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On the Dynamics of the Large-scale Circulation
during the Persistent Severe Rainfall Events in
Southern China

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ABSTRACT

Persistent severe rainfall (PSR) events during the rainy season (April to July) in southern China were studied in terms of the dynamical features of the large-scale circulation. The aim was to understand the formation mechanism and improve forecasting. The circulation field and spatiotemporal distribution of waves at 500hPa, for different types of PSR were analysed. The results reveal the following: (1) During the pre-flood season (April to June) in South China, troughs have the same phase in the middle latitudes as those in the high latitudes. The East Asia major trough (3–5 wave numbers) in the middle latitudes strengthens southwards and interacts with the 30°N subtropical high (1–2 wave numbers) from 3 days prior to the PSR events. (2) During the post-flood season (June to July) in South China, the weather regime transitions occur on 5 days prior to the PSR events. The 40°N trough (2–4 wave numbers) strengthens southwards and interacts with the subtropical high (1–2 wave numbers). It is also affected by the blocking ridge (3 wave number) in the high latitudes. (3) During the Mei-yu period (June to July) over the Yangtze–Huaihe River basin, the transitions of circulation pattern starts on 3 days prior to the PSR events. With the northwest development of the subtropical high, there is a transfer process from long to short waves in terms of energy for the trough at 50°N.

Key words: southern China, persistent severe rainfall, large-scale circulation

1 Introduction

China is located in the East Asian monsoon region, and the occurrence of the
East Asian summer monsoon heralds the arrival of the rainy season (April to September) in China. Persistent severe rainfall (PSR) events are the distinguishing features of the rainy season, causing prolonged flooding every year. In the last 60 years, regional-scale PSR has been occurring with an increased frequency of relatively higher mean intensity, longer mean duration, and a larger affected area, posing considerable threats to people’s safety and their property (Chen and Zhai, 2013). As such, an in-depth study of the formation mechanisms of PSR events would be of great importance, as it may help to improve the forecasting of such high-impact weather.

PSR usually refers to torrential rain with long duration and a large affected area. Also, in general, the water vapour and thermal dynamic conditions of PSR, produced in the context of the weather system, will be abnormal and show less movement (Ding and Reiter 1982; Samel and Liang 2003; Piaget et al. 2015). The amount of precipitation and rainfall duration are associated with continuous anomalies of the atmospheric circulation which favour the continuous confluence of dry/cold and moist/warm air (Qian et al. 2007; Zhou et al. 2009), such as the western Pacific subtropical high, summer monsoon, South Asia high, blocking high, and so on (Berggren et al. 1949; Galarneau et al. 2012; Tao et al. 2004; Li et al. 2004; Zhu et al. 2010; Wang et al. 2011; Wang and Song 1998; Tomassini et al. 2015; He et al. 2016). Therefore, understanding the changes and anomalies of the atmospheric circulation is key for better forecasting of PSR events.

In recent years, much research has been carried out on waves of different scale in
atmospheric circulation. For example: wave interaction between different latitudes and the spectral properties of the 500 hPa geopotential height of the Northern Hemisphere (Blackmon 1976; Hannu 1984); spatiotemporal spectral analyses of tropical convection and planetary-scale waves (Wheeler and Hendon, 2008); analysis of multiscale weather systems in a snow storm event over southern China in January 2008 (Wang et al. 2009; Sun and Zhao 2010); the geographical distribution and regional persistence characteristics of persistent wintertime circulation anomalies in the extratropical Northern Hemisphere (Dole and Gordon 1983); and Rossby wave propagation and its influence on weather regime transitions (Hoskins and Ambrizzi 1993; Michel and Rivière 2011). However, few studies have examined the circulation system characteristics of PSR. In view of the fact that previous studies have indicated that the adjustment of large-scale waves before weather regime transitions, and an abnormally stable development of the large-scale circulation during persistent weather anomalies, have important effects on PSR (Zhai et al. 2013), the role of different scales of circulation for PSR in different planetary-scale systems also indirectly impacts upon rainstorm generation by restricting the synoptic-scale system. In addition, it determines the extent of precipitation, the sources of moisture, and the moisture channel of the severe rain area (Ding 2005; Chow et al. 2008). Therefore, studying the spectral characteristics of the PSR circulation system carries significance, and will undoubtedly help by providing a reference for the development of numerical prediction methods for PSR.

