Tibetan Plateau vortex-associated precipitation and its link with the Tibetan Plateau heating anomaly

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Abstract
The Tibetan Plateau (TP) is known as the Asian water tower that supplies fresh water for millions of people in Asia. The Tibetan Plateau vortices (TPVs) are one of the major precipitation-producing weather systems over the TP. The characteristics of TPV-associated precipitation from 1979 to 2017 are quantitatively analysed based on three daily precipitation datasets. The influence of TPVs on precipitation is more significant in the warm season (May–September) because the precipitation and TPV activities both peak in the warm season. The TPV-associated precipitation (VAP) dominates the total precipitation over most of the TP in the warm season. The VAP contributes more than 50% of the total precipitation in the warm season over 30% of the area over the TP, particularly in the central TP, while the VAP accounts for more than 25% of the total precipitation in the cold season over about 20% of the area over the TP. Therefore, TPVs are the major systems to produce precipitation on the TP in the warm season, and they are also important in the cold season in certain regions. The interannual variation of VAP is mainly determined by the number, rather than the precipitation intensity, of TPVs. Furthermore, the heating anomaly caused by the TP thermodynamic effect is an influential factor of VAP. Stronger (weaker) TP heating and resulting ascending motion strengthen (attenuate) the convergence near the TP surface and the divergence in the upper troposphere. The thermal adaption-associated circulation generates more (less) TPVs and VAP.

KEYWORDS
Tibetan Plateau, Tibetan Plateau heating anomaly, Tibetan Plateau monsoon, Tibetan Plateau vortex (TPV), TPV-associated precipitation

1 INTRODUCTION
The Tibetan Plateau (TP) is the highest and widest plateau in the world, with an average altitude of more than 4,000 m. It is called the “roof of the world” and also known as the third pole of the earth (Ma et al., 2008; Qiu, 2008). The TP is the birthplace of many major rivers in Asia, such as the Yangtze, Yellow, Yarlung-Zangbo, Indus, Lancang-Mekong.
and Ganges Rivers, supporting the livelihoods of more than 1.4 billion people (over 20% of the global population). Therefore, the TP is called the Asian water tower (Xu et al., 2008; Immerzeel et al., 2010).

The TP is the largest natural reservoir outside the Antarctic and the Arctic. The precipitation over the TP is not only the maintenance of river water, but also the most important source of water supply for lakes and glaciers over the TP. These lakes and glaciers account for 52 and 80% of those all over China, respectively. Due to its high elevation and fragile ecological environment, the TP is a highly sensitive and climate-vulnerable area as well as a pilot region under the global climate change (Feng et al., 1998; Duan et al., 2006; Pepin et al., 2015). Thus, the TP precipitation has received wide attention from the scientific community. In the past decades, variations of precipitation have been the dominant factors for the natural environment and ecosystem changes (Yao et al., 2012; Yang et al., 2014), such as changes of lake area, vegetation, and glaciers and permafrost degradation. However, the TP is one of the regions with the highest uncertainty in observations and numerical model simulations (Wang et al., 2017). It is an important challenge for the disaster reduction and the climate change adaptation in the TP.

The precipitation on the TP is closely related to some weather systems such as Tibetan Plateau vortex (TPV) over the TP and its surrounding areas (Ye and Gao, 1979; Luo, 1994). TPVs are the mesoscale systems active at 500 hPa with a typical size of 400–800 km. Most of TPVs are generated over the central-western TP from June to August (Ye and Gao, 1979; Luo, 1994; Curio et al., 2019; Lin et al., 2020). Most of the TPVs dissipate over the TP, while less than 20% of TPVs could move off the TP and bring heavy rain and thunderstorm disasters to the downstream area (Tao and Ding, 1981; Yu et al., 2014; Yu et al., 2016; Li et al., 2018; Lin et al., 2020). Thus, it is of great scientific and socioeconomic value to understand the relationship between TPVs and precipitation on the TP. In the early period, the TPV-associated precipitation is investigated by the typical case study. In hence, although it is known that TPVs play a crucial role for the precipitation over the TP, it is still unclear that how much precipitation is brought by TPVs. Recently, Curio et al. (2019) investigated the ratio of TPV-associated precipitation using the ERA-Interim data. However, the investigations using the multiple precipitation datasets is still needed due to the uncertainties of precipitation in different reanalysis datasets. The primary aim of this study is to quantitatively analyse the effect of TPVs on precipitation over the TP and its adjacent areas.

TPV is a specific weather system generated by the thermodynamic effect of the TP (Luo, 1994; Li et al., 2018), which has played an important role in shaping the Asian monsoon and atmospheric circulation (Ye and Gao, 1979; Wu et al., 2007; Boos and Kuang, 2010; Wu et al., 2015a; 2015b). Due to the towering terrain of the TP, it is a heat source relative to the surrounding free atmosphere in summer (Flohn, 1957; Ye and Gao, 1979; Reiter and Tang, 1984; Tang and Reiter, 1984; Duan and Wu, 2005). Zhao and Chen (2001) pointed out that the heat source of the TP corresponds to the summer monsoon in East Asia. Li et al. (2014) revealed the impacts of the TP heating’s spatial pattern on the development and eastward moving of TPVs. However, the influence of the TP heating on TPV activities and its associated precipitation is still not clear. The quantified precipitation associated with TPVs is used to investigate the impacts of the TP heating in the present study.

This paper is organized as follows. Section 2 describes the data used and methodology to track TPVs and to relate TPVs with the precipitation. Section 3 shows the quantitative influence of TPVs on precipitation. Moreover, section 4 analyses the impacts of the TP heating on TPVs activities and TPV-associated precipitation in the warm season, as well as its mechanism. Finally, it is summarized in section 5.

