1. Introduction

Spring persistent rainfall (SPR), a unique phenomenon in East Asia, frequently occurred over southern China during the thirteen–twenty-seventh pentad (SPR period) with a maximum rainfall center along the mountainous regions (Wan and Wu 2008). Tian and Yasunari (1998) have introduced the concept of SPR from the perspective of climatology first. Wan and Wu (2006) further revealed the features of the SPR and discussed possible factors (i.e., the mechanical and thermal effects of the Tibetan Plateau). During the SPR period, both rainfall frequency and rainfall amount
account for nearly 30% of the annual total frequency and amount over southern China (Fig. 1). Since southern China is densely populated and is an essential economic agricultural region of China, anomalous rainfall in spring has great impact on the economy and people’s lives (e.g., Chen et al. 2014). Thus, it is necessary to understand the variations of SPR and its causes.

Previous studies have suggested a strong linkage between the spring rainfall over southern China and the East Asian subtropical jet (EASJ) (e.g., Lu et al. 2013). For example, Wen et al. (2007) emphasized the contribution of the zonal momentum advection of the EASJ to the vertical circulation over southern China. The variation of the EASJ intensity and the spring rainfall over southern China has been linked by the circulations over the North Pacific (Wang et al. 2002). By numerical simulations, as the EASJ weakened, the total amount of the spring rainfall over southern China decreased and the duration of the spring rainfall events shortened (Deng et al. 2014). In the case of the persistent severe drought in the southern China during January–May 2011, which is associated with the variation of the EASJ and the East Asian trough, a dry flow invaded from the Siberia, which may provide the precursory signals for the drought (Sun and Yang 2012). Additionally, the location of the EASJ is also important. For example, displacement of the EASJ influences the vertical flow over southern China via the secondary circulation around the entrance region of the EASJ (Wang et al. 2011). The northward shift of the EASJ may lead to abundant spring rainfall over southern China, which is associated with the enhanced water vapor transportation (Zhang et al. 2009; Li and Zhang 2013).

In fact, there are two jet streams in the upper troposphere over East Asia: one is the EASJ and the other is the East Asian polar front jet (EAPJ). In spring, the two jets are zonally located along the southern and northern sides of the Tibetan Plateau (TP), respectively (e.g., Sheng 1986; Zou et al. 1990; Hudson 2012). The impact of the EASJ on the spring rainfall over southern China was widely emphasized, while less attention has been paid to the EAPJ. Shao and Zhang (2012) indicated that, associated with the positive (negative) phase of the North Atlantic Oscillation (NAO) in the previous winter, the EASJ strengthened (weakened) and the EAPJ weakened (strengthened) in the following spring; consequently, the spring rainfall over southern China may increase (decrease). It reminds us that we should not ignore the effect of the EAPJ. Recently, many studies highlighted the importance of the concurrent variation of the EASJ and EAPJ (Liao and Zhang 2013; Li and Zhang 2014; Huang et al. 2014; Wang and Zhang 2015; Zhu et al. 2015). Most studies mentioned that the intensity variations of the EASJ and EAPJ may link to the warm- and cold-air activities (Zhang and Zhang 2013; Li and Zhang 2014). Under the interaction between the warm- and cold-air activities, the concurrent variation between the EASJ and EAPJ may lead to unique weather or climate different from the individual variations, for example, the severe snow and ice storms during the 2007/08 winter over central and southern China (Liao and Zhang 2013), the dipole summer rainfall anomaly over eastern China (Huang et al. 2014; Zhu et al. 2015), and typical mei-yu variations (Li and Zhang 2014). In spring, a link is found between anomalous rainfall over southern China and the intensity of warm wet air from tropical oceans and cold dry air from middle-to-high latitudes (Pan et al. 2013), which may induce convergence or divergence of water vapor over southern China (Chen et al. 2014). Since the warm- and cold-air activities may be related to the EASJ and EAPJ, the concurrent effect of the EASJ and EAPJ is
also important. Thus, it is necessary to analyze both the individual and concurrent impact of the EASJ and EAPJ on the variation of SPR.

