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CHARACTERISTICS OF RAINFALL VARIATION OVER EAST CHINA FOR THE LAST 50 YEARS AND THEIR RELATIONSHIP WITH DROUGHTS AND FLOODS

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Abstract: With the precipitation data of 113 stations in East China during the last 50 years, the characteristics of the precipitation, including Precipitation Concentration Degree (PCD) and Precipitation Concentration Period (PCP) and their tendencies, are analyzed. The results show that the PCD in the northern part of the region is markedly higher than that in the southern part, but the PCP in the south is much earlier than that in the north by about one and a half months, which displays significant regional differences in precipitation. With the global warming, precipitation over East China shows an increasing tendency, but PCD displays a trend that is neither increasing nor decreasing. At the same time, the PCP is later than before, which can be mainly found in Jiangxi and southern Henan provinces. As a result, there are strong associations between the precipitation, PCD and PCP, which can be shown in the years with more precipitation, stronger PCD and later-than-usual PCP. In a word, the abnormal distribution of precipitation, PCP, and PCD over East China results in more extreme events of precipitation and more droughts and floods.

Key words: droughts and floods; precipitation concentration degree and period; East China

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1 INTRODUCTION

Located in the lower Yangtze River Delta in the East Asian monsoon region, East China is one of China's important economic zones. In recent years, the rapid development there demonstrates its important position in the economic development of China and also raises great concern about flood and drought disasters in the region. A National Assessment Report on Climate Change[1] clearly pointed out that there have been great changes in the frequency and intensity of extreme weather/climate events in China over the past 50 years, and flooding damages have increased in the Yangtze River basin and southeastern China, in the context of global climate warming. He[2] indicated in a study on precipitation in the Yangtze River basin that extreme weather and climate events such as rainstorms and droughts are showing an increasing trend so that the Yangtze River floods and droughts become more frequent. A research by Fu et al.[3] showed that for the past 45 years effective rainy days (i.e. the number of days with rainfall greater than 0.1 mm) have increased in the middle and lower reaches of Yangtze River and are mainly contributed by the days with heavy rain and storm rain, resulting in an increase of the frequency of precipitation at these rain rates in Yangtze River. Therefore, with droughts and floods aggravating in East China, it is of great importance to analyze the spatial and temporal distribution of the regional precipitation and variation characteristics.

As shown in an analysis of the causes of natural disasters in the middle and lower reaches of the Yangtze River, one of the main reasons for the aggravated droughts and floods is the frequent occurrence of extreme precipitation events, revealing that the uneven spatial and temporal distributions of precipitation are closely related with droughts and floods. On a study of the spatial and temporal variation of extreme precipitation in the Yangtze River basin, Su

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et al.[4] suggested that over the past 45 years, not only the amount of extremely heavy rainfall, precipitation intensity and the number of precipitation days in the middle and lower reaches of the Yangtze River are showing increasing trends, but also the distribution of extremely heavy rainfall events during the year tends to increase and concentrate in June, which is why the Yangtze River basin floods occur. Zhai et al.[5], Li et al.[6] and Jiang et al.[7] agreed that since 1990 events of severe precipitation tend to concentrate and large-scale events of severe droughts and floods increase significantly; the worsening floods and droughts may be attributed to the changes in the degree of spatial and temporal concentration of heavy precipitation events. According to a study by Wang et al.[8] on the variation trends of different intensity levels of rainfall in China, the precipitation tends to increase significantly, the annual rainfall frequency tends to decrease, and the average precipitation intensity is increasing, in East China; the increase in the precipitation of East China is mainly contributed by the increase of the frequency of heavy precipitation. Zhang et al.[9] analyzed the flood and drought situation in the Yangtze River basin and showed that changes in the aggregation degree of precipitation are one of the important reasons leading to increased droughts and floods, and found that the precipitation concentration degree (PCD) of the Yangtze River basin is on a significant increase in time and space. It is, therefore, of great significance to analyze the temporal and spatial characteristics of the precipitation distribution of floods in East China for the causes. However, study is little in this area and so it is necessary to conduct in-depth analysis and research on precipitation concentration of this region. In this paper, information on daily precipitation is used to study the characteristics of distribution and long-term trends of rainfall, PCD and precipitation concentration period (PCP), discuss the mutual relationship among them and their relationship with floods and droughts in this part of China, and explore the causes of natural disasters taking place there.

