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ORIGINAL PAPER

Classification of typical summer rainfall patterns in the East China monsoon region and their association with the East Asian summer monsoon

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Abstract In this study, the summer rainfall patterns in the East China monsoon region during 1951–2015 were objectively classified into four typical categories: the northern China rainfall pattern (NCP), the intermediate rainfall pattern (IRP), the Yangtze River rainfall pattern (YRP), and the South China rainfall pattern (SCP). The periods of the four patterns show significant decadal characteristics. The NCP occurred mainly between the late 1950s and the early 1980s, and the IRP in the late 1950s to the early 1970s and the 2000s. The YRP occurred mainly between the 1980s and the 1990s, and the SCP between the mid-1990s and the early 21st century. The relationship between the East Asian summer monsoon index (EASM I_{WF}) and the four rainfall patterns was comparatively analyzed. The results confirmed that the four rainfall patterns have obvious differences in the EASM. In the NCP, IRP, or SCP years, the EASM I_{WF} primarily showed a positive phase and a strong summer monsoon; in the YRP years, the EASM I_{WF} primarily showed a negative phase and a weak summer monsoon.

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1 Introduction

As viewed from the national range, the summer rainfall prediction for the East China monsoon regions focuses on the northern or southern locations of the rain belt (Huang et al. 1993; Wang et al. 1998; Shi et al. 1999; Zhao and Feng 2014; Zhao et al. 2015). And the rainfall patterns are strongly influenced by the East Asian summer monsoon (EASM) (Shi and Zhu 1996; Wang 2001; Li and Zeng 2002; Zhu et al. 2005; Wang et al. 2008; Ding et al. 2008; Feng et al. 2012; Liu et al. 2014). The primary physical manifestation of the summer monsoon is persistent, heavy precipitation in a coherent, and well-defined rain belt (Samel et al. 1995). In general terms, rain belt movement is characterized by a stepwise northward advance from South China to the Yangtze River valley and to North China (Ding 1992, 1994; Lau and Yang 1996; Zhao, et al. 2013; He, et al. 2015). However, owing to the anomaly of the EASM and other factors, the speed of the rain belt can be accelerated or the belt can remain in a certain region for a long time, thereby forming different rainfall patterns (Wei et al. 2012). While the average rain belt structure and rainfall pattern over East China is well known, precipitation undergoes substantial interannual variability. These variations have an extremely important impact on the economy of China (Hulme et al. 1994; Zheng et al. 2009; Feng et al. 2013), where agricultural production is highly dependent upon the monsoon.

Additionally, whether or not the classification of summer rainfall patterns is appropriate will directly affect the prediction accuracy (Wang et al. 1998). As early as the beginning of the 1980s, Liao et al. (1981) classified the summer rain belt of East

China into three patterns (hereinafter referred to as the "three rainfall patterns"): pattern I, the northern pattern, in which the main rain belt is located in the Yellow River basin and the region to the north, while the Yangtze-Huaihe River Basin has little rainfall in a wide range; pattern II, the central pattern, in which the main rain belt is located between the Yellow River and Yangtze River, and the rainfall center is usually in the Huaihe River Basin; and pattern III, the southern pattern, in which the main rain belt is located in the Yangtze River Basin or regions south of the Yangtze River, while the large regions north of the Huaihe River have little rainfall. This classification has many advantages: first, the limited classification of rainfall patterns can include the main features of summer rainfall and is conducive to pattern analysis and prediction. Second, the rainfall patterns are connected with the position of the rain belt from north to south. The atmospheric circulation for the three rainfall patterns has significant differences and thus has clear climatic significance. In addition, this classification highlights the areas in which major flooding may occur. Furthermore, this classification has been used in a forecasting service during the flood season by the National Climate Center (NCC) of the China Meteorological Administration (CMA) ever since its establishment. However, it is not appropriate to classify the main rain belt in the Yangtze River Basin, in the areas to the south of the Yangtze River, or in the South China as one pattern. For example, the summer rainfall of 1954 and 1997 was classified as pattern III. Floods occurred in the Yangtze River Basin in 1954, but in the areas to the south of the Yangtze River in 1997. However, the precipitation distribution characteristics and causes were quite different between 1954 and 1997 (Wang et al. 1998). Current climate models have low prediction ability for summer rainfall in the East Asian monsoon region (Wang et al. 2009, 2015; Ding 2011). Therefore, it is difficult to predict whether the main rain belt is located in the Yangtze River Basin, or south of the Yangtze River area, or in South China.