2 DATA AND METHODOLOGY

2.1 Data

The TPVs are obtained from the ERA-Interim reanalysis data, a global atmospheric reanalysis product created by ECMWF (Dee et al., 2011). Compared with the previous version, ERA-Interim is produced by improved four-dimension data assimilation, using better bias correction of satellite radiation data and the improved physical model (see Berrisford et al., 2011 for details). The geopotential height and horizontal wind at 500 hPa, with the temporal resolution of 6 h and the spatial resolution of 1° × 1°, are used to track TPVs. Monthly-averaged data are used to analyse the atmospheric circulation. Previous assessments have shown that ERA-Interim is of good quality on the TP, even for times without the observational assimilation (Bao and Zhang, 2013).

Multiple sets of precipitation from different sources are used to reduce the uncertainty due to the lack of ground observations. The precipitation data include the ERA-Interim reanalysis precipitation (hereinafter referred to as ERAI), Global Daily Unified Gauge-based Analysis of Precipitation produced by Climate Prediction Center of NOAA (hereinafter referred to as CPC), and the gauge daily precipitation from China Meteorological Administration (hereinafter referred to as CMA). ERAI is relatively accurate...
The reanalysis data can reflect the close relationship between the precipitation and weather systems, so it is necessary to analyse the ERAI precipitation. The site observation from CMA is of the highest accuracy, but its shortcoming is the low spatial resolution. This is particularly true for high-elevation areas, and most observation stations are located in the central and the eastern TP, while very few in the western TP. CPC is based on the ground observation, combining all the information sources available at CPC and taking advantages of the optimal interpolation objective analysis technique (Xie et al., 2007; Chen et al., 2008). The resolution of CPC is rescaled to 1° × 1°, the same as ERAI and TPVs. The use of three different precipitation datasets can acquire a robust conclusion to avoid the uncertainty of data sources, if multiple data get similar results. The precipitation datasets and the reanalysis datasets used in this study cover the period from 1979 to 2017.

Figure 1 shows the total precipitation from three datasets for the warm season (May–September), the cold season (October–the following April), and annual mean. In general, ERAI overestimates precipitation compared with CPC and in-site observations, especially in the warm season and over the southeastern TP, which is consistent with previous studies (Tong et al., 2014). In contrast, CPC slightly underestimates the precipitation in the eastern part of the plateau compared with in-site observations. Although the three datasets differ in magnitude, the precipitation in the vicinity of the TP reflects the same characteristics of spatial distribution and seasonal variations. Especially, the warm-season precipitation accounts for more than 80% of total precipitation except for the western TP.

### 2.2 TPV tracking and its associated precipitation

The identifying and tracking scheme for TPVs follows the scheme of Lin (2015). It is modified from the scheme of Wernli and Schwierz (2006) according to the characteristics of TPVs. The details of the identification and tracking method of TPVs are described in Lin et al. (2020), and the dataset of the TPVs has been shared in the website of http://www.sciencedb.cn/dataSet/handle/556. By using this algorithm, the domain of TPVs is naturally defined by the region covered by the outermost closed contour (OCC) in the potential height field of 500 hPa with the 1-gpm interval. At each time step, all the grid points embedded in the OCC are recorded as one time influenced by TPVs. The influence frequency of TPVs at each grid point is calculated as the ratio of the cumulative time steps influenced by TPVs to the total time steps. For example, the number of days of the warm season (May–September) in this study is 153 and the number of years is 39. Then, if a grid point embedded by the OCC of TPVs for 500 days, its TPV influence frequency is 500/(153 × 39) = 8.38%. Figure 2 shows the spatial distribution of the percentage of days affected by TPVs. The maximum activity locates in the central and western TP, which is consistent with the studies from Curio et al. (2019), Lin (2015), and Feng et al. (2014). And the TPV is more active in the warm season than in the cold season.

The second step is to determine the precipitation associated with TPVs. In the earlier study, for example, the Yearbook of TPVs (Li et al., 2002–2009; Institute of Plateau Meteorology, 2010–2018), the precipitation over the entire TP during a TPV-active day is considered related to TPVs. In fact, the TPV is a mesoscale weather system (Luo, 1994; Lin, 2015) with an average radius of less than 500 km, which is unlikely to affect such a wide geographical range, and thus it will greatly overestimate the precipitation related to TPVs. In recent studies, Curio et al. (2019) use a geodesic radius of 3° around the TPV centre. Their scheme is similar to the method of Hawcroft et al. (2012) that relates the precipitation with extratropical cyclones, although the cap scale used by Hawcroft et al. (2012) is significantly larger (10°/12° in winter/summer) due to the larger size of the systems. Because of the smaller scale of TPVs and the larger scale of its movement (Feng et al., 2014), the associated precipitation of the weak and small TPV would be overestimated and that of strong and large TPV would be underestimated by using the fixed-radius scheme, especially when the precipitation around TPVs is actually trigged by other systems, such as the shear line (Zhang et al., 2016). Hanley and Caballero (2012, referred to as HC2012 below) used the region covered by OCC instead of a fixed radius to detect the precipitation affected by the extratropical cyclones. In the present study, the scheme proposed by HC2012 is adopted, that is, the precipitation within the coverage of OCC is defined as related to the individual TPV (as shown in Figure S1, Supporting Information). The range of precipitation determined by this method varies with the size of TPVs, and it is positively correlated (but not linearly) with the TPV intensity (see Figure S2). The range of precipitation affected by the weaker TPV is smaller, while the stronger TPV tend to have a broader influencing range.

