An index reflecting mesoscale vortex–vortex interaction and its diagnostic applications for rainstorm area

Yongren Chen1,2,3 | Yueqing Li1,2 | Lan Kang2,3

1Division of Plateau Weather Research, Institute of Plateau Meteorology, China Meteorological Administration, Chengdu, China
2Heavy Rain Analysis Group, Heavy Rain and Drought–Flood Disasters in Plateau and Basin Key Laboratory of Sichuan Province, Chengdu, China
3Division of Weather Disaster Assessment, Meteorological Disaster Defense Technology Center of Sichuan Province, Chengdu, China

Correspondence
Yueqing Li, Institute of Plateau Meteorology, China Meteorological Administration, Chengdu, Sichuan 610072, China.
Email: yueqingli@163.com

Funding information
Chinese Academy of Sciences, Grant/Award Number: XDA23090103; State Key Laboratory of Severe Weather, Grant/Award Number: LASW2012-A03; Sichuan Provincial Science and Technology Department, Grant/Award Number: 2016FY0046; Sichuan Provincial Meteorological Bureau and Nanjing University of Information Science-Technology, Grant/Award Number: SCJXHZ03; National Natural Science Foundation of China, Grant/Award Numbers: 91544109, 91337215

Abstract
The Tibetan Plateau Vortex (TPV) and Southwest China Vortex (SWCV) are important precipitation systems of the upper reaches of the Yangtze River in China in the warm half year (May–October). Sometimes, the vortices both move towards the Sichuan Basin, and encounter one other to merge into a deep vortex that induces mesoscale convective systems (MCSs) and heavy rainfall. In this paper, a formula for the depth of the positive vorticity column (PVC) in two extreme rainstorm events was constructed to reveal the dynamical characteristics of TPV–SWCV interaction. The results showed that: (a) One feature of TPV–SWCV interaction was to form a deep vortex with very deep positive vorticity in the vertical direction, and the occurrence of extreme rainstorms was closely related to the deep vortex. (b) The PVC depth can describe the thickness features of the deep vortex well: MCSs with low brightness temperature were observed in the area of >2 × 10² hPa PVC depth, and their frequent activities were the direct reason for the occurrence of extreme rainstorms. (c) The rainstorm areas were basically consistent with the area of large PVC depth, especially the area of 5–7 × 10² hPa PVC depth where 24-hr accumulated precipitation reached 100 mm or more. The study indicates that the PVC depth can reflect the development of vortices in the vertical direction, and has the potential to be a valuable index for diagnosing heavy rainfall area.

KEYWORDS
positive vorticity column, Southwest China vortex, Tibetan Plateau vortex

1 INTRODUCTION
Owing to its high altitude, complex topography and unique thermodynamic characteristics of the Tibetan Plateau (Ye and Gao, 1979; Yanai et al., 1992), the mesoscale vortices often form over the main body and the lee slope of its eastern side (Tao and Ding, 1981). Among these vortices, the Tibetan Plateau Vortex (TPV) (Kuo et al., 1986; Lu, 1986; Kuo et al., 1988; Chen et al., 2015) at 500 hPa and Southwest China Vortex (SWCV) at 700 or 850 hPa, which occur over the Tibetan Plateau and its eastern side, respectively, are the most representative vortex types (Ye and Gao, 1979; Lu, 1986).
In weather chart, TPV appears as a shallow cyclonic meso-a-scale system with about 500 km horizontal scale and 2–3 km vertical thickness. Also, it often forms over the main body of the Tibetan Plateau. By the complex terrain on the eastern side of it, SWCV, also referred to as a mesoscale low vortex, typically originates in Southwest China (26°–33°N, 98°–108°E) in the lower troposphere. After moving away from their origins, severe weather events (e.g., rainstorms, hail–gale processes and severe thunderstorms) often occur in the downstream area of the Tibetan Plateau such as Sichuan Province and Chongqing Municipality in summer. And many observational studies have shown that TPV and SWCV play a critical role on the occurrence of rainstorm (Tao and Ding, 1981; Kuo et al., 1988; Chen and Li, 2013; Li and Deng, 2013; Xiang et al., 2013; Chen et al., 2015; Chen et al., 2018). Therefore, the understanding for the structures and development mechanisms of the two vortices, as well as the improving for the forecast of their moving, has long been a key concern of meteorological researchers in China. A number of studies have been carried out to improve the understanding of TPV and SWCV, and the fruitful results have been achieved (Wu and Chen, 1985; Shen et al., 1986; Wang, 1987; Chen and Luo, 2003; Wang and Gao, 2003; Li et al., 2011; Li et al., 2014; Yu et al., 2014, 2016; Feng et al., 2016). In recent years, new data have been used to reveal some interesting and original facts about the two vortices (Li and Deng, 2013; Xiang et al., 2013; Lin, 2015; Cheng et al., 2016; Curio et al., 2018a; Curio et al., 2018b). In fact, TPV and SWCV are mesoscale vortices characterized by different height locations (Wang and Orlanski, 1987; Wang et al., 1993; Wang and Tan, 2014). Compared to large-scale low-pressure systems like typhoon and the Upper Polar Vortex, the two vortices have smaller horizontal scales and shallower structures in the vertical direction, specially, in their origins. So, it makes them difficult to be tracked during their movement because of the lack of observational data. This limits the understanding on the activity of TPV and SWCV, and brings difficulties and uncertainties for the prediction of their associated rainstorms in the downstream area of the Tibetan Plateau. In this aspect, one important question is that when TPV and SWCV meet each other at some area, it well recognizes the coupling variation to form a deeper vortex and the developing process of the mesoscale convective systems (MCSs).