Sun et al. (2005) objectively classified the summer rainfall patterns in the East China monsoon region between 1880 and 2002 using the empirical orthogonal function resolution (EOF), principal component analysis, singular value decomposition (SVD), cluster analysis, and other mathematical statistic methods, along with empirical analysis. According to their study, rainfall patterns in the East China monsoon region are divided into four patterns (hereinafter referred to as the "four rainfall patterns"). Pattern 1 is the northern China rainfall pattern (NCP); pattern 2 is the intermediate rainfall pattern (IRP); pattern 3 is the Yangtze River rainfall pattern (YRP); and pattern 4 is the South China rainfall pattern (SCP). Among the previously mentioned three rainfall patterns, pattern III, the southern pattern, was further divided into the YRP and SCP. Meanwhile, the atmospheric circulations of the four rainfall patterns were preliminarily analyzed. However, Sun et al. (2005) did not describe the detailed division methods and steps, and the rainfall patterns after 2002 are not divided. Then, Wang and Huang (2006) also divided the rain belt from 1951 to 2005 into four patterns, according to the locations of the maximum annual summer rainfall anomaly percentage in East China. However, the rainfall patterns are not consistent in the many years between the two classification methods mentioned above. Chen (2010) pointed out that the summer rainfall patterns present new change characteristics under global warming. Moreover, the rain belt over China from 1951 to 2008 was divided into eight patterns according to the EOF analysis and the cluster analysis (hereinafter referred to as the "eight rainfall patterns").

In brief, there are three categories of classification of summer rainfall patterns in the East China monsoon region. One classification (three rainfall patterns) refers to a coarse division that summarizes the main characteristics of summer rainfall over the East China monsoon region with clear circulation causes and is helpful for analyzing the prediction factors. However, this classification is inappropriate because it merges the YRP and SCP into one class. Another classification (eight rainfall patterns) is a subtle and relatively comprehensive division. However, using a large number of rainfall patterns is not appropriate from the perspective of prediction. A coarse division will merge the rainfall patterns with different circulation causes into the same pattern, and a subtle division will divide the rainfall patterns associated with the same circulation into different patterns. Therefore, the "four rainfall patterns" is more appropriate for the East China monsoon region. Moreover, the relationship between the four rainfall patterns and the EASM should be examined. From the above elucidation, it is necessary and meaningful to study the classification of summer rainfall patterns. In this study, we objectively redivided the summer rainfall patterns in the East China monsoon region and extended the analysis to 2015 based on the previous studies and similarity measurement method.

The remainder of this paper is organized as follows. Section 2 describes the data and methods used in this study. The detailed division steps and results are presented in section 3. The relationship between the four rainfall patterns and the EASM is illustrated in section 4. A summary and conclusion are given in section 5.

2 Data and methodology

The main data sets employed in this study include monthly average precipitation data for 160 stations from the CMA for the period from 1951 to 2015 (Wu and Mao 2016). Monthly mean 850 hPa U-wind data, gridded at 2.5° × 2.5° resolution, are taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996). The EASM index (I_{WF}) is defined as U-wind at 850 hPa (5°–15°

N, 90°–130° E) minus U850 (22.5°–32.5° N, 110°–140° E) (Wang and Fan 1999) .

The similarity measurement method discussed by Zeng and Zhang (1998) involves taking the similarity coefficient of two fields as the similarity measurement in order to define the seasonal classification standard of the atmospheric circulation. The anomaly correlation coefficient (ACC) is used as a similarity measurement method, and also to measure the similarity degree of two spatial fields (Shi 2009; Wang et al. 2009, 2015).