2 DATA AND METHODS

2.1 *Data*

The daily rainfall data of East China and adjacent areas (110°E–123°E, 25°N–35°N) used in this paper are provided by the National Meteorological Information Center, from the time since the stations were set up to December 2006. This domain includes 113 weather stations distributing over eight provinces of Henan, Hubei, Hunan, Anhui, Jiangxi, Fujian, Jiangsu, Zhejiang, and the metropolitan of Shanghai (Fig. 1). These selected sites are uniformly distributed in East China, and are representative of the rainfall characteristics without records of observation stations removal. The period used for analysis of interannual variations of precipitation is from 1957 to 2006.

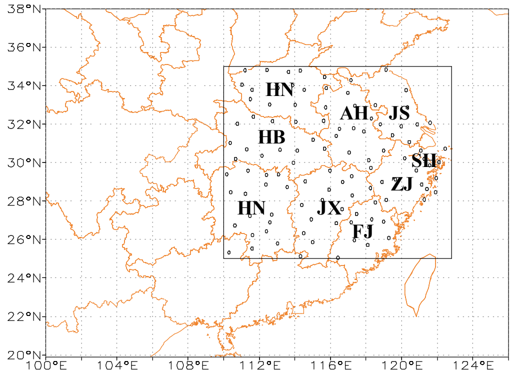

Fig. 1. Location of the nine provinces in East China and distribution of weather stations (dots)

Notes: HN stands for Henan, AH for Anhui, JS for Jiangsu, HB for Hubei, SH for Shanghai, ZJ for Zhejiang, HN for Hunan, JX for Jiangxi and FJ for Fujian.

2.2 *Analyzing methods of PCD and PCP*

The PCD and PCP are the methodology for measuring non-uniform distribution of rainfall during the year and quantitatively characterizing uneven precipitation with spatial and temporal heterogeneity, with PCP being able to identify the time of maximum precipitation peak. The two indices can be used to analyze and discuss the basic characteristics of drought and flood disasters and their formation mechanism[9-11]. Following the specific methods[9], the pentad precipitation within one year is designated as a vector, 72 pentads are designated as a circle, and the precipitation for a particular pentad is designated as a vector mode. Thus the PCD and PCP for a single weather station are defined as $\mathrm{PCD}_i = \sqrt{R_{xi}^2 + R_{yi}^2} / R_i$ and $\mathrm{PCP}_i = \arctan(R_{xi}/R_{yi})$, in which PCD_i and PCP_i are the PCD and PCP within a study period, where $R_{xi} = \sum_{j=1}^{N} r_{ij} \times \sin\theta_j$ and $R_{yi} = \sum_{j=1}^{N} r_{ij} \times \cos\theta_j$, R_i is the total precipitation for a station within the study period, r_{ij} is the precipitation for a pentad, and θ_j is the azimuth corresponding to pentads within the period of study (the azimuth for the entire study period is 360°). In this article, i is the year (i = 1951, 1952, 1953, … …, 2006) and j is the sequence of pentads in a year (j = 1, 2, 3, … …, 72).

In accordance with the above method of calculation, PCD can reflect the degree of concentration of total precipitation in each of the pentads within the study period, while PCP is the azimuth of a composite vector and shows the overall effect of composite rainfall for each pentad, i.e., the angle indicated by the median point of the composite vector, reflecting the time during which the largest pentad precipitation occurs within a year.