In general, associated with warm- and cold-air activities, convergences and ascending motions with abundant water vapor may lead to more precipitation in both intensity and frequency. However, less attention has been paid to rainfall frequency. Even though some studies investigated the frequency, they were mostly focused on heavy rainfall, which may cause great loss (e.g., Zhai et al. 2005; Liu et al. 2008; Li and Zhai 2009; Qiao et al. 2010; Huang et al. 2011). Actually, one of the significant features of SPR is persistence (e.g., Wan and Wu 2008; Zhang et al. 2013). Since spring is the main seeding and planting season in southern China, a persistent rainfall anomaly may bring severe damage to agriculture. For example, excessive rainfall days would suppress downward solar radiation and reduce surface temperature (Wu and Peng 1996), while the deficient rainfall days would lead to droughts. Specifically, southern China has frequently suffered from persistent drought in recent years (e.g., Xin et al. 2006; Feng et al. 2014), for example, the extremely severe and persistent drought in spring 2011 (e.g., Sun and Yang 2012; Jin et al. 2013). These persistent droughts may be closely related to the nonrainfall days. Thus, more attention should be paid to the variations of rainfall frequency over southern China during the SPR period (SPR frequency), particularly in recent years.

Specifically, we try to answer the following questions in this study:
1) What are the features of SPR frequency, particularly in recent years?
2) What is the role of the EASJ and EAPJ playing in the recent variation of SPR frequency?

The rest of the paper is organized as follows. Section 2 introduces the datasets and methods. The features of SPR frequency in recent years are investigated in section 3. The individual and concurrent effects of the EASJ and EAPJ on SPR frequency are investigated in section 4 and section 5, respectively. Section 6 discusses the possible mechanism maintaining the strong EASI–weak EAPJ configuration. The conclusions are provided in section 7.

2. Data and methods

a. Data

The datasets used in this study include the following products that cover the period of 1960–2011:

1) Daily precipitation over the mainland China observed at 765 stations. The dataset is provided by the National Climate Center of China, China Meteorological Administration (Wu and Gao 2013; Kuang et al. 2014);
2) Daily and monthly atmospheric data extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis Project, including variables of specific humidity, zonal winds, meridional winds, vertical pressure vorticity, temperature, and sea level pressure, with a horizontal resolution of 2.5° latitude × 2.5° longitude (Kalnay et al. 1996).

b. Methods

A jet core is identified if 1) the horizontal wind speed at 300 hPa is higher than 30 m s⁻¹, which has been calculated for each day and at each grid point; and 2) the wind speed at the central point is larger than that at its eight surrounding points (Ren et al. 2011). To select the key regions over the EAPJ and EASJ, the occurrences of jet cores at each grid point at 300 hPa in the SPR period are calculated based on the daily data in 1997–2011 (Fig. 2). The reasons for choosing this period are given in section 3. As Fig. 2 shows, the EASJ occurs more frequently than the EAPJ. The active region of the EAPJ is located over 57.5°–62.5°N, 80°–95°E. For the EASJ, there are two maximum jet core centers: one is located over the land along the southern flank of the TP (22.5°–30°N, 71°–113°E) and the other is located over the ocean along the Japanese islands (27.5°–40°N, 130°–160°E). The close relationship between the western branch of the EASJ and the East Asian weather and climate has been revealed by many studies (e.g., Kuang and Zhang 2006; Ma et al. 2011; Xuan et al. 2011). Thus, we focus on the western branch of the EASJ in this study. The region of 22.5°–30°N, 71°–113°E (bottom solid red box), where the western EASJ is located, is
chosen as the active region of the EASJ. The EAPJ and EASJ intensities are defined as the averaged wind speed at 300 hPa over the active region of the EAPJ and EASJ, respectively.