3 Classification of typical summer rainfall patterns in the East China monsoon region

Table 1 shows the years of the four rainfall patterns in East China monsoon region (Sun et al. 2005; Wang and Huang 2006). In the classification results from Sun et al. (2005) during 1951–2002, rainfall patterns 1 (NCP), 2 (IRP), 3 (YRP), and 4 (SCP) occurred for 20, 15, 9, and 8 years, respectively. In the classification results from Wang and Huang (2006) during 1951–2005, patterns 1, 2, 3, and 4 occurred for 15, 14, 16, and 10 years, respectively. Twelve years (accounting for 23.1 %) are not inconsistent with the pattern classification results of Sun et al. (2005) for 1951–2002. Because the two different methods were used, there are different classification results for some of the years.

The specific division methods were not introduced by Sun et al. (2005), and the division was terminated in 2002. However, the rainfall patterns are divided by Wang and Huang (2006) with a higher subjectivity only according to the locations of the annual maximum rainfall anomaly percentages. Therefore, the method of similarity measurement was chosen to objectively re-divide the summer rainfall patterns in the East China monsoon region in this study. The specific division steps are as follows.

Step 1: Composite the summer rainfall anomaly percentage (focusing mainly on the 120 stations to the east of 105° E) of NCP, IRP, YRP, and SCP years from Sun et al. (2005), from 1951 to 2002. Then, calculate the ACC between the annual summer rainfall anomaly percentage field from 1951 to 2002 and the composition summer rainfall anomaly percentage field of the four rainfall patterns. The leading 5 years with maximum ACC are selected from each rainfall pattern. Then, the 5 years are selected as the typical years for each rainfall pattern, respectively (Table 2).

The rainfall anomaly percentages for the five typical years of each rainfall pattern are composited as the typical field for the four rainfall patterns (Fig. 1). In the NRP years (Fig. 1a), the main rain belt of East China is located in the Yellow River Basin and the region to the north, with a positive anomaly center in North China, while the Yangtze River Basin has less

Table 1 Classification of four rainfall patterns in the summer over the East China from 1951 to 2005. 1, 2, 3, and 4 indicate NCP, IRP, YRP, and SCP, respectively. And the italic numbers indicate the different classification results between Sun et al. (2005) and Wang and Huang (2006)

Year	Sun et al. (2005)	Wang and Huang (2006)	Year	Sun et al. (2005)	Wang and Huang (2006)	Year	Sun et al. (2005)	Wang and Huang (2006)
1951	*2*	*3*	1970	*1*	*3*	1989	2	2
1952	4	4	1971	2	2	1990	1	1
1953	1	1	1972	*2*	*4*	1991	*3*	*2*
1954	3	3	1973	1	1	1992	1	1
1955	*2*	*3*	1974	*2*	*3*	1993	*4*	*3*
1956	2	2	1975	*1*	*3*	1994	4	4
1957	2	2	1976	*1*	*4*	1995	1	1
1958	1	1	1977	*1*	*3*	1996	3	3
1959	1	1	1978	1	1	1997	4	4
1960	*2*	*4*	1979	1	1	1998	3	3
1961	1	4	1980	3	3	1999	*4*	*3*
1962	2	2	1981	1	1	2000	2	2
1963	2	2	1982	2	2	2001	4	4
1964	1	1	1983	3	3	2002	4	4
1965	2	2	1984	2	2	2003		2
1966	1	1	1985	1	1	2004		2
1967	1	1	1986	3	3	2005		2
1968	4	4	1987	3	3			
1969	3	3	1988	1	1			

Table 2 The leading five typical years of the four rainfall patterns in the summer over East China

Rainfall patterns	Typical years (ACC)
Rainfall pattern 1(NCP)	1978(0.72), 1959(0.67), 1967(0.66), 1976(0.64), 1961(0.62)
Rainfall pattern 2(IRP)	1963(0.64), 1971(0.61), 1960(0.57), 1957(0.48), 1965(0.44)
Rainfall pattern 3(YRP)	1954(0.72), 1969(0.70), 1998(0.55), 1991(0.51), 1980(0.47)
Rainfall pattern 4(SCP)	2002(0.70), 1997(0.67), 1968(0.59), 2001(0.57), 1994(0.54)

