure 1](#). A TPV was generated at 12 UTC 30 June at around 100°E over the Tibetan Plateau, which moved eastward

and arrived at 102°E at 18 UTC 30 June. The TPV weakened when reaching the eastern edge of the Tibetan Plateau and then transformed into a trough. The trough emigrated from the Tibetan Plateau and continued to move eastward. The eastward movement of TPV and the related trough corresponds to the eastward extension of the positive vorticity and the eastward-propagating rainfall centers shown in [Figure 1](#), indicating that the depression emigrating from the Tibetan Plateau has a close relationship with the rainfall in Kyushu. Additionally, the rainfall at each time is generally located east of the positive vorticity, which implies that the rainfall usually happens east of the depression.

Temporal variation and spatial distribution of the precipitation in Kyushu are shown in [Figure 2](#). [Figure 1](#) reveals that the rainfall episode related to the depression over the Tibetan Plateau was from 00 UTC 03 July to 00 UTC 04 July. As shown in [Figure 2A](#), the precipitation became stronger after 00 UTC 03 July, with the peaks appearing at 06 UTC 03 July and 18 UTC 03 July; after 00 UTC 04 July, the precipitation weakened sharply. The average 6-hourly precipitation from 00 UTC 03 July to 00 UTC 04 July was distributed from southwest to northeast and covered wide areas of Japan, with the maximum being in south Kyushu.



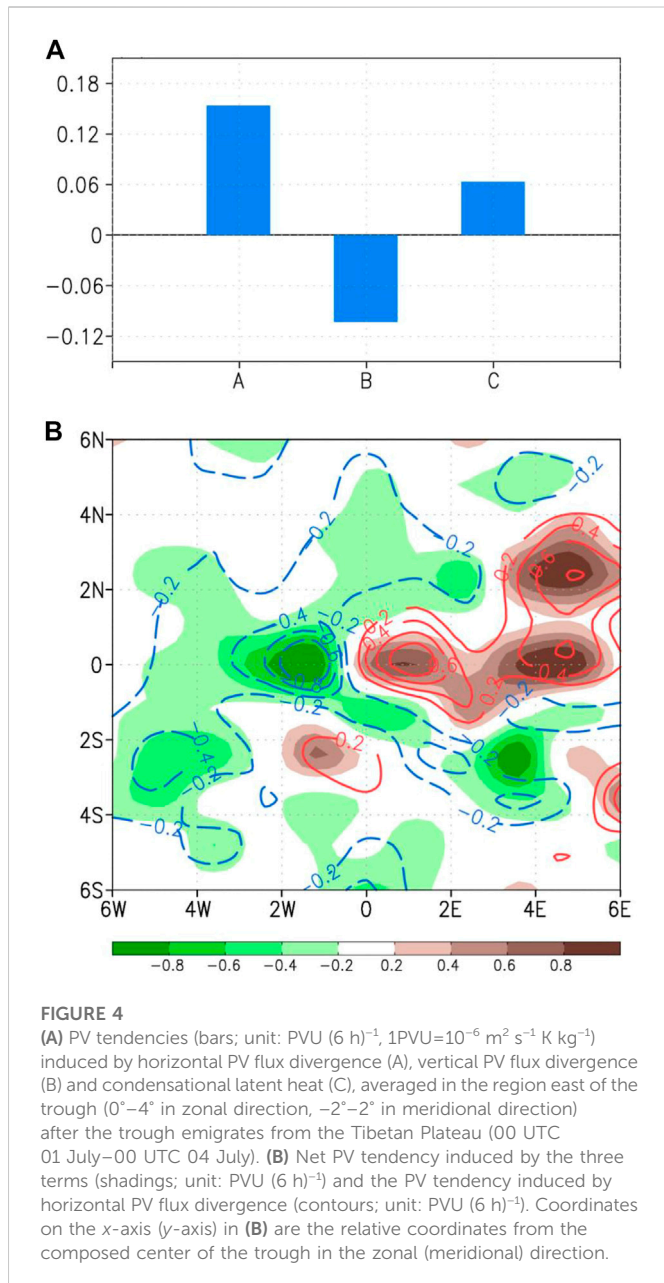
**FIGURE 3**

Geopotential height (red contours; unit: gpm) and wind (vectors; unit:  $\text{m s}^{-1}$ ) at 500 hPa. (A) 06UTC30June, (B) 12UTC30June, (C) 18UTC30June, (D) 00UTC01July, (E) 06UTC01July, (F) 12UTC01July, (G) 18UTC01July, and (H) 00UTC03July. The yellow curves in (D–G) represent the trough. The thick black lines are the topographic contours of 3,000 m, indicating the border of the Tibetan Plateau.

