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Observational Facts Regarding the Joint Activities of the Southwest Vortex and Plateau Vortex after Its Departure from the Tibetan Plateau

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ABSTRACT

Using atmospheric observational data from 1998 to 2013, station rainfall data, TRMM (Tropical Rainfall Measuring Mission) data, as well as annual statistics for the plateau vortex and shear line, the joint activity features of sustained departure plateau vortexes (SDPVs) and southwest vortexes (SWVs) are analyzed. Some new and useful observational facts and understanding are obtained about the joint activities of the two types of vortex. The results show that: (1) The joint active period of the two vortexes is from May to August, and mostly in June and July. (2) The SDPVs of the partnership mainly originate near Zaduo, while the SWVs come from Jiulong. (3) Most of the two vortexes move in almost the same direction, moving eastward together with the low trough. The SDPVs mainly act in the area to the north of the Yangtze River, while the SWVs are situated across the Yangtze River valley. (4) The joint activity of the two vortexes often produces sustained regional heavy rainfall to the south of the Yellow River, influencing wide areas of China, and even as far as the Korean Peninsula, Japan and Vietnam. (5) Most of the two vortexes are baroclinic or cold vortexes, and they both become strengthened in terms of their joint activity. (6) When the two vortexes move over the sea, their central pressure descends and their rainfall increases, especially for SWVs. (7) The two vortexes might spin over the same area simultaneously when there are tropical cyclones in the eastern and southern seas of China, or move southward together if a tropical cyclone appears near Hainan Island.

Key words: plateau vortex, southwest vortex, observational study

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1. Introduction

The Tibetan Plateau vortex (TPV) and southwest vortex (SWV) are generated under the dynamic and thermodynamic actions of the unique complex terrain of the Tibetan Plateau. The TPV forms over the main body of the Tibetan Plateau and is mainly active on the 500 hPa isobaric surface. Ye and Gao (1979) described the horizontal scale of the TPV to be around 500 km and the vertical thickness as ranging within 2–3 km approximately. The SWV, meanwhile, usually occurs on the southeast side of the Tibetan Plateau and in the southwestern part of China, mainly active on the 700 hPa isobaric surface. As documented by Lu (1986), the SWV is a shallow and thin mesoscale system with a scale of 300–500 km, observed mainly on the isobaric surface at 700 hPa.

The TPV is generated in the western part of the Tibetan Plateau and dies away in the eastern part. Some TPVs can move out of the plateau, bringing rainstorms, some severe, to extensive regions of China and even resulting in flooding disasters (Tao and Ding, 1981; Zhang et al., 2001; Yu et al., 2014). Most SWVs form and then disappear in their source region (Chen et al., 2007b), but some will leave their source areas, with substantial impacts on precipitation over China (Lu, 1986; Kuo et al., 1988; Chen et al., 2003).

The study of these vortex phenomena (i.e., TPVs and SWVs) has attracted much attention from meteorologists, both domestically and internationally (e.g., Qian et al., 1984; Chen, 1990; Li et al., 1991; Luo, 1992; Gao, 1987; Wang, 1987; Chang et al., 2000; Chen et al., 2000; Wang and Gao, 2003). In recent decades, increasing concern has been placed on the study of TPVs that shift eastward out of the plateau; specifically, the underlying mechanism involved in their eastward movement. Yu and Gao (2009) pointed out that the departure of the TPV from the Tibetan Plateau is caused by the interaction of the westerlies, subtropical weather systems, and the weather systems of the upper level of the troposphere. Li et al. (2011) concluded that TPVs may contain vortex Rossby waves and inertial-shallow gravity waves. He et al. (2009) found that the interaction of cold and warm air causes

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the convergent flow field to be sustained and strengthened, which is a critical element for the maintenance and intensification of the vortexes. Furthermore, Yu et al. (2008) pointed out that under the condition of reinforced baroclinic instability, the TPV tends to move out of the Tibetan Plateau. Song et al. (2012) suggested that the latent heat of condensation and water vapor plays vital roles in the maintenance of a vortex and the evolution of its structural features. Takahashi (2003) concluded that cold air directly impacts upon the development of the low pressure in the northern part of the plateau. In comparison, with respect to research on SWVs, scientists have been more concerned with studying their dynamics and numerical simulation. Chen et al. (2007c) derived three-dimensional vorticity change equations and analyzed the impact of atmospheric stratification and its changes on the change in three-dimensional vorticity. Using numerical simulation, Chen et al. (2004) found that as the vortex strengthens, the phenomenon of frontogenesis, in the eastward direction, is clear. Zhou et al. (2006) revealed that the northeast airflow of Typhoon Songda blew into the southeast side of the SWV, triggering an extremely severe rainfall event. Chen et al. (2007a) indicated that the large-scale circulation of the “saddle pattern” is conducive to the development of an SWV. Other researchers have also pointed out the basic facts and activity features of TPV (Yu and Gao, 2006; Wang et al., 2009) and SWV (Chen and Min, 1999; Chen et al., 2007b) activity.

Research on TPVs and SWVs has thus far focused mainly on one of these two types of vortexes. Whilst these studies have revealed many important and interesting facts about the two kinds of vortexes, there has been little recognition of their joint activities and changes, which have significant impacts on the occurrence of severe precipitation over China and East Asia. Addressing this knowledge gap is therefore of great significance, not only to further our understanding of their interaction, but also to realize the relationship of these joint characteristics with severe precipitation in China, to improve forecasting technology, and to ultimately reduce the damages caused by the associated rainstorms. In addition, a reliable basis can be formed for studying the eastward movement, development and impact mechanisms of the TPV and SWV. Therefore, it is necessary to use the latest data to carry out research on the dominant activity and variation of the vortexes’ joint activities, as well as their impacts on precipitation over China.

This paper aims to reveal the joint activity characteristics of TPVs with a more than 2 day lifetime after departing the plateau (SDPV) and SWVs. Furthermore, the respective characteristics of an SDPV within the joint activity of an SDPV and SWV (TVSPDV) and that of an SWV within the joint activity of an SDPV and SWV (TVSWV) are discussed in detail.

The remainder of the paper is organized as follows: The data and methods are introduced in section 2. The TVSPDVs and TVSWVs are analyzed in section 3 in terms of their active years and months, paths and seedbeds. The variabilities of the TVSPDVs and TVSWVs are analyzed in section 4. The differences between TVSPDVs and SDPVs and the differences between TVSWVs and SWVs are compared in detail in section 5. And lastly, the conclusions of the study are given in section 6.

2. Data and methods

2.1. *Data*

Four datasets are used in this paper. The first includes geopotential height, temperature, wind direction and wind speed at 500 hPa, and the data are based on twice-daily observations (1998–2013) from 120 radiosonde stations. The second comprises the 24-h accumulated rainfall collected from 1244 national meteorological stations from 1998 to 2013, with quality control applied by the National Meteorological Information Center of the China Meteorological Administration (CMA). The third is the statistics from the Yearbook of the TPV and the shear line, again from 1998 to 2013, published by the Chengdu Institute of Plateau Meteorology of the CMA. And the fourth dataset is the Tropical Rainfall Measuring Mission (TRMM) data from the Goddard Earth Science Data and Information Services Center, National Aeronautics and Space Administration (NASA), United States of America.