Figure 3 shows the ratio of total TPV-associated precipitation (VAP) via the scheme of HC2012 to that via a fixed radius ranging from 1° to 10° with an
interval of 1°. Although the radii of most TPVs are less than 3° (Feng et al., 2014; Lin, 2015; Curio et al., 2019; Lin et al., 2020), the total precipitation via the scheme of HC2012 is approximately equivalent to that via the radius of 4°. It means that most of the precipitation is located inside the OCC, so that the scheme of HC2012 can capture more precipitation than a fixed radius does. In hence, VAP and its ratio to the total precipitation presented
Comparison of the precipitation associated with \( \partial_{\tau}^{2} \) is converted as follows:

\[
P' \approx N' \cdot \bar{\mu} + \bar{N} \cdot \mu'.
\] (3)

2.4 | Apparent atmospheric heat source

To investigate the relationship of the TP heating with the TPVs activity, the atmospheric apparent heat source \( (Q_1) \) is calculated based on the atmospheric thermodynamic equation. The equation used is as follows (Yanai et al., 1973; Li et al., 2014):

\[
Q_1 = c_p \left[ \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{V} + \omega \left( \frac{P}{P_0} \right) \frac{\partial \theta}{\partial p} \right] - Q_{LT} - Q_{HA} - Q_{VA},
\]

where \( T \) and \( \theta \) represent the temperature and the potential temperature, respectively. \( \mathbf{V} \) and \( \omega \) denote the horizontal wind vector and the vertical component in pressure coordinates, respectively. \( P_0 \) is the pressure of 1,000 hPa. \( c_p \) is the specific heat at constant pressure, and \( \kappa \approx 0.286 \). The right hand of Equation (4) is the local temporal variation term \( (Q_{LT}) \), the horizontal advection term \( (Q_{HA}) \), and the vertical advection term \( (Q_{VA}) \), respectively.

\[
\langle Q_1 \rangle = \frac{1}{g} \int_{100} (Q_{LT} + Q_{HA} + Q_{VA}) dp = \langle Q_{LT} \rangle + \langle Q_{HA} \rangle + \langle Q_{VA} \rangle.
\]

where \( \langle \cdot \rangle \) denotes the vertical integration from 100 hPa to the pressure of the ground surface \( P_0 \). \( g \) is the gravity acceleration. The long-term \( Q_1 \), \( \langle Q_1 \rangle \) and their components (seasonal mean and annual mean) are daily averaged. That \( \langle Q_1 \rangle \) is obtained from Equation (5) is called the “inverse algorithm,” it also can be calculated as follows:

\[
\langle Q_1 \rangle = F_{SH} + R_{net} + H_{LP},
\]

where \( F_{SH} \) is the surface sensible heat flux, \( R_{net} \) is the atmospheric net radiation, and \( H_{LP} \) is the precipitation-related latent heat.

3 | CHARACTERISTICS OF TPV-ASSOCIATED PRECIPITATION

3.1 | Average precipitation related to TPVs

Figure 4 shows the contribution ratio of VAP to the total precipitation. There is a good consistency among the spatial distributions of the three precipitation datasets. The precipitation locates in the central and western TP,
covering the high-frequency region of TPV. However, the VAP amplitude differs significantly from season to season. In the warm season (Figure 4a,d,g), the contribution of VAP exceeds one quarter of the total precipitation in most parts of the TP. In the cold season (Figure 4b,e,h), only in a small area of the central TP it is larger than one quarter. Since the precipitation is concentrated in the warm season, the annual-mean contribution ratio shows similar distribution characteristics to that in the warm season (Figure 4c,f,i).

Table 1 gives the proportion of the area with different contribution rates. Due to the uneven distribution of observation stations, only the two types of grid data (i.e., CPC and ERAI) are used. The two datasets reflect the consistency of the TPVs’ influence on precipitation. In the warm season, the contribution of VAP exceeds 25% over 70% of the area, while it is above 30% over half the area. In the cold season, the VAP contributes more than 25% of total precipitation in approximately 20% of the area. Considering the inactivity of TPVs during the cold season, this contribution rate is quite striking.

Figure 5 indicates that the VAP in all seasons is greater than the climatological mean. This is in agreement with the contribution of VAP shown in Figure 4. In terms of the magnitude, the spatial distribution of plateau low-eddy precipitation is similar to the distribution of climatological precipitation shown in Figure 1. It is noted that in the eastern TP and lee of the TP, that is, Sichuan Basin, the VAP is greatly enhanced compared with that in the central and western TP. The intensity of TPV-related precipitation that moves eastward and moves off TP is greater than that over the TP. It may be related to the coupling effects with other weather systems, such as the southwest vortex (Yu et al., 2016), in addition to the structural changes of the TPVs moving eastward (Li et al., 2014).

3.2 | Interannual relationship of TPV activities with its related precipitation

The interannual variation of VAP can be decomposed into two components by using Equation (3)—the contribution of the TPV number \(N' \cdot \tilde{\mu}\) and the contribution of precipitation intensity \(N' \cdot \tilde{\mu}'\). Figure 6 shows the time series of VAP, \(N' \cdot \tilde{\mu}\) and \(N' \cdot \tilde{\mu}'\). Whether it is in the cold season or the warm season, the contribution of \(N' \cdot \tilde{\mu}\) is the primary component for VAP. In other words, the interannual variation of VAP is mainly determined by the TPV activity. The results based on the datasets from...
ERAI and CMA are similar to that from CPC (not shown). Figure 7 shows the scatter of the number of TPVs and the VAP based on CPC. The VAP is interrelated with the number of TPVs \((p < .001)\) both in the warm and cold seasons. On average, for each additional TPV, the VAP at each grid cell in the area affected by TPVs is increased by an average of 3 mm (0.5 mm) in the warm (cold) season. The number of TPVs and the VAP obtained from ERAI and CMA also has a significant linear relationship, although the regression coefficients are different from those based on CPC. The positive relationship remains unchanged when the interannual trend and the inter-decadal variability are removed (Figure S3).