3 DISTRIBUTION AND VARIATION CHARACTERISTICS OF ANNUAL PRECIPITATION, PCD AND PCP

3.1 *Precipitation*

Located near the country's eastern coast and affected by the monsoon and landing typhoons, East China has abundant summer rainfall with its annual precipitation much larger than most of northern China and other inland provinces. From the distribution of annual precipitation (Fig. 2a), it is known that in this region precipitation in the north is less than in the south and the latter is also marked with more precipitation in the east than in the west. On the southeastern coast of Fujian and Jiangxi, rainfall is the most abundant and the annual precipitation amount is more than 1600 mm, while it is about 1500 mm in Zhejiang and Hunan. In northern provinces of Henan, Hubei, Anhui and Jiangsu, there is relatively less rainfall and the annual amount ranges from 800–1200 mm.

Analyzing the trend coefficients of annual rainfall in weather stations from the setup to 2006 (Fig. 2b) in East China shows that the coefficients are mainly positive and show increasing trends, especially in the central part of Jiangxi and Anhui where the coefficients are greater than 0.2 and pass a significance test at the level of more than 90%. In Jiangsu, Hubei, western Hunan, as well as some parts of Fujian, the trend coefficients are negative and annual rainfall shows an insignificant downward trend. According to the National Assessment Report on Climate Change[1], the annual rainfall in the middle and lower reaches of Yangtze River has increased by 60–130 mm. The research findings of Wang et al.[12] and Xiang et al.[13] also indicated that major areas of China with increasing precipitation are mainly located in East China and the precipitation shows a significant trend of increase, although as far as the annual precipitation is concerned, the increasing trend is only seen in Jiangxi and Anhui but it is insignificant in other areas.

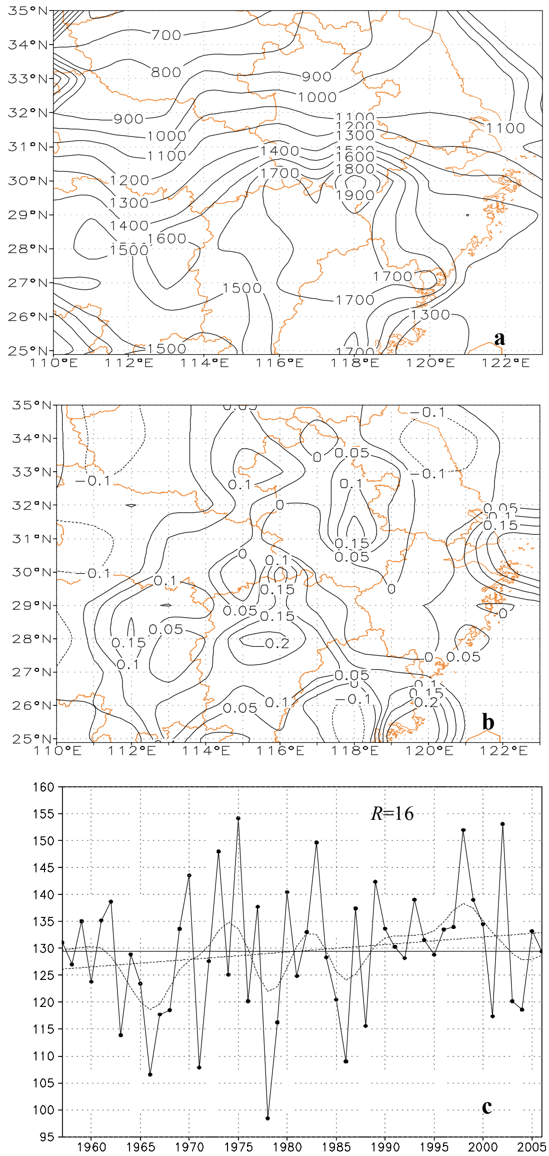

Fig. 2. Annual mean rainfall (a, unit: mm), trend coefficient of annual rainfall (b) and variation curve for the annual mean rainfall (c, unit: 10 mm) of East China. R: trend coefficient; the abscissa: year

