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A Fourteen-Year Climatology of the Southwest Vortex in Summer

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Abstract Statistical studies were conducted on the southwest vortex (SWV) during the summers of 2000–13 using high-resolution reanalysis data with a horizontal resolution of 0.5° × 0.5°. A total of 578 SWVs were detected, with a maximum interannual frequency of 55. The variation of the interannual frequency featured a period of around six years. The most active period of SWVs was early July and the maximum occurrence of SWVs appeared in early morning (0200–0800 Beijing Standard Time (BST)). Most of the SWVs were short-lived, with only 66 cases (11.4%) lasting for more than 24 h. In addition, the moving tracks and three-dimensional shape of long-lived ($\geqslant$ 36 h) SWVs are also presented. For those SWVs that lasted for more than 12 h, four types of SWVs (Types I–IV) were identified using a new method, and the results indicated that the dynamical and thermodynamical conditions before the formation of SWVs are effective indicators of the subsequent evolution of the vortex and associated severe weathers. Moreover, a further level of classification was also constructed for Type II SWVs, which accounted for the largest proportion out of Types I–IV, and the results indicated that the lifespan, radius and maximum 6-h precipitation were all closely related to the intensity of precipitation before the formation of SWVs.

Keywords: southwest vortex, severe weather, vertical stretching

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1 Introduction

The southwest vortex (SWV), which originates around the Sichuan Basin, east of the Tibetan Plateau, is one of the most frequent and severe mesoscale vortices influencing the Yangtze River Basin (Tao, 1980; Lu, 1986; Chen et al., 1998, 2003). It frequently causes torrential rainfall events and flash floods (Lu, 1986; Fu et al., 2011) that put people's lives and property under serious threat. The SWV is a type of meso-α system that can generally be detected in the lower troposphere (Lu, 1986; Chen and Lorenzo, 1984; Chen et al., 1998). After formation, most SWVs maintain a quasi-stationary position around the Sichuan Basin (Chen and Min, 2000; Chen et al., 2007; Yang et al., 2010); however, under intense steering flow, some can move out, influencing the middle and lower reaches of the Yangtze River Basin and even northern and southern China (Lu, 1986; Chen and Min, 2000; Liu et al., 2007; Chen et al., 2007; Yang et al., 2010; Fu et al., 2013).

SWVs have for a long time been the focus of many studies, mainly due to their important role in triggering weather disasters in China, especially in summer (Tao, 1980; Zhao et al., 2004). Previous studies have revealed SWVs' main sources, tracks, and activities (Chen and Min, 2000; Chen et al., 2007), dynamical and thermodynamical structures (Zhao, 1977; Chen et al., 1998; Zhao and Fu, 2007), environmental background circulation features (Lu, 1986; Huang and Xiao, 1989; Fu et al., 2013), and evolution mechanisms (Lu, 1986; Kuo et al., 1988; Fu et al., 2011; Fu et al., 2013), as well as their interactions with other systems (Chen et al., 2003; Fu et al., 2010). However, it should be noted that, most of these previous studies were case studies, which cannot reveal the universal features of the SWV. In addition, although there have been some climatological and statistic analyses of SWVs, these studies were mainly based on low-resolution (1° × 1° or 2.5° × 2.5°) reanalysis data and/or sparse station soundings, both of which are insufficient for the accurate detection of SWVs. Moreover, most of the previous statistic studies were confined to the period before the year 2005 (Chen et al., 2007; Zhan and He, 2008; Gao and Wang, 2009); thus, whether or not there are any new features of SWVs in the most recent decade is unknown.

Based on previous studies, the purpose of the present reported work was to analyze the activities of SWVs during the summers (June–August) of the period 2000–13 using high-resolution reanalysis data (horizontal resolution of 0.5° × 0.5°) from the National Centers for Environmental Prediction (NCEP), to classify SWVs with new dynamical and thermodynamical standards, and to compare the main features of each typical SWV type in detail. The data and methods used in the study are introduced in section 2. The main results are described in section 3, and a discussion is presented in section 4.

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2 Data and methodology

2.1 Data

Reanalysis data (four times a day) with a horizontal resolution of 0.5° × 0.5° (Saha et al., 2010) from the NCEP climate forecast system (CFS) were used for detecting and tracking the SWVs in this study. Twelve-hourly \soundings were used to validate the detected SWVs following the definition of Chen et al. (2007). Conventional surface observational data (eight times a day) were used in the classification of SWVs and these data were also used for analyzing the severe weathers associated with the SWVs.