### Table 1

| Ratio of VAP to total precipitation | ERAI Warm season | ERAI Cold season | CPC Warm season | CPC Cold season |
|------------------------------------|------------------|------------------|----------------|----------------|
| <10%                               | 11.5             | 41.1             | 11.1           | 43.5           |
| 10–25%                             | 18               | 35.9             | 21.9           | 38.8           |
| 25–50%                             | 35.6             | 23               | 32.3           | 17.6           |
| 50–75%                             | 28.8             |                  | 31.7           |                |
| >75%                               | 6.1              |                  |                |                |

**Figure 5** Same as Figure 4, but for the daily mean precipitation related to TPVs. The black dots denote the grid cell or station with \(|R_{TPV} - \overline{R}/\sigma| > 1\), where \(R_{TPV}\) is the daily mean precipitation related to TPVs, \(\overline{R}\) is the climatological daily mean precipitation and \(\sigma\) is the standard deviation of climatological daily precipitation in each grid cell or station [Colour figure can be viewed at wileyonlinelibrary.com]

4 | LINKS BETWEEN VAP AND TP HEATING

4.1 | TP heat source and its relationship with VAP

The warm season is the period with active TPVs (as shown in Figure 2), and also the concentration period of precipitation on the TP (as shown in Figure 1). Therefore, the influence of TPVs on the precipitation is mainly in the warm season (as shown in Figure 4). Because of the high frequency and the concentration of precipitation in the warm season, more than 90% of VAPs happen in the warm season, which is higher than the proportion of
precipitation in the warm season. Therefore, the VAP in the warm season is the main focus of the present study.

In the warm season, the TP heating plays an important role in the forming of Asian monsoon and the precipitation over Asian monsoon areas (Zhao and Chen, 2001; Wu et al., 2018b; Zhao et al., 2019). The previous studies have pointed out that the activity of TPVs is closely related to the TP heating (Dell’Osso and Chen, 1986; Wang, 1987; Li et al., 2014; Liu and Li, 2016). Yet it is still not clear that how the TP heating affects the activity of TPVs and VAP.

To investigate the impacts of the TP heating on TPVs and VAP, the regional averaged heat source (TPHS, as described in section 2.4) is employed as the indicator of the TP heating. The TPHS is calculated based on the ERA-Interim reanalysis dataset by the regional average over the TP [(75–102°E, 30–38°N) and masked by 3,000 m altitude]. It is a characteristic parameter for the TP heating, as pointed by Zhao and Chen (2001) and Zhong et al. (2009). Figure 8a shows the interannual variation of TPHS during 1979–2017. The year in which the TPHS is at least one standard deviation higher than the normal value is selected as the year with strong TP heating, namely 1980, 1999, 2001, 2004, and 2008. The year in which it is lower than the normal value by one standard deviation is selected as the weak-TP-heating year, namely 1979, 1984, 1986, 1993, 2002, 2013, and 2016.

Figure 8b shows the difference of geopotential height at 600 hPa between strong- and weak-TP-heating years. The low-pressure systems are active in the western and central TP and Northwest Asia. On the contrary, there are highs in north China and Mongolian Plateau. It reveals that the stronger TP heating leads to the higher temperature gradients between the TP and surrounding areas. There is a positive anomaly in the upper troposphere over the TP due to the wave train from Europe–West Asia–central TP (as shown in Figure 8c). It leads to the divergent anomaly at the upper level over the TP. The influence frequency in strong-TPHS years is obviously higher than that in weak-TPHS years (Figure 8d), with the frequency of more than 3% distributing in the western and central TP. Thus, the stronger TPHS brings more VAP over the TP and its surrounding areas (as shown in Figure 8e).

### 4.2 Decomposition of the heat source and TPV activity

Figure 9 shows the interannual variation of the TP heat source and its three components in the warm season. The
magnitudes of the three components of $\langle Q_i \rangle$ are obviously different. $\langle Q_{LT} \rangle$ is the smallest to be neglected, with an average (standard deviation) of 0.2 (0.15) W m$^{-2}$. $\langle Q_{HA} \rangle$ and $\langle Q_{VA} \rangle$ are with the average (standard deviation) of 4.1 (4.2) W m$^{-2}$ and 25 (3.2) W m$^{-2}$, respectively. Therefore, $\langle Q_{VA} \rangle$ is the main component of $\langle Q_i \rangle$. As Zhong et al. (2009) pointed out that $\langle Q_{VA} \rangle$ and $\langle Q_{HA} \rangle$ play an equivalent role in the transition period between atmospheric heat source and sink during March and November, while in the other months, $\langle Q_{VA} \rangle$ plays the dominant role. The ascending motion prevails on the TP in the warm season so that the atmospheric heat source is mainly determined by the vertical velocity. Figure 10a shows the vertical distribution of correlation coefficients of the TPV number with the averaged relative vorticity, divergence and vertical velocity to investigate the impacts of the large-scale circulation on the TPV activity in the warm season. The divergence has
a negative (positive) correlation coefficient with the number of TPVs at the lower (upper) level. It is agreed with studies from Feng et al. (2014) and Li et al. (2014). The upper divergence and lower convergence drive the intense ascending motion, because that there is a remarkable positive (negative) correlation between the relative vorticity (vertical velocity) and the TPV activity in the lower-mid troposphere. On account of the increasing of $\theta$ with height, that is, $\partial \theta / \partial p < 0$, and $P_{TPV} \propto - \omega$ is as shown in Figure 10a; thus, $P_{TPV} \propto Q_{VA}$. $Q_{VA}$ contributes most of $Q_1$ so that the strong (weak) $Q_1$ leads to the active (inactive) TPVs and more (less) VAP, as shown in Figure 8.