Analyzing the variations of annual precipitation during 1957–2006 (Fig. 2c) revealed an increasing trend and an obvious interdecadal variation in East China. Before 1970, the annual precipitation was consistently low in the area, but precipitation began to increase and inter-annual differences enlarged in the 1970s. In 1978, the annual rainfall was the lowest in nearly 50 years, only around 980 mm, while in 1975 a maximum value of 1500 mm was reached. In the 1980s, the annual precipitation started to be higher than the historical average. At the same time the inter-annual change reduced, especially after 1990, with the annual precipitation consistently higher than the multi-year average. Since 2000, precipitation was largely less than normal again. The past 50 years in East China witnesses an increasing trend in annual precipitation with increments of more than 50 mm and a trend coefficient of 0.16, which is generally consistent with the results of the National Assessment Report on Climate Change[1]. Overall, the annual precipitation increase in East China is an important characteristic contributing to the increase of precipitation across the country, making it one of the major regions of China where precipitation increases.

In order to analyze the relationship between the changes in inter-annual precipitation and the regional floods and droughts, the first 6 years with the highest values of annual precipitation were identified (in the order from the biggest to the smallest), i.e., 1954, 1975, 2002, 1998, 1983, and 1973 (Table 1). Descriptions of the drought and flood years in East China for 1949–1990 are available in the table[14] as well as the work of Wei et al.[15], Tao et al.[16], Su[17], and Zhang[18] and others. For the years before 1990, they are identified as drought years or flood years if the table[14] makes references to major flood and drought events in the lower reaches of the Yangtze River; for the period after 1990, the years of drought and floods are determined by the climate profiles of individual years as published in the journal of *Meteorological Monthly*. Specifically, floods occurred in large areas of East China in 1954, 1975, 1983 and 1998, which were particularly serious in 1954 and 1998 in the Yangtze River basin. The annual precipitation value was larger than normal in the other two years, but floods did not happen. Similarly, low-value precipitation years were also identified and they are, again, presented from low to high: 1978, 1966, 1971, 1986, 1963, and 1988; only in 1978, 1986 and 1988 there were serious droughts while in the other three years precipitation was less than normal but drought did not happen. Though the amount of precipitation has a certain relationship with flooding in East China, it is not the direct cause of floods and droughts, which means that the years of high-value annual precipitation do not necessarily indicate the appearance of floods while the years of low-value annual precipitation cannot all cause droughts.

3.2 *Precipitation concentration degree*

Studies have shown that a main reason for increased flood and drought disasters is the uneven temporal and spatial distribution of precipitation in the middle and lower reaches of Yangtze River, as well as the unusual PCP of heavy precipitation[6]. The abundant precipitation in East China is impacted by combined allocation of geographical and climatic conditions. In normal years PCPs are separated over different parts of the Yangtze River basin and precipitation is evenly distributed in time and space. However, in some years, precipitation over different reaches of the river is concentrated over the same period, extreme precipitation appears frequently, and precipitation is distributed unevenly, weakening the region's natural mechanisms for disaster prevention and leading to relatively strong droughts and floods[10].

As shown in the distribution of PCD (Fig. 3a), the average PCD of annual precipitation in East China is about 40%, indicating concentrated rain processes over this region and marked rainy season and non-rainy season throughout the year. To the north in Henan, Jiangsu and northern Hubei the PCD is above 39%, significantly higher than other provinces and areas to the south. Therefore rainfall in the northern region has a better consistency, with more obvious rainy season and more concentrated rainfall than in the southern region. On the contrary, in the regions to the south, i.e., Shanghai, Zhejiang and Hunan, the PCD is low, at 33% or less, indicating that precipitation in these regions spreads over a long period and the amount distributes relatively uniform in time.