MCSs that develop near mesoscale vortices are usually the reason behind the ensuing rainstorms (Schumacher and Johnson, 2005, 2008; Sun et al., 2010; Moore et al., 2012; He et al., 2016). In some rainfall cases associated with TPV and SWCV, the MCSs activity is very important (Chen and Li, 2013; Chen et al., 2015), and is a direct inducing system for rainstorm. However, studies in this aspect have not obtained a comprehensive understanding of the conditions of MCS enhancement during the process of TPV–SWCV interaction. Therefore, in this study, to reveal the characteristics of TPV–SWCV interaction, an index that can describe the vorticity features of TPV–SWCV interaction was defined, and its diagnostic applications for MCS development and rainstorm area were discussed. Specifically, two representative extreme rainfall cases (case 1: from July 16, 2007 to July 19, 2007 and case 2: from June 29, 2013 to July 1, 2013) were selected and analyzed.

Following this introduction, Section 2 describes the data and methods; Section 3 analyzes the characteristics of TPV–SWCV interaction and definition of the index; Section 4 discusses the indicative significance of the positive vorticity column (PVC) for MCS activity and rainstorm area; and Section 5 concludes the study.

2 | DATA

The data used in this study are as follows:

1. Sounding data at 0000 UTC and 1200 UTC at the operational meteorological station in China;
2. Global final (FNL) analysis data from the National Centers for Environmental Prediction (NCEP), with a spatial resolution of 1° × 1° and temporal resolution of 6 hr (hereafter referred to as NCEP_fnl; http://rda.ucar.edu/);
3. Brightness temperature (Tb) data from the FY-2D geostationary weather satellite provided by the National Satellite Meteorological Center in China (http://www.nsmc.org.cn/NSMC/Home/Index.html), and observational precipitation data provided by China Meteorological Administration.

3 | CHARACTERISTICS OF TPV–SWCV INTERACTION AND DEFINITION OF ITS INDEX

In fact, the TPV–SWCV interaction is unique phenomenon in rainstorms of the Sichuan Basin. Due to TPV and SWCV to be mesoscale vortices at different height, in most cases, they rarely appear in a rainstorm at the same time. Although many rainstorms were often related to SWCV or TPV, fewer cases were related to both SWCV and TPV. Limited to few cases, only two cases were chosen to analyze from 2007 to 2013.

