Impacts of Tibetan Plateau Vortex Activities on the Ecological Environment in the Yellow River Basin

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Abstract. The Tibetan Plateau vortex (TPV) is the main rain-producing system over the Tibetan Plateau. Once it moves out of the plateau, it can cause heavy rainfall and even lead to flooding, soil erosion, and other impacts on the ecological environment to the east of the plateau, especially in the Yellow River Basin (YRB). Based on sounding data, ground-based observations and Tibetan plateau vortex (TPV) and shear line yearbooks from 1998 to 2018, and using synoptic analysis and statistical analysis methods, the activities and the precipitation of high-influence Tibetan Plateau vortices (HITPVs) activities and their impact on the ecological environment in the YRB are analyzed. The results indicate that the Tibetan Plateau vortices (TPVs) that did not move out of the plateau brought moderate rain and above to the upper reaches of the YRB in 1998 which are beneficial to enrich the water resources of the "water tower" of the YRB. Most of the moving-out TPVs (MTPVs) in 1998 caused moderate rain and above in the upper-middle reaches of the YRB or in the whole YRB, contributing to the enrichment of the water resources of the "water tower" of the YRB. However, the activities of the MTPVs were likely to cause heavy rainfall such as rainstorms and heavy rainstorms, which could result in local flooding and other natural disasters and damage to the local ecological environment in the middle reaches of the YRB. The HITPVs mostly moved eastward and northeastward during late May to mid-August, mainly affecting the middle or lower reaches of the YRB. In addition, these HITPVs had southeastward paths, spinning in the Hetao region. The HITPVs with eastward paths and spinning in the Hetao region influenced the whole YRB, mainly causing rainstorms and heavy rainstorms in the middle or lower reaches. All of the HITPVs resulted in damage to the local ecological environment of the YRB.

Keywords: Tibetan Plateau Vortex · Yellow River Basin · Ecological Environment

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1 Introduction

Tibetan Plateau vortices (TPVs) are essential low-pressure systems affecting China, and once the TPVs move eastward out of the Tibetan Plateau, they can cause disaster weather (such as torrential rain and downpour) over a wide range of China [1–5]. Therefore, the eastward-moving TPVs have become the focus of TPV research.

Several previous studies revealed the impact of the eastward-moving TPVs on precipitation in China. For example, Yu et al. [6] indicated that the TPVs generally resulted in rainfall with an intensity of moderate rain or above after moving out of the plateau, and 60% of them that were active for a long time ($\geq$36 h) caused torrential rain or downpour. Zhang et al. [7] pointed out that a TPV spinning over the Hetao region caused a downpour in northern Shaanxi. Yu et al. [4] noted that the TPVs maintained east of the Tibetan Plateau have a wide range of influence on China and can even affect the Korean Peninsula, Japan and Vietnam. The TPVs lasting for a long time after moving out of the Tibetan Plateau greatly influence heavy precipitation in China and even in East Asia [8].

The Yellow River Basin (YRB) crosses eight provinces in China. Its upper reaches are the water resources of the Yellow River, called the "water tower". The precipitation in this area is vital and directly impacts agriculture, ecology and human survival in the Hexi Corridor region. In addition, it affects the agricultural and livestock production in the Hetao region of the YRB (mid-latitude arid and semi-arid regions) and is closely related to the people's production and livelihood in the lower reaches of the YRB. Further investigation of the relationship between TPV activities and heavy rainfall in China is of great significance for the use of water resources and ecological and environmental protection. However, studies on the impacts of TPV activities on the upper, middle and lower reaches of the YRB are scarce and deserve to be further carried out.

Therefore, in this study, we analyze the impacts of the TPVs in 1998 and the TPVs lasting for a long time after moving out of the Tibetan Plateau during 1998–2018 on precipitation in the YRB, in order to explore how the TPVs affect the ecological environment of the YRB. The remainder of this paper is organized as follows. Section 2 introduces the data and methods used in this research. Section 3 investigates the impacts of the TPVs in 1998 on precipitation and ecology in the YRB. Section 4 describes the activities and impacts of the high-influence TPVs (HITPVs) in the YRB. The main conclusions are presented in Sect. 5.

2 Data and Methods

The data used in this study include the ground-based observations and sounding data at 08:00 and 20:00 (Beijing time, the same as below) from 1998 to 2018 provided by the National Meteorological Information Center of the China Meteorological Administration. The yearbooks of the TPVs and the shear lines from 1998 to 2018 are also used in this research [9, 10].

