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Inter-decadal variability of summer rainfall in Eastern China detected by the Lepage test

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Abstract On the basis of the latest observational datasets, the inter-decadal changes of summer rainfall in East China in the past 50 years are analyzed using the Lepage test. The two traditional methods moving t-test and Mann-Kendall test are also performed on the rainfall data as a comparison. Results indicate four inter-decadal abrupt changes of summer rainfall that occurred near 1979, 1983, 1993, and 1999, and each of them is characterized by remarkable regional features. The abrupt change of summer rainfall around 1979 is accompanied by significant rainfall increase in Yangtze–Huai River Valley and a decrease in its flank. The one near 1983 shows similar structures of the rainfall changes to that near 1979, but with more significant changes in the South China and Northeast China (NEC). The inter-decadal change around 1993 brings a notable increase of summer rainfall to the South China; and the abrupt shift near 1999 exhibits significant decrease in summer rainfall over a large part of North China and NEC. The spatial–temporal features of the inter-decadal changes in summer rainfall are also investigated. Consistent results are observed. Moreover, results indicate that, on the inter-decadal scale, the rainfall variability mode changes from typical tripole to dipole structure since the early 1990s.

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1 Introduction

The variability of rainfall in China exhibits complex spatial–temporal structure and is characterized by large interannual and inter-decadal variability (Chen et al. 1992, 2004; Nitta and Hu 1996; Huang et al. 2003; Yang and Lau 2004; Ding and Chan 2005). Large interannual variability often causes precipitation to vary from year to year as well as region to region. While the inter-decadal and longer time scales variability always bring persistent drought and flood, such changes of rainfall have great impacts on the regional social and economic development, especially during summer when the rainfall amount accounts for nearly 40–80% of the total annual rainfall (Fig. 1). For example, since the 1970s, persistent drought has occupied most parts of Northern China (NC). Meanwhile, it has been reported that due to enhanced rainfall since 1990, the occurrence of floods has increased along the Yangtze River (Gong and Ho 2002; Wang et al. 2004), like those which occurred in 1991, 1996, 1998, 1999, 2003, and 2010. Both of them caused huge losses to the people and society. Thereby, studying the inter-decadal variability of rainfall in China and understanding the underlying mechanism are of great significance, which have attracted more and more attentions from the public.

Numerous studies have indicated that rainfall over China has experienced significant inter-decadal changes. Three major notable changes have been identified, which occurred around the late 1970s, early 1990s, and late 1990s, respectively. Each shows typical regional features of rainfall changes. For example, the change around the late 1970s is accompanied by significant increase of summer rainfall in the Yangtze River Valley (Nitta and Hu 1996; Gong and Ho 2002; Chen et al. 2004; Li et al. 2004; Ding et al. 2008; Qian and Qin 2008; Yao et al. 2008) and
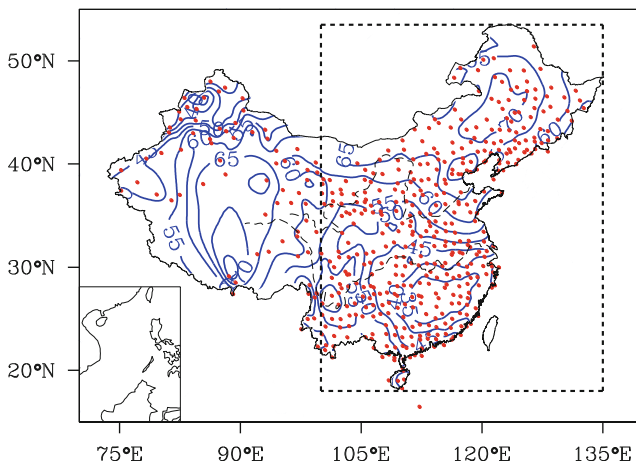
Fig. 1 Geographical distribution of the ratio (in percent) of JJA rainfall to annual total rainfall in China for the period 1958–2009. *Red dots* denote the 496 weather stations. The *dashed rectangular area* represents the domain covered in the study

prolonged drought in North China (Huang et al. 1999, 2003, 2011; Li et al. 2004; Ding et al. 2008; Qian and Qin 2008; Yao et al. 2008; Tu et al. 2010), a decrease in late spring rainfall in southern China (SC) during the late 1970s (Xin et al. 2006), and an increase in summer rainfall in northwest China (Shi et al. 2007; Zhou and Huang 2010). Another significant change marks a notable increase of summer rainfall over southern China around 1992–1993 (Ding et al. 2008; Qian and Qin 2008; Yao et al. 2008; Wu et al. 2010). As for the change around the late 1990s, Zhu et al. (2010) and Huang et al. (2011) pointed out that the summertime rainfall over the northern part of Eastern China showed an abrupt change associated with sharp rainfall decrease since the late 1990s.