The pattern of large-scale circulation related to the TPV activity can be explained by the atmospheric thermal adaptation theory (Wu et al., 2004; Duan and Wu, 2005; Liu and Li, 2016), as shown in Figure 10b. The strong heating of the TP converges the lower atmosphere to the plateau, forming a strong upward motion over the regional TP (Flohn, 1957; Ye and Gao, 1979; Zhao and Chen, 2001). It is just like an air pump that regulates the seasonal evolution of the surrounding atmospheric circulation, namely the sensible heat driven air-pump (Wu et al., 2018a; 2018b). In contrast, the TP is a cooling source in winter. The difference in the thermal effect of the TP leads to the seasonal variation in precipitation and airflow over the TP and its surrounding areas (Ye and Gao, 1979; Reiter and Tang, 1984; Tang and Reiter, 1984; Ge et al., 2018; Zhao et al., 2019). The secondary circulation driven by the TP heating brings active cyclonic systems near surface of the TP, like the TPVs. And it is also related to the anticyclonic systems, for example, the South Asia High (SAH) in the upper troposphere (Wu et al., 2004; Duan and Wu, 2005). The relationship between TPVs and subtropical jets revealed by Hunt et al. (2018) can also be explained by this theory due to the connection of SAH to the jets (Ge et al., 2018).

5 | CONCLUSIONS AND DISCUSSIONS

In the present study, the quantitative impacts of TPVs on the precipitation over the TP and its surrounding areas were investigated. The results could favour the forecast of the VAP and its related secondary disasters. The main conclusions are as follows.

First, the various sources of precipitation datasets reveal the importance of TPVs for the precipitation over the TP. Over up to 60% (30%) area of the TP, the contribution ratio of VAP to the total precipitation accounts for more than 25% (50%) in the warm season, and thus it makes the TPV the major precipitation-producing system over the TP. The impacts of TPVs on the precipitation are also important in the cold season. In about 20% of the area over the TP, the VAP contributes more than 25% to the total precipitation in the cold season.

Second, the interannual variation of precipitation related to TPVs is mainly determined by the contribution of the TPV number. Moreover, there is a significant linear relationship between the amount of precipitation related to TPVs and the number of TPVs.

Third, the TP heating regulates the precipitation over the TP by affecting the TPV activity which is driven by the Tibetan Plateau heating, revealed by the theory of atmospheric thermal adaptation.
In the present study, the “inverse algorithm” is used to calculate the TP heating which is decomposed into three sub-items: the local temporal variation term \( Q_{\text{LTV}} \), the horizontal advection term \( Q_{\text{HA}} \), and the vertical advection term \( Q_{\text{VA}} \). As mentioned in section 2.4, the heat source of the TP can be calculated in another way through the Equation (6), and some previous studies had focused on the impacts of the sensible heat and the latent heat on the generation and formation of TPVs (Wang, 1987; Dell’osso and Chen, 1986; Shen et al., 1986; Luo, 1994; Tian et al., 2015; Li et al., 2018; Wu et al., 2018a; 2018b; Zhang et al., 2019). We have revealed that \( Q_i \) has a close link to the precipitation related to the TPVs. It implies the great impacts of the latent heat on the TPVs, as pointed out by the previous studies (Dell’osso and Chen, 1986; Shen et al., 1986; Wang, 1987). However, there are still no consistent conclusions on the impacts of the sensible heat on TPVs. Some researchers considered that the sensible heat plays a crucial role in the genesis and development of TPVs (Tian et al., 2015; Wu et al., 2018a; Zhang et al., 2019). But some other researchers proposed that the sensible heat has little or even damping effects on the formation of TPVs (Dell’osso and Chen, 1986; Shen et al., 1986). Our results show that the positive contribution of TP heating to TPV activity is mainly determined by the component \( Q_{\text{VA}} \). But, the other decomposition method about the TP heating is not used in the present study.

In the present study, the TP heating is considered as the major influence factor of the TP frequency. The variations of the TP heating are caused by some regional factors, such as the cloud cover (Wu et al., 2015a; 2015b), the precipitation (Zhao and Chen, 2001; Wu et al., 2017), the wind speed (Duan and Wu, 2008), the snow cover (Xiao et al., 2019), the terrain (Pepin et al., 2015), and the remote connection of sea surface temperature (Cui et al., 2015; Jiang et al., 2015). The activity of TPVs and its associated rainfall could also affect the regional weather (e.g., Curio et al., 2019; Li et al., 2020, and the present study), and thus the TPVs can also affect the TP heating. However, the contribution to the regional total heat source from the VAP is not the dominant part in the perspective of the whole TP (Figure S4). The region with a large amount of precipitation related to TPVs is mainly located over the western and central TP, where the heat source is dominantly contributed by the sensible heat (Yang et al., 2011). Therefore, we conclude that the TP heating normally regulates the TPV frequency. However, the interaction between the TPVs and the TP heating in different timescales still need to be investigated by the observations and the simulations.

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AUTHOR CONTRIBUTIONS
Zhiqiang Lin: Investigation; software; visualization; writing-original draft. Weidong Guo: Conceptualization; funding acquisition; project administration; writing-review & editing. Xiuping Yao: Formal analysis; investigation; validation. Jun Du: Data curation; formal analysis; visualization. Wenkai Li: Data curation; formal analysis. Jun Ge: Data curation; formal analysis; visualization.

