Vorticity and moisture budget analyses on a plateau vortex that cause an intense rainfall event within the Qaidam Basin

Wan-Li Li1 | Ru-Di Xia2 | Qi Zhong1 | Ya-Qiang Wang2

1China Meteorological Administration Training Center, Beijing, China
2State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, China

Correspondence
Qi Zhong, China Meteorological Administration Training Center, Beijing 100081, China.
Email: zhongq@cma.gov.cn

Abstract
As one of the most seriously arid areas in China, the Qaidam Basin (QB) features a notable growing probability of intense rainfall under global warming. Compared to a normal/humid region, intense rainfall usually results in more severe disasters in an arid area. Considering that few studies focused on intense rainfall within the QB, there is an urgent need to understand the mechanisms governing intense rainfall in this region. A type of Tibetan Plateau vortex (TPV) associated intense rainfall within the QB was investigated in this study, which partly fills the existing research gaps in the field. The main findings are as follows: (a) the intense-rainfall-producing TPV formed and maintained in a favorable background environment which was characterized by a notable upper-level divergence north of a strong upper-level jet and a strong middle-level warm advection ahead of a shortwave trough over the Tibetan Plateau. (b) Vorticity budget indicates that two factors affected the vortex's formation notably, one was the convergence-related vertical stretching, which dominated the vortex's formation and the other was the import of the horizontal transport of anticyclonic vorticity which was the most detrimental factor for the formation of the TPV. Tilting and vertical transport only exerted weak effects on the TPV’s formation, since convective activities were relatively weak in this event. (c) Moisture budget shows that the southwestern and southern moisture transport channels, which were mainly driven by the wind field associated with the shortwave trough over the Tibetan Plateau, contributed ~70% to the total moisture income of the intense rainfall within the QB. The transport was accomplished primarily through the southern boundary of the QB, with the moisture mainly coming from the Indian Peninsula and Indochina Peninsula.

KEYWORDS
Heavy rainfall, Tibetan Plateau, Tibetan Plateau vortex, Qaidam Basin

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1 | INTRODUCTION

The Qaidam Basin (QB), which is located in the north-eastern section of the Tibetan Plateau (TP) (Figure 1a), is the highest basin in the world (its mean altitude is ~2,800 m). It is situated at the junction region between the mid-latitude westerly belt and the East Asian monsoon system, which results in a notable plateau continental climate (Wang et al., 2020). Because it is difficult for warm and humid air to reach here, the QB is one of the most serious arid areas in China (Dai et al., 2013; Duan, 2018; Lyu et al., 2020).

**FIGURE 1** Panel (a) shows track of the plateau vortex (blue line with open rectangles), where the open blue rectangles show the location of the vortex’s center at each hour, the red closed circle and rectangle mark the formation and dissipation locations, respectively. Terrain height is represented by shading (unit: m). Panel (b) illustrates the accumulated precipitation during the plateau vortex’s life span (shading, unit: mm), where the thick blue solid line outlines the terrain of 3,000 m. Panel (c) is the temporal average (during the plateau vortex’s life span) of geopotential height (black contours, unit: gpm), wind field (a full wind bar is 10 m s$^{-1}$), temperature (red contours, unit: °C), and divergence (shading, unit: 10$^{-5}$ s$^{-1}$) at 200 hPa. Panel (d) is the temporal average (during the plateau vortex’s life span) of geopotential height (black contours, unit: gpm), wind field (a full wind bar is 10 m s$^{-1}$), temperature (red contours, unit: °C), and temperature advection (shading, unit: 10$^{-5}$ K s$^{-1}$) at 500 hPa. Thick gray solid line outlines the terrain height of 3,000 m.
Temporally, precipitation of the QB mainly appears from May to September (with its peak appeared in July), which accounts for 87.4% of the whole year (Han et al., 2019). Spatially, precipitation in the QB is gradually decreasing from southeast to northwest (Han et al., 2020) and from surrounding mountainous areas to the center of the basin (Duan, 2018). On average, the annual precipitation in the southeastern, central, and northwestern sections of the QB is ~200, ~50, and ~25 mm, respectively. Although an arid climate is dominant, according to statistic, intense rainfall can also appear in the QB (e.g., the event on August 23, 2016), which cause great losses to people’s lives and property in this region. Under global warming, the temperature of TP is increasing significantly (Duan and Xiao, 2015), and that of the QB is even more significant (Dai et al., 2013). During the same period, precipitation within the QB also experienced a rapid increase (Lyu et al., 2020), particularly in its eastern section. This means that the probability of intense rainfall is increasing for the QB. So, there is an urgent need to understand the mechanisms accounting for the intense rainfall in this region, which is helpful to improve its prediction accuracy. Thus far, previous related studies mainly focused on the large-scale background conditions that were favorable for the occurrence of intense rainfall in the QB (these studies were helpful to understand the long-term precipitation variation in this region). However, for the mesoscale systems that directly induce the intense rainfall within the QB, few studies were conducted. Therefore, in order to fill the knowledge gap, more efforts should be made to understand the evolution of these mesoscale systems.