### 3.2 Evolution of the depression that originated over the Tibetan Plateau

Geopotential height and wind at 500 hPa are shown in Figure 3. At 06 UTC on 30 June, there were strong westerlies north of the Tibetan Plateau, and no obvious depression was observed at this time. At 12 UTC on 30 June, the westerlies north of the plateau branched into two flows, with one turning into northerlies and the other remaining westerlies. Cyclonic shear is formed by the northerlies and southerlies over the eastern Tibetan Plateau, and

accordingly, a TPV was generated at  $100^{\circ}\text{E}$ ,  $33^{\circ}\text{N}$ . Similar to the previously revealed genesis mechanism of TPVs (Li et al., 2011, 2014a; Ma et al., 2022; Wu et al., 2022), both the cyclonic wind convergence and the condensational latent heating favor the genesis of the TPV, and the vertically uneven heating plays as a dominant role in the genesis process of this TPV, based on the calculations on PV tendency equation (figure not shown). The surface sensible heating can produce favorable early conditions for the later condensational latent heat release, which also has an important but indirect effect on the genesis of TPVs (Dell’Osso and Chen,



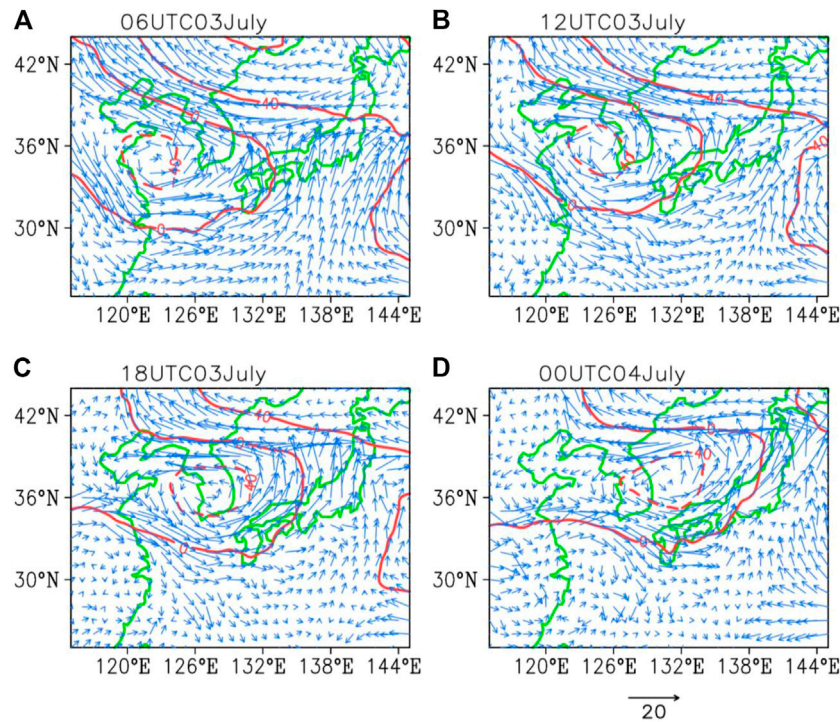
1986; Wang, 1987; Li et al., 2014a; Zhang et al., 2019). At the following time (18 UTC 30 June), the TPV moved eastward and was located at  $102^\circ\text{E}$ ,  $33^\circ\text{N}$ . At 00 UTC 01 July, the westerlies north of the TPV strengthened, which was unfavorable for the maintenance of the TPV's close cyclonic circulation. Thus, the TPV transformed into a trough at 00 UTC on 01 July, which continues to move eastward. The trough transformed from the TPV was relatively weak when it was near the eastern edge of the Tibetan Plateau (at 00 UTC 01 July and 06 UTC 01 July) and became stronger after 12 UTC 01 July (Figure 1), which is similar to the evolution of a TPV emigrating from the Tibetan Plateau (Li et al., 2014b). At 00 UTC 03 July (Figure 3G), the trough was located at the eastern boundary of China, which started affecting the rainfall in Japan. It is of note that the activities of the trough and the related circulations are not provided here, but are introduced in detail in Section 4.