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REFERENCES
Bao, X. and Zhang, F. (2013) Evaluation of NCEP-CFSR/NCEP-NCAR, ERA-Interim, and ERA-40 reanalysis datasets against independent sounding observations over the Tibetan Plateau. Journal of Climate, 26, 206–214. https://doi.org/10.1175/JCLI-D-12-00056.1.
Berrisford, P., Källberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A.J., Poli, P. and Sato, H. (2011) Atmospheric conservation properties in ERA-Interim. Quarterly Journal of the Royal Meteorological Society, 137, 1381–1399. https://doi.org/10.1002/qj.864.
Boos, W.R. and Kuang, Z. (2010) Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. Nature, 463, 218–222. https://doi.org/10.1038/nature08707.
Chen, M., Shi, W., Xie, P., Silva, V.B.S., Kousky, V.E.R., Higgins, W. and Janowiak, J.E. (2008) Assessing objective techniques for gauge-based analyses of global daily precipitation. Journal of Geophysical Research: Atmospheres, 113, D04110. https://doi.org/10.1029/2007JD009132.
Cui, Y.F., Duan, A.M., Liu, Y.M. and Wu, G.X. (2015) Interannual variability of the spring atmospheric heat source over the Tibetan Plateau forced by the North Atlantic SSTA. Climate Dynamics, 45, 1617–1637. https://doi.org/10.1007/s00382-014-2417-9.
Curio, J., Schiemann, R., Hodges, K.I. and Turner, A.G. (2019) Climatology of Tibetan Plateau vortices in reanalysis data and a high-resolution global climate model. Journal of Climate, 32, 1933–1950. https://doi.org/10.1175/JCLI-D-18-0021.1.
Dee, D., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balsamada, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., Van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E. V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., De Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F., (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553–597. https://doi.org/10.1002/qj.828.

Dell’osso, L. and Chen, S.J. (1986) Numerical experiments on the genesis of vortices over the Qinghai-Xizang Plateau. Tellus A, 38, 236–250.

Duan, A.M. and Wu, G.X. (2005) Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. Climate Dynamics, 24, 793–807. https://doi.org/10.1007/s00382-004-0488-8.

Duan, A.M. and Wu, G.X. (2008) Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part I: observations. Journal of Climate, 21, 3149–3164. https://doi.org/10.1175/2007JCLI1912.1.

Duan, A.M., Wu, G.X., Zhang, Q. and Liu, Y.M. (2006) New proofs of the recent climate warming over the Tibetan Plateau as a result of the increasing greenhouse gases emissions. China Science Bulletin, 51, 1396–1400. https://doi.org/10.1007/s11434-006-1396-6.

Feng, S., Tang, M.C. and Wang, D.M. (1998) New evidence for the Qinghai (Tibet) Plateau as a pilot region of climate fluctuation in China. China Science Bulletin, 43, 1745–1749. https://doi.org/10.01007/BF02889798.

Feng, X.Y., Liu, C.H., Rasmussen, R. and Fan, G.Z. (2014) A 10-yr climatology of Tibetan Plateau vortices with NCEP Climate Forecast System reanalysis. Journal of Applied Meteorology and Climatology, 53, 34–46. https://doi.org/10.1175/JAMC-D-13-014.1.

Floh, H. (1957) Large-scale aspects of the summer monsoon in South and East Asia. Journal of Meteorological Society of Japan, 75, 180–186.

Ge, J., You, Q.L. and Zhang, Y.Q. (2018) The influence of the Asian summer monsoon onset on the northward movement of the South Asian high towards the Tibetan Plateau and its thermodynamic mechanism. International Journal of Climatology, 38, 543–553. https://doi.org/10.1002/joc.5192.

Hanley, J. and Caballero, R. (2012) Objective identification and tracking of multicentre cyclones in the ERA-Interim reanalysis dataset. Quarterly Journal of the Royal Meteorological Society, 138, 612–625. https://doi.org/10.1002/qj.948.

Hawcroft, M.K., Shaffrey, L.C., Hodges, K.I. and Dacre, H.F. (2012) How much Northern Hemisphere precipitation is associated with extratropical cyclones? Geophysical Research Letters, 39, L24809. https://doi.org/10.1029/2012GL053866.

Hunt, K.M.R., Curcio, J., Turner, A.G. and Schiemann, R. (2018) Subtropical westerly jet influence on occurrence of western disturbances and Tibetan Plateau vortices. Geophysical Research Letters, 45, 8629–8636. https://doi.org/10.1029/2018GL077734.

Immerzeel, W.W., Van Beek, L.P.H. and Bierkens, M.F.P. (2010) Climate change will affect the Asian water towers. Science, 328, 1382–1385. https://doi.org/10.1126/science.1183188.

Institute of Plateau Meteorology. (2010–2018) Year Book of Tibetan Plateau Vortex and Shear Line (2009–2016). Beijing: Science Press.

Jiang, X.W., Li, Y.Q., Yang, S., Yang, K. and Chen, J.W. (2015) Interannual variation of summer atmospheric heat source over the Tibetan Plateau and the role of convection around the Western Maritime Continent. Journal of Climate, 29, 121–138. https://doi.org/10.1175/JCLI-D-15-0181.1.

Li, L., Zhang, R.H. and Wen, M. (2018) Modulation of the atmospheric quasi-biweekly oscillation on the diurnal variation of the occurrence frequency of the Tibetan Plateau vortices. Climate Dynamics, 50, 4507–4518. https://doi.org/10.1007/s00382-017-3887-3.

Li, L., Zhang, R.H., Wen, M. and Liu, L.K. (2014) Effect of the atmospheric heat source on the development and eastward movement of the Tibetan Plateau vortices. Tellus A, 66, 24451. https://doi.org/10.3402/tellusa.v66.24451.

Li, L., Zhu, C.W., Zhang, R.H., and Liu, B.Q. (2020) Roles of the Tibetan Plateau vortices in the record Meiyu rainfall in 2020. Atmospheric Science Letters, 22, e1017. https://doi.org/10.1002/asl.1017.