Analysis of the variation trends of PCD (Fig. 3b) shows that the trend coefficients are both small, indicating insignificant change of PCD for the entire region of East China. However, the trend coefficients of PCD are positive at the edge of the area and show a weak upward trend, especially in Hunan where the PCD is significantly increasing. The trend coefficients of PCD are mostly negative in other areas and show a trend of weakening, especially in Jiangsu and Shanghai. An analysis by Zhang and Qian[9] on the precipitation of the Yangtze River basin showed a significantly increasing trend in PCD. While Hunan is the only place in East China that witnesses remarkable enhancement in PCD, Jiangsu and other places observes decreases rather than increases in PCD, which may be related with inconsistent time period in data analysis.

From the curve of inter-annual variations of average PCD for the past 50 years (Fig. 3c), it is known that the PCD is, on average, about 39% during the time in East China, showing characteristics of strong concentration of rainfall. In addition, there are significant inter-annual variations of PCD, with the maximum (more than 50%) appearing in 1995, and the minimum (27%) in 1972. On average, the trend coefficient of PCD is close to 0 in East China, indicating no features of decreasing or increasing trends.

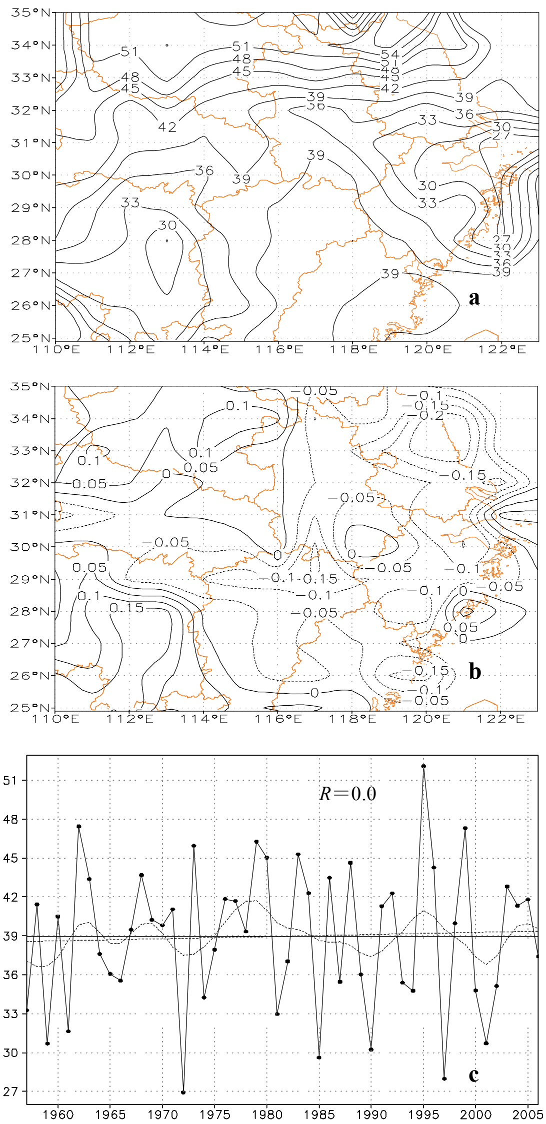

Fig. 3. Distributions of mean PCD (a) and trend coefficient of PCD (b) and annual variation curves of mean PCD in East China (c, *R*: trend coefficient; the abscissa: year)

Comparisons of the inter-annual variation of PCD with the characteristics of floods and droughts in East China found that high PCD (45% or more) concentrates in the years of 1954, 1955, 1956, 1962, 1973, and 1979 (Table 1), indicating relative concentration of precipitation processes during these years. In contrast to the floods in this region, 1954, 1962 and 1979 are the years that experienced relatively severe flooding. On the contrary, in the low-value years of PCD, namely, 1978, 1997, 1953, 1985, 1990 and 1959, rainfall is more evenly distributed in these years, leading to speculations that there should be less drought or flood disaster. In fact, although there was no flood disaster, serious droughts were frequent and occurred in 1978, 1953, 1959 and 1985. It then follows that lower PCD does not necessarily indicate less disaster. Usually in East China, the precipitation tends to concentrate in the flood season, which can increase the rainfall effectively and result in less droughts. When the PCD is too low, however, precipitation disperses, corresponding rainfall decreases in the flood season, making the incidence of drought probably higher. In short, the PCD is closely related to droughts and floods in East China.