Although the evolution mechanisms of the TPVs are analyzed in our previous work, and the convergence east of the TPVs is considered the primary factor dominating the evolution of TPVs after they emigrate from the Tibetan Plateau (Li et al., 2019), the maintenance and eastward movement mechanism of the trough originated over the Tibetan Plateau is not clear yet. Therefore, the evolution mechanism of the trough is investigated by diagnosing the PV tendency equation. The 500 hPa PV tendencies east of the trough induced by the horizontal PV flux divergence, the vertical PV flux divergence, and the condensational latent heat, after the trough emigrates from the Tibetan Plateau, are presented in Figure 4A. The horizontal PV convergence and condensational latent heat have positive effects on the increase in PV east of the trough, and the former is obviously larger than the latter. Meanwhile, because of the strong ascending motion around the trough, negative PV tendency induced by the vertical PV divergence is found east of the trough, which is unfavorable for the maintenance and eastward movement of the trough. Thus, the horizontal PV flux convergence contributes the most to the positive PV tendency among these three terms, indicating that the maintenance and eastward movement of the trough is mainly supported by the horizontal PV flux convergence to its east. Actually, the horizontal PV flux convergence contributes to the enhancement of the trough at 12 UTC on 01 July. To further confirm the role of the horizontal PV flux divergence, its spatial distribution and that of the net PV tendency induced by the three terms are shown in Figure 4B. Positive net PV tendency is observed east and northeast of the trough, which corresponds to the general eastward moving direction with a slight northeastward shift. Moreover, the distribution of the horizontal PV flux divergence coincides well with that of the net PV tendency, implying the dominant role of the former. Therefore, horizontal PV flux convergence east of the trough, which is induced by both the PV advection and the wind convergence there, plays a very important role in the maintenance and eastward movement of the trough.

## 4 Effects of the trough on the rainfall in Kyushu

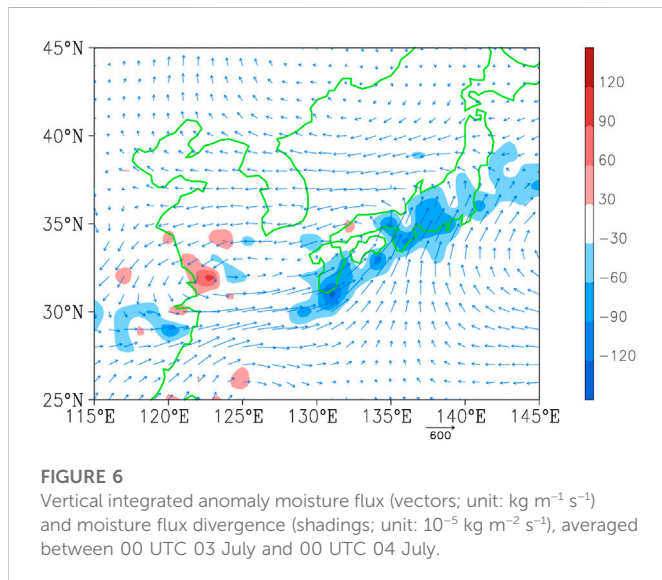
To highlight the activities of the trough that originated over the Tibetan Plateau when it approached Japan, the anomalies of geopotential height and wind at 500 hPa from 06 UTC 03 July to 00 UTC 04 July are shown in Figure 5. We found that the high north of the trough was stronger than the climatic mean state, whose anomaly easterlies were beneficial for the maintenance of the cyclonic system in the south from 06 UTC 03 July to 00 UTC 04 July. Kyushu was located southeast of the trough before 18 UTC 03 July and south of the trough at 00 UTC 04 July. Accordingly, Kyushu was affected by the southwesterlies associated with the trough in the former period and by the northwesterlies in the latter. Locations of the trough from 06 UTC 03 July to 00 UTC 04 July are  $122^\circ\text{E}$ ,  $35^\circ\text{N}$ ,  $125^\circ\text{E}$ ,  $36^\circ\text{N}$ ,  $128^\circ\text{E}$ ,  $36^\circ\text{N}$ , and  $130^\circ\text{E}$ ,  $37^\circ\text{N}$ , respectively.