Li, Y.Q., Yu, S.H., Peng, J., Xu, H.M., Xiao, D.X., Tu, N.N., and Luo, Q. (2002–2009) Year Book of Tibetan Plateau Vortex and Shear Line (2001–2008). Beijing: Science Press.

Lin, Z.Q. (2015) Analysis of Tibetan Plateau vortex activities using ERA-Interim data for the period 1979–2013. Journal of Meteorological Research, 29, 720–734. https://doi.org/10.1007/s13351-015-4273-x.

Lin, Z.Q., Guo, W.D., Jia, L., Yao, X.P. and Zhou, Z.B. (2020) Climatology of Tibetan Plateau vortices derived from multiple reanalysis datasets. Climate Dynamics, 55, 2237–2252. https://doi.org/10.1007/s00382-020-05380-6.

Lin, Z.Q., Yao, X.P., Guo, W.D. and Du, J. (2021). Vertical structure of Tibetan Plateau vortex in boreal summer. Theoretical and Applied Climatology. https://doi.org/10.1007/s00704-021-03640-x.

Liu, Y.F. and Li, G.P. (2016) Climatic characteristics of atmospheric heat source over the Tibetan Plateau and its possible relationship with the generation of the Tibetan Plateau vortex in the summer. Chinese Journal of Atmospheric Sciences, 40, 864–876. https://doi.org/10.1016/S1003-6326(09)60084-4.

Luo, S.W. (1994) A Study of Some Kinds of Weather Systems over and around the Qinghai-Xizang Plateau. Beijing: Meteorology Press, p. 205.

Ma, Y., Kang, S., Zhu, L., Xu, B., Tian, L. and Yao, T. (2008) Roof of the world: Tibetan observation and research platform. Bulletin of American Meteorological Society, 89, 1487–1492. https://doi.org/10.1175/2008BAMS2545.1.

Pepin, N., Bradley, R.S., Diaz, H.F., Baraa, M., Caceres, E.B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M.Z.X., Liu, D., Miller, J.R., Ling, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöniger, W., Seversky, I., Shahgedanova, m., Wang, M.B., Williamson, S.N., and Yang, D.Q. (2015) Elevation-dependent warming in mountain regions of the world. Nature Climate Change, 5, 424–430. https://doi.org/10.1038/NCLIMATE2563.

Qiu, J. (2008) China: the third pole. Nature, 454, 393–396. https://doi.org/10.1038/454393a.

Reiter, E.R. and Tang, M.C. (1984) Plateau effects on diurnal circulation patterns. Monthly Weather Review, 112, 638–651. https://doi.org/10.1175/1520-0493(1984)112<0149:REOPDE>2.0.CO;2.
Shen, R.J., Reiter, E.R. and Bresch, J.F. (1986) Some aspects of the effects of sensible heating on the development of summer weather systems over the Qinghai-Xizang Plateau. *Journal of the Atmospheric Sciences*, 43, 2241–2260. https://doi.org/10.1175/1520-0469(1986)0432.0.CO;2.

Tang, M.C. and Reiter, E.R. (1984) Plateau monsoons of the Northern Hemisphere: a comparison between North America and Tibet. *Monthly Weather Review*, 112, 617–637. https://doi.org/10.1175/1520-0493(1984)112<0617:PMOTNH>2.0.CO;2.

Tao, S.Y. and Ding, Y.H. (1981) Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. *Bulletin of American Meteorological Society*, 62, 23–30.

Tian, S.R., Duan, A.M., Wang, Z.Q. and Gong, Y.F. (2015) Interaction of surface heating, the Tibetan Plateau vortex, and a convective system: a case study. *Chinese Journal of Atmospheric Sciences*, 39, 125–130. https://doi.org/10.3878/j.issn.1006-9895.2014.13311.

Tong, K., Su, F.G., Yang, D.Q., Zhang, L.L. and Hao, Z.C. (2014) Tibetan Plateau precipitation as depicted by gauge observations, reanalyses and satellite retrievals. *International Journal of Climatology*, 34, 265–285. https://doi.org/10.1002/joc.3682.

Wang, B. (1987) The development mechanism for Tibetan Plateau warm vortices. *Journal of the Atmospheric Sciences*, 44, 2978–2994. https://doi.org/10.1175/1520-0469(1987)044<2978:tdmftp>2.0.co;2.

Wang, X., Pang, G., Yang, M. and Zhao, G. (2017) Evaluation of climate on the Tibetan Plateau using ERA-Interim reanalysis and gridded observations during the period 1979–2012. *Quaternary International*, 444, 76–86. https://doi.org/10.1016/j.quaint.2016.12.041.

Wernli, H. and Schwierz, C. (2006) Surface cyclones in the ERA-40 dataset (1958–2001). Part I: novel identification method and global climatology. *Journal of the Atmospheric Sciences*, 63, 2486–2507. https://doi.org/10.1175/JAS3766.1.

Wu, D., Zhang, P. and Wang, C. (2018a) Impacts of diabatic heating on the genesis and development of an inner Tibetan Plateau vortex. *Journal of Geophysical Research Atmospheres*, 123, 11691–11704. https://doi.org/10.1029/2018JD029240.

Wu, G.X., Duan, A.M., Liu, Y.M., Mao, J.Y., Ren, R.C., Bao, Q., Liu, B.Q. and Hu, W.T. (2015b) Tibetan Plateau climate dynamics: recent research progress and outlook. *National Science Review*, 2, 100–116. https://doi.org/10.1093/nsr/nwu045.

Wu, G.X., He, B., Duan, A.M., Liu, Y.M. and Yu, W. (2017) Formation and variation of the atmospheric heat source over the Tibetan Plateau and its climatic effects. *Advances in Atmospheric Sciences*, 34, 1169–1184. https://doi.org/10.1007/s00376-017-7014-5.