The two similar extreme rainstorm events occurred from July 16, 2007 to July 19, 2007 (case 1) and from June 29, 2013 to July 1, 2013 (case 2), which result from the interaction between 500-hPa TPV and 850-hPa SWCV in the Sichuan Basin at the eastern side of the Tibetan Plateau. In case 1, the 500-hPa TPV occurred near Yushu, China, at
After 24 hr of moving and evolving eastwards, the TPV moved to the Sichuan Basin at 1200 UTC July 16, and stagnated over the Basin until 0000 UTC July 19. Correspondingly, the SWCV occurred near Jiulong in the southeastern Tibetan Plateau at 0000 UTC July 15, 2007. After 12 hr, it began to affect the southern Sichuan Basin and gradually moved towards the north. Afterwards, it encounters the move-south TPV, and the two systems fully coupled each other at 1200 UTC July 16, becoming a deeper vortex to continue evolution until 0000 UTC July 19, 2007.

In case 2, the TPV occurred at 0000 UTC June 29, 2013 and reached the Sichuan Basin after 24 hr. The SWCV occurred in the southeastern Tibetan Plateau at 1200 UTC July 15, 2007. After 24 hr of moving and evolving eastwards, the TPV moved to the Sichuan Basin at 1200 UTC July 16, and stagnated over the Basin until 0000 UTC July 19. Correspondingly, the SWCV occurred near Jiulong in the southeastern Tibetan Plateau at 0000 UTC July 15, 2007. After 12 hr, it began to affect the southern Sichuan Basin and gradually moved towards the north.
June 29, 2013 and moved to the Sichuan Basin after 12 hr. And the two vortices met each other in the Sichuan Basin, fully coupled into a deeper vortex at 0600 UTC June 30, and continued evolution until 0000 UTC July 2, 2013.

About the time of the two vortices’ formation, the SWCV’s formation was earlier than that of the TPV in case 1, and it reached the Basin’s rainfall area earlier. However, in case 2, the TPV’s formation was earlier than that of the SWCV, but the two vortices reached the rainstorm area almost at the same time. Regarding their moving paths, the TPV’s path in the two cases was very similar, that of the SWCV differed slightly (Fig. 1a). Furthermore, the SWCV in case 1 early moved from its generated source to the southern Sichuan Basin, and then moved northwards to the rainstorm area. However, in case 2, the SWCV moved northeastwards from its source to the rainstorm area. With respect to the interaction between the two vortices, the long stagnation period and coupled development in the Sichuan Basin were the important features.

During the TPV–SWCV interaction, the two extreme rainfall events took place in the Sichuan Basin to the east of the Tibetan Plateau (Fig. 1b and c), causing considerable flooding and substantial economic and human losses. The two events were similar in several ways. For example, they were both associated with a deep vortex created by TPV–SWCV interaction, and their extreme precipitation was obvious, with maximum values of 72-hr accumulated precipitation 547.6 mm at Chongqing meteorological station in case 1 (Fig. 1b) and 499.6 mm at Suining meteorological station in case 2 (Fig. 1c). Also, the daily precipitation of the two stations reached 273.8 mm and 416 mm, respectively, breaking the observational record for the period 1981–2013. Additionally, the precipitation distributions of the two events were concentrated in the east of Sichuan basin and their precipitation efficiencies were very high. From the evolution of the weather situation

**Figure 2** The 500-hPa (a, b), 700-hPa (c, d), and 850-hPa (e, f) mean wind vector (m/s), mean geopotential height (contoured in solid lines every 0.5 gpdam) and mean positive vorticity \( \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, 10^{-5}/s \) based on NCEP_fnl data: (a, c, e) average time from 1200 UTC July 16, 2007 to 0000 UTC July 19, 2007; (b, d, f) average time from 1200 UTC June 29, 2013 to 1200 UTC July 1, 2013. Black region: Terrain of the Tibetan Plateau
(not shown), the TPV and westerly trough formed a “north trough and south vortex” pattern at 500 hPa. The TPV and SWCV stagnated in the Sichuan Basin for a long time and merged into a deep vortex. As can be seen from Figure 1b and c, the rainstorm distributions in case 1 (Fig. 1b) and case 2 (Fig. 1c) were basically near the region of the deep vortex. But what kind of thermodynamic characteristics did the deep vortex possess? To answer this question, the horizontal and vertical characteristics of the vortex were first analyzed based on NCEP_fnl data, and then an index to reflect the variation of the deep vortex was defined.