3. The spatial–temporal variation of SPR frequency

Figure 3 shows the rainfall frequencies over China during the SPR period in 1960–2011. Here, a rainfall day is defined as a day with precipitation intensity above 0.1 mm day$^{-1}$. Stations with high frequencies (above 35 rainfall days) are mostly located in regions with an elevation higher than 200 m in southern China. Moreover, stations with more than 45 rainfall days concentrate in the higher-elevation regions along the mountains, suggesting the rainfall occurrence may be closely associated with terrain. Previous studies also revealed similar results, but they focused on SPR intensity (Tian and Yasunari 1998; Wan and Wu 2008; Li et al. 2010). The possible mechanism is that the mountains can block and lift cold and warm air, and therefore strengthen the frontogenesis and SPR rainfall (Wan and Wu 2008). Combined with the previous related studies, stations with high frequencies in southern China are chosen as representative stations for SPR. These stations are mainly located over the region of 22.5$^\circ$–30$^\circ$N, 105$^\circ$–120$^\circ$E, which can also be recognized as the SPR region in this study.

To obtain the dominant mode of SPR frequency over southern China, the empirical orthogonal function (EOF) analysis is applied. The first EOF mode explains 55% of the total variance and shows a homogeneous pattern over all of southern China (figure omitted). Thus, regional-mean SPR frequency (averaged over the representative stations) is analyzed in the following. In the recent two decades, the SPR frequency anomaly shows almost negative values (Fig. 4a). Specifically, lower SPR frequency has become more prevalent. To analyze the regime shift of SPR frequency, the running $t$ test is performed. A significant interdecadal shift exists around 1997 (Fig. 4b). To confirm this, climatological differences of rainfall frequency in 1997–2011 and 1960–96 are further investigated. An apparent negative center covers southern China, suggesting a severe deficit of SPR frequency after 1997 (Fig. 4b). Additionally, a significant decreasing trend of SPR frequency is also detected after 1997 (thick solid line in Fig. 4a). These
were the reasons for choosing the studying period of 1997–2011. However, in comparison, there is no significant regime shift for either principle component or regional mean of SPR intensity. Moreover, no obvious decreasing trend of SPR intensity exists in the recent two decades. Consequently, there should be some factors influencing the variation of SPR frequency rather than SPR intensity. In the following, the causes for the variation of SPR frequency in 1997–2011 will be analyzed from the perspective of the EASJ and EAPJ.

4. The individual effect of the EASJ and EAPJ on SPR frequency

As reviewed in the introduction, previous studies indicated a close relationship between the EASJ intensity and the spring rainfall over southern China. Thus, we first analyze how the EASJ influences SPR frequency in 1997–2011 by the regressed circulations with respect to the EASJ intensity (Fig. 5). For the vertically integrated moisture transport (VIMT) from
1000 to 300 hPa (Fig. 5a), significant southwesterly VIMT anomalies dominate over southern China. It may increase the water vapor over southern China and promote rainfall. Meanwhile, positive geopotential height anomalies at 850 hPa (Fig. 5b) indicate that the southwesterly VIMT anomalies may be mainly related to the intensified and westward South China Sea subtropical high (SCSSH) (Fig. 5c). As the SCSSH strengthened, the anomalous southwesterly along the northwest edge of SCSSH and the northerly of the anticyclonic anomaly around the TP converged over southern China, which may favor the SPR (Wan et al. 2008). For the regional circulation (Fig. 5d), significant ascending motion with increased moisture covers southern China, which may benefit the precipitation (Emori and Brown 2005). Thus, these circulations accompanied with EASJ intensity provide a favorable condition for the SPR occurrence. For comparison, the EAPJ-related atmospheric circulations in 1997–2011 are also analyzed (figure omitted). The circulations seem to be opposite of those related to the EASJ intensity, but the results cannot pass the significance test. It suggests that the EASJ intensity may play a more important role in the variation of SPR frequency than the EAPJ intensity.