2.2. *Methods*

Using synoptic and statistical analysis methods, the different processes of SDPVs that accompanied SWVs are investigated and analyzed in this paper.

First, an SPDV is demarcated as a low pressure system with closed isoheight or a vortex with cyclonic winds, at three adjacent stations at 500 hPa, generated over the Tibetan Plateau, with a longer than 2-day lifetime after departing the plateau. A TVSPDV is an SDPV that possesses joint activity with an SWV. By contrast, a DPV is a departure plateau vortex.

Second, an SWV is demarcated as a low pressure system with closed isoheight or a vortex with cyclonic winds, at three adjacent stations, at 700 hPa, generated over the leeward slope (26°–33°N, 99°–109°E) of the Tibetan Plateau. A TVSWV is an SWV that possesses joint activity with an SDPV.

According to their areas of origin, SWVs can be divided into the Jiulong vortexes, the Sichuan Basin vortexes (basin vortexes for short) and the Xiaojin vortexes (Institute of Plateau Meteorology, China Meteorological Administration, Chengdu, and Plateau Meteorology Committee of Chinese Meteorological Society, 2013).

Third, the TVSDPVs (TVSWVs) are sorted into three groups according to their activities: the warm, the cold, and the baroclinic, based on the temperature distribution of the vortexes on the 500 hPa (700 hPa) synoptic map. If a vortex is situated in the warm spine at 500 hPa (700 hPa) without cold air incursion, it is categorized as a warm vortex. However, a vortex is categorized as baroclinic if it is swarmed into the cold air obviously, regardless of its location in the warm trough or the frontal zone. The cold, of course, indicates that the vortex exists in the cold environment entirely (Yu et al., 2014). The cold or warm vortexes are barotropic.

Fourth, the rainy area of a TVSDPV or TVSWV is determined by both the vortex circumfluence range and the observed rainfall distribution, including the rainfall incurred by three SDPV, SWV and synoptic systems, which are hard to distinguish.

The identification of continuously regional rainstorms, the interception of precipitation areas impacted by TVSDPVs and TVSWVs, and the distinction between the plateau's east and west vortexes are made using the methods described by Yu et al. (2014).

Finally, based on the definitions above, all of the TVSPDVs and TVSWVs that occurred during 1998–2013 are identified and studied.

3. Activities of TVSPDVs and TVSWVs during 1998–2013

The active period, origins and paths of TVSPDVs and TVSWVs during 1998–2013 are analyzed in detail here.

3.1. *Active period*

Figure 1 shows the total number of SDPVs and TVSWVs in each year and each month over 1998–2013. As shown, the highest number is in 2013, with a total of five (Fig. 1a). Such joint activities in 2013 contributed greatly to the floods in the Yangtze River valley, Yellow River and Huaihe River as well as the Sichuan Basin, which indicates that SDPV processes joined by SWV activities have significant impacts on the widespread occurrence of summer flooding in China. In comparison, 2012 has the fewest SDPVs, with none recorded (Fig. 1a). The figure also shows that during the 16 years, 63% of SDPV processes are accompanied by SWV activities. Generally, if there are more (fewer) SDPV processes in a year, more (fewer) accompanying SWV activities appear accordingly (Fig. 1a). This suggests that the joint activity features of SDPVs and SWVs are highly prominent. In addition, we see that the first two-vortex joint activity process appears in early March and the last is in late October, and that such joint activities mainly take place from May to August, of which July is the month with the most cases, followed by June. Therefore, the two-vortex joint activity process is primarily seen from June to July (Fig. 1b)—different from the activities of SDPVs, which mainly occur from June to August (Yu et al., 2014), and also different from the similar occurrence number of DPVs from June to August (Yu and Gao, 2006). Moreover, TVSWVs, which are different from SWVs, mainly occur from April to July, but the frequency is the highest in April and June (Chen et al., 2007b).

3.2. *Origins*

Figure 2 shows the starting places of TVSPDVs from the 16-yr statistics. The shading in Fig. 2 represents the Tibetan Plateau. The serial numbers of TVSPDVs are marked.

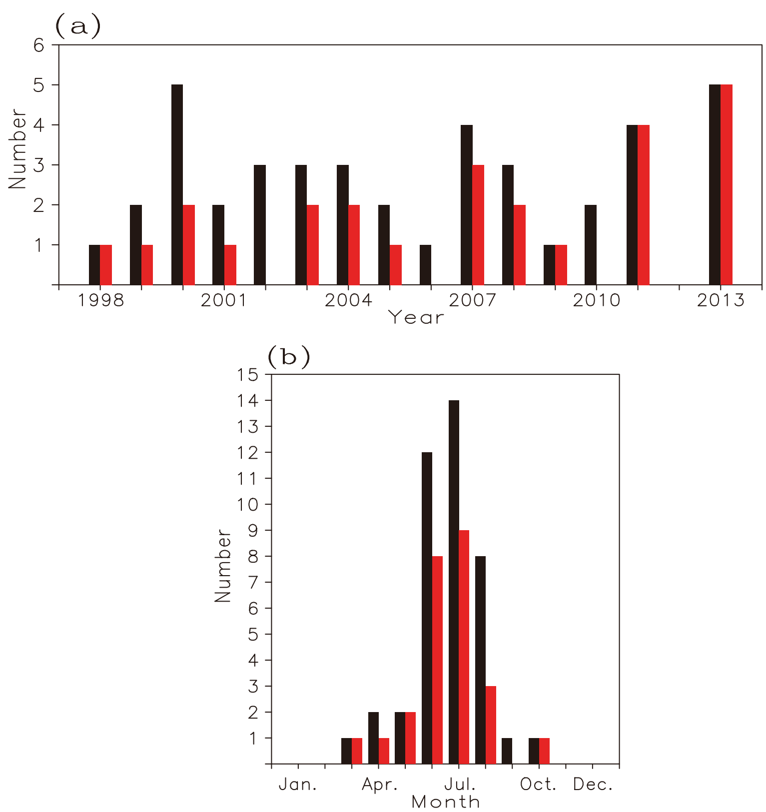

Fig. 1. The (a) annual and (b) monthly appearance numbers of SDPVs (black) and TVSWVs (red) from 1998 to 2013.

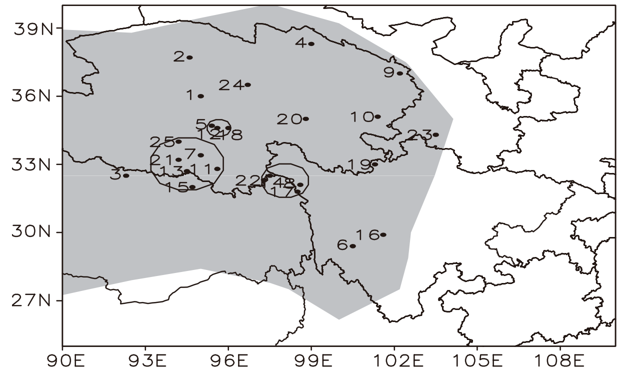

Fig. 2. The origins of TVSPDVs during 1998–2013. The sequential numbers indicate the movement order of TVSPDVs and the circles indicate the regions with concentrated occurrence (two or more) of TVSPDVs. The shaded area is the region with altitude higher than 2500 m.