The synoptic analysis and statistical analysis methods [4] are used to analyze the activities of the moving-out TPVs (MTPVs), the activities of the TPVs not moving out of the plateau (NMTPVs) in 1998 and their relationships with precipitation. Also, the activities and precipitation of the TPVs with a longer activity periods (more than 24 h after moving out of the plateau) from 1998 to 2018 are investigated. The impact of HITPVs in the YRB on the ecological environment is explored as well.

The TPVs are generated on the Tibetan Plateau and appear at 500 hPa, which refers to low-pressure systems with closed contours or with cyclonic circulations in terms of the wind direction at three stations [11]. Their number is composed of the letter "C" at the beginning, the second and third digits are the last two digits of the year, and the fourth and fifth digits are the two digits of the low vortex sequence in the corresponding year [9].

A HITPV refers to a TPV activity process that can cause precipitation of 100 mm or more in the upper, middle or lower reaches of the YRB after moving out of the plateau for more than 24 h.

3 Impacts of the TPVs in 1998 on Precipitation and Ecology in the Yellow River Basin

During the floods in the Yangtze River Basin in 1998 (from late June to August), there were 13 heavy rainfall events corresponding to eight flood peaks in the upper reaches of the Yangtze River, all of which were caused by low vortices with shear lines formed by the combination of a TPV and a westerly trough [12]. The impacts of TPV activities were considerable on the Yangtze River floods in 1998. Therefore, the TPV activities and the impacts of the MTPVs and the NMTPVs on precipitation and ecology in the YRB during 1998 are discussed as follows.

3.1 TPV Activities in 1998

Figure 1 presents the monthly occurrences of the TPVs, MTPVs and NMTPVs in 1998. The results indicate that the earliest occurrence of the TPVs in 1998 was in early March, and the last appeared in early December. Except for January, February and November, the TPVs appear in each month. June to August is the peak period for the occurrence of the TPVs, especially for the NMTPVs, while the MTPVs are more frequent in July–August.

The source locations of the TPVs, MTPVs and NMTPVs are also analyzed in this research, as shown in Fig. 2. It can be found that in 1998, most of the TPVs and MTPVs were generated in the east and south of the Tibetan Plateau. However, the TPVs generated in the northeastern and central plateau have higher probabilities of moving out of the plateau, with probability values of 67% and 50%, respectively.

3.2 Impacts of the NMTPVs in 1998 on the Precipitation and Ecology in the Yellow River Basin

Table 1 presents the precipitation situation in the YRB affected by the NMTPVs in 1998. Obviously, the NMTPVs in 1998, most of which (19/26) brought precipitation to the YRB, affected the upper reaches, with 37% (7/19) resulting in drizzle ($\leq$10 mm) and 63% (12/19) causing moderate rain and above ($>$10 mm). In addition, the maximum rainfall caused by the NMTPVs is 38 mm. Most of the NMTPVs resulting in moderate rain and above appeared in June and July (8/12 = 67%). Compared with Fig. 1, it can

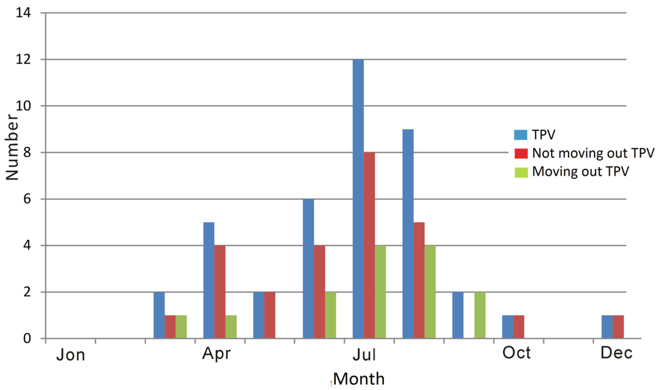

Fig. 1. Monthly occurrence of the Tibetan Plateau vortices (TPVs), moving-out TPVs (MTPVs) and TPVs not moving out of the plateau (NMTPVs) in 1998.