Figure 2 shows the mean circulations of TPV–SWCV interaction at 500, 700, and 850 hPa. The mesoscale cyclone structure was very obvious; the TPV and SWCV coupled each other in the heavy-rain area, building a deep structure of relative vorticity, and this was a key dynamical condition for extreme rainstorm's occurrence. The combined vortex’s center fell to 582 gpdam at 500 hPa, 306 gpdam at 700 hPa, and was less than 140 gpdam at 850 hPa. Additionally, the values of relative vorticity exceeded $6 \times 10^{-5}/s$ in the heavy-rain area. On the right-hand side of the vortices, the southwesterly flow at 700 and 850 hPa exceeded 12 m/s (low-level jet: Bonner, 1968; Tao and Ding, 1981) and water vapor transport was favorable for strong precipitation.

In the vertical direction, Figure 3 shows the distribution of equivalent potential temperature (Davies-Jones, 2009).
and positive vorticity before (Fig. 3a and d), during (Fig. 3b and e), and after (Fig. 3c and f) the TPV–SWCV interaction. The distributions of both equivalent potential temperature and positive vorticity were tilted along the steep terrain of the Tibetan Plateau, and the positive vorticity overlapped with the dense belt of equivalent potential temperature. This indicates that the cyclonic vorticity had begun to develop on the inclined dense belt of equivalent potential temperature, and generally had two centers: one was near 500–450 hPa in the middle troposphere and associated with the TPV; and the other was located at 700–850 hPa in the low troposphere and associated with the SWCV. When the TPV moved eastwards and met the SWCV, the vertical vorticity was no longer slanted, but formed a PVC from 850 to 300 hPa. This illustrates that the deep vortex had thicker positive vorticity.

An obvious feature was that the values of positive vorticity were both large in the rainstorm area and very deep in the vertical direction. It is well known that the maximum positive vorticity of a cyclone’s center can characterize the intensity of vortex’s development at a certain layer of the atmosphere. However, when vortices at different height merge into a deep vortex, using the positive vorticity at a certain layer has its limitation and cannot effectively identify the deep vortex again. Such a deep vortex not only has a large value of positive vorticity on the horizontal surface, but also has deep positive vorticity similar to a “vorticity column.” So, using the depth of the PVC to reflect the thickness of the deep vortex is more appropriate. Here, based on horizontal (Fig. 2) and vertical (Fig. 3) features of positive vorticity, a schematic diagram of the PVC (Fig. 3g) was presented. Obviously, the thicker the PVC, the deeper the vortex, correspondingly. Thus, to represent the depth of the PVC in vertical direction, an index was defined based on the pressure difference between two adjacent positive vorticity (values of $\geq 2 \times 10^{-5}/s$) levels, and called it as PVC depth as below:

$$PVC_d = \sum_{k=1}^{n-1} (p(k) - p(k+1)), \quad (1)$$

where $p(k) > p(k+1) > p(n)$; $n$ is the number of layers in the vertical direction; $p(k)$ and $p(k+1)$ are the pressure of the $k$th and $(k+1)$th levels, respectively; the unit of the PVC$_d$ is hPa. Considering the positive vorticity distribution not necessarily to produce rainstorm, the thickness of vorticity values $\geq 2 \times 10^{-5}/s$ was only calculated and analyzed. The thickness of vorticity was calculated using the data between 850 and 200 hPa in high-altitude areas on the east side of the Tibetan Plateau, which deducts the terrain effect below 850 hPa, whereas, in other low-altitude areas, the PVC depth was calculated using the data between 1,000 and 200 hPa. Formula (1) means the greater the PVC depth, the thicker the positive vorticity and the deeper the development of vortex. Based on it, the relationship between the PVC depth and the MCS activity will be discussed below.

## 4 INDICATIVE SIGNIFICANCE OF THE PVC DEPTH FOR MCS ACTIVITY AND RAINSTORM AREA

As direct systems of heavy rain, the development of MCSs is closely related to positive vorticity. Here, the relationship between MCSs and PVC depth is discussed based on Figure 4. It shows there was deep PVC in the heavy rain area; its depth reached $3–6 \times 10^2$ hPa and it was located in the southwest wind on the right-hand side of the two vortices’ centers (the 700-hPa wind was the low-level jet with wind speed $\geq 12$ m/s). MCSs developed or regenerated in the area with obvious PVC.