The circle implies that two or more TVSPDVs have occurred within the enclosed area. Obviously, most TVSPDVs form in the eastern portion of the Tibetan Plateau, especially in Zaduo, Yushu and Quma, but not in Qumalai and Dege where DPVs form (Yu and Gao, 2006). This is also different from the frequency distribution of SDPVs, which lies primarily near Qumalai, and secondarily, near Yushu, Zaduo and Aba (Yu et al., 2014). All these phenomena reflect the fact that TVSPDVs have different sources to DPVs and SDPVs.

The origins of TVSWVs from 1998 to 2013 are exhibited in Fig. 3. It is shown that, during the 16-yr period, Jiulong vortexes and basin vortexes are the main members of TVSWVs; each of them account for 41% of the total, while the Xiaojin vortexes account for 18% only. For the Jiulong and basin vortexes, their origins are mostly in Jiulong, and then near Daocheng, Quxian, Tongnan, Tongjiang, Dianjiang and Huili. This finding is different from the analysis of Chen et al. (2007b), that the main two generation centers lie near Jiulong and Santai, reflecting the origin of TVSWVs is different from that of SWVs. In addition, Fig. 3 also shows that most TVSWVs are generated before TVSPDVs move out of the Tibetan Plateau, and the particularly prominent vortex type is the Jiulong Vortex, accounting for 75%.

The origins of the TVSPDVs are concentrated in the eastern part of the plateau. This is possibly because there are fewer radiosonde stations in the western part of the plateau, and thus there are fewer related data. Therefore, it is difficult to verify whether or not TVSPDVs tend to originate from the western part of the plateau.

3.3. *Paths*

Statistical data show that 4/5, or 80%, of TVSPDVs in the 16-yr period move to north of the Yangtze River. Figure 4 shows that most TVSPDVs move eastward or northeastward, some southeastward first, and then turn to the southwest, or southeastward first, and finally to the northeast. Such paths are different from the paths of SDPVs, most of which move eastward or northeastward (Yu et al., 2014). Therefore, the typical movement path of TVSPDVs is more complex than that of SDPVs, which may be caused by the interaction between SDPVs and SWVs.

The movement paths of TVSWVs during 1998–2013 are essentially in the Yangtze River valley, accounting for 2/3 or 67%. The vast majority of TVSWV movement paths are to the south of the paths of TVSPDVs, accounting for 89%. Figure 4 reveals that, in the last 16 years, most TVSWVs have moved northeastward or eastward. This finding is different to that of SWVs, for most of these quickly dissipate in their source areas and only a small number move out of their generation regions (Chen et al., 2007b).

By analyzing the movement directions of TVSPDVs and TVSWVs during 1998–2013 (table omitted), it is found that in most cases the TVSPDVs and TVSWVs move in similar directions, gradually, or in the same direction during the

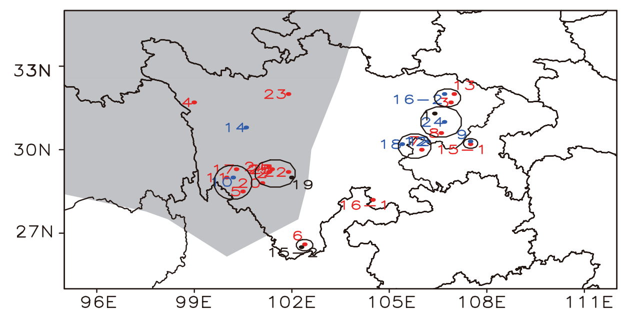

Fig. 3. The origins of TVSWVs during 1998–2013. The sequential numbers indicate the movement order of TVSWVs and the circles indicate the regions with concentrated occurrence (two or more) of TVSWVs. The red, blue and black numbers represent the SWVs before, at the point of, and after the SDPV moves out of the Tibetan Plateau. The shading is the same as in Fig. 2.

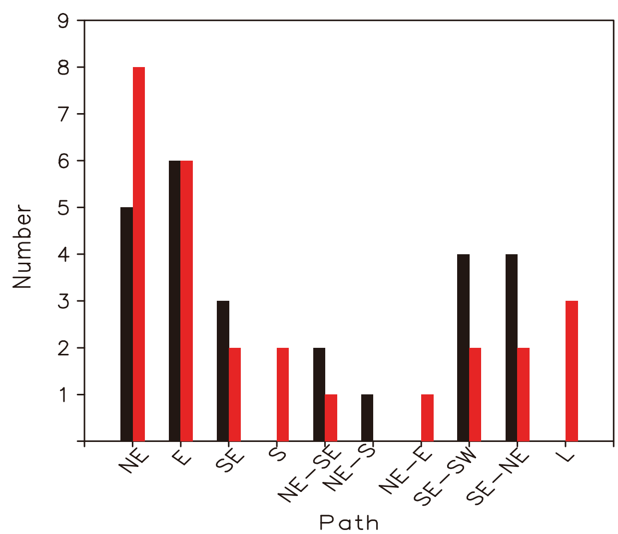

Fig. 4. The frequency of different movement paths of TVSPDVs (black) and TVSWVs (red) from 1998 to 2013. NE means northeastward; the dash between two letters, e.g., NE–SE, signifies a veer. L means less movement or dissipating *in situ*.

same activity process, especially during long-lasting activity processes (longer than 84 h) after the TPV departs from the plateau. This phenomenon reflects the fact that it is clearly noticeable that TVSPDVs and TVSWVs usually move together during their common activity processes.

3.4. *Active stages*

Figure 5 shows the different active stage numbers of TVSPDVs and TVSWVs from 1998 to 2013. It is shown that 72% of TVSPDVs survive for 48–72 h and the longest for 144 h. This is different from SPDVs, whose percentage of active stages after they leave the plateau is 61% (48–72 h) and the longest duration is 192 h (Yu et al., 2014). In contrast, the active stages of TVSWVs last for 36–72 h (56%), and only a small number of the vortexes live for 96–108 h, and the longest for 156 h. This finding is different from the SWVs, for 75% of the vortexes die away in 1–24 h (Chen et al., 2007b). Besides, analysis also shows that it is mainly the Jiulong vortexes that can sustain for 60–96 h and 108–144 h, which together account for 56%. The secondary type is the basin vortex, which can last for 60–96 h (37%) and 108–144 h (29%). In addition, the basin vortex is a TVSWV, which has the longest active stage (156 h). This phenomenon indicates that, in the case of TVSWVs, more attention should be paid to the activity of Jiulong vortexes and, meanwhile, the basin vortexes should also be closely monitored.