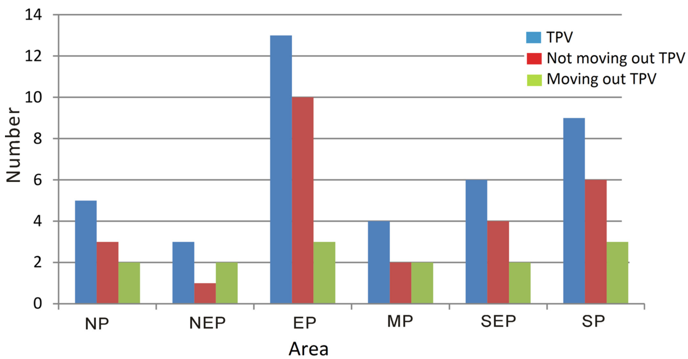

Fig. 2. Numbers of the TPVs, MTPVs and NMTPVs with various source locations. "NP" represent the northern plateau, "NEP" the northeastern plateau, "EP" the eastern plateau, "MP" the middle part of the Tibetan Plateau, "SEP" the southeastern plateau, and "SP" the southern plateau.

be found that the majority of the NMTPVs in June and July (11/12) brought rainfall to the upper reaches of the YRB, and most of them (8/12) caused moderate rain and above. These NMTPVs generally stayed at the source or moved southeastward. This result suggests that the NMTPVs greatly influence the precipitation in the upper reaches of the YRB, mostly causing rainfall with an intensity of moderate rain and above, especially in June and July.

Moreover, in 1998, the activity periods of the NMTPVs resulting in precipitation in the YRB were relatively short, mostly within 24 h (17/19), with 63% (12/19) of 24 h and the longest of 36 h (only two cases). There were only two NMTPVs causing more than 30 mm of precipitation, and their activity periods were 12 h and 24 h. As can be shown from Fig. 2, the NMTPVs generated in the northeastern and southeastern plateau in 1998 all could bring rainfall to the upper reaches of the Yellow River, and the majority of the NMTPVs (3/4) generated in the southeastern plateau caused rainfall of moderate rain and above, with an activity period of 24 h. The majority (9/10) of the

NMTPVs generated in the eastern plateau could bring rainfall to the upper reaches of the YRB, with more than half of them causing moderate rain and above. These results demonstrate that the activity periods of the NMTPVs are relatively short, and regardless of the activity periods, the influences of the NMTPVs should be taken into account. In particular, the NMTPVs generated in the northeastern, southeastern and eastern plateau should receive more attention as they can bring precipitation to the upper reaches of the YRB, especially for the NMTPVs originating from the southeastern plateau.

Table 1. Precipitation situation in the Yellow River Basin (YRB) affected by the Tibetan Plateau vortices not moving out of the plateau (NMTPVs) with different source locations.

Source locations	Number	Generation time	Activity period	Affected area of the YRB	Maximum rainfall (mm)	Path
		(month/day/hour.)	(hours)		(UR MR LR)	
Northern plateau	C9802	3/24/08	12	UR	2.7	
	C9808	5/11/20	12	UR	14.6	
Northeastern plateau	C9825	7/24/08	12	UR	8.2	
Eastern plateau	C9803	4/13/20	12	UR	13.5	
	C9807	4/22/08	12	UR	<10	
	C9809	5/28/08	12	UR	33.6	
	C9810	6/3/08	12	UR	11.4	
	C9815	6/30/20	12	UR	21.8	
	C9820	7/15/20	24	UR	<10	Southeastward
	C9822	7/10/08	24	UR	16.6	Southeastward
	C9826	7/26/08	12	UR	10	
	C9827	7/27/20	36	UR	16.1	Southeastward
Central plateau	C9819	7/14/20	12	UR	26.7	
Southeastern plateau	C9804	4/14/08	12	UR	<10	
	C9811	6/4/20	24	UR	12.5	Southeastward
	C9813	6/8/20	24	UR	26.3	Southwestward
	C9816	7/5/20	24	UR	38.0	Eastward
Southern plateau	C9829	8/7/08	36	UR	21.9	Eastward
	C9839	10/3/20	12	UR	<10	

Note: "UR", "MR" and "LR" denote the upper, middle and lower reaches of the Yellow River Basin, respectively

Overall, the activities of the NMTPVs are favorable for enriching the water resources of the "water tower" of the Yellow River. Especially in June–July when the agricultural and pastoral water use reaches its peak in the YRB, the NMTPV activities increase the water volume in the upper reaches of the YRB, positively regulating the water resources in the middle and lower reaches of the YRB.