Based on reanalysis and observational data, 27 PSR events that occurred during
2000–2013 were selected for analysis of the associated circulation characteristics. The spatiotemporal distributions of waves for the different types of PSR were then explored. The aim was to produce an in-depth study of the formation mechanisms of PSR events, and thus provide a useful reference for the development of numerical prediction methods and their application to PSR.

2 Methodology

The rainy season in southern China includes torrential rain in the pre-flood and post-flood seasons in the South China region, and Mei-yu front rainstorms over the Yangtze–Huaihe River basin (Bao 2007). The timings of the different PSR types differ in accordance with the movement and changes of the western Pacific subtropical high, summer monsoon, South Asia high over the Tibetan Plateau, and the subtropical westerly jet. The study region and timings of the different PSR types are shown in Fig. 1.

The main data used in this study were: (1) The precipitation dataset of national surface weather stations in China, provided by the National Meteorological Information Center. The data covered the period from May 2000 through August 2013, and comprised basic meteorological variables on a daily basis. (2) The NCEP FNL (Final) Operational Global Analysis data (horizontal resolution: 1°×1°; temporal resolution: 6 hours), mainly at the geopotential height (gpm) of 500 hPa, from 2000 to 2013, April to September. The isobaric level of 500 hPa had been chosen in this study based on two considerations: First, the most prominent difference between different
persistent severe rainfall (PSR) cases in China lies in the long-lived circulation pattern at 500 hPa (Chen and Zhai, 2014). And second, fields of 500 hPa heights were constrained by observations from numerous radiosondes and satellite retrievals, they were relatively free from surface effects, and they captured upper-level wave patterns (Francis and Vavrus, 2012).

2.1 Harmonic filtering

Scale separation of the spatial field was carried out in order to study the role of the different scales of circulation. Harmonic filtering was selected from the many methods of scale separation available (Chen 1962; Huang 2004), in which the meteorological field is decomposed into a harmonic over the hemisphere or a certain latitude band, before discussing the contribution and role of each harmonic. The first step is to expand the zonal height field \( z(\lambda, \varphi) \) of the isobaric surface into harmonic forms. This can be achieved using the equation

\[
z(\lambda, \varphi) = \frac{1}{2} a_0(\varphi) + \sum_{k=1}^{\infty} \left[ a_k(\varphi) \cos k \lambda + b_k(\varphi) \sin k \lambda \right],
\]

(1)

where \( \lambda \) is the longitude, \( \varphi \) is the latitude, \( k \) is the wave number, and the zero wave is the fundamental wave. \( a_k \) and \( b_k \) are the Fourier coefficients, which can be denoted in the summation form

\[
a_k(\varphi) = \frac{2}{n_x} \sum_{x=1}^{n_x} z(\lambda, \varphi) \cos k \lambda
\]

(2)

and

\[
b_k(\varphi) = \frac{2}{n_x} \sum_{x=1}^{n_x} z(\lambda, \varphi) \sin k \lambda
\]

(3)
where $n_x$ is the number of the zonal grid.

### 2.2 Variance ratio

The variance ratio $I_k(\phi)$ represents the percentage of the $k$ wave accounting for the latitude circle variance $\sigma$, and a wave with relatively large variance corresponds to the predominant wave band at that latitude. The formula is as follows:

$$I_k(\phi) = \frac{A_k^2(\phi)}{2\sigma^2(\phi)} \times 100\%.$$  \hspace{1cm} (4)

The amplitude of the $k$ wave can be represented as

$$|A_k(\phi)| = \left( a_k^2(\phi) + b_k^2(\phi) \right)^{\frac{1}{2}},$$  \hspace{1cm} (5)

and the variance of the geopotential height on the latitude $\phi$ can be written as

$$\sigma^2(\phi) = \frac{1}{n_x} \sum_{x=1}^{n_x} \left[ z(\lambda, \phi) - \frac{1}{2} a_0(\phi) \right]^2,$$  \hspace{1cm} (6)

where $\frac{1}{2} a_0(\phi)$ is the zonal mean value of geopotential height, also called the zero wave.

### 3 Circulation characteristics of PSR

#### 3.1 PSR case selection

Based on the definition of PSR in previous studies (Chen and Zhai 2013; Tao 1980; Bao 2007; Niu et al. 2012), regional PSR events were defined in this study using the following procedure: After interpolating the rainfall to a grid with a resolution of $0.25^\circ$ (latitude) $\times$ $0.25^\circ$ (longitude), an event was identified as PSR if 10 continuous grid points in the selected area ($21^\circ$–$35^\circ$N, $105^\circ$–$122^\circ$E) featured rainfall
of greater than 50 mm, and the duration was more than 3 days. Also, if the amount of overlap between the rainfall area of two adjacent days with daily precipitation greater than 25 mm was greater than or equal to 20% on at least three consecutive days, and the total precipitation was greater than 100 mm.