In case 1 (Fig. 3a–i), the MCSs with Tb values of $< -40^\circ C$ had close relationship with the large PVC. Long-life MCSs were continually located in the large-PVC area. At 0000 UTC July 16, 2007, the PVC depth reached $5–6 \times 10^2$ hPa, correspondingly, MCS with Tb $< -40^\circ C$ was observed. At 0600 UTC July 16, 2007, the positive vorticity increased significantly in the southern part of the rainstorm area, and the PVC depth was $3–6 \times 10^2$ hPa. Although no significant MCSs developed, new MCSs developed strongly at 1200 UTC July 16, 2007. The maintenance of the PVC was important for the long duration of MCS activity. For example, the MCS activity was in the areas where the PVC depth reached $3–6 \times 10^2$ hPa from 1800 UTC July 16 to 0000 UTC July 17, 2007. Shortly afterwards, the MCSs weakened at 1200 UTC July 17, 2007. However, the PVC remained with its depth values of $3–6 \times 10^2$ hPa. So, MCSs developed again and continued until 0600 UTC July 18, 2007.

In case 2 (Fig. 3j–o), the relationship between MCSs and the PVC had some similarities to case 1. The MCSs within $100^\circ–102^\circ E$ gradually moved towards the region with large PVC, and continued until 1200 UTC June 30, 2013. At the same time, a new MCS was located in the area with significant PVC growth. For example, at 0600 UTC June 30, 2013, the PVC increased in the southern part of the heavy rain area, and there was a new MCS growing at 1200 UTC June 30. The new MCSs merged with the old MCSs, and developed again. Compared to the new-MCS growth, the increase in the depth of the PVC took place earlier. The relationship showed that the activity of MCSs often occurred in these PVC depth areas of $3–6 \times 10^2$ hPa, and this revealed that the strong convection system mainly occurred in the areas with deep positive vorticity.

In terms of the spatial distribution of both precipitation and the PVC depth, the shaded area in Figure 5 is the 24-hr accumulated precipitation (values $\geq 25$ mm), and the
FIGURE 4  Distribution of the PVC depth (contour line, ×100 hPa), 500-hPa (gray) and 700-hPa (black) wind vector (gray, m/s), and Tb (shaded, °C) at different time points. Gray region: Terrain above 700-hPa. Case 1 (a–i): (a) 0000 UTC July 16, 2007; (b) 0600 UTC July 16, 2007; (c) 1200 UTC July 16, 2007; (d) 1800 UTC July 16, 2007; (e) 0000 UTC July 17, 2007; (f) 0600 UTC July 17, 2007; (g) 1200 UTC July 17, 2007; (h) 1800 UTC July 17, 2007; (i) 0000 UTC July 18, 2007. Case 2 (j–o): (j) 1800 UTC June 29, 2013; (k) 0000 UTC June 30, 2013; (l) 0600 UTC June 30, 2013; (m) 1200 UTC June 30, 2013; (n) 1800 UTC June 30, 2013; (o) 0000 UTC July 1, 2013
The contour line is the 24-hr mean PVC depth (vorticity values $\geq 2 \times 10^{-5}$/s). The variations of both the heavy rain and the PVC were related with each other, which the rainstorm usually occurs in the area of deep positive vorticity. At all stages of the precipitation, the PVC's depth exceeded $5 \times 10^2$ hPa in the area of above 100 mm precipitation. In case 1 (Fig. 5a–c) and case 2 (Fig. 5d–f), the PVC was located near the center of the two vortices' interaction, and the maximum precipitation was also located in the maximum area of PVC depth. The PVC depth could reach more than $2 \times 10^2$ hPa to produce precipitation of more than 25 mm. This indicates that to produce precipitation more severe than heavy rain, a greater positive vorticity thickness is needed in the vertical direction, and vorticity layer with value $\geq 2 \times 10^{-5}$/s could reach above 500 hPa in the severe precipitation area. Therefore, for rainstorm processes caused by the vortices at different height, the PVC depth can be calculated to analyze the vortex–vortex coupling conditions and the corresponding rainfall area. The areas with large PVC depth are not only the most remarkable interaction between vortex systems but also of the severe rainstorm weather.
5 | CONCLUSIONS

By using two cases of TPV–SWCV interaction, the vorticity features of vortex–vortex coupling were analyzed, and based on observational and NCEP_fnl data, a PVC index was defined to discuss the indicative significance for MCS activity and rainstorm area. The following conclusions can be drawn:

1. The process of TPV–SWCV interaction was that both vortices coupled with each other and then formed a deep mesoscale vortex. Horizontally, the cyclonic structure from 500 to 850 hPa was obvious and the vorticity of circulation center exceeded $7 \times 10^{-5}$/s. In the vertical direction, strong positive vorticity formed the PVC, which was a key dynamical condition for rainstorm occurrence.