Aforementioned studies were largely achieved based on regional mean rainfall or empirical orthogonal function (EOF) analysis over one area concerned, which were subject to area selection. However, in light of the complexity of spatial–temporal summer rainfall variability over China, it is difficult to describe the complex rainfall structure simply with a regional average of precipitation. And, the EOF method also shows spatial limitations. Thus, to investigate the inter-decadal features of the rainfall change over China more objectively and to avoid the drawbacks in selecting the climate regime, some effective methods are required.

One such method is the Lepage test statistic (Lepage 1971). The Lepage test has been demonstrated more statistically powerful than other similar tests, such as the Student's t test, the chi-square test, and the Wilcoxon–Mann–Whitney test (Hirakawa 1974). This method has few underlying assumptions and has been widely adopted to detect kinds of types of climate changes including linear

trends, cyclical variations, step-like changes, and discontinuous changes (Yonetani 1992, 1993; Yonetani and McCabe 1994; Kwon et al. 2007; Yang et al. 2009). However, it has never applied to the study of the rainfall variability over China. The present study will use this method and the latest observation datasets to investigate the inter-decadal variability of the summer rainfall over Eastern China, and aims to achieve and provide a comprehensive understanding the features of the inter-decadal rainfall changes over Eastern China in the past 50 years. In addition, results with two traditional methods in detecting abrupt climate change such as moving t-test (MTT) and Mann–Kendall test (symbol as MK, Mann 1945; Kendall 1975) are given as a comparison in this paper.

2 Data and methods

The daily observational rainfall dataset of 756 weather stations in mainland China are used in this study, which is provided by the National Meteorological Information Center of Chinese Meteorological Administration, spanning the period 1951–2009. To achieve temporal continuity in terms of coverage from each station, 496 stations (Fig.1) with shorter period of 1958–2009 are chosen from the data archive. Owing to the inhomogeneous distribution of the stations in the mainland, this study is concerned with East China, in the domains of 100–136° E, 18–55° N, including in total 423 stations that are relatively homogeneously distributed (rectangle area in Fig. 1).

The Lepage test statistic is employed to evaluate the statistical significance of inter-decadal change. It is a nonparametric, two-sample test for location and dispersion, and for significant difference between two samples, even if the distributions of parent populations are unknown. The Lepage test [HK, symbol used by Yonetani and McCabe (1994)] is a combination of the squares of the standardized Wilcoxon's and Ansari–Bradley's statistics (Eq. 1).

$$HK = \frac{[W - E(W)]^2}{V(W)} + \frac{[A - E(A)]^2}{V(A)} \qquad (1)$$

It follows the chi-square distribution with two degrees of freedom. If HK exceeds 5.99 (4.21, 9.21), then the difference between two sample means corresponds to a significant confidence level of 95% (90%, 99%). The Lepage test is calculated as follows. Let $x=(x_1, x_2,..., x_{n1})$ and $y=(y_1, y_2,..., y_{n2})$ be two independent samples with sizes n_1 and n_2, respectively. $XY=(x_1, x_2,..., x_{n1}, y_1, y_2,..., y_{n2})$ is the combined sample of x and y. Assume that $u_i=1$ if the ith smallest data in XY belongs to x and $u_i=0$ if it belongs to y.

The statistics in Eq. 1 can be derived based on the following equations:

$$W = \sum_{i=1}^{n_1+n_2} i u_i \tag{2}$$

$$E(W) = \frac{n_1(n_1 + n_2 + 1)}{2} \tag{3}$$

$$V(W) = \frac{n_1 n_2 (n_1 + n_2 + 1)}{2} \tag{4}$$

$$A = \sum_{i=1}^{n_1} i u_i + \sum_{i=n_1+1}^{n_1+n_2} (n_1 + n_2 - i + 1) u_i \tag{5}$$