3.3 Impacts of the MTPVS in 1998 on the Precipitation and Ecology in the Yellow River Basin

As illustrated in Table 2, the precipitation in the YRB affected by the MTPVs in 1998 indicates that the majority (12/14 = 86%) of the MTPVs brought precipitation to the YRB, mostly affecting the upper and middle reaches of the YRB, only one influencing the whole basin, and 42% (5/12) impacting only the upper reaches of YRB. In terms of the MTPVs, only 17% (2/12) of the MTPVs resulted drizzle ($\leq$10 mm), 83% of the cases caused precipitation with an intensity of moderate rain and above ($>$10 mm), and one third led to downpour (maximum rainfall of 178.9 mm). The MTPVs that caused moderate rain and above mainly appeared in June–September (9/10), with two in June, July and September, respectively, and three in August. Compared with Fig. 1, it can be found that the MTPVs in both June and September brought precipitation with an intensity of moderate rain or above to the upper or upper to middle reaches of the YRB. Half of the MTPVs in August caused moderate rain or above in the upper to middle reaches of the YRB, with torrential rain in the upper or middle reaches. Half of the MTPVs in July resulted in torrential rain or downpour in the middle reaches. Therefore, it can be concluded that both in terms of rainfall area and intensity, the influence of the MTPVs on precipitation in the YRB is greater than that of the NMTPVs. Most of the MTPVs can cause moderate rain and above in the upper to middle reaches of the YRB, especially in July and August when half of the MTPVs caused torrential rain or downpour, which should be considered a concern.

Moreover, the activity periods of the MTPVs affecting precipitation in the YRB in 1998 are relatively longer, mostly more than 36 h (8/12), of which more than 48 h account for 76% (6/8). Three MTPVs have the longest activity period of 60 h. One of them caused heavy rain in the whole YRB, and the other resulted in moderate and heavy rain in the upper to middle reaches of the YRB, accompanied by downpours in the upper or middle reaches. Only two MTPVs led to precipitation greater than 90 mm, both with an activity period of 48 h. Combined with Fig. 2, we can find that the 1998 MTPVs generated in the northern, northeastern, eastern, central and southeastern plateau all brought precipitation to the upper or upper to middle reaches of the YRB. Except the MTPVs generated in the southeastern plateau, which only brought drizzle to the upper reaches of the YRB, most of the MTPVs (6/9) generated in the northern, northeastern, eastern and central plateau caused moderate rain and above in the upper to middle reaches or the whole YRB, with an activity period of 36–60 h, which mostly moved eastward or northeastward. This result indicates that the MTPVs with an activity period of more than 48 h deserve our attention, especially for those with an activity period of 60 h. The MTPVs generated in the northern and eastern plateau can cause moderate to heavy rain and above in the upper-middle reaches or middle-lower reaches of the YRB, especially for those generated in the eastern plateau.

Overall, the MTPV activities are beneficial to the enrichment of the water resources of the Yellow River "water tower". However, the MTPV activities are prone to cause heavy rainfall such as torrential rain and downpour in the middle reaches of the YRB on the Loess Plateaus, leading to local flooding and other natural disasters, damaging the already fragile ecological environment. In particular, in July and August when agricultural and pastoral water use reaches its peak in the YRB, the activities of the MTPVs can increase more water volume than the NMTPVs in the upper reaches of the YRB, with more positive impacts on water regulation in the middle and lower reaches of the YRB. However, it is not favorable to the local ecological environment in the middle reaches of the YRB.

Table 2. Precipitation situation in the YRB affected by the moving-out Tibetan Plateau vortices (MTPVs) generated in different source locations.

Source location	Number	Generation time	Activity period	Affected area of the YRB	Maximum rainfall (mm)	Path
		(month/ day/ hour)	(hours)		(UR MR LR)	
Northern plateau	C9801	3/7/08	60	Whole YRB	<10 32.8 33.2	Eastward
	C9831	8/18/08	60	UR and MR	52.8 27.6	Southeastward
Northeastern plateau	C9814	6/10/08	24	UR	12.7	Northeastward
	C9838	9/3/20	36	UR and MR	18<10	Eastward
Eastern plateau	C9812	6/5/20	60	UR and MR	24.2 45.7	Northeastward
	C9818	7/8/20	48	UR and MR	36.7 178.9	Northeastward
	C9837	9/2/08	24	UR	11.8	Eastward
Central plateau	C9817	7/7/08	24	UR and MR	<10 77.3	Eastward
	C9834	8/27/08	48	UR	17.5	Northeastward to southeastward
Southeastern Plateau	C9823	7/21/20	36	UR	<10	southeastward
	C9833	8/23/08	24	UR	<10	Northeastward
Southern Plateau	C9828	8/4/08	48	UR and MR	17.2 91.4	Eastward

Note: "UR", "MR" and "LR" denote the upper, middle and lower reaches of the Yellow River Basin, respectively