Does the close relationship between the EASJ intensity and SPR frequency indicate that spring rainfall
be identified. Similar to the recent study of Li and Zhang (2014), based on the NSJI and NPJI, four configurations are identified as follows: the strong EASJ–strong EAPJ configuration (NSJI ≥ 0.5 and NPJI ≥ 0.5, denoted by “++”), strong EASJ–weak EAPJ configuration (NSJI ∈ [0.5, 0.5] and NPJI ≤ −0.5, denoted by “+-”), weak EASJ–strong EAPJ configuration (NSJI ∈ [−0.5, 0.5], NPJI ≤ 0.5, denoted by “−+”), and weak EASJ–strong EAPJ configuration (NSJI ≤ −0.5 and NPJI ≤ −0.5, denoted by “−−”). There are 94, 120, 85, and 110 days corresponding to the abovementioned four configurations separately during the SPR period in 1997–2011. The correlation coefficients between SPR frequency and the frequencies of the four configurations are listed in Table 2. For comparison, the correlation coefficients are also calculated during the whole period of 1960–2011. In Table 2, only one value (0.78) is above the 90% significance level, indicating a significant positive correlation only exists between SPR frequency and the frequency of the “+-” configuration in 1997–2011. This correlation coefficient is also higher than that when considering the individual effect of EASJ or EAPJ (Table 1). It indicates that the concurrent effect of the “+-” configuration is more closely related with the SPR occurrence in 1997–2011 than their individual effects. However, in 1960–2011, no significant relationship exists between any jet configuration and SPR frequency. This may be related to the decadal variation of the two jets and their concurrent configurations. Zhang and Huang (2011) mentioned that the changes in location and intensity of the EASJ in the early 1990s were probably associated with the shift of the rainfall regime over eastern China around 1992 (Ding et al. 2008). Recent studies revealed another rainfall shift over eastern China around 2000 (e.g., Si et al. 2009; Huang et al. 2011; Zhu et al. 2013). Corresponding to this rainfall shift, whether there is another corresponding variation of the two jets also needs further discussion. Overall, although the EASJ is very important for the SPR occurrence as revealed in section 4, the modulation effect of the EAPJ should not be ignored.

To investigate how the “+-” configuration influences SPR frequency, the regional and large-scale

### Table 1. Correlation coefficients between regional-mean SPR frequency and the frequencies of strong EASJ, weak EASJ, strong EAPJ, weak EAPJ events (based on the NPJI and NSJI). Boldfaced numbers are significant at the 90% confidence level.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Strong EASJ</th>
<th>Weak EASJ</th>
<th>Strong EAPJ</th>
<th>Weak EAPJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSJI ≥ 0.5</td>
<td>NSJI ≤ −0.5</td>
<td>NPJI ≥ 0.5</td>
<td>NPJI ≤ −0.5</td>
</tr>
<tr>
<td>1997–2011</td>
<td>0.52</td>
<td>−0.09</td>
<td>0.05</td>
<td>0.44</td>
</tr>
</tbody>
</table>