2.2 Methodology

There are several available definitions of the SWV, and in this study the detection of SWVs relied upon the vorticity and stream field at 700 hPa in the area of (26–34°N, 103–110°E) (Fu et al., 2011). For each time step, if a closed circulation center coupled with a positive vorticity area was detected within the aforementioned area, the closed circulation was defined as an SWV. After detection of an SWV, the vertical stretching of the vortex was determined by examining continuous vertical levels that also possessed obvious cyclonic circulation features at a step of 50 hPa, and moreover, the vortex centers at neighboring levels were required to be less than 0.5° of longitude/ latitude.

James and Johnson (2010) used the precipitation and surface low center as standards for the classification of mesoscale vortices, and their results were proven to be very effective in clarifying the features of mesoscale convective vortices (MCVs). Therefore, this method was also utilized in the present study. Based on the three-hourly surface observational data, those SWVs with a lifespan of more than 12 h were classified into four types according to whether or not there was obvious precipitation (the thermodynamical standard) and/or a surface low center (the dynamical standard) within six hours before the initiation of the SWV. After the classification of SWVs, statistical analyses of maximum vertical stretching, maximum horizontal radius, precipitation, and severe weathers during the life cycles of SWVs were conducted, in order to reveal the different features of different types of SWVs.

3 Results

3.1 Frequency of SWVs and their lifespan

The reanalysis data used in this study had a temporal resolution of 6 h; therefore, compared with some previous studies that used a time step of 24 h or 12 h (Chen et al., 2007; Zhan and He, 2008; Gao et al., 2009), more SWVs were detected. During the summers of 2000–13, a total of 578 SWVs were detected (Fig. 1a), with a maximum of 55 appearing in 2001 and a minimum of 19 appearing in 2013. It was clear that the interannual frequency was descending gradually during the periods 2001–06 and 2007–13. It seems that the interannual frequency of SWVs varied with a period of about six years, a feature that can also be found in the results of Chen et al. (2007). The ten-day frequency of SWVs is shown in Fig. 1b, from which it

