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Dominant Patterns of Summer Rainfall Anomalies in East China during 1951–2006

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ABSTRACT

The dominant patterns of summer rainfall anomalies in East China were studied using Empirical Orthogonal Function (EOF) analysis. The results indicate that after the late 1970s, the first and second dominant patterns switched. During the period before the late 1970s, the spatial pattern of the first (second) dominant mode was the "Yangtze River pattern" (the "South China pattern"), but this changed to the "South China pattern" (the "Yangtze River pattern") after the late 1970s. This decadal change in the dominant patterns resulted from a significant decadal change in summer rainfall over South China after the late 1970s, i.e., a negative phase during 1978–1992 and a positive phase during 1993–2006. When the decadal variation of rainfall in East China is omitted from the analysis, the first and second dominant patterns represent the "Yangtze River pattern" and the "South China pattern", respectively. These results suggest that when decadal variation is included, the rainfall in China may be dominated by one mode during certain periods and by another in other periods. For the interannual variability when decadal variation is excluded, however, the first and second modes can be easily distinguished, and their order has been stable since at least 1951.

Key words: dominant patterns, summer rainfall, interannual variability, South China, decadal variation

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1. Introduction

East China frequently suffers severe floods and droughts due to its typical monsoon climate. Understanding the year-to-year variation of summer rainfall is essential and much work has been dedicated to this (Webster and Yang, 1992; Wang et al., 2001; Huang et al., 2003; Lu, 2004; Ding and Chan, 2005). Empirical Orthogonal Function (EOF) analysis is the most common approach to investigating the variation of summer rainfall in East China because it is useful for grasping the most dominant modes and their temporal evolution.

Previous work using EOF analysis to study summer rainfall in East China is summarized in Table 1. Most studies have indicated that the first dominant mode of summer rainfall is associated with anomalous rainfall located in the middle-lower reaches of the Yangtze River valleys (simplified as the "Yangtze River pattern" in Table 1). The second mode is characterized by a seesaw-like pattern with rainfall anomalies between South China and the Yellow River-Huaihe River valleys (the "seesaw pattern"), although some studies have linked the second mode with main anomalies concentrated over South China (the "South China pattern"). This difference in the second mode between the "seesaw pattern" and the "South China pattern" in these previous studies relates to whether the variation in rainfall over the Huaihe River Valley is significant or not, which is likely due to the use of different spans of rainfall data.

However, the first two modes obtained in previous studies explain roughly similar variance (Table 1). This suggests that the two modes are difficult to separate. For instance, as Han and Zhang (2009) indicated, the first leading mode of summer rainfall cannot be distinguished from the sample error, according to North et al. (1982). Furthermore, a few works show the "seesaw pattern" as the dominant mode (Table 1, Deng et al., 1989; Wang and Wu, 1996), which illustrates the

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Table 1. Previous and the present results of EOF analysis of East China summer rainfall, including rainfall data information and spatial patterns of the two most dominant leading modes. "A" is the abbreviation for the "Yangtze River pattern", "B" for the "South China pattern" and C for the "Seesaw pattern".

Paper	Analysis period	EOF1 (variance)	EOF2 (variance)
Deng et al. (1989)	1951–1989	C (21.2%)	A (15.4%)
He and Li (1992)	1980–1989	A (30.6%)	Atypical (19.8%)
Zhu and Chen (1992)	1951–1987	A	C
Shen and Lau (1995)	1956–1985	A (17.5%)	C (13.7%)
Wang and Wu (1996)	1959–1994	C (12.4%)	Atypical (11.4%)
Zou and Ni (1997)	1961–1988	A (20%)	Atypical (14%)
Weng et al. (1999)	1955–1997	A (15.1%)	B (11.0%)
You et al. (2003)	1951–2000	A (15.9%)	C (12.3%)
Zhou and Yu (2005)	1951–1999	A (16.3%)	C (12.4%)
Chen et al. (2006)	1951–2000	A (16%)	C (12%)
Huang et al. (2006)	1951–2000	A (16.4%)	Not Given
Huang et al. (2007)	1958–2000	A (15.6%)	B (12.7%)
This study	1951–2006	A (15.4%)	B (13.2%)

sensitivity of results to rainfall data and confirms the flexibility of the first two modes. On the other hand, the EOF results may be dependent on the analyses used, which are generally manifested by using original or normalized rainfall anomalies, or the percentage of rainfall anomalies before EOF analysis.