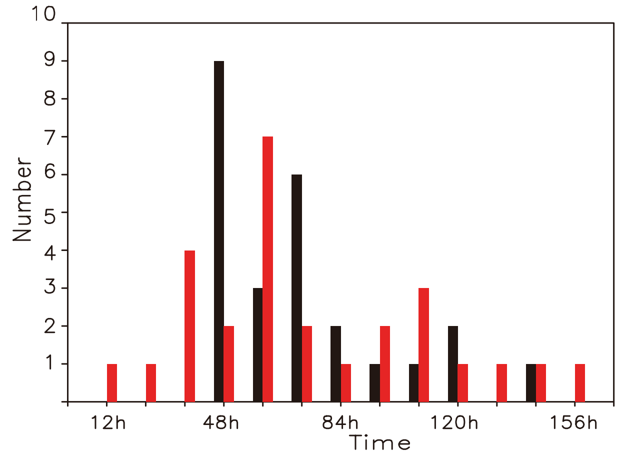

Fig. 5. The frequency of different active stages of TVSPDVs (black) and TVSWVs (red) from 1998 to 2013.

4. Variability of TVSPDVs and TVSWVs

The above facts indicate that TVSPDVs and TVSWVs are different in many aspects, such as their active period, origins, paths, and active stages. Next, we examine the variability of TVSPDVs and TVSWVs in terms of their intensity, properties, precipitation and related movement path, as well as their interaction with other synoptic weather systems.

4.1. *Variations of TVSPDVs and TVSWVs during their lifetime*

By analyzing the thermodynamic characteristics of TVSPDVs in the 16-yr period at the beginning of departure and their lifetime after departing the plateau (Table 1), two key results are found, as follows: (1) The lifetime of a TVSPDV after moving out of the plateau is, to some extent, related to its thermodynamic properties. The TVSPDVs, with a lifetime of 48 h, are often of baroclinic nature or cold, and those surviving for 60 h after moving out of the plateau are mostly cold, accounting for 67%. This means that the impact of cold air on TVSPDVs is more obvious than on TPVs, after their moving out of the plateau (Yu and Gao, 2006). (2) Most TVSPDVs experience lowered geopotential height during the lifetime after they depart from the plateau, compared to at the beginning of their departure, especially for those persisting longer than 108 h, all of which are declining. This is different from the drop in geopotential height of SPDVs lasting for 72–96 h, after they have left the plateau (Yu et al., 2014).

Table 2 compares the characteristics of TVSWVs when and after they drift out of their source areas over the period 1998–2013. As shown, the properties of TVSWVs change. Most of the basin vortexes and Jiulong vortexes are baroclinic vortexes when and after they move out of their vortex source areas, with a small number being cold vortexes; and moreover, such cold vortexes become more frequent after moving out. When Xiaojin vortexes move out from their source areas, most are baroclinic vortexes; some are warm, but all become cold vortexes after they have moved out. In addition, it can also be seen from the results in the table that the intensity of TVSWVs change. The vast majority of TVSWVs are able to move out of their source areas, including 10/12 of the basin vortexes, 11/12 of the Jiulong vortexes, and 3/3 of the Xiaojin vortexes. After the basin vortex and Jiulong vortexes depart from their source areas, the centers of most vortexes or zones usually experience a drop in geopotential height, causing the vortex to intensify. More precisely, those vortexes that shift out of their source areas and can sustain for a long time (e.g., the basin vortexes, which live longer than 48 h, and the Ji-

Table 1. Comparison of the percentages of TVSPDVs with different lifetimes.

	Geopotential height			Beginning of departure		After departure	
Lifetime	Decreased	Unchanged	Increased	Warm	Baroclinic	Cold	Baroclinic
48 h	78%	11%	11%	22%	78%	22%	78%
60 h	33%	33%	33%	0%	100%	67%	33%
72–96 h	89%	11%	0%	0%	100%	11%	89%
>108 h	100%	0%	0%	0%	100%	25%	75%

Table 2. Comparison of the percentages of TVSWVs with different source area.

	Geopotential height			Beginning of departure			After departure	
	Decreased	Unchanged	Increased	Cold	Warm	Baroclinic	Cold	Baroclinic
Basin vortex	86%	0%	14%	10%	0%	90%	29%	71%
Jiulong vortex	73%	9%	18%	18%	0%	82%	36%	64%
Xiaojin vortex	0%	33%	67%	0%	33%	67%	100%	0%

ulong vortexes, which live longer than 72 h), all experience a decline in the geopotential height of their vortex centers or zones. This phenomenon is different from that seen with the SWVs, which are warm at formation (Lu, 1986) and can seldom develop further (Chen et al., 2007b). But most TVSWVs that leave their source areas are impacted by cold air and can develop and intensify.

4.2. *Intensity variation of precipitation*

The rainfall events produced by the joint activity of TVSPDVs and TVSPDVs to the east of the plateau are brought about by the common impact of the vortexes, so it is difficult to distinguish their separate effects clearly. Moreover, during the joint activities of the two vortexes, the precipitation created mainly by the TVSPDV circulation usually envelopes the rainfall generated by the TVSWV. Therefore, the following analysis focuses on the variation of precipitation brought about by TVSPDVs during the joint activities of the two vortexes.

Table 3 displays the percentages of the TVSPDVs with rainfall at different intensity grades and their variations over 1998–2013. As summarized in the table, precipitation is strengthened by 75% of the TVSPDVs, regardless of how long they sustain. In general, TVSPDVs give rise to rainfall at least at the grade of extremely heavy rain (50–99.9 mm), more often to downpours. When TVSPDVs survive longer than 72 h, there is an 83% possibility that a downpour will happen. So, the precipitation in such cases is much stronger than the intensities of light rain events produced by SWVs (Lu, 1986), and rain events by SDPVs (Yu et al., 2014).

Analysis of the TVSPDVs and their related sustained regional rainstorms reveals that 82% of TVSPDVs can lead to sustained regional rainstorms in China during summer (May–August), mainly in Guizhou, Chongqing, Anhui, Guangdong, and Henan, sometimes even in Sichuan, Shaanxi, Yunnan, Jiangxi, Hubei, Hunan, Guangxi, Jiangsu and Shanghai (table omitted).

As shown, TVSPDVs usually incur extremely heavy rain or downpours. In most cases, they result in sustained regional rainstorms. They therefore constitute one of the most important factors inducing sustained regional rainstorms in China, especially to the south of the Yellow River.

4.3. *Variations of TVSPDVs and TVSWVs moving over the sea*

The statistics show that TVSPDVs and TVSWVs move over the sea area together five times in the 16-yr period (Table 4). Three TVSPDVs and TVSWVs move over the Yellow Sea, and two over the Bohai Sea. In terms of monthly variation, there are two in June over the Yellow Sea, one in April over the Yellow Sea, one in May over the Bohai Sea and another one in July over the Bohai Sea (Fig. 6).

In addition, during one June process the TVSPDV moves

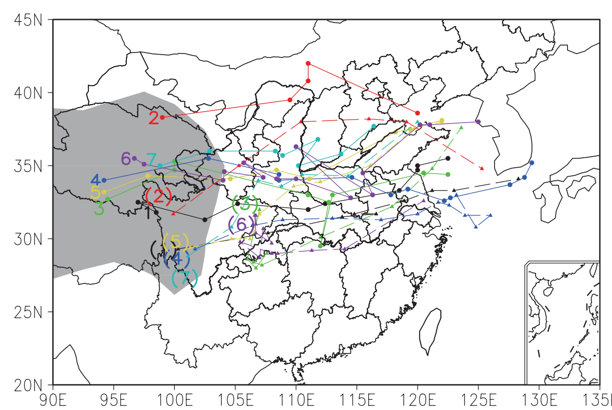

Fig. 6. Tracks of the TVSPDVs and TVSWVs that moved over the sea together. The solid circles represent TVSPDVs; solid triangles represent TVSWVs. The shading is the same as in Fig. 2.