According to the above procedure, 27 PSR events were identified as having occurred during the period 2000–2013, and were used in this study (Table 1), which is the case study and not focused on the all PSR events since the history recorded. Also, using the precipitation range to distinguish between precipitation over the regions of South China and the Yangtze–Huaihe River basin, the 27 events were classified into three categories, according to the timing of occurrence relative to the flood season, for detailed analysis: (1) the pre-flood season in South China (6 cases); (2) the post-flood season in South China (12 cases); and (3) the Mei-yu period over the Yangtze–Huaihe River basin (9 cases).

Figure 2 shows the mean spatial distribution of the 27 PSR events by category. As can be seen, the pre-flood season (Fig. 2a) and post-flood season (Fig. 2b) in South China have a similar spatial distribution. For instance, the severe rainfall over 50 mm is mainly located in Hunan, Jiangxi, Fujian, Guangxi and Guangdong provinces, south of the Yangtze River, with greater precipitation in northern Fujian, and the precipitation distribution range of the post-flood season is slightly larger than that of the pre-flood season in South China. The PSR events in the Mei-yu period over the Yangtze–Huaihe River basin shows an zonal distribution (Fig. 2c), mainly located over areas north of the Yangtze River, such as Jiangsu, Anhui, Henan and Hubei, with
the precipitation over 100 mm mainly in northern Jiangsu and Anhui, and southern
Henan.

3.2 Large-scale circulation patterns

The composite circulation field evolution at 500 hPa prior to and during different
types of PSR was analysed (figures omitted), and then the typical circulation fields of
particular days were selected (Fig. 3). For the pre-flood season in South China (Figs.
3a1–a4), the circulation in the middle latitudes exhibits a ‘two troughs and one ridge’
pattern, with a small trough in the high latitudes beginning to move eastwards from
−5th day prior to the PSR events (Fig. 3a1). Its phase overlaps with the East Asia
major trough, causing the East Asia major trough to strengthen southwards to South
China from −3rd day (Fig. 3a2). Meanwhile, the subtropical high continuously
extends westwards and maintains stably after extending to South China, interacting
with the trough to steer cold/dry air from the mid–high latitudes and encounter
anomalously warm/moist air from the lower latitudes (Lau and Kim 2012). During the
PSR, the high-pressure ridge in the middle latitudes retains its stability, which is
conducive to the development and maintenance of a meridional circulation which
promotes southward intrusions of cold/dry air (Ding and Chan 2005).

For the post-flood season in South China (Figs. 3b1–b4), the circulation in the
high latitudes of the East Asia region is different to that during pre-flood season PSR
events. Specifically, it exhibits a ‘two ridges and one trough’ pattern, in which the
trough moves constantly to the southeast, and then strengthens southwards after
moving to northeastern China (Fig. 3b1). The direction of the trough line is northeast–southwest. During the PSR, the circulation pattern in the middle latitudes is the same as that in the pre-flood season, and South China is located at the entrance of the confluence between the southwest airflow before the westerly trough and the southeast airflow from the northwest side of the subtropical high, which is the air stream and water vapour convergence zone. The north of the trough causing the PSR over South China is a high-pressure ridge, and this kind of long-lived circulation system interaction is conducive to stable maintenance of the trough.