4 Activities and Impacts of the HITPVs in the Yellow River Basin

Based on the identification criteria for the HITPVs described in Sect. 2, the TPVs with high impacts on the YRB from 1998 to 2018 and their paths are shown in Table 3. It can be found that there was a total of thirteen HITPVs from 1998 to 2018, i.e., the annual average was less than 1. 2000 and 2002 are the years with the most HITPVs, both with two. Additionally, in nearly half of the years (10/21), no HITPVs were observed. The relative concentration periods of the HITPVs are 1999–2002 and 2007–2010, suggesting that the occurrences of the HITPVs are related not only to the weather systems affecting TPV activities, but also to atmospheric circulations. Moreover, the HITPVs were mostly

Table 3. High-influence Tibetan Plateau vortices in the YRB from 1998 to 2018.

Path	Number	Activity period	Source	Activity period	Maximum rainfall (mm)
	number	(month/day/hour–month/day/hour)	location	(hours)	(UR MR LR)
Northeastward	C0526	6/23/08–6/28/08	Southeastern plateau	72	103.0 157.8
	C0730	6/19/20–6/25/20	Eastern plateau	84	111.8
	C1026	7/17/20–7/19/20	Southeastern plateau	24	217.8
	C1321	5/24/08–5/27/20	Central plateau	60	123.0 132.2
Southeastward	C9922	7/14/08–7/16/20	Northern plateau	36	104.0
	C0223	8/12/08–8/20/08	Northeastern plateau	168	108.0
Eastward	C0010	6/17/08–6/23/08	Northeastern plateau	108	129.0
	C0319	7/12/20–7/14/20	Northeastern plateau	36	114.1
	C0831	7/20/08–7/23/08	Eastern plateau	24	116.0
	C0943	8/2/08–8/4/08	Northeastern plateau	24	141.0
	C1741	7/25/20–7/29/08	Central plateau	36	103.6
Spinning in the Hetao region	C0014	7/2/20–7/7/20	Eastern plateau	72	409.0
	C0216	7/1/20–7/5/08	Eastern plateau	108	341.9

Note: "UR", "MR" and "LR" denote the upper, middle and lower reaches of the Yellow River Basin, respectively

generated in the eastern or northeastern plateau, mainly moving eastward or northeastward. The majority of the HITPVs remained active for 24 h to 72 h after moving out of the plateau, mainly affecting the middle or lower reaches of the YRB.

Additionally, the HITPVs for the YRB from 1998 to 2018 mainly moved eastward and northeastward, and also some of them had a southeastward paths or spun in the Hetao region.

The HITPVs with an eastward path (Figs. 3a, b, c, d and e) mainly occurred from the second half of June to early August and affected the whole YRB, generally resulting in moderate to torrential rain. These HITPVs were generally generated in the northeastern plateau and caused torrential rain or downpour in the middle or lower reaches of the YRB, leading to local flooding and other natural disasters in the middle or lower reaches of the YRB and causing severe ecological damage.