Table 3. Comparison of precipitation intensities associated with the TVSPDVs. The percentage values represent the proportion of TVSPDVs that induce a certain intensity of rainfall.

Duration after departure	Alteration of precipitation intensity: Weakened	Alteration of precipitation intensity: Strengthened	Moderate (10–29.9 mm)	Heavy (30–49.9 mm)	Extremely heavy (50.0–99.9 mm)	Downpour (>100 mm)
108–192 h	0%	100%	0%	0%	0%	100%
72–96 h	12%	88%	0%	0%	25%	75%
60 h	25%	75%	0%	25%	25%	50%
48 h	0%	100%	0%	0%	0%	100%

over the Bohai Sea, whereas the TVSWV moves to the coastline of the Yellow Sea, affecting the Korean Peninsula. Instead, during the early August process, the TVSWV moves over the Bohai Sea, while the TVSPDV moves to the coastline of the Bohai Sea (Fig. 6).

Comparative analysis of the geopotential height of the six TVSPDVs and the six TVSWVs moving over the sea reveals that all of them enhance as geopotential height decreases (Table 4). Usually, geopotential height decreases by 1–3 dgpm during 24 h. The maximum decrease of TVSPDVs of 6 dgpm and TVSWVs of 9 dgpm happens during the period from 0800 LST 15 to 0800 LST 19 April 2004, when they finally move over the Yellow Sea.

Based on the TRMM rainfall data, all six of the TVSPDVs and all six of the TVSWVs that move over the sea later occur with higher precipitation. The hourly rainfall could increase by 0.7–9 mm h^{-1} for TVSPDVs and could increase by 2.9–11.9 mm h^{-1} for TVSWVs. The maximum augmentation appears during 0800 LST 1 to 2000 LST 5 June 2001, when the TVSPDV shifts to the Yellow Sea. After moving over the sea at 0800 LST 5 June, the TVSPDV increases the rainfall by 9 mm h^{-1} (Figs. 7a and b). The maximum augmentation appears during 2000 LST 14 to 0800 LST 19 April 2004 when the TVSWV shifts to the Yellow

Table 4. Geopotential height changes and 3-h rainfall related to the TVSPDVs and TVSWVs moving over the sea together. ΔH (24h) is the daily geopotential height change at 500 hPa calculated at the time of the vortex moving over the sea. The superscript "hour" of 8 or 20 denotes local station time. "Time into sea" denotes the time of TVSPDVs and TVSWVs moving over the sea. "Before" denotes before TVSPDV or TVSWV moving over the sea. "After" denotes after TVSPDV or TVSWV moving over the sea. Because one TVSPDV and one TVSWV move to Seaside, they do not move over the Sea. So the data of before/after TVSPDV or TVSWV moving over the sea are not shown.

Serial No.	Year Month	vortex Type	Start-end time ($Date^{hour}$)	Position	Destination	Time into sea ($Date^{hour}$)	Geopotential height (dgpm) Before	After	ΔH (24 h)	Maximum rainfall Before ($mm\ h^{-1}$)	After
1	2001	TVSPDV	1^{8}–5^{20}	35.0°N, 120.2°E	Yellow Sea	5^{8}	573	570	−3	6.120	15.120
	Jun.	TVSWV	2^{8}–6^{8}	33.3°N, 121.2°E	Yellow Sea	5^{20}	304	301	−3	0.113	6.590
2	2003	TVSPDV	12^{20}–14^{20}	38.6°N, 120°E	Bohai Sea	14^{20}	577	576	−1	7.630	8.330
	Jul.	TVSWV	12^{20}–15^{8}	37.6°N, 119.0°E	Bohai Sea	14^{20}	307	306	−1	17.610	20.528
3	2004	TVSPDV	15^{8}–19^{8}	34.5°N, 120.5°E	Yellow Sea	18^{20}	564	558	−6	21.392	28.164
	Apr.	TVSWV	14^{20}–19^{8}	34.8°N, 121.2°E	Yellow Sea	18^{20}	303	294	−9	9.500	21.392
4	2013	TVSPDV	4^{20}–10^{8}	32.6°N, 122.2°E	Yellow Sea	8^{8}	578	572	−6	13.338	20.926
	Jun.	TVSWV	5^{8}–10^{20}	32.5°N, 121.7°E	Yellow Sea	8^{8}	304	301	−3	13.338	20.926
5	2013	TVSPDV	24^{8}–27^{20}	38.1°N, 122.0°E	Bohai Sea	27^{8}	574	569	−5	8.250	16.251
	May	TVSWV	23^{20}–27^{20}	37.6°N, 119.8°E	Bohai Sea	27^{8}	301	299	−2	8.250	16.251
6	2007	TVSPDV	6^{20}–13^{20}	37.8°N, 121°E	Bohai Sea	13^{8}	577	575	−2	0.621	9.146
	Jun.	TVSWV	8^{8}–14^{8}	-	Yellow Seaside	-	-	-	-	-	-
7	2011	TVSPDV	30^{20}–8.3^{8}	-	Bohai Seaside	-	-	-	-	-	-
	Jul.	TVSWV	31^{8}–8.3^{8}	37.8°N, 120.0°E	Bohai Sea	3^{8}	309	308	−1	12.909	19.320

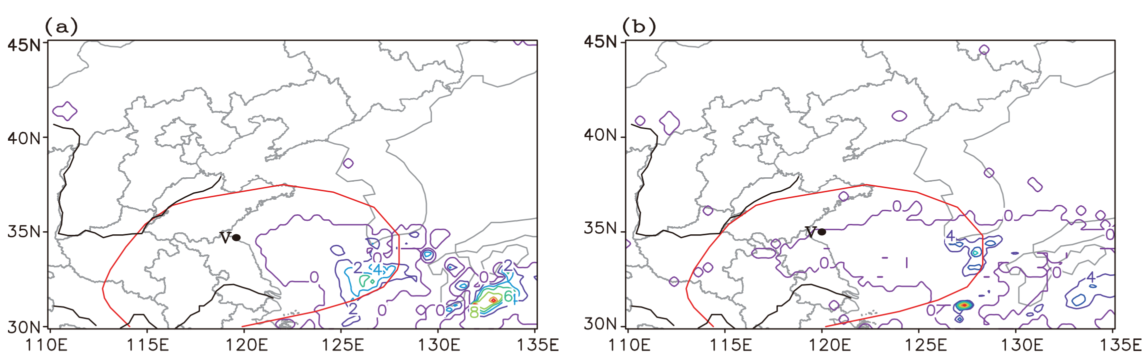

Fig. 7. TRMM rain rate distribution (a) before (at 0500 LST 5) and after (at 0800 LST 5) the TVSPDV moves over the sea, during 1–5 June 2001. The "v" denotes the TVSPDV position and the bow line represents the area influenced by the TVSPDV. Units: mm h^{-1}.