Table 1. Distribution of years with extreme precipitation and drought and flood disasters in East China

Type	High-value years					
Rainfall	**1954**	1973	**1975**	**1983**	**1998**	2002
PCD	**1954**	1955	1956	**1962**	1973	**1979**
PCP	**1962**	1972	1974	1982	**1999**	2000
Type	Low-value years					
Rainfall	1963	1966	1971	*1978*	*1986*	*1988*
PCD	*1953*	*1959*	*1978*	*1985*	1990	1997
PCP	1951	*1959*	1966	**1991**	**1998**	*2003*

Notes: Bold numerals indicate the floods and slanted numerals the droughts.

3.3 *Precipitation concentration period*

As shown in the distribution of average PCP for the 50 years in East China (Fig. 4a), PCP is significantly different, i.e., it unevenly distributes and rainfall processes appear at different time, indicating that this region has a natural defense mechanism against flood disaster. The average PCP for East China is at the 33.8th pentad, that is, around mid-June. In the southern provinces of Jiangxi, Fujian and Hunan, the PCP is about 10 pentads ahead of the northern ones, or about more than one and a half months. Shanghai (in the eastern part of the region) lagges behind other regions on the same latitude by 7 pentads. Jiangxi has the earliest PCP that starts from the 28th pentad, or around mid-May, while the stations in Shanghai have PCP at the 36th pentad in early July, having a difference of about a month. To the north, the PCPs for Henan, Hubei and Anhui fall on a time between the 32nd and 40th pentad, or between early June and mid-July. These significant differences in the PCP are one of the prominent features of temporal and spatial distribution of precipitation in this region. The PCP differs by more than a month in different parts of the northern and southern region. The specific performance of PCP in East China reflects the north-south shifts of rain belts in summer across China and shows an important defensive role of north-south differences in PCP in mitigating the regional floods caused by the relative concentration of summer precipitation in the middle and lower reaches of the Yangtze River and East China.

The trend coefficients of the PCP (as shown in Fig. 4b) in the East China region are positive, with high positive value up to 0.2 or above in some areas and mainly located in Jiangxi and the south of Henan, indicating that the PCPs in these areas tend to occur at later time. On the contrary in the eastern and western edge of the region, the trend coefficients are mildly negative and cannot pass the significance test, indicating no significant change in PCP in these areas. In short, the PCPs for the past 50 years tend to delay in East China, especially in the central part of the region.