Given that the moisture condition and vertical motion are crucial to trigger rainfall, the effects of the trough on these two factors are investigated in the following text. The moisture condition is analyzed first.



**FIGURE 5**

Same as Figure 3, but for anomaly geopotential height (red contours; unit: gpm) and wind (vectors; unit:  $\text{m s}^{-1}$ ) at 500 hPa from 06 UTC 03 July to 00 UTC 04 July. (A) 06UTC03July, (B) 12UTC03July, (C) 18UTC03July, and (D) 00UTC04July.



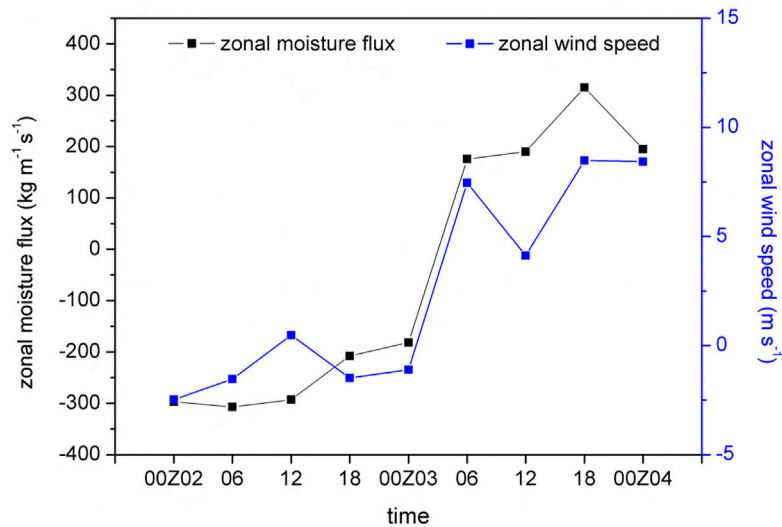
**FIGURE 6**

Vertical integrated anomaly moisture flux (vectors; unit:  $\text{kg m}^{-1} \text{s}^{-1}$ ) and moisture flux divergence (shadings; unit:  $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ ), averaged between 00 UTC 03 July and 00 UTC 04 July.

The anomalies of vertically integrated (from surface to 100 hPa) moisture flux and its divergence in the rainfall episode from 00 UTC 03 July to 00 UTC 04 July are presented in Figure 6. The moisture converged in Kyushu, which is greatly attributed to the moisture transported by the westerlies west of Kyushu. According to the circulations at 500 hPa shown in Figure 5,

strong westerly anomalies were observed south of the trough, which greatly contributed to the eastward transportation of the moisture. To further confirm the role of anomaly westerlies associated with the trough in transporting the moisture, time series of the anomaly vertically integrated zonal moisture flux and speed of westerlies at the western boundary of Kyushu (approximately  $129^{\circ}\text{E}$ ) averaged between  $30^{\circ}\text{N}$  and  $35^{\circ}\text{N}$  are shown in Figure 7. It is found that the moisture transported through the western boundary of Kyushu increased sharply at 06 UTC 03 July, corresponding to the robust increase in westerly speed at this time. Actually, the westerlies associated with the trough in Kyushu were apparently stronger at 06 UTC 03 July than those at 00 UTC 03 July because the trough was located farther from Kyushu at the latter time. The eastward transported moisture increased during the following times, reached the peak at 18 UTC 03 July, and then decreased at 00 UTC 04 July. Variation of the moisture transported by the westerlies generally coincides with that of the westerly speed and the precipitation in Kyushu, indicating that the trough that originated over the Tibetan Plateau contributed to the favorable moisture condition for the rainfall in Kyushu.