2. Based on the PVC variation, an index for estimating the PVC depth was constructed by using the pressure difference between two adjacent positive vorticity centers at two different levels, and then its relationship with MCS strength and rainstorm area was studied. Results showed that the PVC depth was a good indicator for MCS activity and rainstorm area. MCSs with low Tb values were observed in the area with $>2 \times 10^2$ hPa PVC depth. Rainstorm area was basically consistent with the area of large PVC depth, especially in the area of $5-7 \times 10^2$ hPa PVC depth, where 24 hr-accumulated precipitation reached 100 mm or more. So, in this type of vortices interaction, normally the thicker the PVC, the more severe the corresponding precipitation. Clearly, the PVC depth not only reflects the development of vortex in the vertical direction but also is a good indicator for the rainstorm area. Moreover, there is potential to integrate the index into the numerical forecasting to diagnose rainstorm area, and thus it could prove to be a useful forecasting tool.

It is important to note that the TPV–SWCV interaction is unique phenomenon in the rainstorm of the Sichuan Basin. Due to TPV and SWCV to be mesoscale vortices at different height, in most cases, they rarely appear in a rainstorm at the same time. Limited to the two cases, this study attempted to calculate the depth of PVC to diagnose the rainstorm area, and some meaningful results were obtained. But, the PVC depth is whether universal for rainstorm events, more cases would be needed to further analysis.

ACKNOWLEDGEMENTS

This work was jointly sponsored by the projects of a special program of Strategic Science and Technology (Class A) in Chinese Academy of Sciences (XDA23090103), the State Key Laboratory of Severe Weather (LASW2012-A03), the National Natural Science Foundation of China (No. 91337215; No. 91544109), the cooperation research between Sichuan Provincial Meteorological Bureau and Nanjing University of Information Science-Technology in 2019 (No. SCJXHZ203), and a key project of the Applied Basic Research Plan of Sichuan Provincial Science and Technology Department (No. 2016YJ0046). We are grateful to the strong convection forecasting team of China Meteorological Administration for the assistance they provided.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

ORCID

Yongren Chen https://orcid.org/0000-0002-9422-5483

REFERENCES

Bonner, W.D. (1968) Climatology of the low level jet. Monthly Weather Review, 96, 833–850.
Chen, Y.R. and Li, Y.Q. (2013) Characteristics of mesoscale convective system and its effects on short-time severe rainfall in Sichuan Basin during 21-July 22, 2012. Meteorological Monthly, 39, 848–860 (in Chinese).
Chen, L.S. and Luo, Z.X. (2003) A preliminary study of the dynamics of eastward shifting cyclonic vortices. Advances in Atmospheric Sciences, 20, 323–332.
Chen, Y.R., Li, Y.Q. and Zhao, T.L. (2015) Cause analysis on eastward shifting cyclonic vortices. Advances in Atmospheric Sciences, 32, 382–391.
Chen, Y.R., Li, Y.Q. and Qi, D.M. (2018) Analysis of the convective characteristics during the mutual evolution of an inverted trough-low vortex and its induced rainstorm over the northeastern Sichuan basin, China. Meteorology and Atmospheric Physics. https://doi.org/10.1007/s00703-018-0607-4.
Cheng, X.L., Li, Y.Q. and Li, X. (2016) An analysis of an extreme rainstorm caused by the interaction of the Tibetan plateau vortex and the Southwest China vortex from an intensive observation. Meteorology and Atmospheric Physics, 128, 373–399.
Curio, J., Chen, Y.R., Schiemann, R., Turner, A.G., Wong, K.C., Hodges, K. and Li, Y.Q. (2018a) Comparison of a manual and an automated tracking method for Tibetan plateau vortices. Advances in Atmospheric Science, 35, 965–980.
Curio, J., Schiemann, R., Hodges, K.I. and Turner, A.G. (2018b) Climatology of Tibetan Plateau vortices in reanalysis data and a high-resolution global climate model. Journal of Climate, 32, 1933–1950.
Davies-Jones, R. (2009) On formulas for equivalent potential temperature. Monthly Weather Review, 137, 3138–3147.
Feng, X.Y., Liu, C.H., Fang, G.Z., Liu, X.D. and Fang, C.Y. (2016) Climatology and structures of southwest vortices in the NCEP climate forecast system reanalysis. Journal of Climate, 29, 7675–7701.
He, Z.W., Zhang, Q.H. and Sun, J. (2016) The contribution of meso-scale convective systems to intense hourly precipitation events during the warm seasons over central East China. *Advances in Atmospheric Sciences*, 33(11), 1233–1239.