The Tibetan Plateau vortices (TPVs) are a unique type of mesoscale vortices that are generated over the TP (Ni et al., 2017; Fu et al., 2019). According to statistic (Feng et al., 2014; Curio et al., 2019), TPVs have a mean horizontal scale of 200–500 km and they are closely related to intense rainfall. Precipitation associated with TPVs can appear anywhere over the Tibetan Plateau, particularly for the southern and eastern sections of the plateau. For the QB, as it is situated in the northern section of the Tibetan Plateau, only a small proportion of TPVs could affect it as the vortices formed and/or moved through the basin. How were those TPVs that caused intense rainfall within the QB generated? Where did their moisture for precipitation come? These two unsolved scientific questions are partly addressed in this study by conducting detailed vorticity and moisture budgets to a typical TPV case that appeared in mid-May 2017 (intense rainfall mainly appeared within the eastern and southeastern sections of the vortex). The remaining of the article is structured as follows: Section 2 describes the data and methods used in this study; Section 3 presents an overview of the event; Section 4 provides detailed results of the vorticity and moisture budgets; and finally, a conclusion and discussion is reached in Section 5.

2 | DATA AND METHODS

2.1 | Data

The 3-hourly, 0.25° × 0.25° precipitation dataset produced by using the US Climate Prediction Center morphing technique (CMORPH) (Shen et al., 2014) was employed in this study to investigate the precipitation variation. As documented in Shen et al. (2010, 2014), the CMORPH precipitation is a reliable estimate of real precipitation over the TP. The fifth-generation reanalysis product of the European Centre for Medium Range Weather Forecasts (ERA5) with a temporal resolution of hourly and a spatial resolution of 0.25° × 0.25° (Hersbach et al., 2020) was used for synoptic analyses and budget calculations.

2.2 | Vorticity budget

According to Holton (2004), the velocity circulation is an effective indicator for a vortex. Green’s theorem indicates that a surface integral of vorticity in a region equals the velocity circulation along the boundary line of this region. This means that the area mean vorticity can also be used as an effective indicator of a vortex (Fu et al., 2017). In this study, the vorticity budget (Kirk, 2003; Fu et al., 2017) was used for investigating the TPV’s formation. Its expression is as follows:

\[
\frac{\partial \zeta}{\partial t} = - (\zeta + f) \nabla_h \cdot V_h + k \left( \frac{\partial V_h}{\partial p} \times \nabla_h \omega \right) - V_h \cdot \nabla_h \zeta - \omega \frac{\partial p}{\partial t} - \beta v,
\]

where \( \zeta \) is relative vorticity in the \( \mathbf{k} \) direction (i.e., zenith), \( f \) is the Coriolis parameter, \( \nabla_h = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} \) (\( \mathbf{i} \) and \( \mathbf{j} \) are the unit vectors in the east and north directions, respectively), \( V_h = u_i + v_j \) denotes horizontal wind vector, \( p \) is pressure, \( \omega = \frac{\partial v}{\partial y} \) and \( \beta = \frac{\partial f}{\partial y} \). Terms STR and TIL represent vorticity production/extinction due to stretching and tilting, respectively. Terms HAV and VAV

\[
\begin{align*}
\text{STR} & = \frac{\partial}{\partial y} \left( \frac{\partial V_h}{\partial x} \right) \\
\text{TIL} & = \frac{\partial}{\partial x} \left( \frac{\partial V_h}{\partial y} \right) \\
\text{HAV} & = - \omega \frac{\partial p}{\partial t} \\
\text{VAV} & = \beta v
\end{align*}
\]

1
stand for the horizontal and vertical advection of relative vorticity, respectively. Term BTE indicates the “β effect” (i.e., advection of planetary vorticity). Term TOT is defined as $\text{TOT} = \text{STR} + \text{TIL} + \text{HAV} + \text{VAV} + \text{BTE}$, which represent the total effect of all right-hand-side terms of Equation (1).