If $n_1 + n_2$ is even, $E(A)$ and $V(A)$ are estimated as:

$$E(A) = \frac{n_1(n_1 + n_2 + 2)}{4} \tag{6}$$

$$V(A) = \frac{n_1 n_2 (n_1 + n_2 - 2)(n_1 + n_2 + 2)}{48(n_1 + n_2 - 1)} \tag{7}$$

Otherwise,

$$E(A) = \frac{n_1(n_1 + n_2 + 1)^2}{4(n_1 + n_2)} \tag{8}$$

$$V(A) = \frac{n_1 n_2 (n_1 + n_2 + 1)\left[(n_1 + n_2)^2 + 3\right]}{48(n_1 + n_2)^2}. \tag{9}$$

In this paper, the Lepage test was performed on the summer rainfall data from the 423 weather stations in Eastern China. The calculation of HK consulted the paper of Yonetani and McCabe (1994). Intervals of data along each single time series are compared in the following manner: data for N years previous to a specified year Y_c (sample a) is compared to the data for year Y_c plus the $N-1$ years following year Y_c (sample b). The year Y_c is moved successively at 1-year increments along the time series, and the Lepage test is conducted for each year Y_c. Here, we choose period $N=9$ to test the inter-decadal changes, and for each Y_c, the number of weather stations indicating a significant change beyond 95% confidence level in rainfall anomaly was calculated.

Likewise, for a comparison, the MTT, a method for significant difference between two sample means, was applied on the rainfall data, and the number of weather stations calculated. The MK method is also performed on the regional mean rainfall based on the area detected.

3 Results

As previous studies revealed, the abrupt rainfall changes showed notable regional features, it is expected that there will be an abrupt increase in the number of the stations that the Lepage test suggests a significant change in the summer rainfall (blue curve in Fig. 2a). Figure 2a illustrates the time evolution of the number of stations with significant rainfall change beyond 95% confidence level. Clearly, the time variations show sharp increases in number and have four noticeable peaks observed at specific years of 1979, 1983, 1993, and 1999, including 31, 33, 47, and 40 stations, respectively. Thus, it can be concluded that, based on the Lapage test, the summer rainfall in Eastern China experienced remarkable inter-decadal changes around 1979, 1983, 1993, and 1999. The four abrupt shift periods agree well with previous studies (Gong and Ho 2002; Inoue and Matsumoto 2007; Ding et al. 2008; Zhu et al. 2010; Huang et al. 2011). Here, it should be mentioned that, as the inter-decadal changes feature typical regional structure, the shift period may vary from region to region, so the period around 1983 is credibly achieved 4 years following that around 1979.

However, results in Fig. 2a also reveal several peaks with less station number such as around the late 1960s, 1972, and 1977 whether they represent shift periods. And what about the spatial–temporal features of the inter-decadal changes? This needs further analysis. Therefore, in order to demonstrate the spatial–temporal features of the inter-decadal changes of summer rainfall in Eastern China, the Lepage test is applied to the meridional averaged summer rainfall within 100–136° E. As shown in Fig. 2b, four significant abrupt changes of summer rainfall in East China emerge in the past 50 years, having abrupt shift periods (regions) in the late 1970s [Yangtze–Huai River Valley (YHR) and South China], early 1980s [Northeast China (NEC)], early 1990s (South China), and late 1990s (North China and Northeast China), respectively, which are consistent with the above analysis, though an abrupt shift around the late 1960s over NEC is obtained as well.

The results detected by the MTT show considerable similarity to those by Lapage test, except that, corresponding each shift period, the number of stations (Fig. 2a red curve) and the areas (Fig. 2c) exceeding 95% confidence level are larger, which may be due to different test method. Hereto, we can conclude that the summer