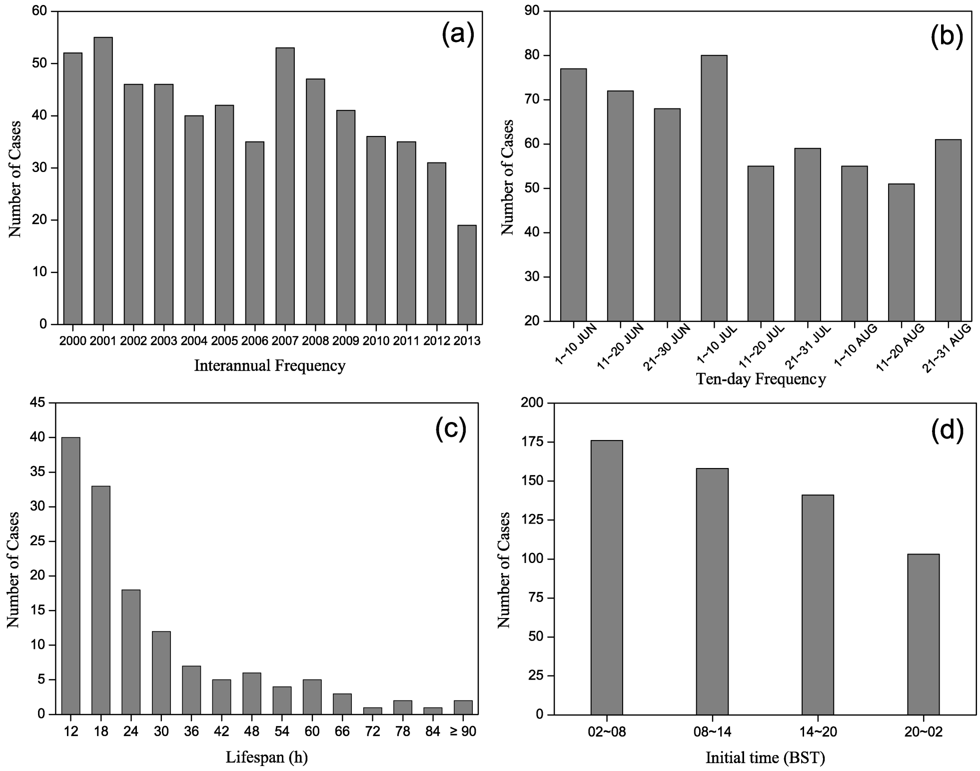

Figure 1 (a) The interannual frequency, (b) the ten-day frequency, (c) lifespan distribution, and (d) diurnal cycle of southwest vortex (SWV) initiation (Beijing Standard Time (BST)).

can be seen that, during early June to early July, the frequency was relatively higher than during other periods. The maximum ten-day frequency occurred in early July, including 80 cases, while the minimum frequency appeared in the middle of August containing only 51 cases.

In this study, there were 139 cases (24%) out of the 578 SWVs that lasted for more than 12 h (Fig. 1c), and only 66 cases (11.4%) that lasted for more than 24 h. There were five cases that lasted for more than three days, and the longest case appeared during the period 21 July to 27 July 2008, which coupled with an upper-level vortex and maintained for around 156 h.

Further insight into the variation of SWVs was obtained by examining the initial time with respect to the diurnal cycle. As shown in Fig. 1d, there was a strong prevalence of SWVs occurring in the early morning (0200–0800 Beijing Standard Time (BST)), and from day to night the occurrence of SWVs decreased gradually, with the minimum occurrence appearing in the evening (2000–0200 BST). It should be noted that this result is different from that of Chen and Min (2000), and the reason for the difference may be: (1) the horizontal resolution of the data in the present study was much higher than in the previous study, guaranteeing a more accurate detection of SWVs; and (2) short-lived SWVs with a lifespan of around 6 h were also taken into consideration in our statistical analysis, whereas Chen and Min (2000) detected SWVs using a dataset with a temporal resolution of only 24 h.

3.2 Classification of SWVs and their main features

Following James and Johnson (2010), SWVs with a lifespan of more than 12 h (total of 139 cases) were classified according to the thermodynamical and dynamical standards discussed in section 2.2 as follows: 'no precipitation-no surface low' (Type I); 'precipitation only' (Type II); 'surface low only' (Type III); 'precipitation and surface low' (Type IV). The results are illustrated in Table 1, from which it is clear that Type II accounted for the largest percentage, followed by Type IV, and the smallest percentage belonged to Type III. During the lifetime of SWVs, almost all Type II and IV cases triggered obvious precipitation, whereas for the other two types the probability of precipitation was less than 50%. The maximum probability of the occurrence of thunder belonged to Type IV SWVs (up to 84.1%), followed by Type II, while Type I had the smallest probability. Meanwhile, the probability of lightning occurrence was least in Type I SWVs, which were almost completely without lightning events. Therefore, precipitation and/or surface lows may provide favorable conditions for lightning events associated with SWVs. Type III and IV SWVs had almost the same probability of lightning occurrence, and the probability of Type II was slightly less than Types III and IV. Generally, the SWVs were stretched in the middle and lower troposphere (Table 1), and Type II and IV SWVs were thicker than the other two types. From the above analysis, it can be concluded that the dynamical and thermodynamical features associated with the SWVs before their formation were indeed vital for their later evolution. These statistical results may prove helpful in forecasting disastrous weathers associated with SWVs.

The lifespan, radius and precipitation of SWVs that lasted for more than 12 h are presented in Fig. 2. From Fig. 2a, we can see that Type IV SWVs generally had the longest lifetimes (mean lifespan of 30.7 h), although the longest case was a Type II SWV, which was coupled with an upper-level vortex and lasted for about 156 h. In addition, the lifetimes of Type I SWVs were shortest (mean lifespan of 20.3 h). Therefore, latent heat release associated with the precipitation before initiation of the SWVs made a great contribution to their maintenance, and the surface low was also favorable. From Fig. 2b, the radius of SWVs was largest in the Type II category (mean maximum radius of 245.5 km). Meanwhile, Type IV SWVs ranked second (mean maximum radius of 227.5 km), and Type III SWVs had the smallest radius (mean maximum radius of 143.6 km). From the above analysis, it can be concluded that there is no obvious relationship between an SWV's horizontal size and lifespan. Most of the 139 cases (88.5%) caused rainfall (Table 1). The maximum single-station 6-h accumulated precipitation during the lifetime of the SWVs is shown in Fig. 2c, which also illustrates that this parameter was largest in Type IV SWVs (mean value of 56.2 mm), followed by Type II SWVs, but was least in Type I SWVs (mean value of 5.5 mm). These results suggest that the initial conditions of precipitation and surface low center can be effective signs for the intensity of precipitation during the lifetime of an SWV.