**FIGURE 2** The 500-hPa stream field, wind field (a full wind bar is 4 m s$^{-1}$) and vorticity (shading, unit: 10$^{-5}$ s$^{-1}$), where the gray boxes show the key area of the plateau vortex and the thick blue solid lines outline the terrain height of 3,000 m.
2.3 Moisture budget

The HYSPLIT model (Stein et al., 2015) was used in this study for tracking the air particles' trajectories into the QB, which were then used for calculating the moisture budget as follows: (a) specify the location (including the number of points) and period for backward trajectory analyses using HYSPLIT; (b) calculate the moisture contribution of the k-th trajectory (i.e., Qk) using the method proposed by Sun et al. (2016):

\[
Q_k = \left( \frac{\sum_{i=1}^{t=T} q_k}{\sum_{k=1}^{N} \sum_{i=1}^{t=T} q_k} \right) \times 100\%; \quad (2)
\]

and (c) sum the contributions of a group of trajectories (i.e., Qk) for their total contribution. In Equation (2), t denotes time, T represents the time length for calculating the budget, qk means the instantaneous specific humidity at each time, and N is the total number of trajectories.

3 OVERVIEW OF THE EVENT

In mid-May 2017, a TPV formed over northwestern section of the TP (Figures 1a and 2). This vortex was located north of the upper-level jet around 25–35°N (Figure 1c), where strong upper-level divergence appeared. The upper-level divergence was favorable for maintaining ascending motions that contributed to precipitation and convergence (near the TP surface). In the middle troposphere, a shortwave trough was located over the central region of the TP (Figure 1d). Ahead of the trough, warm advection was dominant, which was conducive to lowering pressure and promoting ascending motions (Markowski and Richardson, 2010). The TPV was mainly located in the central region of the shortwave trough, and was controlled by westerly wind, since the horizontal mean wind within this region was westerly wind (not shown). Under the steering flow of westerly wind, the vortex mainly showed an eastward displacement (Figure 1a). During the 41-hr lifespan of the TPV (from 1400 UTC 17 to 0700 UTC 19 May 2017), intense rainfall occurred along its track (Figure 1b), with two precipitation centers of above 25 and 65 mm appeared in the central and eastern sections of the QB, respectively. The former was about one-half of the mean annual precipitation in that region (Duan, 2018). Further analysis indicates that intense precipitation associated with the TPV mainly occurred in the eastern and southeastern sections of the vortex, which was located within the warm-advection region ahead of the shortwave trough (Figure 1b,d).

Evolution of the TPV can be divided roughly into four stages. The first stage is the vortex's formation stage (from 0600 UTC to 1400 UTC 17 May 2017), during which the TPV's key area (the key area is a box of a size of 4° × 6°, which was determined by the mean size of the TPV during its lifetime) featured rapid growing cyclonic vorticity and convergence (Figures 2a and 3a,b). The second stage is the vortex's development stage (from 1400 UTC 17 to 0000 UTC 18 May 2017), during which the TPV kept a quasi-stationary behavior (Figure 1a), and the cyclonic vorticity within the key area varied slowly, and the wind speed in the northern and eastern sections of the vortex was large (Figure 2b,c). The third stage is the vortex's maintenance stage (from 0000 UTC 18 to 0000 UTC 19 May 2017), during which the vortex moved eastward (Figure 1a), and the cyclonic vorticity within its key area kept strong intensity (Figure 2d–g). The last stage is the vortex's dissipation stage (from 0000 UTC to 0700 UTC 19 May 2017), during which the TPV showed its largest moving speed (Figure 1a) and heaviest precipitation within the QB (Figure 4a), whereas the cyclonic vorticity within the key area decreased rapidly (Table 1), indicating the dissipation of the vortex (Figure 2g–h).

4 VORTICITY AND MOISTURE BUDGETS

4.1 Vorticity budget

The key-area averaged vorticity budget using Equation (1) was used to understand the formation mechanisms of the TPV. Before analyses, at first, sensitivity tests were conducted and it can be found that the budget results were insensitive to relatively small changes to the size of the key area (±0.25° to each boundary). This means the key area-based calculation results were representative of the TPV's variation. Then, the balance of Equation (1) was checked and it was shown that the ratio of TOT to the time derivative (on the left-hand side of the equation) was between 0.92 and 1.23 (i.e., relative error was from 8% to 23%). This means that the balance of Equation (1) was good, and therefore the budget results can be used for further investigation. It should be noted that the imbalance of Equation (1) was mainly caused by friction, subgrid processes, and calculation errors. As the imbalance only accounted for a contribution of 8% to 23%, the vorticity budget could effectively show the dominant mechanisms for the TPV's formation.
As Figure 3a shows, during the TPV's formation stage, TOT kept positive and enhanced gradually. This means that cyclonic vorticity within the vortex's key area was intensifying and its increasing rate became larger with time (Figure 3b), which was corresponding to the vortex's formation. Strong convergence dominated the key area, as Figure 3c illustrates. Panel (a) shows the key area averaged vorticity budget terms (unit: $10^{-9}$ s$^{-2}$) at 500 hPa. Panel (b) shows the key area averaged vertical velocity (green line, unit: cm s$^{-1}$), vorticity (red line, unit: $10^{-4}$ s$^{-1}$) and divergence (blue line, unit: $10^{-4}$ s$^{-1}$) at 500 hPa. Panel (c) shows the temporal average during the plateau vortex's life span of wind field (a full wind bar is 4 m s$^{-1}$), and vorticity (shading, unit: $10^{-5}$ s$^{-1}$) at 500 hPa, where the thick green solid line outlines the terrain height of 3,000 m, green box marks the key region of the vortex, and the purple open vectors mark the main transport accounting for a negative HAV term.