rainfall in a wide range. In the IRP years (Fig. 1b), the main rain belt is located between the middle and lower reaches of the Yellow River and Yangtze River, with the positive anomaly center falling in the Huaihe River Basin. Meanwhile, more rainfall occurs in northeast China, and less rainfall occurs in the west of North China and the areas to the south of the Yangtze River. In the YRP years (Fig. 1c), the main rain belt is located in the Yangtze River Basin, and the east of North China and northeast China has more rainfall, while the west of North China and South China has less rainfall. In the SCP years (Fig. 1d), the main rain belt is located in South China, including the regions south of the Yangtze River. And more (less) rain occurs in the west of North China (the regions south of North China to the Yangtze River Basin). That is, there are generally two rain belts in SCP years.

Step 2: Calculate the ACC between the typical field for the four rainfall patterns and the annual summer rainfall anomaly percentage fields of 120 stations from 1951 to 2015. The ACC is taken as a measurement for the rainfall pattern classification (Fig. 2). The red histograms in Fig. 2a–d represent the NCP, IRP, YRP, and SCP years divided by Sun et al. (2005), respectively. Because the sample size in this spatial field is 120, an ACC greater than 0.187 indicates a confidence level of 95 %. ACC of +0.187 is taken as the standard threshold (blue solid line in Fig. 2). If the ACC exceeds this threshold, the annual summer rainfall distribution is determined to belong to this rainfall pattern. It is determined that the greater the ACC, the

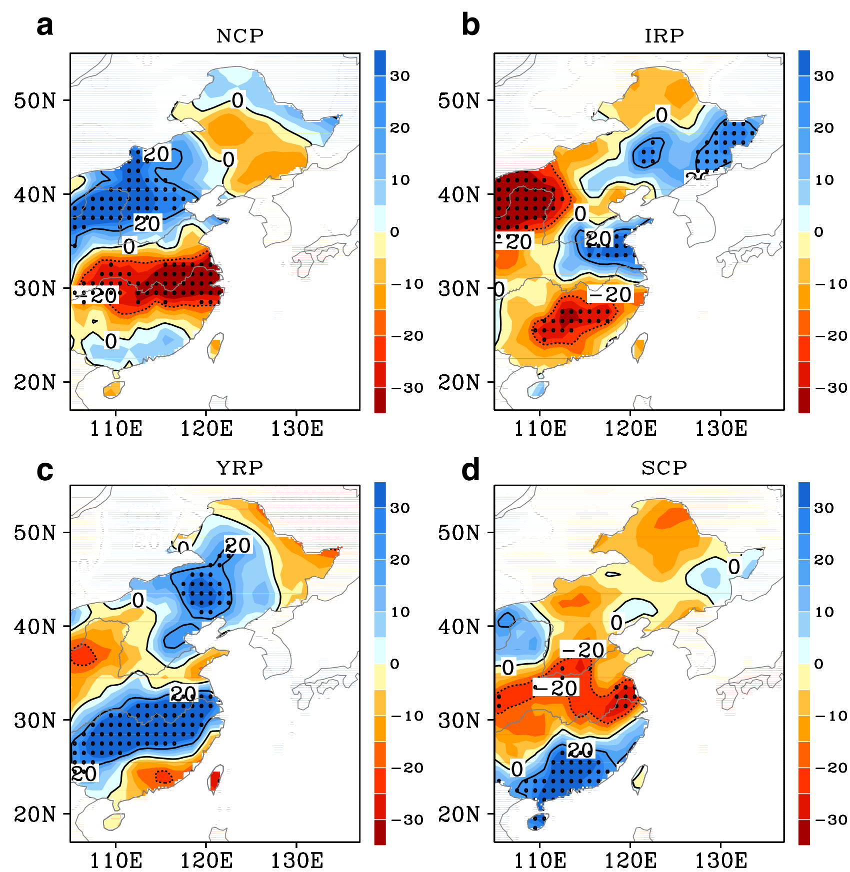

Fig. 1 The summer (JJA-averaged) precipitation anomaly percentage compositions of the five typical years of **a** NCP, **b** IRP, **c** YRP, and **d** SCP in East China. The *black spots* indicates the significant correlations above the 95 % confidence levels