Second, the effect of the trough on the vertical motion in the region around Kyushu is explored. The anomaly vertical velocity at 500 hPa averaged in  $127^{\circ}\text{E}$ – $135^{\circ}\text{E}$ ,  $30^{\circ}\text{N}$ – $35^{\circ}\text{N}$ , which includes Kyushu, is shown in Figure 8A to demonstrate the variation of the vertical motion there under the influence of the eastward-moving trough. The ascending motion strengthened during the eastward movement of the trough, was the strongest at 18 UTC 03 July, and



**FIGURE 7**

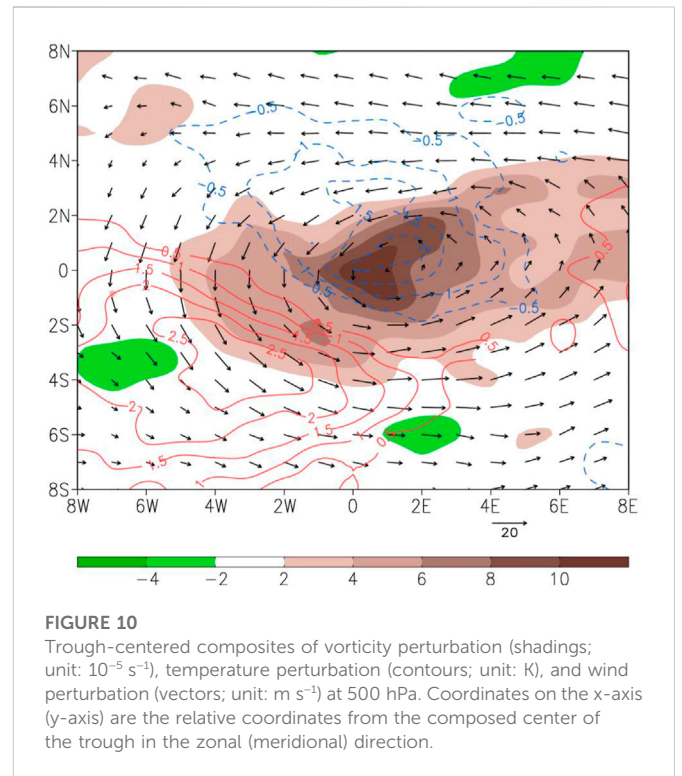
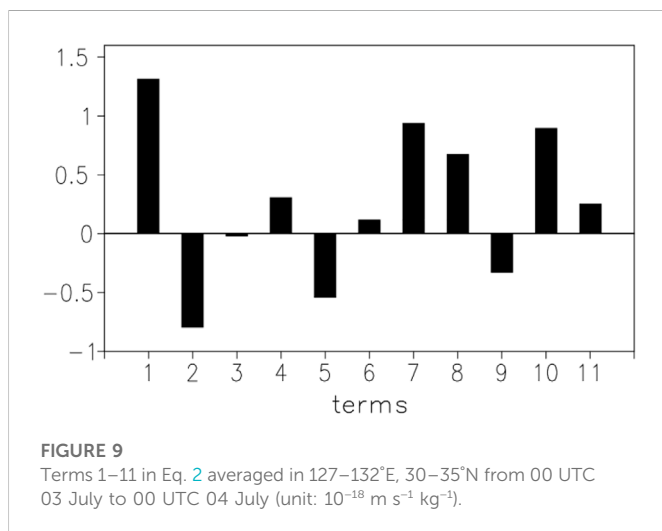
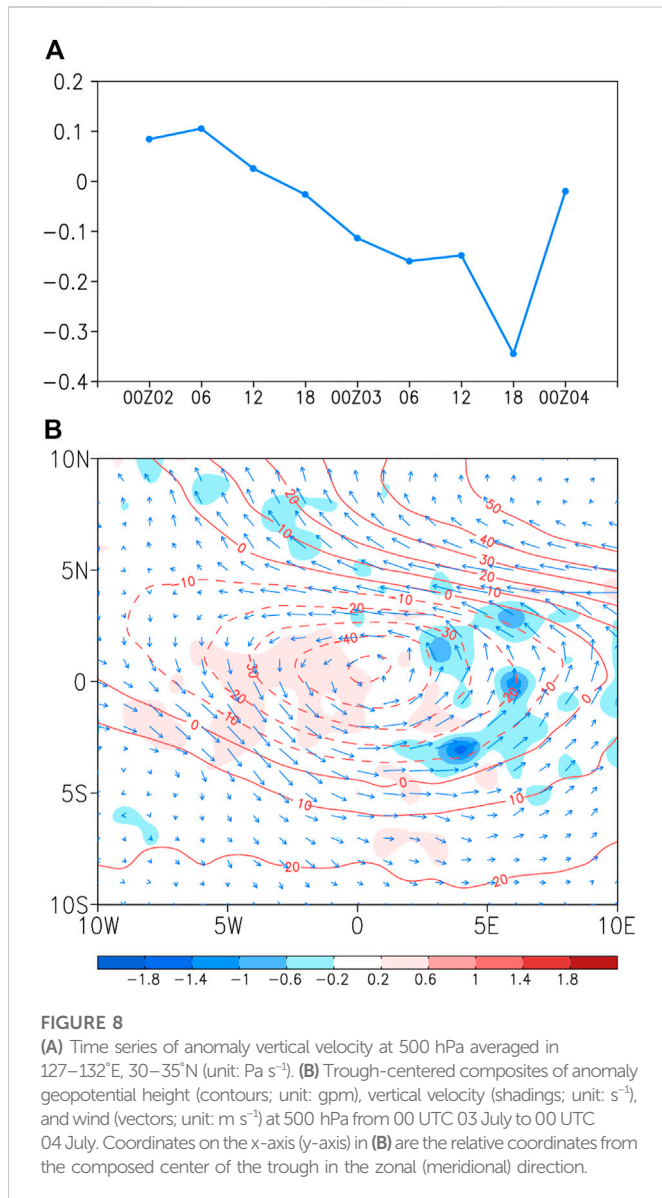
Average vertically integrated zonal moisture flux (black line; unit:  $\text{kg m}^{-1} \text{s}^{-1}$ ) and 500-hPa zonal wind speed (blue line; unit:  $\text{m s}^{-1}$ ) anomalies at  $129^\circ\text{E}$  (approximately the most west longitude of Kyushu) between  $30^\circ\text{N}$  and  $35^\circ\text{N}$ .