The rainfall data used in most of the studies mentioned above start from the beginning of the 1950s, and thus the data span more than 30 years. Therefore, variations on interannual and decadal timescales may be mixed together. For instance, the corresponding series of the first principle component shows a period of 2–3 years after the late 1970s (Huang et al., 2007), and the second principle component represents an increasing trend or a decadal variation (Weng et al., 1999; Ding et al., 2008). The dominant modes obtained by EOF analysis on original rainfall data are mainly based on interannual variability, since interannual variability is much more dominant than variability over longer timescales. The results of EOF analysis, however, might be modified by the variability of these longer timescales, particularly due to decadal variations of summer rainfall in China. Unfortunately, previous studies have not distinguished interannual variability from the lower frequency variability, when performing EOF analysis.

Many studies have investigated the decadal changes of East Asian summer rainfall (e.g. Chang et al., 2000; Gong and Ho, 2002; Ren et al., 2004). By analyzing regional rainfall in South China, the middle and lower basins of the Yangtze River and North China, respectively, Ding et al. (2008) studied the period 1951–2004 and suggested that there was a common changing point in the late 1970s for all three regions, and other shifts occurred in the mid-1960s over North China and in the early 1990s over South China. Huang et al. (2011) recently focused on the decadal variation of rainfall in China and further confirmed all three decadal changes. More specifically, two major features of the decadal change around the late 1970s were identified: (1) the weakness of the EASM circulation after the late 1970s (Wang, 2001); (2) following this change, weakened northward moisture transport and flooding conditions over the middle-lower reaches of the Yangtze River valley and Korea, and prolonged droughts over North China in recent decades (Gong and Ho, 2002; Ho et al., 2003; Huang et al., 2007), which is consistent with the shift of the first principle component around the late 1970s (Weng et al., 1999).

A deep understanding of the dominant modes of rainfall anomalies in China is crucial for improving seasonal forecasts and would help to explain the mechanisms responsible for rainfall variability in China. Considering the decadal changes of summer rainfall, it is natural to imagine how they manifest in the dominant modes of East China summer rainfall and whether or not, as a consequence, the modes change, for example, after the late 1970s. This question is examined in the present study. The dataset used is described in section 2. Section 3 presents the dominant patterns of rainfall anomalies during the period 1951–2006. In section 4, we discuss the possible reasons for the changes in dominant rainfall patterns. Conclusions are given in section 5.

2. Data and methods

The monthly precipitation dataset of 160 stations in China during the period 1951–2006, provided by the Chinese Meteorological Administration, was used in this study. Of the 160 stations, 139 located east of 100°E were chosen for the study of the variation of