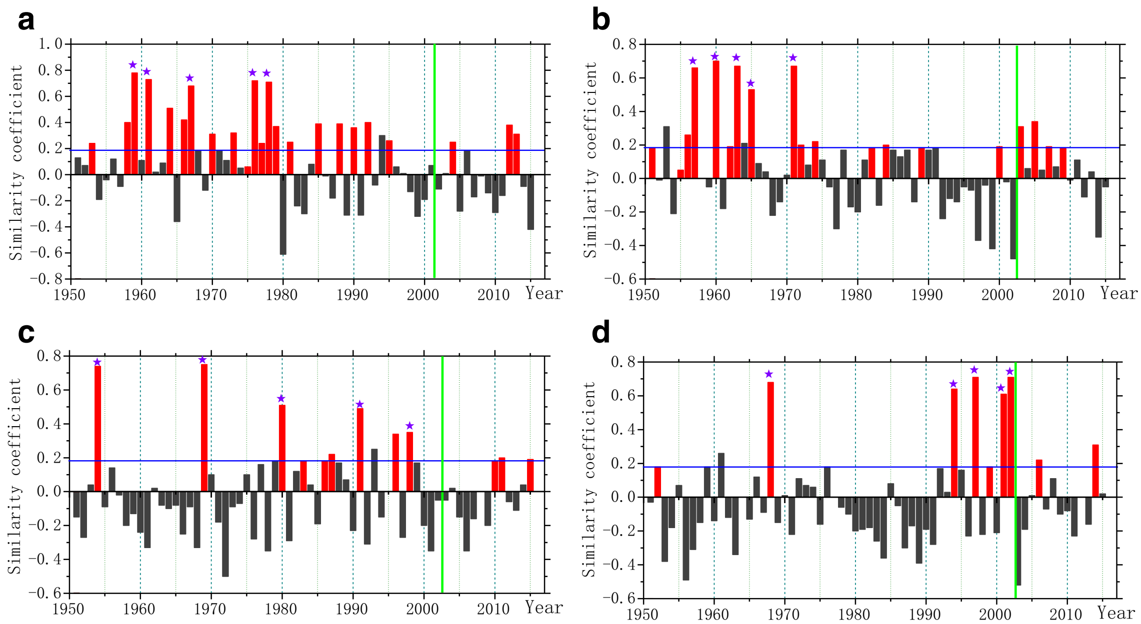

Fig. 2 The ACC between the yearly summer precipitation anomaly percentage fields of 1951–2015 and the summer precipitation anomaly percentage of **a** NCP, **b** IRP, **c** YRP, and **d** SCP in East China. The *pentagram* indicates the typical rainfall pattern years in Table 2. The *blue line* indicates a 95 % confidence level. The *red bars* indicate the pattern as divided by Sun et al. (2005)

more significant the distribution characteristics of such a rainfall pattern in this year, and the more typical the rainfall pattern would be. When the ACC is less than the standard threshold or negative, this indicates that particular year represents fewer or no distribution characteristics of such a rainfall pattern. When the ACC of a certain year reaches the standard of two (or three) rainfall patterns, screening and classification are carried out according to the summer rainfall anomaly percentage figure.

As shown by the red histograms in Fig. 2a, there are 19 years with ACC exceeding the critical threshold for the 20 NRP years defined by Sun et al. (2005) from 1951 to 2002, except for 1975. There are 3 years (2004, 2012, and 2013) with ACC exceeding the critical threshold during 2003–2015, and they are classified as NRP years in this study.

As shown by the red histograms in Fig. 2b, among 15 IRP years from 1951 to 2002, there are 14 years (except for 1955) with ACC exceeding the critical threshold. From the summer rainfall anomaly percentage figures in 1955 (Fig. 3a), there are scattered positive anomaly centers in eastern China that display atypical rainfall pattern characteristics. There are 5 years (2000, 2003, 2005, 2007, and 2009) with ACC exceeding the critical threshold from 2003 to 2015, and they are classified as IRP years in this study.