then weakened sharply at 00 UTC 04 July. Actually, the ascending motion associated with the trough appeared on its east and southeast sides, and the descending motion on its west side (Figure 8B). Because Kyushu was located south of the trough at 00 UTC 04 July and southeast at the previous times, the ascending motion in Kyushu at 00 UTC 04 July was much weaker than that at the previous times. According to the aforementioned analyses, the ascending motion in the region around Kyushu is closely related to the eastward movement of the trough. Furthermore, the variation of the vertical motion coincides well with the precipitation variation from 00 UTC 03 July to 00 UTC 04 July, which further verifies the significant impact of the trough on the rainfall in Kyushu by changing the vertical motion there.

The quasi-geostrophic  $\omega$  equation is calculated to diagnose the vertical motion at 500 hPa in Kyushu, and the results are shown in Figure 9. In Figure 9, terms 1, 7, 8, and 10 are the four primary contributors to the ascending motion in the region around Kyushu, among which term 1 is the leading factor. To help understand the meanings of these four primary terms, the horizontal structure of the trough at 500 hPa is provided in Figure 10. Term 1 represents the vertical differential of vorticity perturbation advection by the mean zonal flow. The trough is a cyclonic circulation with positive vorticity (Figure 10), and accordingly, there is positive zonal gradient of vorticity perturbation in the region east of the trough. Meanwhile, mean westerlies control East Asia, which transports the positive vorticity perturbation associated with the trough eastward. Thus, positive advection of vorticity perturbation by mean westerlies is produced in the region around Kyushu. Additionally, the maximum vorticity perturbation advection by