### Table 2. Correlation coefficients between regional-mean SPR frequency and frequencies of four configurations of the EASJ and EAPJ (based on the NPJI and NSJI). Boldfaced number is significant at the 90% confidence level.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Strong EASJ–strong EAPJ (+ +)</th>
<th>Strong EASJ–weak EAPJ (+ −)</th>
<th>Weak EASJ–strong EAPJ (− +)</th>
<th>Weak EASJ–weak EAPJ (− −)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSJI ≥ 0.5 and NPJI &gt; 0.5</td>
<td>NSJI &gt; 0.5 and NPJI &gt; 0.5</td>
<td>NSJI &lt; − 0.5 and NPJI &gt; 0.5</td>
<td>NSJI &lt; − 0.5 and NPJI &gt; 0.5</td>
</tr>
<tr>
<td>1960–2011</td>
<td>0.32</td>
<td>−0.31</td>
<td>−0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>1997–2011</td>
<td>0.35</td>
<td>0.78</td>
<td>−0.04</td>
<td>0.12</td>
</tr>
</tbody>
</table>
atmospheric circulations associated with this configuration are further examined by linear regression. Based on the conceptual model, precipitation is dependent on the location of the jet. The convergence in the low troposphere, which will lead to heavy precipitation, easily occurs near the right (left) side of the exit (entrance) region of the jet core (Holton et al. 2003, 1043–1055; Yang et al. 2002). As shown in Figs. 6a and 6b, significant divergence anomalies are located over southern China at 200 hPa (i.e., at the exit region of the EASJ), while the convergence anomalies exist at 850 hPa. These anomalies are under the secondary circulation stimulated by the EASJ. Figure 6c further confirms the results of convergence in the lower troposphere and divergence in the upper troposphere over southern China. It will induce strong upward motion anomalies (Fig. 6d) and may trigger precipitation. Similar to the individual effect of the EASJ (Fig. 5a), positive VIMT anomalies associated with the “+ −” configuration are located over southern China. It suggests more water vapor will be transported from the Bay of Bengal and the South China Sea to southern China (figure omitted). These are quite similar to the results of Shang et al. (2013, 2014), focusing on the preceding-summer circulations.
In fact, the precipitation events are also tied to the dry cold-air activities (e.g., Spencer and Stensrud 1998; Chen et al. 2014), which are linked with the variation of the EAPJ (e.g., Liao and Zhang 2013). Northerly wind ($V$) (e.g., Chan et al. 2002) and the large dewpoint depression ($T_{2Td}$) (e.g., Yao and Yu 2005) are chosen to represent the dry cold-air activity. The regressed $V$ at 850 and 500 hPa are shown in Figs. 7a and 7b, respectively. Associated with the “+ −” configuration, the entire eastern region of China is dominated by the anomalous southerly wind in both the lower and middle troposphere. Meanwhile, the negative $T - T_d$ anomalies indicate air with high humidity (Figs. 7c, d). The same analysis is applied to investigate the individual effects of the EASJ and EAPJ (figure omitted). The results proved that the dry cold-air activities influencing SPR frequency are mainly connected to the EAPJ but not to the EASI. It can be proposed that, associated with the weak EAPJ events, the northerly winds weaken. This weakening of the northerly winds may allow warm wet southerly wind covering the entire southern China region, promoting ascending motion over the region.

As mentioned above, we can infer that associated with the “+ −” configuration, the convergence of moist air from the Bay of Bengal and the South China Sea and the weakened northerly wind in the upper troposphere are important conditions that promote the occurrence of SPR in 1997–2011. The effect of the EASJ is important for the ascending motion and the water vapor transportation to southern China. However, without the weakened northerly wind in the upper troposphere associated with the weak EAPJ events, the ascending motion may not develop.
Based on the principle of thermal wind, the variation of wind velocity with height mainly depends on the meridional temperature gradient (MTG; Wallace and Hobbs 2005; Zhang and Huang 2011). Figure 8 presents the regression of the SPR-period MTG changes averaged from 500 to 200 hPa. It is known that the climatological MTG is generally negative over the Northern Hemisphere resulting from the decreasing temperature from south to north. Thus, the significant negative MTG anomaly over the active region of the EASJ may intensify the EASJ. Meanwhile, the positive MTG anomaly appears over the active region of the EAPJ, which may weaken the EAPJ.

For the external forcing, the thermal effect of the TP will affect the circulations in the upper troposphere (Hahn and Manabe 1975; Kuang and Zhang 2005). To investigate the relationship between the TP heating and the variations of the two jets, the apparent heating rate $Q_1$ and moisture sinks $Q_2$ are used, which are defined as the residual terms of the thermodynamic equation (Yanai et al. 1973, 1992). The expressions are

$$Q_1 = C_p \left( \frac{\partial T}{\partial x} + \mathbf{V} \cdot \nabla T + \left( \frac{P}{P_s} \right) \frac{R_e C_p}{\omega} \frac{\partial \theta}{\partial p} \right)$$

and

$$Q_2 = -L \left( \frac{\partial q}{\partial x} + \mathbf{V} \cdot \nabla q + \omega \frac{\partial q}{\partial p} \right),$$