| STR  | Development stage | Maintenance stage | Dissipation stage |
|------|-------------------|-------------------|------------------|
| Positive | Positive          | Positive          | Positive         |
| TIL  | Negative          | Positive          | Negative         |
| Negative | Negative          | Negative          | Neutral          |
| VAV  | Positive          | Negative          | Positive         |
| TOT  | Positive          | Positive          | Negative         |

Notes: “Positive” means that the term was overall favorable for cyclonic-vorticity's increase, “negative” means that the term was overall detrimental for cyclonic-vorticity's increase, and “neutral” means that the overall effect of the term was close to zero. The term dominated the cyclonic-vorticity's increase during the formation, development and maintenance stages are highlighted in bold, and the term dominated the cyclonic-vorticity's decrease during the dissipation stage are highlighted in italic.

As Figure 3a shows, during the TPV's formation stage, TOT kept positive and enhanced gradually. This means that cyclonic vorticity within the vortex's key area was intensifying and its increasing rate became larger with time (Figure 3b), which was corresponding to the vortex's formation. Strong convergence dominated the key area,
which produced cyclonic vorticity through vertical stretching. This (i.e., term STR) was the most favorable factor for the TPV's formation (Figure 3a, Table 1). The second favorable factor for the process was the vertical transport of vorticity (i.e., VAV in Figure 3a) by ascending motion (Figure 3b). Terms HAV and TIL mainly acted as reducing cyclonic vorticity within the key area which decelerated the vortex's formation (Figure 3a). The former showed a strong negative effect, which was mainly due to the import transport of anticyclonic vorticity through the western section of key area’s northern boundary (by northeasterly wind) (as purple open arrows in Figure 3c show), the northern section of key area’s eastern boundary (by northeasterly wind) and the middle section of key area’s southern boundary (by southwesterly wind); and the export transport of cyclonic vorticity through the southern section of key area’s eastern boundary (by westerly wind). The latter showed a weak negative effect (Figure 3a) as vertical motions mainly tilted horizontal vorticity into anticyclonic vorticity within the key area (not shown).

Effects of different budget terms during the four typical stages of the TPV (Section 3) were shown in Table 1. It can be found that, overall, during the development and maintenance stages of the vortex, STR acted as the most favorable factor for the TPV’s evolution. During the dissipation stage, the term TOT changed from positive to negative, implying that the cyclonic vorticity began decreasing. This was consistent with the TPV’s dissipation. Tilting (i.e., TIL) was the dominant factor

**Figure 4**
Panel (a) shows the 6-hr accumulated precipitation from 0000 UTC to 0600 UTC 19 May 2017 (shading, unit: mm), where the red number marks the largest precipitation, the thick blue solid line outlines the terrain height of 3,000 m, and the gray box outlines the region for the backward trajectory analysis. Panel (b) shows the air particles’ trajectories (shading lines, where shading of the trajectories represents the specific humidity of air particles during moving, unit: g kg⁻¹). The small open boxes mark the locations of the air particles at 0300 UTC 16 May and the small open circles (c) mark the locations of the air particles at 0300 UTC 19 May. Brown shading shows the terrain above 3,000 m and the thick curved orange arrows mark the southwestern and southern moisture transport channels determined by a clustering analysis. Panel (c) is an enlarging view of the gray box shown in panels (a–b), where shading marks the terrain above 3,000 m, and the open circles mark the locations of terminal points (at 0300 UTC 19 May) of the trajectory analysis.
for this stage, while STR and VAV mainly decelerated the vortex's dissipation.