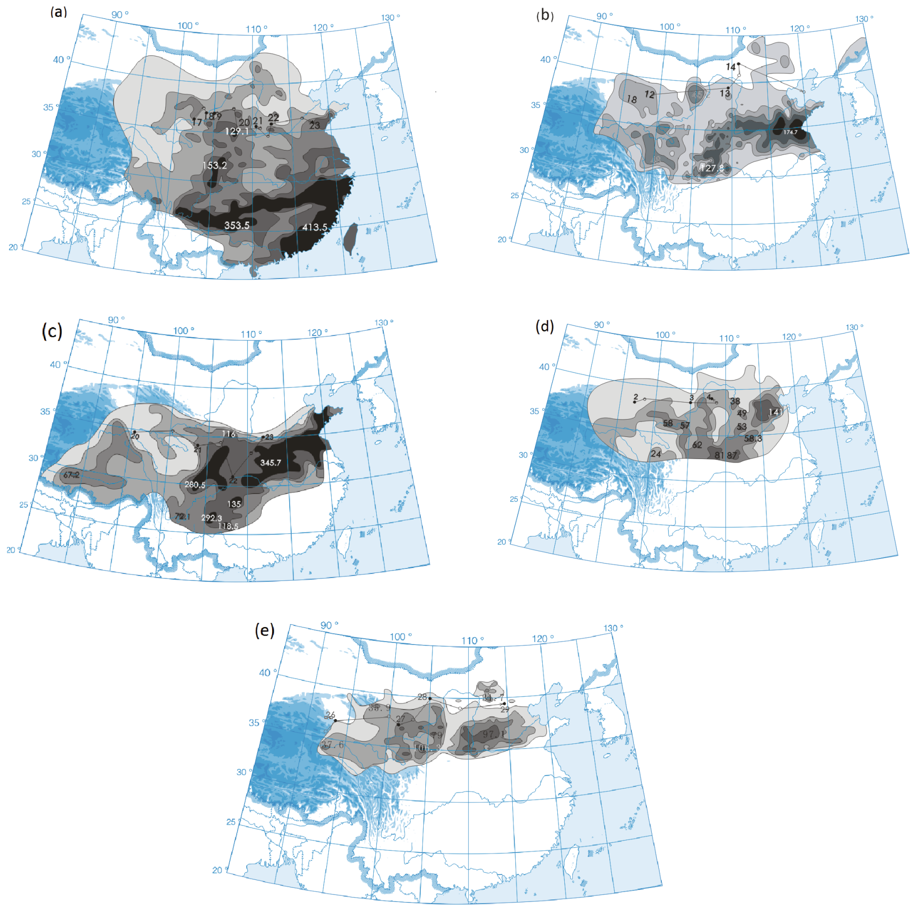

Fig. 3. The total rainfall caused by the high-influence Tibetan Plateau vortices (HITPVs) with an eastward path in the YRB, i.e., (a) C0010, (b) C0319, (c) C0831, (d) C0943 and (e) C1741.

The HITPVs with a northeastward path (Figs. 4a, b, c and d) mostly appeared from late May to mid-July and generally generated in the southeastern and eastern plateau. Half of them caused torrential rain or downpour in the middle and lower reaches of the YRB, and the other half resulted in torrential rain or downpour in the lower reaches of the YRB, leading to natural disasters such as local flooding in the middle and lower reaches of the YRB, especially in the lower reaches. The ecological damage brought by the northeastward-moving HITPVs is greater than that of the eastward-moving ones in the middle and lower reaches of the YRB.

The HITPVs with a southeastward path (Figs. 5a and b) typically occurred from late July to mid-August, causing moderate to torrential rain in the upper and middle reaches of the YRB. These TPVs were generated in the northern and northeastern plateau, leading to torrential rain in the upper or middle reaches of the YRB, resulting in natural disasters such as local flooding and thereby bringing ecological damage to these areas. However, the impact of the southeastward-moving HITPVs is weaker than that of the northeastward-moving and eastward-moving HITPVs.

The HITPVs spinning in the Hetao region in the YRB (Figs. 6a and b) mainly occurred in early July and had impacts on the entire YRB, with widespread drizzle to torrential rain. They were generated in the eastern plateau, leading to torrential rain and downpour in the middle or lower reaches of the YRB and thereby causing local flooding and other natural disasters in these areas. The impact of the HITPVs spinning in the Hetao region on the ecological environment in the middle or lower reaches of the YRB is greater than that of the eastward-moving HITPVs.

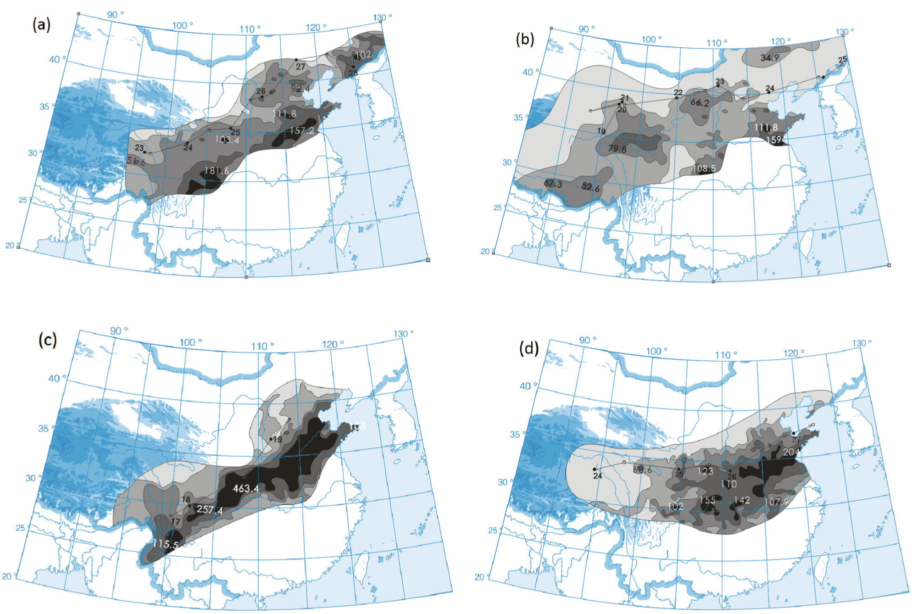

Fig. 4. Same as Fig. 3, but for the HITPVs with a northeastward path, i.e., (a) C0526, (b) C0730, (c) C1026 and (d) C1321.