Figures 3c1–c4 show the composites of circulation at 500 hPa for the Mei-yu period over the Yangtze–Huaihe River basin. Again, a ‘two troughs and one ridge’ circulation pattern is apparent in the middle latitudes, which begins to strengthen on −3rd day (Fig. 3c2), with a westward and northward extension of the subtropical high in the low latitudes, and interaction with the trough in the westerlies. The circulation fields of the nine Yangtze–Huaihe River basin cases were analysed (figures omitted), with the results showing that there are two main troughs forming during PSR events: one resulting from the steady subtropical high, in which it remains stable or the direction of the trough line changes from northwest–southeast to northeast–southwest only; and another in which two adjacent troughs in the westerly zone develop successively and interact with the subtropical high so as to favour the water vapour transport that is associated with the southerly flow from the South China Sea and the southeasterly flow from the southern flank of the subtropical high (Zhou and Yu 2005; Chow et al. 2008; Simmonds et al. 1999; Wang and Chen 2012).
As mentioned above, the circulation patterns of the selected PSR events in the middle latitudes are mostly of the ‘two troughs and one ridge’ type, and the formation and maintenance of PSR are related to the development of the trough in the middle to high latitudes and the shift of the subtropical high. The development of the middle latitudes trough in the pre-flood season and post-flood season in South China is affected by the circulation pattern in the high latitudes. The troughs in the middle and high latitudes have the same phases, which causes the East Asia major trough to strengthen southwards in the pre-flood season in South China. On the other hand, the key trough of the post-flood season in South China develops after the deepening and southward shift of the middle latitudes trough. For the PSR events of the Mei-yu period over the Yangtze–Huaihe River basin, the trough comes mainly from the eastward-moving westerly disturbance. The subtropical high mainly shows westward extension during PSR events in South China, and a northern lifting and then stable maintenance in the Mei-yu period over the Yangtze–Huaihe River basin. These weather regime transitions occur mainly on –5th and –3rd day. The above analysis shows that the long-lived pattern at 500 hPa continuously steers cold/dry air from the mid–high latitudes and encounters warm/moist air from the lower latitudes. On the other hand, Chen and Zhai (2014) indicated that the displacement of the South Asian High and the jets result in robust divergences of the circulation patterns in the upper troposphere (200 hPa), combining persistent anomalies from lower to upper levels to cause the PSR. The wave characteristics of the circulation system evolution will be analysed in the next section.
4 Large-scale atmospheric wave activity

The variance ratio over different latitudes and wavelength ranges at 500 hPa during PSR was analyzed (Fig. 4). Since the variance ratios of the cumulative waves from 1 to 8 reach 90% in all of the different latitudes, the 1–8 wave band is mainly addressed in this paper.

4.1 Pre-flood season in South China

Figure 5a shows the latitude–time distribution of the cumulative waves from 1 to 8 for PSR events in the pre-flood season in South China. There is an obvious high-pressure system in the high latitudes, and the areas south of 30°N are dominated by a weak low pressure system. The development of the subtropical high in the low latitudes begins on −3rd day, and the trough develops in the range 45°–60°N. The trough in the high latitudes (70°N) moves eastwards and develops during the early stage of PSR, and the troughs in the middle and high latitudes have the same phases, which causes the East Asia major trough to strengthen southwards.

Figure 5b shows the longitude–time distribution characteristics. It can be seen that the subtropical high moves to the South China area (near 115°E) and then strengthens from −3rd day, which is the same as in the analysis shown in Fig. 5a. After the precipitation begins, the trough appears to strengthen from east of 125°E, and then extends westwards to South China, which is shown as a northeast–southwest transverse trough in the circulation situation.

Combined with the circulation pattern analysis in Fig. 3, the distribution of the
waves is the same as the ‘two troughs and one ridge’ circulation pattern in the middle latitudes, with coinciding phases of the troughs in the middle and high latitudes. The high latitudes area (near 60°N) is mainly composed of a stable ridge system before a PSR event. On the other hand, the East Asia major trough, which is located ahead of the ridge, strengthens southwards, and the subtropical high in the low latitudes starts to move to South China and enhances on −3rd day. During PSR, the trough in the high latitudes begins moving eastwards and its phase overlaps with the East Asia major trough, which is generally characterized by a transverse trough. Meanwhile, the East Asia major trough strengthens southwards to South China and interacts with the subtropical high to induce PSR.

Next, based on the above analysis, the main wave and energy transfer characteristics of the circulation system were further analysed. Figure 6 shows the composites of different wavelength height field changes over time at 50°N, 40°N and 30°N. The major system of influence at 50°N is the shortwave trough with mainly 4–6 waves, and the transfer of energy is from 4 and 6 waves to 5 waves. The East Asia major trough in the middle and low latitudes is the important weather system (blue low-value area at 40°N and 30°N), which is contributed to mainly by 3 and 5 waves with the low-value energy transmitted from the ultralong waveband (2 waves and below). The subtropical high is contributed to by 1–2 waves.

4.2 Post-flood season in South China

The latitude–time distributions of the cumulative waves from 1 to 8 of the 12
PSR events in the post-flood season in South China were analysed (Fig. 7a). As can be seen, the subtropical high develops south of 35°N from −5th day, with the low-pressure system occurring in the range 35°N–50°N. The juncture between the high and low pressure system continues to move south from −5th day and reaches South China (near 25°N) when the precipitation process begins. Unlike the PSR events in the pre-flood season, the high-pressure system develops strongly in the range 40°N–50°N and shifts southwards during the precipitation process. The precipitation ends with a continuous diminishing of the trough and subtropical high in the low latitudes.