Fig. 2 a Time variations of the number of stations where the Lepage test (MTT) reveals the difference between the averages of summer rainfall over 9 years prior to and from the period Y_c significant beyond the 95% confidence level. **b** Time–latitude cross-section of the sliding Lepage test (HK) of JJA mean rainfall longitudinally averaged between 100° E and 136° E. *Shaded areas* denote the HK exceeding a significant level of 95%. *Positive* (*negative*) means the 9-year mean rainfall from the Y_c is greater (less) than that prior to the Y_c. **c** Same as **b** but for MTT
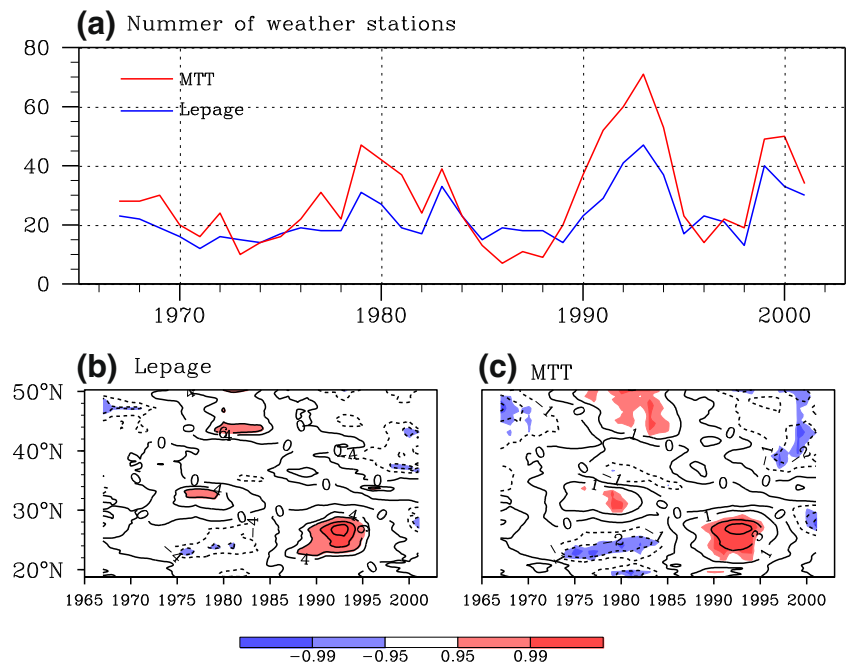
rainfall in Eastern China experienced four remarkable inter-decadal changes with shift period around 1979, 1983, 1993, and 1999, respectively. And notably, around the late 1970s and early 1980s, the 9-year mean summer rainfall anomalies underwent a sign shift with quadrupole structure ("−+−+"), suggesting significant inter-decadal change occurred over the whole part of Eastern China. In addition, it can be seen that on the inter-decadal scale, the rainfall variability mode changes from typical "tripole" (previous study area often focused on the domain south of 42° N) to dipole structure since the early 1990s.

The spatial differences of the inter-decadal changes in summer rainfall corresponding to the four periods Y_c are shown in Fig. 3, and the location of associated stations beyond 95% confidence level detected by Lepage test is displayed as well. Figure 3a reveals the spatial feature of rainfall difference between 1979–1987 and 1970–1978. A notable quadrupole structure of rainfall changes presents over East China, having positive anomalies in YHR and the NEC, and negative in SC and NC. The stations with significant rainfall changes around 1979 are mainly located in Yangtze–Huai River Valley. This is consistent with the earlier finding by Gong and Ho (2002).

For the period around 1983, as shown in Fig. 3b, the structure of rainfall changes resembles Fig. 3a but with narrowed positive anomaly region in Yangtze–Huai River Valley, and the stations with evident rainfall changes situates mostly in South China and Northeastern China. Figure 3c exhibits the features of rainfall changes 9 years from and prior to 1993. Remarkably, it reveals an abrupt increase of summer rainfall in South China, having almost all the locations over the region, confirming the earlier

finding by Ding et al. (2008), Yao et al. (2008), and Wu et al. (2010). The magnitude of this increase is much larger than that seen around the above two periods.

Figure 3d displays the features of abrupt rainfall changes around 1999. The summer rainfall over the north part of the mainland China experiences a distinct decrease, and that shows opposite shift trends over Huai River and Yangtze River Valley, with positive over Huai River and negative over Yangtze River. The stations with significant changes are mostly located over the areas of North China and Northeast China. Thus, the Lepage test indicates an abrupt change in summer rainfall in North China and Northeast China, which agrees well with Zhu et al. (2010) and Huang et al. (2011).