4.2 | Moisture budget

The TPV focused in this study had induced an intense rainfall within the QB. An accumulated precipitation center of 27 mm appeared in the QB's central section (Figure 4a), which was about one-half of the mean annual precipitation there (Duan, 2018). This rainfall center was produced in a 6-hr period (0000 UTC – 0600 UTC 19 May 2017), which means the precipitation intensity was large. During the same period, the QB's eastern section also experienced intense precipitation (Figure 4a). A moisture budget analysis was conducted to determine the moisture sources and transport channels for the precipitation. The moisture budget was calculated by using the method shown in Section 2.3, which was based on a backward trajectory analysis. A total of 169 equidistant points (with a grid interval of 0.25°) within the gray box of Figure 4a were used (as open circles in Figure 4c show) in the HYSPLIT model. Hourly ERA5 reanalysis data were utilized as the input data to the model, and the period for the backward trajectory analysis was 72 hr. The contribution of the moisture transport across each boundary of the gray box (Figure 4a) was calculated and shown in Table 2. It can be seen that moisture for the precipitation was transported into the box through all of its four boundaries. Of these, the moisture transport across the southern boundary made the largest contribution (68.8%), and that across the eastern boundary ranked second place (15.1%). The moisture transport across the northern and western boundaries accounted for 11.2 and 1.6% of the total moisture import, respectively. All these four moisture transport channels (which transported moisture outside the box into inside the box) made a total contribution of 96.7% (Table 2), and the remaining 3.3% was contributed by the moisture transport inside the box. For the moisture transport across the southern boundary, which had the largest contribution of 68.8%, we used the trajectory clustering method developed by Lee et al. (2007) to determine the main transport channels. Two main moisture transport channels were obtained as the two thick orange curved arrows in Figure 4b show, which included a southwestern and a southern transport channel, respectively. The former made a contribution of 46.3% to the total moisture import (Table 2), with its moisture mainly coming from the Indian Peninsula (Figure 4b). The latter occupied a proportion of 18.7% in the total moisture import (Table 2), and its moisture mainly came from the Indochina Peninsula (Figure 4b). Synoptic analysis shows that the southwestern and southern transport channels were mainly driven by the wind associated with the shortwave trough over the TP (Figure 1d). For the moisture transport across the eastern boundary (its contribution was 15.1%), its moisture mainly came from the regions northeast of the TP (Figure 4b). This moisture transport channel was mainly driven by the wind field associated with the cyclone that was located around 37°N, 107°E (Figure 1d).

5 | CONCLUSION AND DISCUSSION

As one of the most seriously arid areas in China, the QB showed a rapid warming rate in recent decades (Duan and Xiao, 2015). A significant increasing trend in precipitation was also found (Duan, 2018), implying that the probability of intense rainfall was growing in this region (IPCC, 2014; Duan, 2018). For an arid region such as the QB, intense rainfall can usually cause more severe disasters than that of a normal/humid region. However, thus far, few studies have focused on the mechanisms directly inducing the intense rainfall in the QB, therefore, it is necessary to apply detailed investigations. The present study investigated an intense rainfall event within the QB that was induced by a TPV. This partly fills the existing research gaps in the field. It is found that the TPV (which directly induced the intense precipitation within the QB) formed and maintained within an upper-level divergent region north of a strong upper-level jet. In the middle troposphere, the vortex was mainly located in the central region of a shortwave trough, where warm advection was strong. Vorticity budget indicates that the TPV was generated mainly through the convergence-related vertical stretching (i.e., STR), and the vertical vorticity transport (i.e., VAV) also accelerated this process. In contrast, the import horizontal transport of anticyclonic vorticity (i.e., HAV) was the most detrimental factor, which
decelerated the vortex formation. Southwest vortices are a type of mesoscale vortices that form east of the TP, within/around the Sichuan Basin (Fu et al., 2013; Feng et al., 2019; Zhang et al., 2019). There are significant interactions between TPVs and southwest vortices, particularly after TPVs move out from the TP (Fu et al., 2019). Compared to the factors governing SWVs’ formation, it can be seen that the intensity of vertical transport and tilting were much weaker for the TPV. This means that the convective activities associated with TPVs may be weaker than those associated with southwest vortices, which can also be reflected by the contrast of their precipitation. Moisture budget indicates that moisture for the precipitation within the QB mainly came from outside regions, with the transport through the southern boundary occupying the maximum proportion (68.8%). Further analysis shows that the southwestern moisture transport channel, which was mainly driven by the wind field associated with the shortwave trough over the TP, made the largest contribution (46.3%), and its moisture mainly came from the Indian Peninsula.

It should be noted that this study only provides the mechanisms for a type of intense rainfall within the QB. We believe that there are other types of intense rainfall in this region, which need a series of investigations in the future.

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ORCID
Wan-Li Li https://orcid.org/0000-0003-4354-4094

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