The longitude–time distribution characteristics are shown in Fig. 7b. A large difference compared with the PSR events in the pre-flood season is apparent. The subtropical high begins to develop from −5th day and gradually withdraws from South China because of the development of the trough in that region. The juncture between the trough and subtropical high shifts from 130°E towards the west.

The weather regime transitions mainly occur on −5th day, which is different from −3rd day in the pre-flood season PSR events, with the subtropical high in the low latitudes and the trough in the middle latitudes moving southwards to South China. South China is located at the entrance of the airflow confluence at the juncture between the trough and subtropical high, which facilitates the occurrence of PSR.

The overall distribution of the waves reflects the circulation characteristics in the post-flood season in South China, as shown in Fig. 8, which covers the main waves (1–8 waves). At 50°N, the high value of 3-wave energy increases from the start of
precipitation, and 6-wave energy changes from a low system to a strong high-value system, which is the blocking ridge in the high latitudes. The trough at 40°N and the subtropical high at 30°N are respectively attributed to the contribution of 2–4 and 1–2 waves before the PSR, and the transfer of the low-value energy at 40°N is shown from 3 waves to 2 waves, and 4 waves. During the PSR process, the blocking ridge in the high latitudes has high-value energy transmitted from 6 waves to 5 waves, as well as 3 waves to 1 wave.

4.3 Mei-yu period over the Yangtze–Huaihe River basin

For the Mei-yu period over the Yangtze–Huaihe River basin, the trough develops in the range 30°N–50°N from −5th day (Fig. 9a). It can be seen from Fig. 3 that the ridge and subtropical high, which are respectively located along the northwest and southeast edge of the trough, strengthen, causing the trough to deepen continuously and shift into the Jianghuai area, thus forming an interface with the subtropical high that provides adequate moisture conditions for precipitation. Meanwhile, the subtropical high expands continuously to the north and the PSR is preserved.

Figure 9b shows the composite of the longitude–time distribution over 20°N–30°N, in which the subtropical high starts to develop towards the west and then extends to the north. This is the largest difference from the South China events; its interface with the trough on the north side extends to west of 120°E and promotes the transport and accumulation of water vapour in the Yangtze–Huaihe River basin. It can be seen that the trough in the middle latitudes begins to develop southwest from −3rd
day, which is influenced by the northwest high pressure system, and interacts with the subtropical high, providing favourable moisture conditions for severe rainfall.

In addition, changes in the height field of the different wavelengths with time show the main waves and energy transfer characteristics of the critical systems (Fig. 10). The trough at 50°N is mainly contributed to by 2–4 waves, and the low-value energy is transmitted from 2 waves to 4 waves. The subtropical high is contributed to by 5–6 waves and 2 waves at 30°N and 40°N, which is shorter than the wavelength in the South China PSR events. With the northwest development of the subtropical high, there is an energy transfer from 5 to 6 waves at 30°N and from 6 to 5 waves at 40°N.

5 Conclusion

PSR is a highly disruptive and damaging weather phenomenon. The ability to accurately forecast its occurrence is of paramount importance. To this end, an in-depth analysis of the formation mechanisms of PSR events was undertaken in the present study. Twenty-seven PSR events were selected and classified for the period 2000–2013 using reanalysis and surface weather station precipitation data. Based on these data, the circulation field and spatiotemporal distribution of waves at 500 hPa, for different types of PSR were analysed. The conclusions of the analysis can be summarised as follows:

(1) For PSR events in the pre-flood season in South China, the circulation in the middle latitudes exhibits a ‘two troughs and one ridge’ pattern, with the troughs possessing the same phase in the middle latitudes as they do in the high latitudes.
The East Asia major trough in the middle latitudes starts to develop from −3rd day prior to the event, and its phase overlaps with that in the high latitude trough, promoting a southward strengthening of the East Asian trough (3–5 waves). Furthermore, it interacts with the subtropical high (1–2 waves), which extends west to South China on −3rd day.

(2) The circulation in the high latitudes during the post-flood season in South China also exhibits a ‘two troughs and one ridge’ pattern in the middle latitudes. However, in the high latitudes, it exhibits a ‘two ridges and one trough’ pattern, which is different from PSR events in the pre-flood season. The weather regime transitions mainly occur on −5th day prior to PSR events, and the trough (2–4 waves) at 40°N strengthens southwards and interacts with the subtropical high at 30°N, contributed to mainly by 1–2 waves. Accordingly, South China is located at the entrance to the airflow confluence at the juncture between the trough and the subtropical high. Furthermore, the blocking ridge (3 waves) at 50°N strengthens southwards and promotes southward intrusions of cold/dry air.