At the end, aiming to validate the results revealed by the Lepage test, the time series of regional-averaged summer rainfall over the four regions of Eastern China: SC (20–28° N), YRH (28–36° N), NC (36–42° N), and NEC (42–50° N) are depicted in Fig. 4a–d. Results in Fig. 4a–d reveal that rainfall corresponding each region experiences notable inter-decadal changes and remarkable coherency with those by the Lepage test. For instance, the summer rainfall over SC (Fig. 4a) indicates abrupt increase around 1993, with above normal and below normal rainfall anomalies after and prior to 1993, respectively. And comparing the 9-year-averaged summer rainfall over SC before and after 1979, significant difference can be obtained as well. The time series in Fig. 4b displays the variability of rainfall in YRH. It also exhibits clear inter-decadal change and has notable rainfall increase since the late 1970s. Fig. 4c shows a prolonged decrease of rainfall over NC from the mid-1960s, with slight increase during the mid-1990s and significant

Fig. 3 The distributions of the difference between 9-year-averaged JJA mean rainfall from and prior to the period Y_c indicated in each figure (*shaded areas with white contour*). The corresponding weather stations significant beyond 95% confidence level to each Y_c are also plotted (*blue dots*)
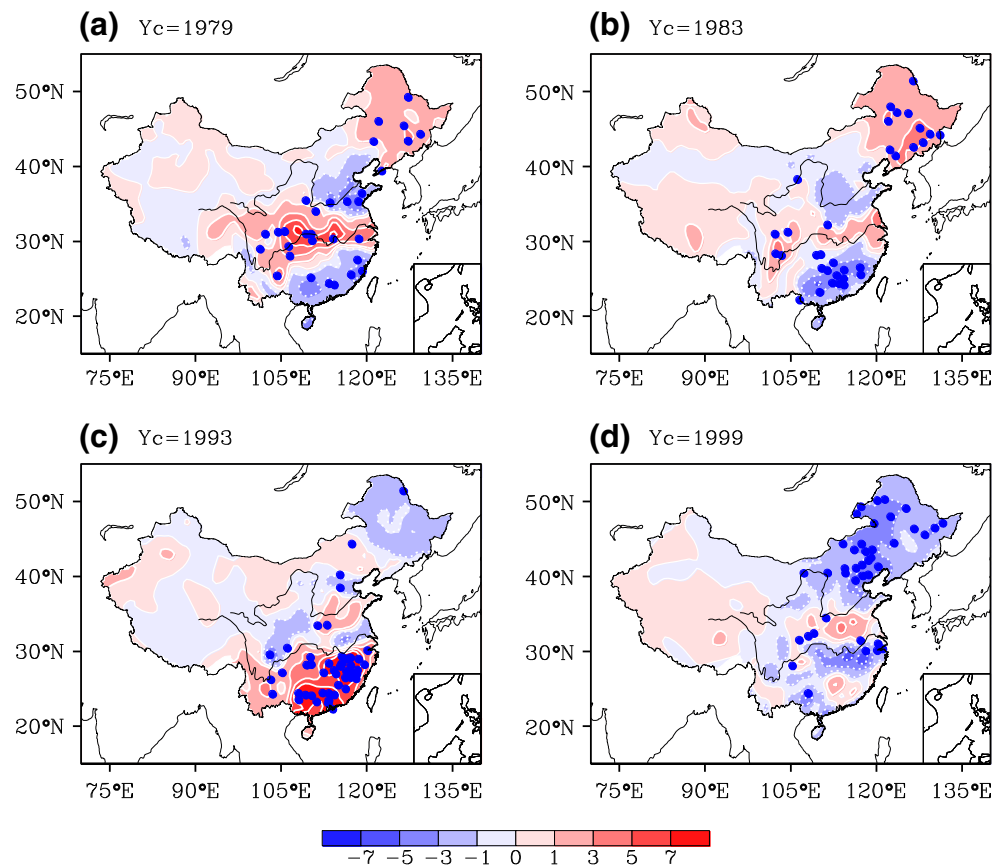
decrease since the late 1990s. The rainfall variation over NEC (Fig. 4d) reveals large inter-decadal variability and has abrupt changes around the late 1960s, early 1980s, and late 1990s, showing sharp decrease since the late 1990s.

Moreover, as a comparison, the MK test is performed on the time series of each region to test the abrupt changes. The forward and backward statistic rank series (UF and BF) in the MK test are depicted in Fig. 4e–f. Based on the principle of MK, if the cross point of UF and BF is within ±1.96 which corresponds to the 95% significance level, the associated time indicates the start of an abrupt change. Thereby, with respect to Fig. 4e–f, the cross points associated to each region can be identified: SC (1993), YRH (1979), NC (1979), and NEC (1967, 1999, 2005). Although it seems to be hard to decide the start of an abrupt when the UF and BF cross several points, and the shift period around 1983 over NEC is not captured, the shift periods detected mostly agree well with those by Lapage test and MTT.