where the constants of $C_p$, $R_e$, and $L$ are the specific heat for dry air, the gas constant for dry air, and the latent heat of deposition, respectively. Variable $T$ is temperature. Variables $P$ and $P_s$ are pressures at a specific level and at the reference level, respectively. Variables $\mathbf{V}$, $\theta$, $\omega$, and $q$ are the horizontal wind vector, the potential temperature, the vertical pressure ($p$) velocity, and the specific humidity, respectively. The vertical integration of $Q_1$ minus $Q_2$ ($Q_1 - Q_2$) measures the sensible and latent heat fluxes from the surface to the atmosphere (Gong et al. 2011). The positive values indicate net heat gains of the atmosphere and vice versa. Previous studies have revealed that the TP acts as a sensible heat source during the summer season, generating a warm anticyclone in the upper troposphere (Flohn 1960). Likewise, the importance of the latent heating is also emphasized (Riehl 1959). Thus, in this study, $Q_1 - Q_2$ is used to measure the net heating.
Figure 9a shows the regressed $Q_1 - Q_2$ with respect to the frequency of the “+ −” configuration in 1997−2011. Significant negative $Q_1 - Q_2$ anomalies cover the TP, especially the northern and eastern parts, indicating the heat loss of the tropospheric atmosphere. As Wu and Zhang (1998) and Song and Liu (2014) indicated, the significant cooling over the eastern part of the TP resembles a giant air pump extruding air from the upper to the lower atmosphere. As a result, the air is drawn to the TP in the upper troposphere, which may lead to cyclonic circulations. Accordingly, the regressed wind anomalies in respect to the frequency of the “+ −” configuration show significant cyclonic anomalies at the upper troposphere over TP (Fig. 9b). The southern flank of the cyclonic anomalies may accelerate the EASJ, while the northern flank of the cyclonic anomalies may decelerate the EAPJ. Thus, the analysis above shows that the cooling over the northern and eastern parts of the TP is an important external forcing for maintaining the “+ −” configuration.

7. Conclusions

SPR frequency over southern China significantly decreases in 1997−2011. The different roles of the EASJ and EAPJ play in this decrease of SPR frequency are investigated. Associated with strong EASJ, ascent motion dominates over southern China. Accompanied with the strengthened SCSSH, enhanced water vapor is transported to southern China. All these circulations provide a favorable condition for SPR occurrence. Different from the EASJ, no significant relationship exists between SPR frequency and the EAPJ intensity. However, frequencies of both the strong EASJ and the weak EAPJ events are detected to be positively correlated to SPR frequency.

To investigate the concurrent effect of the EASJ and EAPJ impacting SPR frequency, four configurations have been identified: strong EASJ–strong EAPJ, strong EASJ–weak EAPJ, weak EASJ–strong EAPJ, and weak EASJ–weak EAPJ configurations. Significant positive correlation is only detected between SPR frequency and the frequency of the “+ −” configuration in 1997−2011. Associated with the “+ −” configuration, enhanced water vapor is transported from the Bay of Bengal and the South China Sea to southern China, providing favorable moisture conditions for SPR occurrence. Significant divergence (convergence) anomalies are located over southern China at 200 hPa (850 hPa), which stimulate the ascending motion. These circulations may be mainly affected by the strong EASJ. Meanwhile, as the EAPJ weakens, northerly winds weaken in the upper troposphere. This permits the ascending motion to develop further. Overall, the EASJ may play a dominant role in the variation of SPR frequency during the period of 1997−2011, while the EAPJ may play a modulation role.

Finally, the possible mechanism for maintaining the “+ −” configuration has been proposed. Significant negative MTG anomalies are located over the active region of the EASJ, which may strengthen the EASJ. Meanwhile, the positive MTG anomalies over the EAPJ active region may be responsible for the weakened EAPJ. Significant cooling over the eastern Tibetan Plateau induces cyclonic anomalies in the upper troposphere, which may result in an accelerating EASJ and a decelerating EAPJ.

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