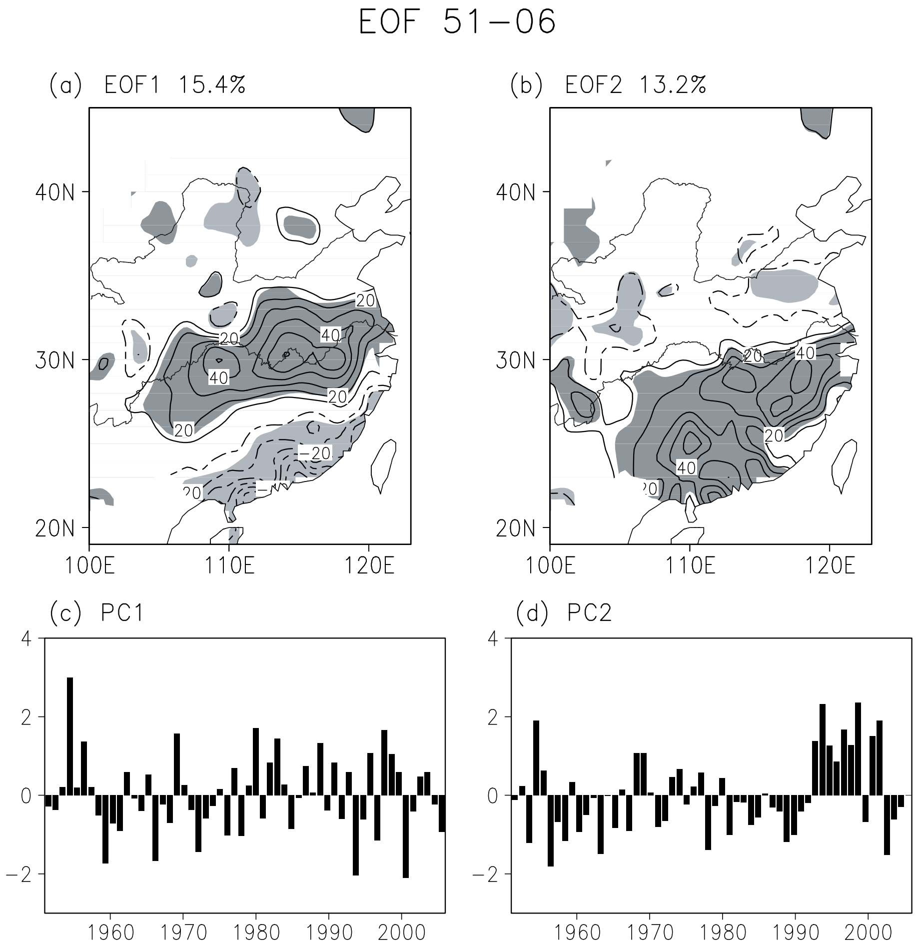

Fig. 1. The dominant modes of EOF analysis of summer rainfall in East China during 1951–2006. EOF1 (a), EOF2 (b), and corresponding normalized principle components, PC1(c), and PC2 (d). Spatial patterns are shown as a regression of summer rainfall onto the corresponding normalized PC. Shadings denote significant areas at 95% confidence level and the contour interval is 20 mm month^{-1}.

summer rainfall in East China.

EOF analysis was applied in this study to illustrate the dominant modes of rainfall anomalies in summer (June to August). Each principal component (PC) was scaled by its standard deviation. The spatial modes are displayed in the form of regression of rainfall onto the corresponding scaled PCs.

To separate the decadal variation and the interannual variation of summer rainfall, a 9-year running mean was applied. The 9-year running mean values are regarded as decadal variation and the remaining parts as interannual variation.

3. The change in dominant rainfall anomaly patterns

Figure 1 shows the first two dominant modes of summer rainfall in East China during the period 1951–2006. EOF1 accounts for 15.4% of the total variance. The corresponding spatial pattern shows that positive rainfall anomalies are located in the middle and lower reaches of the Yangtze River valley, and negative anomalies lie along the south coast (Fig. 1a). Due to the high correlation coefficient (0.91) between PC1 and the rainfall anomaly sequence of the Yangtze River Valley (27°–33°N, 105°–125°E), this pattern is called the "Yangtze River pattern" in the following.

The spatial pattern of EOF2 shows positive rainfall anomalies south of the middle and lower reaches of the Yangtze River (Fig. 1b). In addition, there are weak negative anomalies between the Yellow River and the Yangtze River. The variation accounted for by this mode is 13.2%. A prominent feature of PC2 is a sudden decadal transition around the early 1990s. This spatial pattern is called the "South China pattern", and the correlation coefficient is as high as 0.86