4 Conclusions and discussion

On the basis of the latest observational datasets, the inter-decadal changes of summer rainfall in East China in the past 50 years are analyzed using the Lepage test. The two traditional methods MTT and MK are also performed on the rainfall data as a comparison. Results indicate four inter-decadal abrupt changes in summer rainfall with periods near 1979, 1983, 1993, and 1999, and these changes are associated with remarkable regional features.

The abrupt change around 1979 is accompanied by significant increase of summer rainfall in Yangtze–Huai River Valley and decrease in its flank. The abrupt shift near 1983 shows similar structures of rainfall changes to that near 1979, except that it primarily occurs in the Northeast China. The inter-decadal change around 1993 brings a notable increase of summer rainfall to the South China, and that near 1999 exhibits significant decrease in summer rainfall over a large part of North China and Northeast China. The spatial–temporal features of the inter-decadal changes in summer rainfall are also investigated by applying the Lapage test and MTT on the meridional mean summer rainfall in East China. Consistent results are observed that summer rainfall in East China experiences four inter-decadal changes, and each change shows significant rainfall differences varying from region to region. And, it can be seen that the mode of inter-decadal variability in summer rainfall changes from typical "tripole" to dipole structure since the early 1990s.

The three methods are widely used in the climate research, have powerful performance on the abrupt change

Fig. 4 **a–d** Normalized time series (*solid lines*) of JJA mean rainfall averaged in the four domains denoted as SC, YHR, NC, and NEC. The *dashed lines* elucidate the associated 9-year running averaged time series. **e–h** MK statistics for each time series
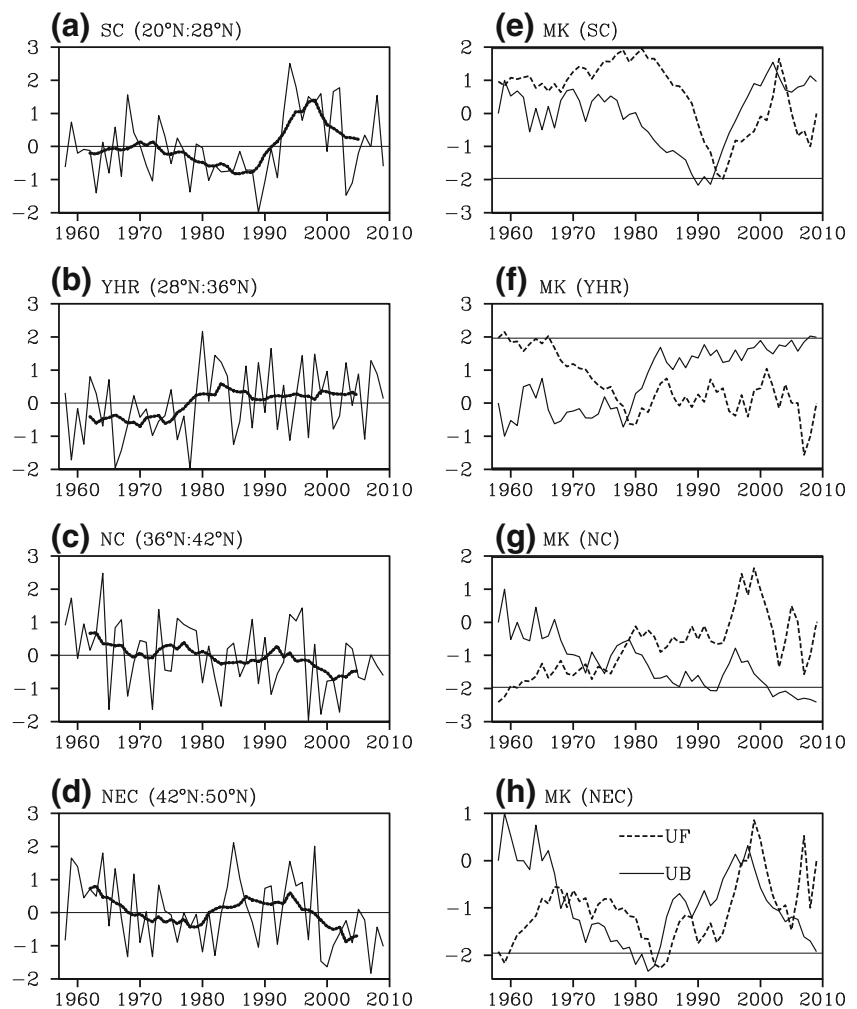
detection, and show great similarity between them, especially between Lapage test and MTT, which has been confirmed by the present study. However, they still exhibit limitations. For example, the results tested by MK depend on the area selection. It often brings uncertainty to the decision on the change point and could not illustrate the spatial evolutions of the rainfall change as well. The result by Lepage test (MTT) is able to present the spatial–temporal evolution of the rainfall changes, but it is based on the selected moving window, which is subject to the sample size, the longer time scale changes may not be addressed quite well. While, for this study, the window ($N=9$) is reasonable and results could credibly represent the inter-decadal scale changes.