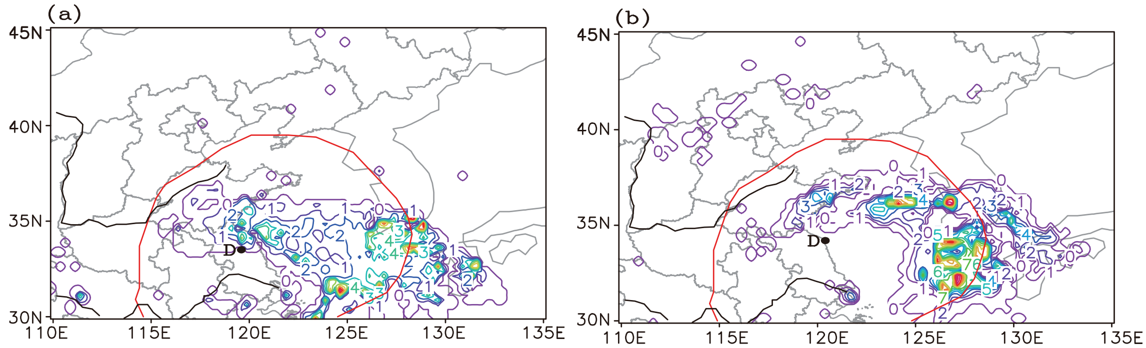

Fig. 8. The TRMM rain rate distribution (a) before (at 1400 LST 18) and (b) after (at 1700 LST 18) the TVSWV moves over the sea, during 14–19 April 2004. The label "D" denotes the TVSWV position and the bow line denotes the area influenced by the TVSWV. Units: mm h^{-1}.

Sea. After moving over the sea at 1700 LST 18 April, the TVSWV increases the rainfall by 11.892 mm h^{-1} (Figs. 8a and b).

Thus, TVSPDVs and TVSWVs could be strengthened after moving over the sea, as reflected by the decreasing geopotential height and enhanced rainfall. This reflects different behavior compared to landing tropical cyclones.

4.4. *Path variations of TVSPDVs and TVSWVs affected by different synoptic systems*

Over 1998–2013, most TVSPDVs and TVSWVs move in the same direction (64%). Analyzing the 500 hPa synoptic system during the process of the two-vortex movements in similar directions, we find that 69% (2/3) of the TVSPDVs move eastward along with the eastward-moving low trough (Figs. 9a–e), 19% of them move eastward with the movement of the shear line (Fig. 9f) and only 12% of them move in the shear flow field (Fig. 9g). The main movement directions affected by the 500 hPa trough are northeast, east, east to northeast, and northeast to east. The main movement directions affected by shear lines include east to southeast, and northeast. The main movement directions affected by sheared surroundings are southeast to southwest, and east. In short, the TVSPDVs are somewhat different from the SPDVs, nearly half of which shift eastward in sheared surroundings (Yu et al., 2014). Also the TVSWVs are somewhat different from the SWVs, most of which move along the direction of the 500 hPa flow (Lu, 1986).

We find that two processes of TVSPDVs and TVSWVs in the 16-yr period simultaneously recurve and turn around at the same place. They all behave actively in sheared surroundings and, meanwhile, there are active tropical lows over the oceans to the east and south of China. This result is likely to be caused by the obstruction of tropical low pressure to the activity of TVSPDV and TVSWV (Fig. 10).

We also find that two TVSPDVs move in opposite fashion to TVSWVs. Specifically, in the two processes from 2000 LST 20 to 0800 LST 22 July 2008, and from 0800 LST 14 to 0800 LST 15 July 2013, the TVSPDV moves towards the southeast while the TVSWV moves to the northeast, i.e., the two vortexes shift in opposite directions. The 500 hPa weather systems that impact the TVSPDV and TVSWV in the first process are the sheared surroundings and the southwest airflow outside the subtropical high, respectively. During the second process, the 500 hPa weather system that affects the TVSPDV is the low trough in the first two time levels and then the shear line in the later one; while the 500 hPa weather system influencing the TVSWV is the TPV in the first two time levels and then the low trough in the later one. Therefore, it is concluded that the cause of the opposite movement of the TVSPDVs and TVSWVs lies in their different 500 hPa weather systems.

We even find that in the 16 years there are two TVSPDVs parting from TVSWVs in terms of their travelling processes, which are from 0800 LST 3 to 0800 LST 5 July 2000 and 0800 LST 5 to 0800 LST 7 July 2013. In the first process the 500 hPa weather systems that affect the TVSPDV and TVSWV are the sheared surroundings and the Hetao low pressure, respectively; while in the second process the 500 hPa weather systems impacting the TVSPDV and TVSWV are the shear line in the trough tail and the low trough, respectively. So, it can be seen that the departure of the two vortexes is mainly determined by the movement direction of the 500 hPa weather systems affecting the TVSPDV and TVSWV.

One TVSPDV and one TVSWV are even found to move simultaneously southward into Vietnam from 2000 LST 3 to 2000 LST 5 August 2009. The 500 hPa weather system for them is the sheared surroundings that remain between the Tibetan High and the western pacific subtropical high, and at the same time there are activities of tropical lows near Hainan Island.

In summary, different weather systems can affect the path trends of TVSPDVs and TVSWVs during the two-vortex joint activity processes, which indicates that the interaction of TVSWVs and TVSPDVs is substantial.