(3) The weather regime transitions of the circulation pattern in the Mei-yu period over the Yangtze–Huaihe River basin start on −3rd day. There is a transfer process from long-wave to short-wave trough energy at 50°N. The subtropical high (2 waves) in the low latitudes has a constant westward and northward extension, and interacts with the southwest deepened trough at 50°N so as to steer cold and dry air from the mid–high latitudes and encounter warm and moist air from the lower latitudes.
To summarise, the dynamical features of the large-scale circulation during PSR events in southern China were analysed in this study. Further work should focus on the evolution characteristics and mutual effects of the multi-scale waves at various heights, such as the upper-tropospheric westerly jet, lower-tropospheric moisture flux, as well as the strong local convection activity and so on (Wang et al. 2000; Chen and Zhai 2013; Li et al. 2015), to enable an in-depth understanding of the formation mechanisms of PSR events, which would be beneficial in improving forecasting ability. Additionally, long-term statistical studies are needed for PSR events over different regions of Asia. In this context, the present study helps to enhance the validation period of PSR events, and, as a result, subsequent research can make full use of the results of the spectral analysis to explore methods for improving the numerical prediction of PSR (Zhao et al. 2016).

Acknowledgments

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References

Bao, M., 2007: The statistical analysis of the persistent heavy rain in the last 50 years over China and their backgrounds on the large scale circulation. *Chinese Journal of*


Ding, Y. H., 2005: *Advanced synoptic meteorology*. China Meteorological Press:
Beijing, 423-572.


Table 1. Temporal distribution and precipitation classification of PSR events during the flood period (April to July) in southern China.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Year</th>
<th>Start date</th>
<th>End date</th>
<th>Duration (days)</th>
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<td>June 9</td>
<td>June 12</td>
<td>4</td>
</tr>
<tr>
<td>in South China</td>
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<tr>
<td></td>
<td>2011</td>
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<td></td>
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<td>May 19</td>
<td>May 21</td>
<td>3</td>
</tr>
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<td>July 21</td>
<td>5</td>
</tr>
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Fig. 1. Map of the study region, with the terrain shaded and the time periods for the different PSR types indicated.
Fig. 2. Average spatial distribution of PSR events in the (a) pre-flood season in South China, (b) post-flood season in South China, and (c) Mei-yu period over the
Fig. 3. Composites of the averaged daily circulation field at 500 hPa on (a1–c1) −5th day, (a2–c2) −3rd day, (a3–c3) the start day, and (a4–c4) 3rd day, of PSR events in the (a1–a4) pre-flood season in South China, (b1–b4) post-flood season in South China, and (c1–c4) Mei-yu period over the Yangtze–Huaihe River basin.
Fig. 4. Variance ratio of the cumulative waves at different latitudes (30°N, 40°N, 50°N, 60°N and 70°N) at 500 hPa during PSR events.
Fig. 5. Standardisation composite of the cumulative waves from 1 to 8 in the 500 hPa circulation field of PSR events in the pre-flood season in South China: (a) latitude–time distribution of the zonal average over 95°–145°E; (b) longitude–time
distribution of the meridional average over 10°–40°N. The black solid indicates the start date of PSR; red arrows reflect the variation tendency of the low-pressure systems; and black arrows reflect the variation tendency of the high-pressure systems.

Fig. 6. Standardisation composite of the different wavelength waves (1–8 waves) in the 500 hPa circulation field of PSR events in the pre-flood season in South China for the zonal average over 95°–145°E at (a) 50°N, (b) 40°N, and (c) 30°N. The blue dotted line indicates the start date of PSR; red arrows reflect the variation tendency of the low-pressure systems; and black arrows reflect the variation tendency of the high-pressure systems.
Fig. 7. As in Fig. 5 but for the post-flood season in South China.
Fig. 8. As in Fig. 6 but for the post-flood season in South China.
Fig. 9. As in Fig. 5 but for the Mei-yu period over the Yangtze–Huaihe River basin, with the longitude–time distribution meridionally averaged over 20°–30°N in (b).
Fig. 10. As in Fig. 6 but for the Mei-yu period over the Yangtze–Huaihe River basin.