As a main contributor to the variation of the summer rainfall in Eastern China, the inter-decadal variability has always been a hot topic in climate study. Plenty of works had been paid to the study on the possible causes. Results indicated that the inter-decadal changes of summer rainfall over Eastern China were coincident with significant abrupt climate changes in other regions or other variables. For

example, the shift around the late 1970s is accompanied by large-scale inter-decadal changes in sea surface temperature (SST) and atmospheric circulation over tropical and extratropical areas. Notable weakening of the East Asian summer monsoon is observed since the late 1970s (Hu 1997; Wang 2001; Huang et al. 2003; Ding et al. 2008). And, possible causes to the rainfall inter-decadal changes were discussed that the SST warming over tropical Pacific and Indian oceans may play an important role by modifying the location of the western North Pacific (WNP) anticyclone and rain belt (Ju and Slingo 1995; Chang et al. 2000; Li et al. 2001; Gong and Ho 2002; Hu et al. 2003; Xie et al. 2009; Huang et al. 2010). The winter/spring snow cover over Eurasia Continent and Tibetan Plateau (TP) is also considered to be one of the possible contributors (Chen and Wu 2000; Wu and Qian 2003; Zhang et al. 2004; Wu and Kirtman 2007; Zhao et al. 2007; Ding et al. 2009; Wu et al. 2009, 2010). Since Kwon et al. (2005) indicated the decadal change in the relationship between East Asian and WNP summer monsoons around the mid-1990s. The inter-decadal change of East Asian summer climate caught

more and more attentions (Kwon et al. 2005, 2007; Ding et al. 2008, 2009; Yim et al. 2008; Wu et al. 2010). Results suggested that this inter-decadal shift concurred with a decadal change in the monsoon circulation which brought large rainfall increase to the South China, and possible crimes were also attributed to the SST warming over tropical Indian–WNP oceans and climate variation over TP.

Recently, another inter-decadal change of Eastern China summer rainfall around the late 1990s was revealed by Zhu et al. (2010) and Huang et al. (2011). It led to a sharp decrease of rainfall in Northeastern China. Huang et al. (2011) suggested that it is closely related to the high-level teleconnection, which was in agreement with the document of Yun et al. (2010) that the decadal cooling in the Indian summer monsoon after 1998/1999 may affect East Asian summer monsoon (EASM) through the Eurasia wave-train pattern and cause rainfall decrease over northern EASM.

In addition, plenty of studies had shown the close linkage between the Pacific Decadal Oscillation (PDO, Mantua et al. 1997; Zhang et al. 1997) and the inter-decadal variations over East Asia (Gong and Ho 2002; Mantua and Hare 2002; Deser et al. 2004; Yang and Lau 2004; Shen et al. 2006; Ma 2007; Yoon and Yeh 2010; Zhu et al. 2010). The PDO is the leading mode of the inter-decadal variability of SST in the North Pacific and considered to the major contributor to the 1970s shifts, and recent works also identified new inter-decadal change of the SST pattern in North Pacific around 1998/1999 which changed from PDO pattern to Victory pattern (Bond et al. 2003; Peterson and Schwing 2003; Litzow 2006; Overland et al. 2008). The study of Zhu et al. (2010) attributes the late 1990s shift to the PDO as well. However, how the PDO affects the climate over East Asia and the physical processes underneath the close linkage is still unclear, which needs further investigation.

Because of the complexities in spatial–temporal structure of and potential causes to the inter-decadal variation of summer rainfall over Eastern China, there is still a long way to achieve a comprehensive understanding of the laws of the inter-decadal changes. And so, two urgent questions came up: what are the changes in large-scale circulation and global SST before and after the pattern shift since the early 1990s, and what are the possible causes underneath which need further investigation.

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