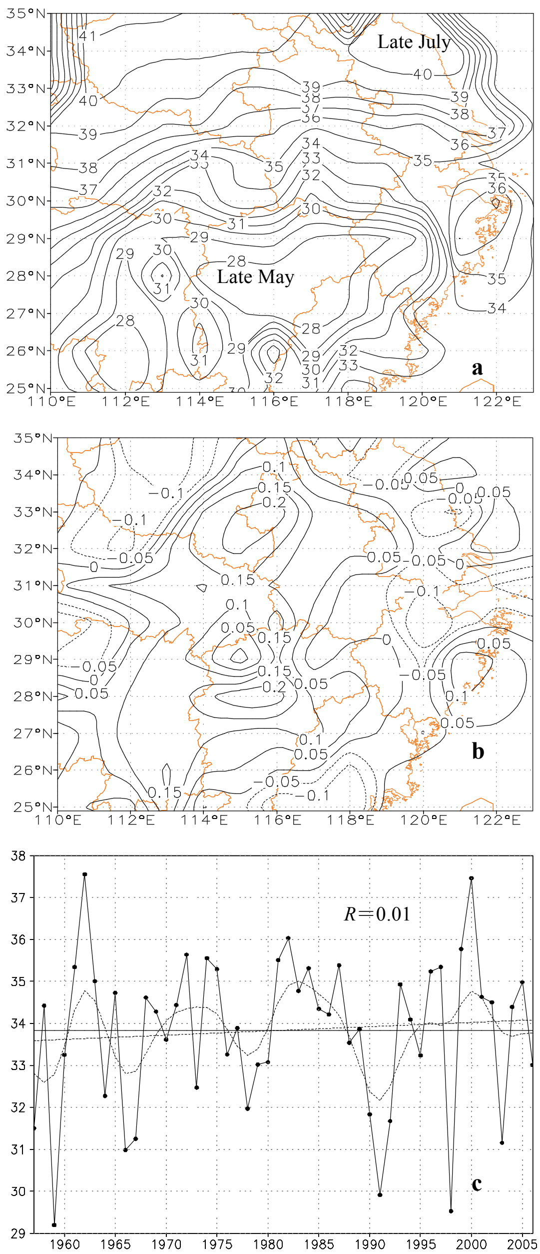

Fig. 4. Distributions of mean PCP (a), trend coefficient of PCP (b) and annual variation curves for mean PCP in East China (c, unit: pentad; *R*: trend coefficient; the abscissa: year)

The inter-annual variation curve for the past 50 years of the average PCP (as shown in Fig. 4c) is usually between the 32nd and 35th pentad in East China, that is, around mid-June. On the long-time scale, the trend coefficient of PCP is 0.01, showing a tendency of slight postponement. It suggests the delay of PCP and main flood season in East China, probable overlapping of the main flooding season in the middle reach of the Yangtze River and accumulation of basin-wide precipitation in the region, resulting in flood damage. At the same time, the flood-season rainfall processes appear later and spring rainfall decreased, which in turn results in inadequate precipitation and consequently leads to the occurrence of spring droughts. Therefore, the changes in PCP in East China are worthy of concern.

Comparative analysis of the relationship between PCP and droughts and floods in East China showed that in the high-value years of 1962, 2000, 1982, 1999, 1972, and 1974, PCP occurred relatively late. Historical floods, instead of droughts, took place in 1962 and 1999. In the low PCP-value years of 1959, 1998, 1991, 1951, 1966 and 2003, the PCP had relatively early appearance, and droughts occurred in 1959 and 2003 while floods appeared in 1991 and 1998. Therefore, floods usually occur in the years of late PCP while droughts and floods are both likely to take place in the years of early PCP.

On the scale of inter-annual variations, the anomalous years of annual precipitation, PCD and PCP are compared with the distribution of droughts and floods in East China (Table 1). In the high-value years of the three elements above, floods occur by a chance of 50% while in the low-value years, disasters take place by frequencies of more than 60%, with droughts by more than 50% and floods by 11%. Therefore, high values of precipitation or high PCD are likely to lead to severe floods in East China. In contrast, with less-than-normal rainfall or lower PCD, the region often suffers from droughts. In addition, if the PCP is late, it is highly likely that floods occur in East China while early PCP will possibly result in both droughts and floods. In short, the three elements interact with each other in such a way that they have an important impact on the formation of floods in this part of China.

4 ANALYSIS OF CORRELATION BETWEEN PRECIPITATION AND PCD/PCP

The disasters of droughts and floods in East China are related with both precipitation and the PCD/PCP (to some degree). As shown in a study by Zhang et al.[9], if the PCP delays in the middle and lower reaches of Yangtze River, it will result in the superposition of flood peaks across the whole basin, thereby increasing the intensity of floods. Therefore, it is necessary to analyze the relationship between precipitation and the PCD/PCP in the context of inter-annual changes.

Analysis of the distribution of correlation coefficients between the precipitation and PCD in the past 50 years in East China (Fig. 5a) revealed that the precipitation and PCD are closely related to each other. The central and northern parts of the region are areas of high positive values, with the correlation coefficients above 0.3. The south of Henan, north of Hubei and part of Jiangsu have the highest correlation coefficients (more than 0.6), indicating a high degree of correlation between the precipitation and PCD. The precipitation and PCD have consistent patterns of variation: the latter is high in the years of high precipitation. In contrast, in the southern part of the region, the correlation coefficient is relatively low, usually below 0.3, with slightly worse correlation between the precipitation and PCD. Therefore, in the years with more precipitation in East China, the rain processes are usually relatively concentrated, especially in the northern part, and severe floods can easily form.