5. Comparison of the characteristics of TVSPDVs vs SDPVs, and TVSWVs vs SWVs

Table 5 compares the characteristics of TVSPDVs and

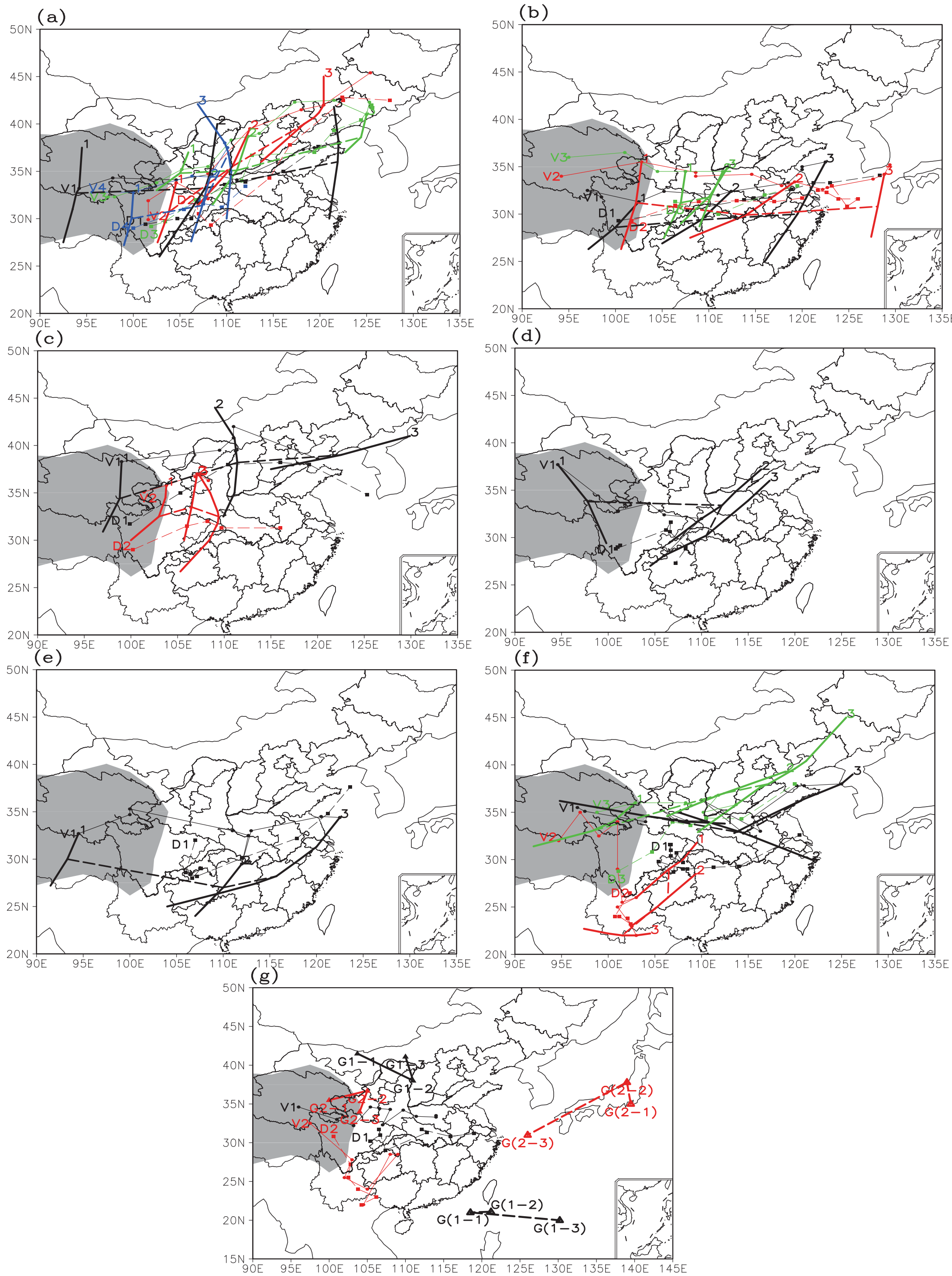

Fig. 9. Synoptic system sketch map of similar movement tracks of TVSPDVs and TVSWVs. TVSPDVs are denoted by closed circles, TVSWV by closed squares, and the trough line or shear line by the thick solid line. The central points of the trough line or shear line are linked by thick dashed lines with the time numbers 1, 2 or 3 on its right side of the line's beginning. In two vortices with the same movement direction, the 1, 2 and 3 indicate the beginning, middle and end times. In two vortices with changed movement direction, the 1, 2 and 3 indicate the beginning, turning direction and end time. High-pressure centers are denoted by the capital letter "G". (a) Moving northeastward along with the 500 hPa trough. (b) Moving eastward along with the 500 hPa trough. (c) Moving northeastward along with the 500 hPa trough and then changing to southeastward. (d) Moving southeastward along with the 500 hPa trough and then changing southwestward. (e) Moving southeastward along with the 500 hPa trough and then changing northeastward. (f) Moving along with the 500 hPa shear line. (g) Moving in the 500 hPa sheared field. The shading is the same as in Fig. 2.

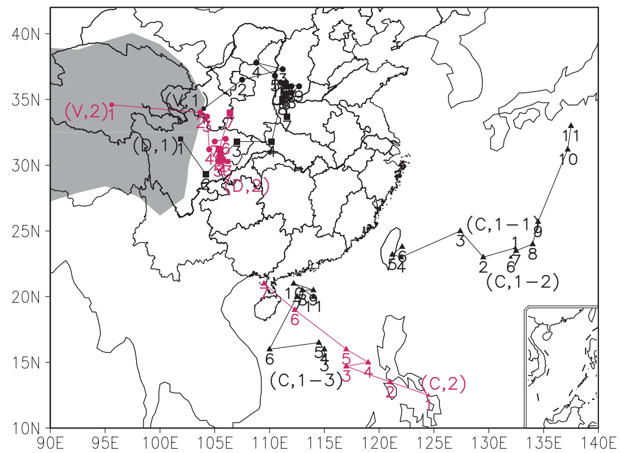

Fig. 10. Paths of tropical lows and the simultaneously spinning TVSPDVs and TVSWVs. The "V" denotes TVSPDVs, while "D" denotes TVSWVs and "C" denotes tropical pressure lows. The shading is the same as in Fig. 2.

SDPVs in different aspects, such as the active period, sources, paths, thermodynamic properties, leading synoptic system, and path alteration; and Table 6 does the same but for TVSWVs and SWVs. It can be seen from Tables 5 and 6 that TVSPDVs (TVSWVs) are totally different from SDPVs (SWVs). It is interesting to note that, with the presence of a tropical low pressure system over the sea to the east and south of China, TVSPDVs and TVSWVs have a higher chance to recurve over the same area simultaneously, and to move southward together due to the tropical low near Hainan Island.

6. Conclusions

(1) TVSPDVs and TVSWVs are dynamically active from May to August, with most occurrences in June and July.

(2) The main vortex source of TVSPDVs is near Zaduo, then near Yushu and Qumalai; and the primary vortex source of TVSWVs is in Jiulong, then in Daocheng, Quxian and Tongnan.

(3) In most cases, TVSWVs possess similar movement directions as TVSPDVs, moving eastward together with the eastward-moving low trough. Meanwhile, TVSPDVs dominantly move in the area to the north of the Yangtze River, while TVSWVs are active in the Yangtze River valley.

(4) TVSPDVs and TVSWVs are important factors leading to sustained regional rainstorms in China, especially to the south of the Yellow River. Their impact may reach a much wider area of China, and may even affect the weather on the Korean Peninsula, in Japan, and Vietnam.

(5) TVSPDVs and TVSWVs alter their intensities and thermodynamic properties during their movement. Most TVSPDVs and all TVSWVs are baroclinic or cold and can be strengthened, leading to extremely heavy rainfall, downpours, or sustained regional rainstorms.

(6) Some TVSPDVs and TVSWVs may move over the sea and become strengthened, with enhanced rainfall and declined geopotential height, especially TVSWVs.

(7) TVSPDVs and TVSWVs might spin over the same area simultaneously as a result of the influence of remote tropical cyclonic activity. The tropical low near Hainan Island can push TVSWVs and TVSPDVs southward together.

Table 5. The characteristics of TVSPDVs and SDPVs.