As shown by the red histograms in Fig. 2c, among 9 YRP years defined by Sun et al. (2005) from 1951 to 2002, there are 8 years (except for 1986) with ACC exceeding the critical threshold. In the summer rainfall anomaly percentage figure of 1986 (Fig. 3b), a positive (negative) anomaly is located in the east of North China and northeast China (the west of North China and South China). That is, 1986 displays more obvious characteristics of NCP. Moreover, the ACC of 1993 is also up to the standard. From the summer rainfall anomaly percentage figure of 1993 (Fig. 3c), showing multiple areas with more rain in East China, the maximum positive center is located in the middle reaches of the Yangtze River and the southward extension to the areas south of the Yangtze River. This led to the relatively obvious characteristics of YRP. There are 3 years (2010, 2011, and 2015) with ACC exceeding the critical threshold from 2003 to 2015, and they are classified as SCP years in this study.

As shown by the red histograms in Fig. 2d, among the 8 SCP years between 1951 and 2002, there are 7 years with ACC exceeding the critical threshold, except for 1993 (for which the ACC is 0.02). There are 2 years (2006 and 2014) with ACC exceeding the critical threshold from 2003 to 2015, and they are classified as SCP years in this study.

In addition, there are three years (1955, 1975, and 2008) with ACC with the four rain patterns that do not reach the critical threshold. When viewed from the summer rainfall anomaly percentage figures in East China for these years, multiple rainfall centers are found to have existed in East China. The rainfall pattern characteristics of these years are not obvious or typical. Additionally, the summer atmospheric circulation systems of these years are not very stable and strong seasonal oscillations are experienced, leading to the

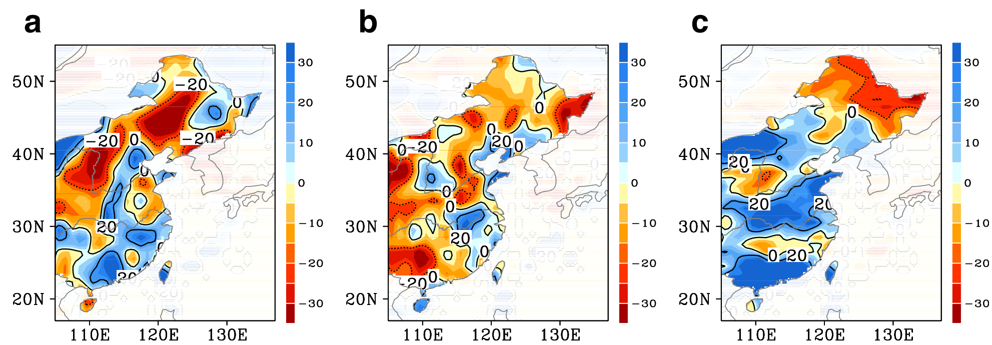

Fig. 3 The summer precipitation anomaly percentage of atypical pattern year. **a** 1955, **b** 1975, and **c** 2008

irregular distribution of droughts and floods. Therefore, the formation mechanism and the predictions of the four rainfall patterns will be affected if these years are included in the four rainfall patterns. As a result, these years are classified as atypical rainfall pattern years in this study.

The rainfall patterns in East China from 1951 to 2015 are reclassified according to the similarity measurement method in this study (Table 3). In our rainfall pattern classification results, there are 48 years that are consistent with the divided by Sun et al. (2005), among the 52 years from 1951 to 2002. The concordance rate is 92.3 %. The typical NCP has 23 years (accounting for 35.4 % of the total years), which occurred mainly in the late 1950s to the early 1990s. The typical IRP has 18 years (accounting for 27.7 %), which occurred mainly in two stages: the late 1950s to the early 1970s and the 2000s. Twelve years classified as YRP (accounting for 18.5 %) occurred mainly in the 1980s to 1990s. Nine years are classified as SCP (accounting for 13.8 %), which occurred mainly in the mid-1990s to the early 21st century. There are 3 years with atypical rainfall patterns, which account for 4.6 % of the total years. Therefore, the periods of the four rainfall patterns have significant decadal variability. This conclusion is consistent with Zhao et al. (2008). And previous studies suggested that the decadal variability of summer rain pattern in China is influenced by the Pacific Decadal Oscillation (PDO; Zhu and Yang 2003; Liu 2012), EASM (Ding et al. 2008), and other climatic factors.