Therefore, it can be concluded that the generation locations are different for the HITPVs with different paths. The eastward-moving HITPVs were generated in the northeastern plateau, the northeastward ones were generated in the southeastern and eastern plateau, the southeastward ones were generated in the northern and northeastern plateau, and the HITPVs spinning in the Hetao region were generated in the eastern plateau. Moreover, the impacts of the HITPVs with different paths on the YRB vary in range and intensity, causing different severity of ecological damage to the YRB. Specifically, the damage to the local ecological environment in the middle and lower reaches of the YRB was the greatest caused by the HITPVs with northeastward paths, followed by the TPVs spinning in the Hetao region, the third for the eastward-moving HITPVs, and the weakest for the HITPVs with southeastward paths.

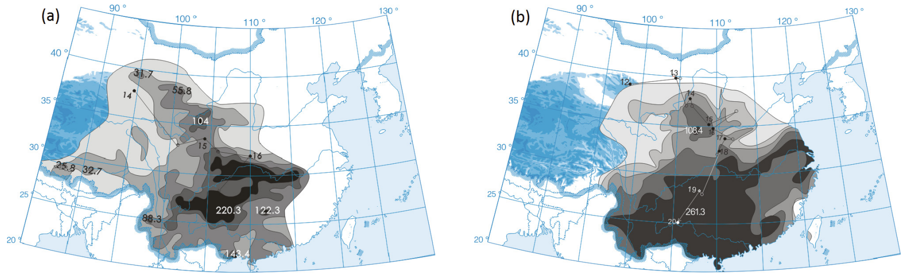

Fig. 5. Same as Fig. 3, but for the HITPVs with a southeastward path, i.e., (a) C9922 and (b) C0223.

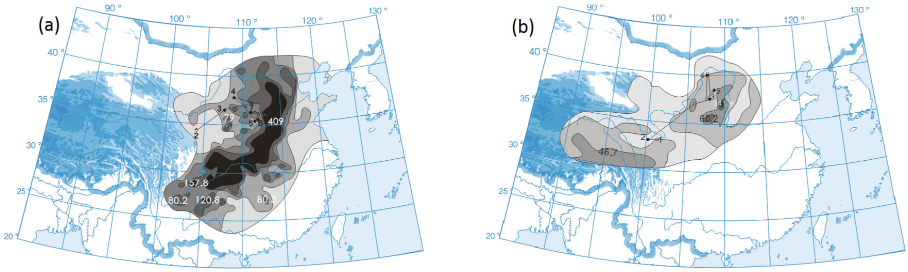

Fig. 6. Same as Fig. 3, but for the HITPVs spinning in the Hetao region, i.e., (a) C0014 and (b) C0216.

5 Conclusions

In this study, the impacts of TPVs activities in 1998 on the ecological environment of the YRB are investigated by analyzing the activities and precipitation of the MTPVs and NMTPVs in 1998. The HITPV activities in the YRB and the precipitation caused by them from 1998 to 2018 are also discussed, and finally their impacts on the ecological environment of the YRB are obtained. The study is of great significance for the use of water resources and ecological and environmental protection. The main conclusions are as follows.

All the NMTPVs generated in the northeastern and southeastern plateau in 1998 brought rainfall to the upper reaches of the YRB. The NMTPVs generated in the southeastern plateau caused precipitation with an intensity of moderate rain and above. The NMTPVs generated in the eastern plateau mostly brought precipitation to the upper reaches of the YRB, more than half of which caused moderate rain and above. Therefore, these NMTPVs are conducive to enriching the water resources in the "water tower" of the YRB, which can increase the water volume in the upper reaches of the YRB and play a positive role in regulating water volume in the middle and lower reaches of the YRB.

All the MTPVs in 1998 brought rainfall to the upper or upper-middle reaches of the YRB. The MTPVs originating from the northern, northeastern, eastern and central plateau mostly caused precipitation with an intensity of moderate rain and above in the upper-middle reaches of the YRB or the whole YRB, mainly moving eastward or northeastward. The MTPVs with a longer activity periods (60 h or more), especially for those generated in the eastern plateau, resulted in stronger rainfall intensities. Compared with the NMTPVs, the increase of the water volume increase caused by the MTPVs activities is more, especially during July–August when agricultural and pastoral water use reaches its peak in the YRB. Thus, the MTPVs are more favorable to enriching the water resources in the "water tower" of the YRB. However, in terms of the middle reaches of the YRB, the MTPVs are likely to cause heavy rainfall such as torrential rain and downpour, leading to local flooding and other natural disasters and resulting in damage to the local ecological environment in these areas.