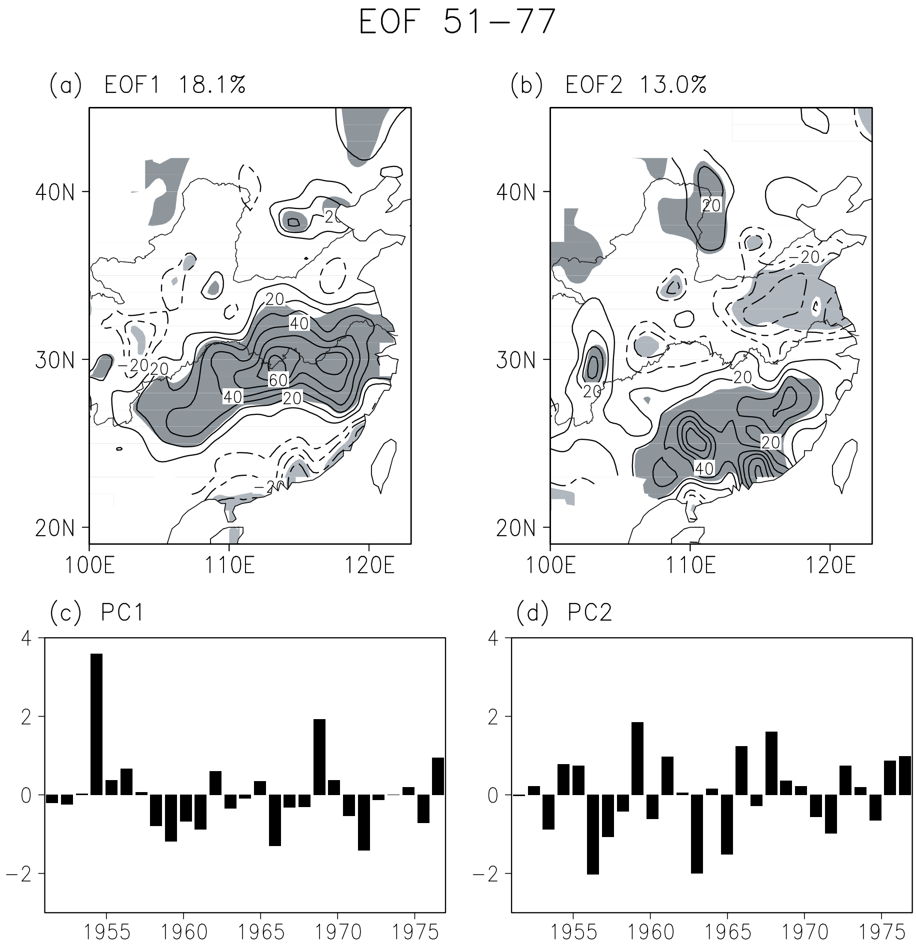

Fig. 2. As in Fig. 1, but during 1951–1977.

between PC2 and the South China (22°–28°N, 105°–125°E) rainfall anomaly sequence.

The variances accounted for by the first two dominant modes are similar, and these modes cannot be distinguished from sampling errors, while the second and third modes are distinguishable in terms of the criterion of North et al. (1982). EOF3 shows dominant rainfall anomalies mainly over North China (figure not shown) and explains 6.9% of the total variance, which is approximately half of EOF2. The spatial patterns shown in Fig. 1 are consistent with many previous studies (e.g. Weng et al., 1999; Zhou and Yu, 2005; Huang et al., 2007).

Figure 2 presents the first two leading modes of anomalous summer rainfall during 1951–1977. These modes explain 18.1% and 13.0% of the total variance, respectively, and they are distinguishable (North et al., 1982). The spatial pattern of the first mode can be identified as the "Yangtze River pattern", and the pattern correlation coefficient of spatial pattern between Fig. 2a and Fig. 1a is 0.904. The second mode is similar to the "South China pattern", with positive rainfall anomalies to the south of the Yangtze River. The pattern correlation coefficient between Fig. 2b and Fig. 1b is 0.677. In comparison with Fig. 1b, Fig. 2b shows stronger negative anomalies between the Yangtze River and the Yellow River. Therefore, the first two dominant modes during 1951–1977 are similar to those over the entire analysis period, but they are distinguishable.

However, the dominant modes changed completely after the late 1970s, compared to the first period (or the whole period). The spatial pattern of EOF1 is no longer the "Yangtze River pattern", but is similar to the "South China pattern", which is the second most dominant mode before the late 1970s. The pattern correlation coefficient between Figs. 3a and 2a is −0.405, while it is 0.481 between Figs. 3a and 2b. Instead, EOF2 is associated with the "Yangtze River pattern", and the pattern correlation coefficient between Figs 3b and 2a is 0.775, but 0.134 between Figs. 3b and 2b. Additionally, PC1 indicates a noticeable decadal shift from a negative phase to a positive one around 1992 (Fig. 3c), representing a transition from overall