Attribute	SPDVs	TVSPDVs
Active period	Mainly in Jun to Aug, mostly in Jul.	Mainly in Jun to Aug, mostly in Jun. to Jul
Source	Mainly near Qumalai	Mainly near Zaduo
Path	Eastward or northeastward	Eastward, northeastward, southeast to southwest, or southeast to northeast
Property type	Mostly baroclinic	Mostly cold
Rain intensity	Downpours or sustained regional rainstorms	Sustained regional rainstorms
Leading system	Sheared surroundings	Trough
Path alteration	Spinning over the bend of the Yellow River with a tropical low in the East China Sea; moving oppositely to the tropical low to the east of Taiwan or over the South China Sea	Spinning with the TVSWV in the same area simultaneously due to a tropical low over the sea to the east and south of China; moving together with the TVSWV southward due to the tropical low near Hainan Island

Table 6. The characteristics of TVSWVs and SWVs

Attribute	SWVs	TVSWVs
Active period	Mainly in Apr to Jul, mostly in Apr and Jun	Mainly in Jun to Jul
Source	Mainly near Jiulong and Santai	Mainly near Jiulong, Daocheng and Quxian
Path	Mostly quickly dissipating or not moving in their source area	Northeastward, eastward
Property type	Mostly Warm	Mostly baroclinic or cold
Rain intensity	Light rain	Sustained regional rainstorms
Leading system	Moving along the direction of the 500 hPa flow	Trough

APPENDIX

Summary of the TVSPDV and TVSWV activities from 1998 to 2013

Number	Year	Vortex type	Dates	Origin	Path
1	1998	TVSPDV	0800 LST 7 to 2000 LST 9 Mar	36°N, 95°E	E
		TVSWV	2000 LST 8 to 0800 LST 10 Mar	31.3°N, 106.4°E	E
2	1999	TVSPDV	0800 LST 14 to 2000 LST 16 Jul	37.7°N, 94.6°E	SE–SW
		TVSWV	0800 LST 13 to 0800 LST 17 Jul	29.2°N, 101.3°E	NE–S
3	2000	TVSPDV	2000 LST 2 to 0800 LST 5 Jul	32.5°N, 92.3°E	SE–SW
		TVSWV	0800 LST 3 to 0800 LST 5 Jul	31.7°N, 106.9°E	SE
4	2000	TVSPDV	2000 LST 2 to 2000 LST 7 Jul	34.3°N, 103.5°E	NE
		TVSWV	2000 LST 2 to 0800 LST 6 Jul	32.0°N, 101.9°E	NE
5	2001	TVSPDV	0800 LST 1 to 2000 LST 5 Jun	31.8°N, 98.5°E	E
		TVSWV	0800 LST 2 to 0800 LST 6 Jun	29.3°N, 100.3°E	E
6	2003	TVSPDV	2000 LST 12 to 2000 LST 14 Jul	38.3°N, 99°E	NE–SE
		TVSWV	2000 LST 12 to 0800 LST 15 Jul	31.7°N, 99°E	NE–E
7	2003	TVSPDV	2000 LST 28 to 0800 LST 31 Oct	37°N, 102.2°E	SE–NE
		TVSWV	0800 LST 29 to 2000 LST 29 Oct	30.3°N, 107.5°E	E
8	2004	TVSPDV	0800 LST 15 to 0800 LST 19 Apr	32.7°N, 94.5°E	SE–NE
		TVSWV	2000 LST 14 to 0800 LST 19 Apr	32.0°N, 107.0°E	SE–NE
9	2004	TVSPDV	0800 LST 3 to 0800 LST 6 Aug	32.5°N, 97.5°E	SE–SW
		TVSWV	2000 LST 3 to 0800 LST 5 Aug	30.8°N, 100.6°E	SE –SW
10	2005	TVSPDV	0800 LST 23 to 2000 LST 28 Jun	32.3°N, 97.3°E	NE
		TVSWV	0800 LST 24 to 2000 LST 27 Jun	29.2°N, 101.9°E	NE
11	2007	TVSPDV	2000 LST 6 to 2000 LST 13 Jun	36.5°N, 96.7°E	SE–NE
		TVSWV	2000 LST 8 to 0800 LST 14 Jun	31.0°N, 106.7°E	NE
12	2007	TVSPDV	2000 LST 24 to 2000 LST 28 Jun	29.9°N, 101.6°E	NE
		TVSWV	0800 LST 24 to 0800 LST 26 Jun	28.2°N, 104.5°E	S
		TVSWV	2000 LST 25 to 0800 LST 29 Jun	32.0°N, 106.7°E	SE–NE
13	2007	TVSPDV	0800 LST 30 Jul to 0800 LST 4 Aug	32°N, 94.7°E	NE–S
		TVSWV	0800 LST 31 Jul. to 2000 LST 1 Aug	30.2°N, 107.5°E	L
		TVSWV	0800 LST 2 to 0800 LST 4 Aug	26.5°N, 102.3°E	S
14	2008	TVSPDV	2000 LST 5 to 2000 LST 10 Jun	34.6°N, 96°E	E
		TVSWV	0800 LST 7 to 0800 LST 11 Jun	30.2°N, 105.4°E	E
15	2008	TVSPDV	0800 LST 20 to 0800 LST 23 Jul	34.7°N, 95.4°E	SE–NE
		TVSWV	2000 LST 20 to 0800 LST 23 Jul	28.5°N, 100.5°E	NE
16	2009	TVSPDV	0800 LST 3 to 0800 LST 5 Aug	32.8°N, 95.6°E	SE–SW
		TVSWV	2000 LST 3 to 2000 LST 5 Aug	26.6°N, 102.4°E	SE
17	2011	TVSPDV	0800 LST 16 to 2000 LST 18 Jun	35.1°N, 101.4°E	NE–SE
		TVSWV	2000 LST 16 to 2000 LST 18 Jun	29.0°N, 100.2°E	NE–SE
18	2011	TVSPDV	2000 LST 20 to 0800 LST 23 Jul	33°N, 101.3°E	E
		TVSWV	0800 LST 23 Jul	29°N, 102.0°E	L
19	2011	TVSPDV	2000 LST 30 Jul to 0800 LST 3 Aug.	35°N, 98.8°E	E
		TVSWV	0800 LST 31 Jul to 0800 LST 3 Aug.	28.8°N, 101.1°E	NE

(continued)

Number	Year	Vortex type	Dates	Origin	Path
20	2011	TVSPDV	0800 LST 3 to 2000 LST 5 Aug	32.8°N, 95.6°E	NE
		TVSWV	2000 LST 3 to 0800 LST 6 Aug	29°N, 100°E	NE
21	2013	TVSPDV	2000 LST 13 to 0800 LST 16 May	33.4°N, 95°E	SE
		TVSWV	0800 LST 14 to 0800 LST 15 May	30°N, 106°E	L
22	2013	TVSPDV	0800 LST 24 to 2000 LST 27 May	33.2°N, 94.2°E	NE
		TVSWV	0800 LST 23 to 2000 LST 27 May	29.4°N, 101.3°E	NE
23	2013	TVSPDV	2000 LST 4 to 0800 LST 10 Jun	34°N, 94.2°E	E
		TVSWV	0800 LST 5 to 2000 LST 10 Jun	29.3°N, 101.4°E	E
24	2013	TVSPDV	0800 LST 29 Jun to 0800 LST 2 Jul.	34.6°N, 95.6°E	SE
		TVSWV	0800 LST 30 Jun. to 0800 LST 2 Jul	30.3°N, 106.2°E	NE
25	2013	TVSPDV	0800 LST 4 to 2000 LST 7 Jul	32.1°N, 98.6°E	SE
		TVSWV	0800 LST T 5 to 0800 LST 7 Jul	30.6°N, 106.6°E	E

Note: E,S,SE,SW and NE mean eastward, southward, southeastward, southwestward and northeastward respectively. The dash between two letters, e.g., NE–SE signifies a veer. ”L” means less movement or dissipating *in situ*.

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