mean zonal flow appears at approximately 400 hPa (figure not shown), which is in favor of the ascending motion at 500 hPa in Kyushu ( $\omega' \propto -\frac{\partial}{\partial p} \overline{u'_g \frac{\partial \zeta'_g}{\partial x}} < 0$ ). Term 7 indicates temperature perturbation advection by mean zonal flow, which is the secondary contributor to the ascending motion in Kyushu. The horizontal thermodynamic structure of the trough shows that the warm center is located on its southwest side (Figure 10). Because Kyushu was located southeast and south of the trough from 00 UTC 03 July to 00 UTC 04 July (Figure 5), warm advection by mean westerlies was produced in Kyushu, which favored the ascending motion there ( $\omega' \propto \overline{u'_g \frac{\partial T'}{\partial x}} < 0$ ). Term 8 represents the temperature perturbation advection by zonal wind perturbation. As mentioned above, a warm center is located on the southwest side of the trough, and simultaneously, the westerlies prevail there (Figure 10). Thus, the warm advection by westerly perturbation ( $\omega' \propto u'_g \frac{\partial T'}{\partial x} < 0$ ) is also an important contributor to the ascending motion. Term 10 means the mean temperature advection by meridional wind perturbation. The trough is a cyclonic system with southerly perturbation on its east side (Figure 10), and zonal mean temperature decreases from south to north. Thus, southerly perturbation induces warm advection in Kyushu, contributing to the ascending motion there ( $\omega' \propto v'_g \frac{\partial T'}{\partial y} < 0$ ). Horizontal gradients of vorticity and temperature perturbations, as well as the wind perturbation discussed earlier, are all linked to the circulation of the trough that originated over the Tibetan Plateau, implying the important effect of the trough on the vertical motion in Kyushu, and thereby, the rainfall there.

In a word, the trough that originated over the Tibetan Plateau enhanced the rainfall in Kyushu on 3–4 July 2020 by intensifying the moisture transportation to Kyushu and the ascending motion there.



## 5 Conclusion

Heavy rainfall affected Kyushu in early July 2020, causing huge damage and life and economic losses. The rainfall episode on 3–4 July 2020 is found to be greatly related to the Tibetan Plateau vortex (TPV) over the Tibetan Plateau, which transformed into a trough near the eastern edge of the Tibetan Plateau. This work analyzes the maintenance and eastward movement mechanism of the trough transformed from the TPV and further investigates the effects of the trough on the rainfall in Kyushu. The results are beneficial for understanding the causation of the rainfall in Kyushu and helpful for future precipitation prediction in this region. The results are summarized as follows:

A TPV is generated over the eastern Tibetan Plateau and transformed into a trough at the eastern edge of the Tibetan Plateau. The trough transformed from the TPV continues to move eastward and affects the rainfall in Kyushu when it approaches Japan in the zonal direction. The eastward movement and maintenance mechanism of the trough emigrating from the Tibetan Plateau are subsequently investigated. It is found that the horizontal PV flux convergence and condensational latent heat east of the trough are beneficial for its eastward movement and maintenance, and the contribution of the former is apparently larger than that of the latter.

The trough that originated over the Tibetan Plateau enhances the rainfall by increasing the moisture transportation and intensifying the ascending motion in Kyushu. First, there are anomaly westerlies south of the trough, which enhances the zonal moisture transportation to Kyushu. Generally, variation of the zonal moisture flux at the western boundary of Kyushu coincides well with that of the zonal wind speed, indicating the important role of the trough in producing favorable moisture condition for the rainfall in Kyushu. Second, the ascending



motion in Kyushu becomes stronger when the trough is zonally approaching Kyushu, indicating that the vertical motion in Kyushu is closely related to the eastward-moving trough. The influencing mechanism of the trough on the vertical motion in Kyushu is further explored by diagnosing the quasi-geostrophic  $\omega$  equation. It is found that the vertical differential of vorticity perturbation advection by the mean zonal flow, temperature perturbation advection by mean zonal flow, temperature perturbation advection by zonal wind perturbation, and mean temperature advection by meridional wind perturbation are the four primary contributors to the ascending motion in Kyushu, among which the first one is the leading factor. The four aforementioned terms are related to the positive vorticity, warm center, and wind perturbation associated with the trough, which implies that the trough is responsible for the ascending motion in Kyushu to a great extent.

It should be noted that there were several rainfall episodes in Kyushu in early July 2020, and we only selected the one during 3–4 July 2020 that was affected by the trough that originated over the Tibetan Plateau. Additionally, the rainfall in Kyushu is the result of the coaction of multi-scale circulations. Although the trough emigrating from the Tibetan Plateau plays an important role in the rainfall in Kyushu, it is just part of the causations. This work aims to reveal the effect of the trough that originated over the Tibetan Plateau; thus, the roles of the other weather systems are not discussed here. Moreover, understanding the quantitative contribution of the trough to the record-breaking rainfall is important to understand the effect of the trough, which is not involved in the present work but is worthy of further investigation by conducting numerical experiments in future works.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

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## Author contributions

LL and CZ designed the manuscript, and LL and HH wrote the draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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