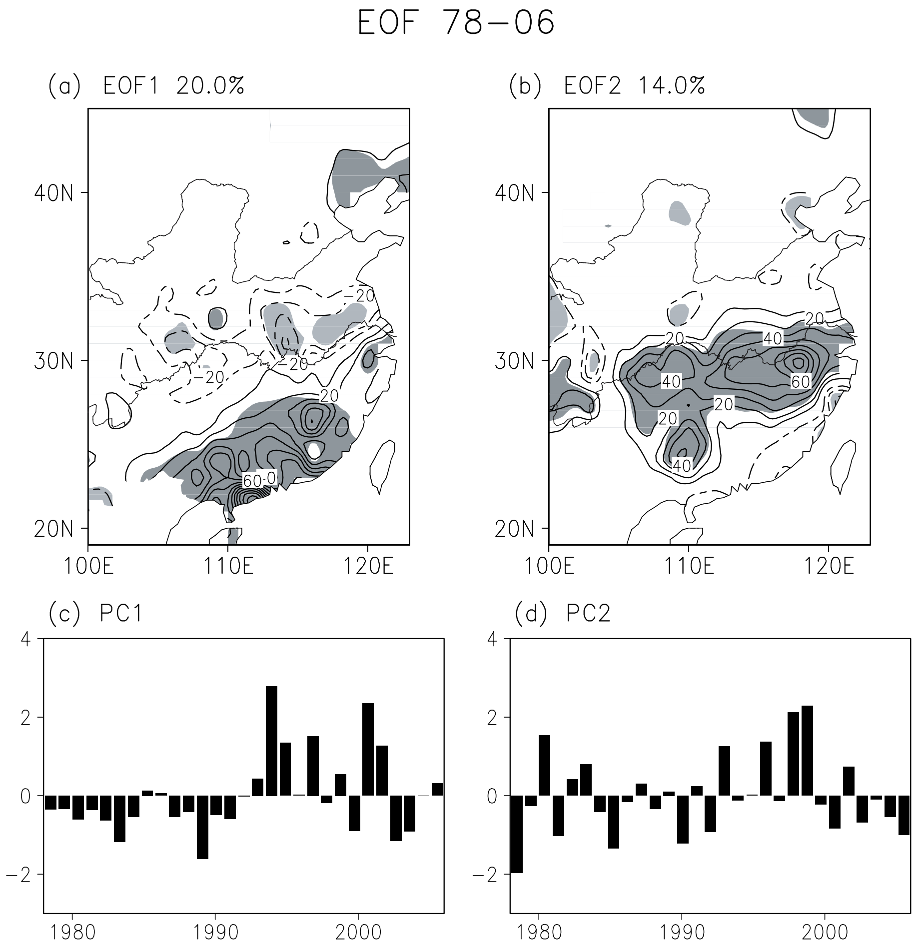

Fig. 3. As in Fig. 1, but during 1978–2006.

negative rainfall anomalies prior to the early 1990s to overall positive anomalies since the early 1990s over South China. The first two dominant modes account for 20.0% and 14.0% of the total variance, respectively, and are also distinguishable with respect to North et al. (1982).

The results shown in Figs. 1 to 3 suggest that the summer rainfall in East China has two typical modes: the "South China pattern" and the "Yangtze River pattern". After the late 1970s, the order of the dominant modes is reversed. The dominant mode is the "Yangtze River pattern" in the former period, but changes to the "South China pattern" in the latter period, and the second most dominant mode transforms from the "South China pattern" to the "Yangtze River pattern" in the latter period. This conversion between the two modes after the late 1970s indicates an unsustainable feature of rainfall modes.

Our result is consistent with Wang et al. (2001), who examined proxy data and suggested that the rainfall types, which are similar to the dominant modes of rainfall anomalies, changed many times in China dur-

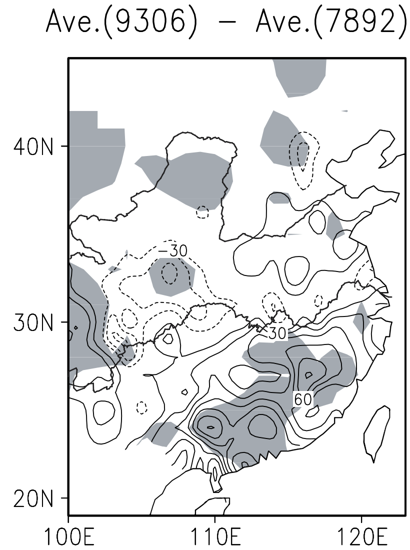

Fig. 4. Difference in summer rainfall between 1993–2006 and 1978–1992. Shading shows significant differences at a 95% confidence level by Lepagy test. The contour interval is 20 mm month^{-1}.

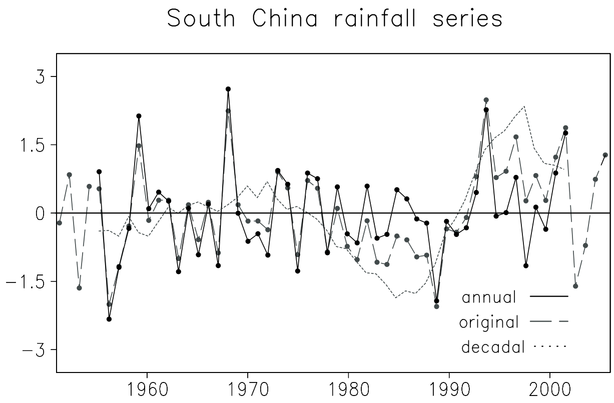

Fig. 5. Normalized time series of rainfall anomaly over South China (105°–125°E, 22°–28°N) during 1951–2006. The dashed, dotted and solid lines are sequences of the original rainfall, the 9-year running mean and the interannual rainfall with the 9-year running mean omitted, respectively.

ing the past millennium. It should be noted that decadal or lower frequency variations were included in their study. In the following section, we show that the dominant modes of rainfall in China can change significantly after removing decadal variation from original rainfall data.