4 East Asian summer monsoon and four rainfall patterns

One of the prominent features of the EASM is the rainfall concentration in a nearly east-west-elongated rain belt (Wang et al. 2008). The rain belt is associated with a quasi-stationary subtropical front that is the primary rain-producing system in the EASM. The relationship between the EASM and China's summer rainfall manifests itself on the north-south position of the rain belt. The position of the summer belt is northward when the monsoon is strong and southward when the monsoon is weak (Shi and Zhu 1996). To our knowledge, many EASM strength indices have been proposed to measure the EASM intensity (Shi and Zhu 1996; Wang and Fan 1999; Wang 2001; Li and Zeng 2002; Zhu et al. 2005; Wang et al. 2008). Wang et al. (2008) elaborated on the climatic meanings of the existing EASM indices and examined their relationships to the large scale precipitation and circulation anomalies associated with the EASM. They also recommended a simple index, the reversed Wang and Fan (1999) index (EASM I_{WF}), which is nearly identical to the leading principal component of the EASM and greatly facilitates real-time monitoring. Therefore, we used the EASM I_{WF} to analyze the relationship between the four rainfall patterns and EASM.

Figure 4a shows the relationship between the four rainfall patterns and EASM I_{WF}. It can be seen that (1) when the EASM I_{WF} is positive (strong summer monsoon), mostly NCP (15/39), IRP (13/39) or SCP (9/39) is experienced, and YRP

Table 3 Classification of typical four rainfall patterns in the summer over the East China monsoon region during 1951–2015

Rain pattern	Years	Sample number	Frequency (%)
NCP	53, 58, 59, 61, 64, 66, 67, 70, 73, 76, 77, 78, 79, 81, 85, 86, 88, 90, 92, 95, 04, 12, 13	23	35.4
IRP	51, 56, 57, 60, 62, 63, 65, 71, 72, 74, 82, 84, 89, 00, 03, 05, 07, 09	18	27.7
YRP	54, 69, 80, 83, 87, 91, 93, 96, 98, 10, 11, 15	12	18.5
SCP	52, 68, 94, 97, 99, 01, 02, 06, 14	9	13.8
Atypical pattern	55, 75, 08	3	4.6