Kuo, Y.H., Cheng, L.S. and Anthes, R.A. (1986) Mesoscale analyses of the Sichuan flood catastrophe, 11-15 July 1981. *Monthly Weather Review*, 114, 1984–2003.

Kuo, Y.H., Cheng, L.S. and Bao, J.W. (1988) Numerical simulation of the 1981 Sihuan flood. Part I: evolution of a Mesoscale southwest vortex. *Monthly Weather Review*, 116, 2481–2504.

Li, L. and Zhang, R.H. and Wen, M. (2011) Diagnostic analysis of the evolution mechanism for a vortex over the Tibetan plateau in June 2008. *Advances in Atmospheric Sciences*, 28, 797–808.

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.

Lu, J.H. (1986) *Generality of the Southwest Vortex*. Beijing: China Meteorological Press (in Chinese).

Moore, B.J., Neiman, P.J., Ralph, F.M. and Barthold, F.E. (2012) Physical processes associated with heavy flooding rainfall in Nashville, Tennessee, and vicinity during 1–2 May 2010: the role of an Atmospheric River and mesoscale convective systems. *Monthly Weather Review*, 140, 358–378.

Schumacher, R.S. and Johnson, R.H. (2005) Organization and environmental properties of extreme-rain-producing mesoscale convective systems. *Monthly Weather Review*, 133, 961–976. https://doi.org/10.1175/MWR2899.1.

Schumacher, R.S. and Johnson, R.H. (2008) Mesoscale processes contributing to extreme rainfall in a midlatitude warm-season flash flood. *Monthly Weather Review*, 136, 3964–3986. https://doi.org/10.1175/2008MWR2471.1.

Shen, R.J., Reiter, E.R. and Bresch, J.F. (1986) Numerical simulation of the development of vortices over the Qinghai-Xizang plateau. *Meteorology and Atmospheric Physics*, 35, 70–95. https://doi.org/10.1007/BF01029526.

Sun, J.H., Zhao, S.X., Xu, G.K. and Meng, Q.T. (2010) Study on mesoscale convective vortex causing heavy rainfall during the Mei-yu season in 2003. *Advances in Atmospheric Sciences*, 27, 1193–1209. https://doi.org/10.1007/s00376-009-9156-6.

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 the American Meteorological Society*, 62, 23–30. https://doi.org/10.1175/1520-0477(1981)062<0023:OEOTIO>2.0.CO;2.

Wang, B. (1987) The development mechanism for Tibetan plateau warm vortices. *Journal of the Atmospheric Sciences*, 44, 2978–2994.

Wang, Z. and Gao, K. (2003) Sensitivity experiments of an eastward-moving southwest vortex to initial perturbations. *Advances in Atmospheric Sciences*, 20, 638–649.

Yu, S.H., Gao, W.L., Peng, J. and Xiao, Y.H. (2014) Observational facts of sustained departure plateau vortexes. *Bulletin of the American Meteorological Society*, 95, 808–820. https://doi.org/10.1175/BAMS-D-12-00180.1.

Yanai, M., Li, C. and Song, Z. (1992) Seasonal heating on the Tibetan plateau and effects of the evolution of the Asian summer monsoon. *Journal of the Atmospheric Sciences*, 49, 1370–1393.

Ye, D.Z. and Gao, Y.X. (1979) *Meteorology of the Tibetan Plateau*. Beijing: China Scientific Press 278 pp.