4. Reasons for the change in the dominant modes after the late 1970s

After the late 1970s, the "South China pattern" becomes the most dominant mode of summer rainfall in East China, replacing the "Yangtze River pattern". Additionally, PC1 indicates a clear decadal shift around the early 1990s (Fig. 3c). This decadal shift is associated with a difference in summer rainfall in South China between 1993–2006 and 1978–1992 (Fig. 4), which is consistent with previous studies (Ho et al., 2005; Kwon et al., 2007; Ding et al., 2008; Wu et al., 2010). After the early 1990s, South China experienced a period of flooding.

Figure 5 shows the time series of South China rain-

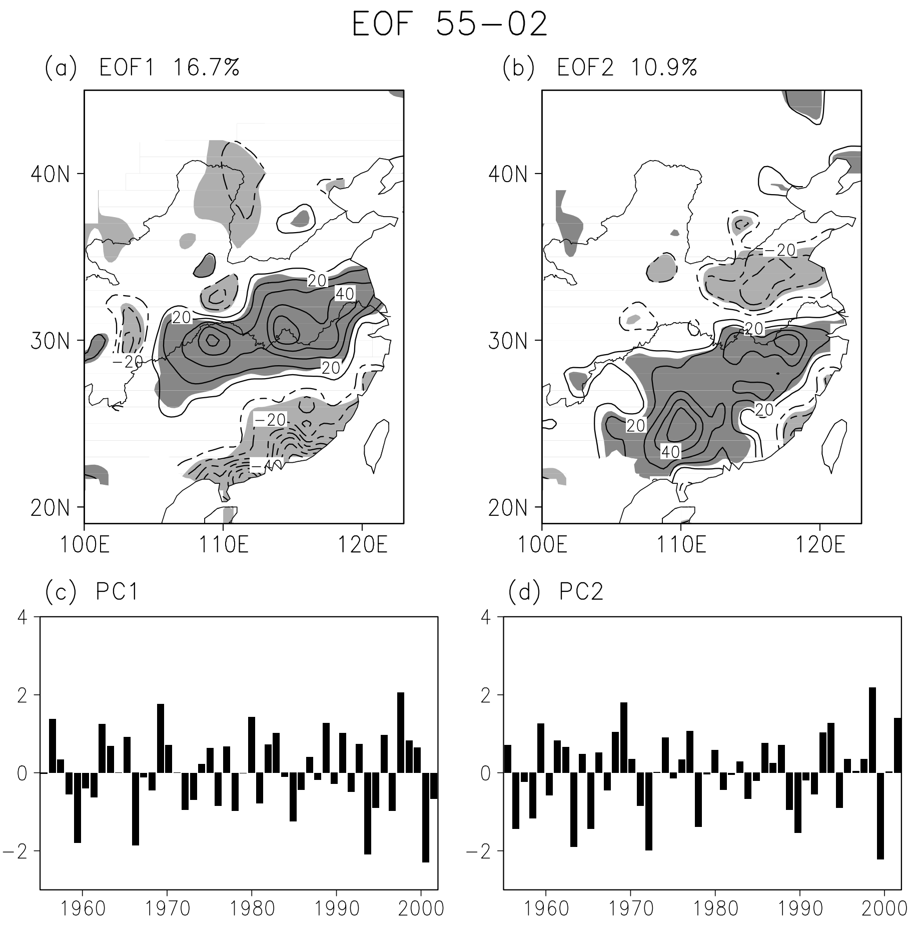

Fig. 6. As in Fig. 1, but with the 9-year running mean omitted.