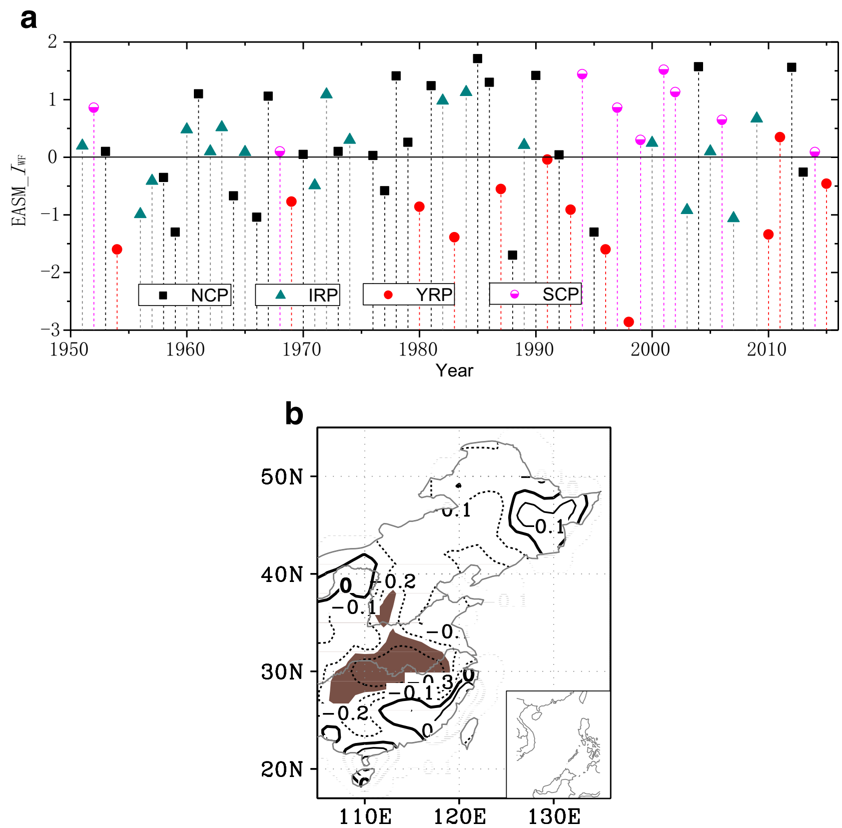

Fig. 4 **a** The relationship between the EASM I_{WF} and the four rainfall patterns, and **b** the correlation coefficient between the EASM I_{WF} and summer rainfall in East China during 1951–2015. 1, 2, 3, and 4 in **a** indicate NCP, IRP, YRP, and SCP, respectively. The shading in **b** indicates the significant correlations above the 95 % confidence levels

(1/39, that is 2011) seldom occurs. When the EASM I_{WF} is negative (weak summer monsoon), mostly YRP (11/26) or NCP (8/26) is experienced, and IRP (5/26) or SCP (0/26) seldom occurs; (2) when East China experiences NCP, IRP, or SCP in summer, the EASM I_{WF} mainly shows a positive phase (15/24, 13/18, or 9/9, respectively) and a strong summer monsoon. When East China experiences YRP in the summer, the EASM mainly shows a negative phase (11/12) and a weak summer monsoon. This suggests that the strong (weak) EASM pushes the rain belt farther north (south).

In Fig. 4b, we show the correlation coefficient between the EASM I_{WF} and summer rainfall in East China between 1951 and 2015. There is a significantly negative correlation in the Yangtze River Basin. That is, wet years over the Yangtze River Basin are related to a weak monsoon, whereas with a strong summer monsoon, dry years are often observed.

5 Summary

In this study, based on the summer rainfall observations at 120 stations in the East China monsoon region, a similarity measurement and other methods were adopted in combination with previous research for objective reclassification of rainfall patterns from 1951 to 2015. The specific conclusions of this research study are as follows.

Four typical rain patterns were classified: the northern China rainfall pattern (NCP), the intermediate rainfall pattern (IRP), the Yangtze River rainfall pattern (YRP), and the South China rainfall pattern (SCP) in the East China monsoon region. The periods of these four rainfall patterns have significant decadal characteristics. The NCP occurred mainly between the late 1950s and the early 1980s, and the IRP occurred mainly in the late 1950s to the early 1970s and the 2000s. The YRP occurred mainly between the 1980s and the 1990s, and the SCP occurred mainly between the mid-1990s and the early 21st century.

The relationship between the East Asian summer monsoon index (EASM I_{WF}) and the four rainfall patterns was comparatively analyzed. The results confirmed that the four rainfall patterns have obvious differences in the EASM. In the NCP, IRP, or SCP years, the EASM I_{WF} primarily shows a positive phase and a strong summer monsoon; in the YRP years, the EASM primarily shows a negative phase and a weak summer monsoon. The strong (weak) EASM pushes the rain belt farther north (south). Wet years over the Yangtze River Basin are related to a weak monsoon, whereas with a strong summer monsoon, dry years are often observed.

Clearly, the EASM has a good matching relationship with the four rainfall patterns. However, there are still some discrepancies;

for example, why do some NCP years (e.g., 1959, 1966, 1988, and 1995) have a very weak EASM, and why do all SCP years have a strong EASM? As it is well known, the EASM is a prominent factor in precipitation and circulation anomalies over East Asia, but it is not the only one. Many studies have shown that the El Niño Southern Oscillation (ENSO) (Kinter, et al. 2002; Yuan and Yang 2012; Yang and Jiang 2014) and the extratropical atmospheric circulation in the Northern Hemisphere (Yang, et al. 2002; Sung, et al. 2009; Wang, et al. 2010; Zhao, et al. 2016) also play important roles in precipitation and circulation anomalies over East Asia. Therefore, in future work, we will analyze the other components of the Asian climate system associated with the four rainfall patterns.

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