As shown in Table 1, the Type II category accounted for more than half (51.1%) of the 139 SWVs. Moreover, this type was characterized by longevity, a large three-dimensional shape, heavy rainfall events, and a high probability of lightning and thunder occurrence. Therefore, in order to clarify the main features of this important type of SWV, a further level of classification was applied to the Type II category. Based on the intensity of precipitation

Table 1 Characteristics of SWV types.

SWV type	No.	Percentage	Probability of precipitation	Probability of thunderstorm	Probability of lightning	Average lowermost level (hPa)	Average uppermost level (hPa)
Type I	13	9.4%	46.2%	30.8%	0.0%	823	608
Type II	71	51.1%	97.2%	70.4%	22.5%	865	561
Type III	11	7.9%	45.5%	54.5%	27.3%	831	590
Type IV	44	33.7%	97.7%	84.1%	27.3%	874	570
All SWVs	139	100%	88.48%	72.93%	23.31%	861	569

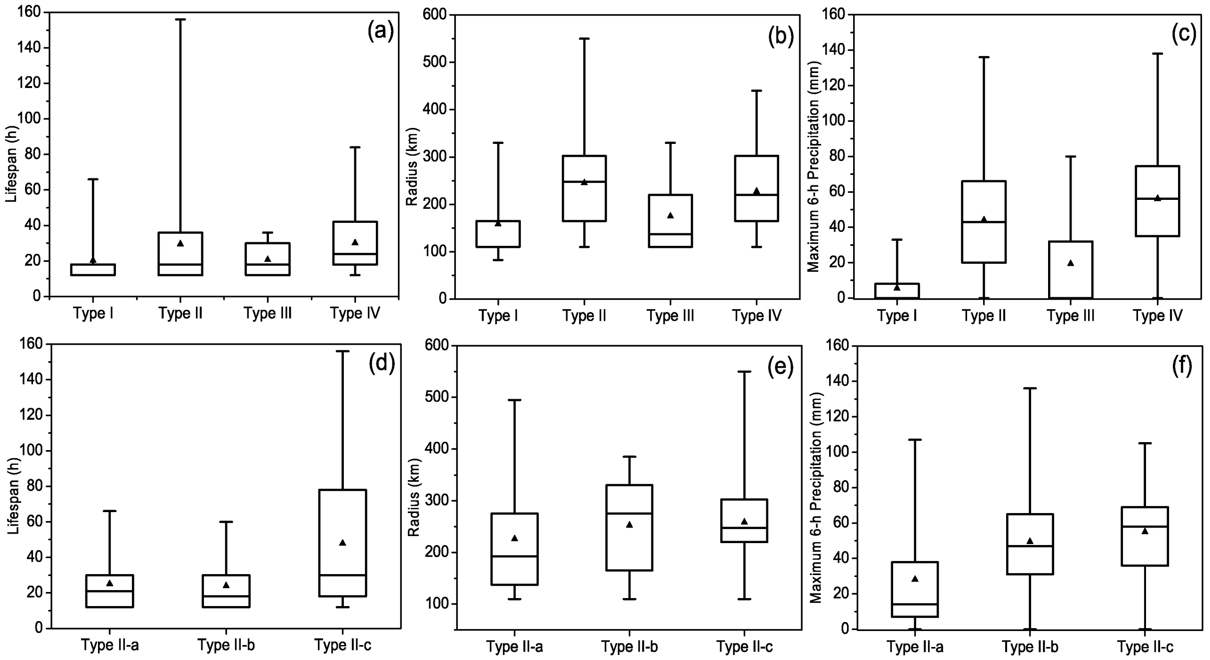

Figure 2 Upper row: Classification of SWVs that lasted for more than 12 h (averages are marked by triangles; maximums and minimums are marked by segments): (a) lifespan; (b) radius; (c) maximum 6-h precipitation. Lower row: Classification of type II SWVs based on the intensity of precipitation (0–20 mm, 20–50 mm, and ⩾ 50 mm) before the initiation of the SWV (averages are marked by triangles; maximums and minimums are marked by segments): (d) lifespan; (e) radius; (f) maximum 6-h precipitation.