Wu, G.X., Liu, Y.M., He, B., Bao, Q. and Wang, Z.Q. (2018b) Review of the impact of the Tibetan Plateau sensible heat driven air-pump on the Asian summer monsoon. *Chinese Journal of Atmospheric Sciences*, 42, 488–504. https://doi.org/10.3878/j.issn.1006-9895.1801.17279.

Wu, G.X., Liu, Y.M., Mao, J.Y., Liu, X. and Li, W.P. (2004) Adaptation of the atmospheric circulation to thermal forcing over the Tibetan Plateau. In: *World Scientific Series on Asia-Pacific Weather and Climate: Observation, Theory and Modeling of Atmospheric Variability*, Singapore: World Scientific, pp. 92–114. https://doi.org/10.1142/9789812791139_0004.

Wu, G.X., Liu, Y.M., Zhang, Q. and Duan, A.M. (2007) The influence of the mechanical and thermal forcing of the Tibetan Plateau on the Asian climate. *Journal of Hydrometeorology*, 8, 770–789. https://doi.org/10.1175/JHM609.1.

Wu, H., Yang, K., Niu, X.L. and Chen, Y.Y. (2015a) The role of cloud height and warming in the decadal weakening of atmospheric heat source over the Tibetan Plateau. *Science China Earth Sciences*, 58, 395–403. https://doi.org/10.1007/s11430-014-4973-6.

Xiao, Z.X., Duan, A.M. and Wang, Z.Q. (2019) Atmospheric heat sinks over the western Tibetan Plateau associated with snow depth in late spring. *International Journal of Climatology*, 39, 5170–5180. https://doi.org/10.1002/joc.6133.

Xie, P., Yatagai, A., Chen, M., Hayasaka, T., Fukushima, Y., Liu, C. and Yang, S. (2007) A gauge-based analysis of daily precipitation over East Asia. *Journal of Hydrometeorology*, 8, 607–626. https://doi.org/10.1175/JHM583.1.

Xu, X., Lu, C., Shi, X., Gao, S., Xu, A., Lu, X., Shi, C. and Gao, X. (2008) World water tower: an atmospheric perspective. *Geophysical Research Letters*, 35, L20815. https://doi.org/10.1029/2008GL035867.

Yanai, M., Ebensense, S. and Chu, J.H. (1973) Determination of Bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *Journal of the Atmospheric Sciences*, 30, 611–627. https://doi.org/10.1175/1520-0469(1973)30<0611:dbpscc>2.0.co;2.

Yang, K., Guo, X.F., He, J., Qin, J. and Koike, T. (2011) On the climatology and trend of the atmospheric heat source over the Tibetan Plateau: an experiments-supported revisit. *Journal of Climate*, 24, 1525–1541. https://doi.org/10.1175/2010JCLI3848.1.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W. and Chen, Y. (2014) Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. *Global and Planetary Change*, 112, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H. and Xu, B. (2012) Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, 2, 663–667. https://doi.org/10.1038/nclimate1580.

Ye, D.Z. and Gao, Y.X. (1979) *Meteorology of Qinghai-Xizang (Tibetan) Plateau*. Beijing: Science Press, pp. 45–53 (in Chinese).

Yu, S.H., Gao, W.L., Peng, J. and Xiao, Y.H. (2014) Observational facts of sustained departure plateau vortexes. *Journal of Meteorological Research*, 28, 296–307. https://doi.org/10.1007/s13351-014-3023-9.

Yu, S.H., Gao, W.L., Xiao, D. and Peng, J. (2016) Observational facts regarding the joint activities of the southwest vortex and plateau vortex after its departure from the Tibetan Plateau. *Advances in Atmospheric Sciences*, 33, 34–46. https://doi.org/10.1007/s00376-015-5039-1.

Zappa, G., Hawcroft, M.K., Shaffrey, L., Black, E. and Brayshaw, D. J. (2015) Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models. *Climate Dynamics*, 45, 1727–1738. https://doi.org/10.1007/s00382-014-2426-8.
Zhang, F., Wang, C. and Pu, Z. (2019) Genesis of Tibetan Plateau vortex: roles of surface diabatic and atmospheric condensational latent heating. *Journal of Applied Meteorology and Climatology*, 58, 2633–2651. [https://doi.org/10.1175/JAMC-D-19-0103.1](https://doi.org/10.1175/JAMC-D-19-0103.1).

Zhang, X., Yao, X.P., Ma, J.L. and Mima, Z.G. (2016) Climatology of transverse shear lines related to heavy rainfall over the Tibetan Plateau during boreal summer. *Journal of Meteorological Research*, 30, 915–926. [https://doi.org/10.1007/s13351-016-6952-7](https://doi.org/10.1007/s13351-016-6952-7).

Zhao, P. and Chen, L.X. (2001) Interannual variability of atmospheric heat source/sink over the Qinghai-Xizang (Tibetan) Plateau and its relation to circulation. *Advances in Atmospheric Sciences*, 18, 106–116. [https://doi.org/10.1007/s00376-001-0007-3](https://doi.org/10.1007/s00376-001-0007-3).

Zhao, Y., Yu, X.J., Yao, J.Q., Dong, X.N. and Li, H.J. (2019) The concurrent effects of the South Asian monsoon and the plateau monsoon over the Tibetan Plateau on summer rainfall in the Tarim Basin of China. *International Journal of Climatology*, 39, 74–88. [https://doi.org/10.1002/joc.5783](https://doi.org/10.1002/joc.5783).

Zhong, S.S., He, J.H., Guan, Z.Y. and Wen, M. (2009) Climatic characteristics of the atmospheric heat source over the Tibetan Plateau during 1961–2001. *Acta Meteorologica Sinica*, 67, 407–416.

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