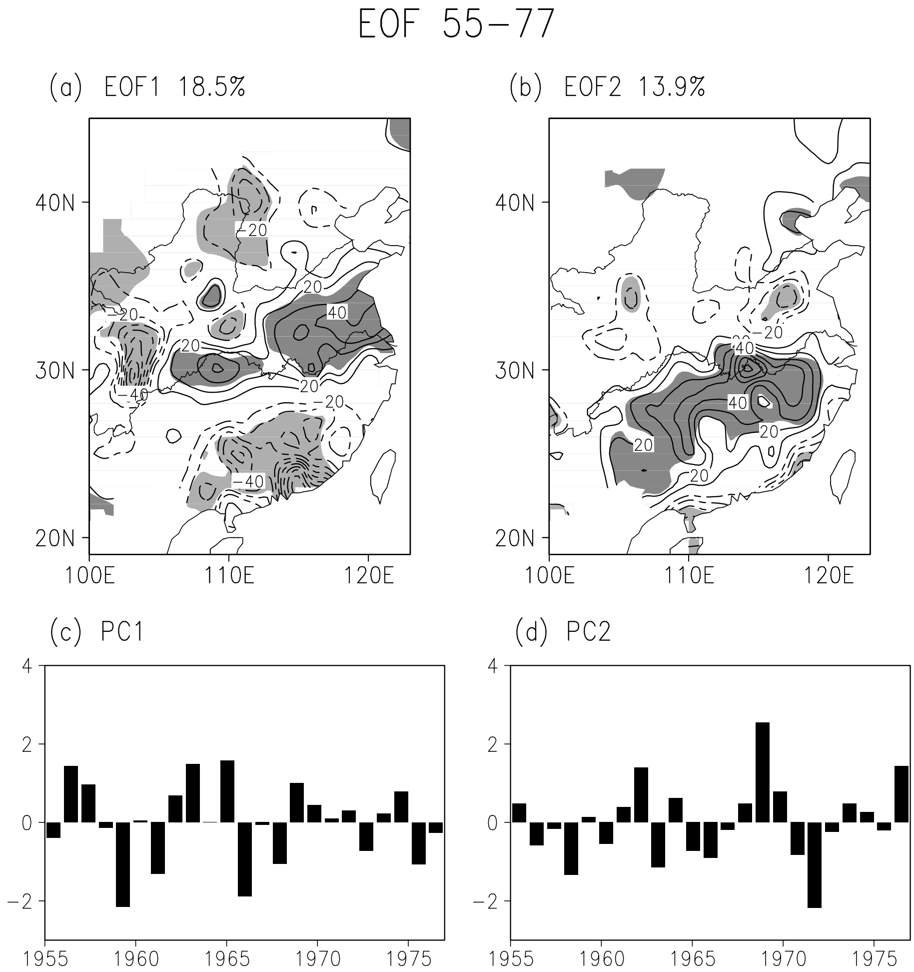

Fig. 7. As in Fig. 6, but during 1955–1977.

fall anomalies, including original, decadal and interannual variations. It should be noted that these variations are normalized, and the standard deviations for decadal and interannual variations are 16.2 and 41.5, respectively. Figure 5 indicates that the decadal variation is strong after the late 1970s, with a phase transition from below normal to above normal around the early 1990s. As a result, the deviation between the original series and the interannual series is remarkable after the late 1970s.

These results show that the original China rainfall data contain both interannual and decadal variation. Since physical mechanisms for variation over these two timescales might be different, it is appropriate to investigate interannual and decadal variations separately. Decadal variations, however, are highly auto-correlated, and thus the equivalent sample size would be much smaller than the time span of the analysis period (from 1951 to 2006). We cannot attempt to obtain reliable results for the dominant modes of decadal variations by using data from the past 5–6 decades. In this study, therefore, it is reasonable to focus on the dominant modes for interannual rainfall variations.

The significant decadal variation of South China rainfall after the late 1970s, however, may affect the results of the dominant modes of interannual variation in East China. To verify this hypothesis, we applied EOF analysis to the rainfall data after the 9-year running mean was removed, and the results are shown in Fig. 6. The first dominant mode for interannual variability is the "Yangtze River mode" (Fig. 6a), which is similar to that shown in Fig. 1a. This mode accounts for 16.7% of the total variance. This second mode accounts for 10.9% of the total variance and has some similarities to Fig. 1b: the negative anomaly between the Yangtze River and the Yellow River and positive anomaly in South China, but with slight differences; the negative rainfall between the Yangtze River and the Yellow River being stronger (Fig. 6b). It should be noted that when the decadal variation was omitted, the two modes are distinguishable.