before the formation of Type II SWVs, three subtypes of SWVs—Type II-a (0–20 mm), Type II-b (20–50 mm), and Type II-c (⩾ 50 mm)—were classified. From Fig. 2d, the average lifespans of the Type II-a and Type II-b subtypes were almost the same; whereas, Type II-c vortices spanned a much longer lifetime. Therefore, torrential rainfall above a threshold may be a favorable condition for the longevity of SWVs. The radius of Type II SWVs generally increased with precipitation before their initiation (Fig. 2e), since latent heat release is vital for the evolution of an SWV (Fu et al., 2010). The maximum 6-h precipitation during the lifetimes of the SWVs also increased with precipitation before their formation (Fig. 2f), because the background environmental circulations and moisture conditions were generally more favorable in Type II-c cases (not shown).

3.3 Moving tracks and three-dimensional shape of long-lived SWVs

As shown in Fig. 1c, SWVs with a lifetime above 36 h could be regarded as long-lived. For these long-lived SWVs, the moving tracks were investigated in detail. In the study period, there were a total of 30 cases that lasted for more than 36 h. Most of the vortices were quasi-stationary, and only nine of them (30%) moved out of the Sichuan Basin. Most of these moved-out vortices were along the northeastward track (44%), while those that moved along the southward and eastward tracks accounted for 30% and 22%, respectively.

This study also confirms that the SWV is a type of meso-α vortex (Fig. 2b), with a mean maximum radius of 245.5 km (Type II) and a mean minimum radius of 143.6 km (Type III). The mean maximum vertical stretching of SWVs was 304 hPa (Table 1), which applied to Type II and Type IV SWVs; while the minimum stretching of SWVs was 215 hPa (Type I). The central level of the SWVs studied here was around 700 hPa.

For those SWVs with a lifespan above 36 h, three typical stages were defined to show the variation in their average vertical stretching. The 'developing stage' was defined as the time average of the initiation time and 6 h later; the 'maintaining stage' was defined as the average of a continuous 12 h during the mid-life of the SWV; and the 'dissipating stage' was defined as the average of the dissipation time and 6 h before dissipation. The results indicated that, in the developing stage, the mean vertical stretching of the 30 long-lived SWVs was 850–650 hPa; in the maintaining stage, it was 850–575 hPa; and during the dissipating stage, it was 800–675 hPa. Therefore, the SWVs were mainly located in the middle and lower troposphere, their vertical stretching reached a maximum (275 hPa) during the maintaining stage, and was at a minimum in the dissipating stage (125 hPa).

4 Summary and conclusions

Based on NCEP CFS reanalysis data with a horizontal resolution of 0.5° × 0.5°, statistical analyses were applied to SWVs that occurred during the summers of 2000–13. The main results can be summarized as follows:

A total of 578 SWVs were detected during the summers of 2000–13, and the maximum interannual frequency was 55. SWVs were very active during early June to early July, and the most active period was early July. There was a strong prevalence of SWVs occurring in the early morning (0200–0800 BST), and the occurrence of

SWVs reached a minimum in the evening (2000–0200 BST). Most SWVs were short-lived, and there were 66 cases (11.4%) that lasted for more than 24 h. In addition, for the long-lived SWVs (⩾ 36 h), most of the vortices were quasi-stationary, and their vertical stretching reached a maximum (275 hPa) during the maintaining stage and a minimum in the dissipating stage (125 hPa).

The dynamical and thermodynamical conditions before the formation of SWVs are effective signs of their subsequent evolution, as well as the development of their associated severe weathers. Therefore, this statistical study is helpful to those involved in the forecasting of disastrous weather events associated with SWVs. Moreover, a further level of classification was made to the Type II SWVs, and the results indicated that the lifespan, radius and maximum 6-h precipitation were all closely related to the intensity of precipitation before the formation of SWVs.

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