Most of the HITPVs in the YRB were generated in the eastern and northeastern plateau and generally moved eastward or northeastward. Their main activity periods were 24–72 h after moving out of the plateau, and the major influenced areas were the middle or lower reaches of the YRB.

The HITPVs mostly moved eastward and northeastward, and some of them moved southeastward or spun in the Hetao region. These TPVs mainly appeared from late May to mid-August, and the occurrence periods are different for the HITPVs with different paths, successively for the northeastward-moving HITPVs, the eastward-moving HITPVs, the HITPVs spinning in the Hetao region and the southeastward-moving HITPVs.

The impacts of the HITPVs with different paths on the YRB varied in range and intensity. The eastward-moving HITPVs and those spinning in the Hetao region had influences on the whole YRB, mainly causing torrential rain and downpour in the middle or lower reaches. The impacts of the eastward-moving HITPVs were greater than those spinning in the Hetao region. The northeastward-moving HITPVs caused torrential rain and downpour in the middle and lower reaches of the YRB, especially in the lower reaches. The HITPVs with southeastward paths led to moderate rain and above in the upper and middle reaches of the YRB.

This research also indicates that the HITPVs with different paths in the YRB all resulted in damage to the local ecology in the YRB, but the severity of the damage was different. The damage to the local ecological environment in the middle and lower reaches of the YRB was the greatest caused by the northeastward-moving HITPVs, followed by the HITPVs spinning in the Hetao region, the third for the eastward-moving HITPVs, and the weakest for the southeastward-moving HITPVs.

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References

1. Tao, S.Y., Ding, Y.H.: Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. Bull. Amer. Meteor. Soc. **62**(1), 23–30 (1981)
2. Zhang, S.L., Tao, S.Y., Zhang, X.L.: Meteorological and hydrological characteristics of severe flooding in China during the summer of 1998. Q. J. Appl. Meteorol. **12**(4), 442–457 (2001)
3. Liu, X.C., Chen, Y.R.: Comparative analysis of two heavy rainfall processes under interaction of Plateau Vortex and Southwest Vortex. Plateau Mt. Meteorol. Res. **34**(1), 1–7 (2014)
4. Yu, S.H., Gao, W.L., Peng, J., Xiao, Y.H.: Observational facts of sustained departure plateau vortexes. Meteor. Res. **28**, 296–307 (2014)
5. Chen, B., Gao, W.L.: The causing storm rain in Southwest Sichuan basin characteristic analysis of Tibetan Plateau vortex. Plateau Mt. Meteorol. Res. **35**(1), 9–15 (2015)
6. Yu, S.H., Gao, W.L.: Observational analysis on the movement of vortices before/after moving out Tibetan Plateau. Acta Meteor. Sinica **64**(3), 392–399 (2006)
7. Zhang, H., Chen, W.D., Sun, W.: Analysis of the influence of a Typhoon and mesoscale vortex in inner-mongolia irrigation area of Yellow River on rainstorm in north Shaanxi. Plateau Meteor. **25**(1), 52–59 (2006)
8. Yu, S.H., Gao, W.L., Xiao, D.X., Peng, J.: Observational facts regarding the joint activities of the Southwest Vortex and Plateau Vortex after its departure from the Tibetan Plateau. J. Adv. Atmos. Sci. **33**(1), 34–46 (2016)
9. Li, Y.Q., et al.: Tibetan Plateau Vortex and Shear Line Yearbook 1998. China Scientific Press, Beijing (2010)
10. Institute of Plateau Meteorology, China Meteorological Administration, Chengdu, and Plateau Meteorology Committee of Chinese Meteorological Society.: Tibetan Plateau Vortex and Shear Line Yearbook 2018. China Scientific Press, Beijing (2020)
11. The Lhasa Focus Group on Tibetan Plateau Meteorology Research.: The Research of Vortex and Shear Line on 500 hPa of Tibetan Plateau in Summer Half Year. Science Press, Beijing (1981)
12. Yang, K.M., Bi, B.G., Li, Y.A., Dong, L.Q.: On flooding-causing torrential rainfall in the upstream district of Changjiang River in 1998. Meteor. Mon. **27**(8), 9–14 (2001)