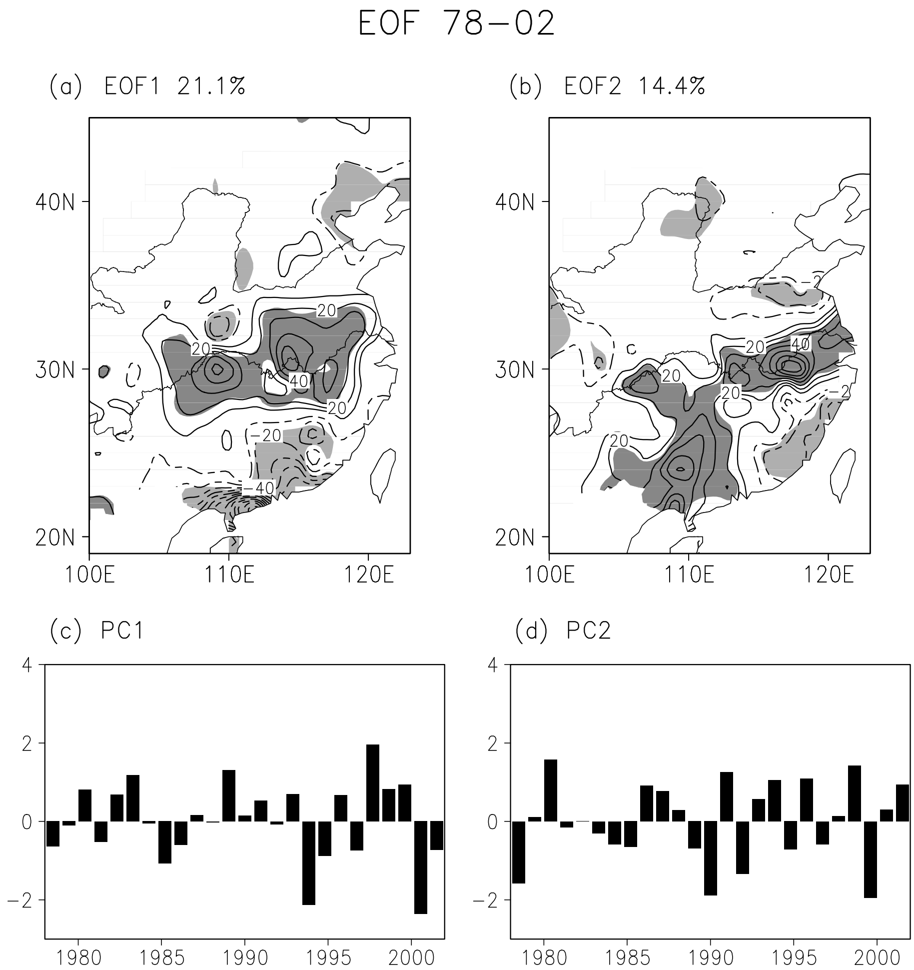

Fig. 8. As in Fig. 6, but during 1978–2002.

The results of the former and latter periods are shown in Figs. 7 and 8, respectively. Generally speaking, the two modes during the former period (Fig. 7) are similar to those over the whole period (Fig. 6). The pattern correlation coefficients between Figs. 6 and 7 are 0.753 and 0.755 for EOF1 and EOF2, respectively. The spatial patterns of the dominant modes for the latter period (Fig. 8) are also similar to those in Fig. 6. The pattern correlation coefficients are 0.925 and 0.686 for EOF1 and EOF2, respectively. The EOF results for the latter period change significantly after the decadal variation is removed (Figs. 3 and 8). In particular, the "Yangtze River pattern", which is the second most dominant mode from raw rainfall data (Fig. 3b), is the most dominant one over the interannual timescale (Fig. 8a). Therefore, Figs. 6–8 indicate that after removing the decadal variation of rainfall, the first two dominant modes of interannual variation are similar for the entire analysis, the former period, and latter period. Also note that after removing the decadal variation, the EOF patterns are all distinguishable during both periods. The results support the hypothesis that the change in the dominant patterns is affected by the decadal variation of rainfall, particularly by the significant decadal change in rainfall over South China after the late 1970s.

5. Conclusions

The spatial structure and temporal variation of summer rainfall over East China were analyzed using the EOF method in this study. During 1951–2006, the most dominant mode is associated with the "Yangtze River pattern", with the most significant rainfall anomalies over the middle and lower reaches of the Yangtze River valley. The second mode is related to the evident variation over South China, which is called the "South China pattern" in this paper. These results are consistent with many previous studies, and these two modes cannot be distinguished.

We found that the two dominant modes of rainfall anomaly are not stable. In the former period before the late 1970s, the spatial pattern of the first EOF is still the "Yangtze River pattern", and the second seems to be the "South China pattern". In contrast, in the latter period, the first leading mode is related to the "South China pattern", while the second mode is similar to the "Yangtze River pattern". The most dominant mode of summer rainfall over East China switched from the "Yangtze River pattern" to the "South China pattern" in the late 1970s.

Further analyses illustrate that this transition in the order of the dominant modes after the late 1970s is due to a significant decadal change in summer rainfall over South China. Rainfall over South China tended to be below normal during 1978–1992 and above normal during 1993–2006. When decadal variation in rainfall was omitted, the first and second dominant modes of interannual variation represent the "Yangtze River pattern" and the "South China pattern", respectively, and they are distinguishable, for the entire period (1951–2006), for the former period (1951–1977) and for the latter period (1978–2006).

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