Similarly, analysis of the correlation coefficients between the precipitation and PCP for the past 50 years (Fig. 5b) indicated that the correlation coefficients between the two are mainly positive, especially in central and southern parts of the region, in which the high values of correlation coefficient are usually above 0.3. The maximum value appears in Hunan, Jiangxi, Zhejiang and Shanghai, where the correlation coefficients are more than 0.5. In other areas, the coefficients are positive too, but the values are below 0.3. Therefore, precipitation is positively correlated with PCP by large margin in East China in that the PCP is usually late in the years with more precipitation.

In short, the inter-annual changes in annual precipitation are closely related to the PCD and PCP in East China, in that the PCD is usually high in the years with more rainfall, especially in the northern region. At the same time the PCP is usually late in the years with more precipitation. The abnormal changes of the three elements easily lead to droughts and floods in this region.

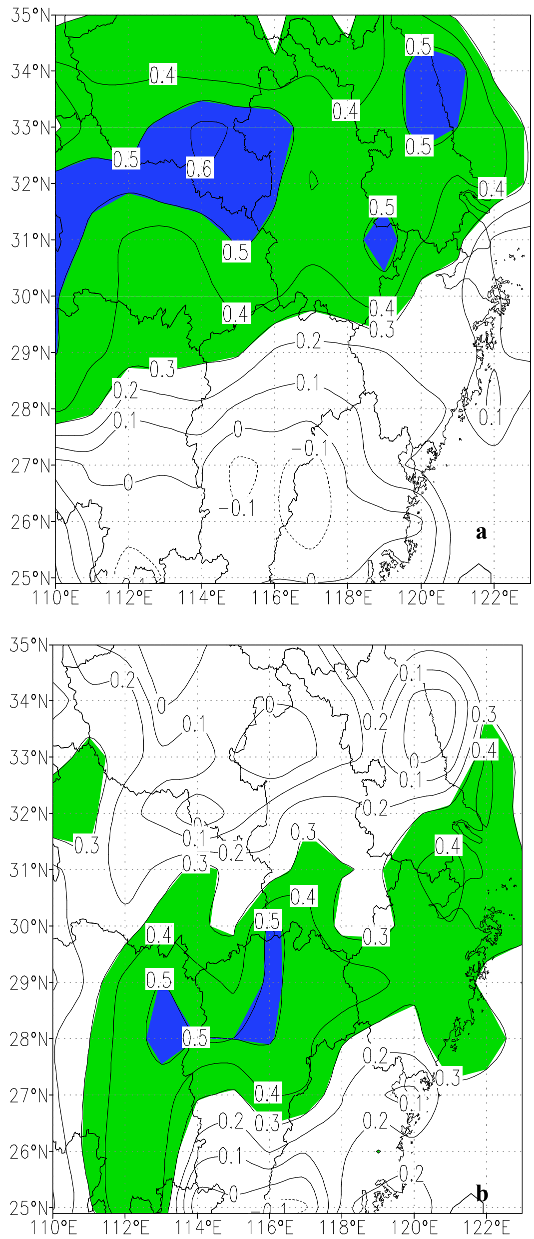

Fig. 5. Distributions of correlation coefficients between the annual precipitation and PCD (a) and PCP (b) in East China. The green and blue areas denote areas with correlation coefficients above 0.3 and 0.5, respectively.

5 DISCUSSION AND SUMMARY

Through an analysis and discussion of precipitation, PCD and PCP and the correlation between the three elements for the past 50 years in East China, we found that with global warming in recent years, precipitation shows a trend to increase and PCP begins on later dates. For this region, the uneven spatial and temporal distribution of precipitation leads to increased frequency of extreme precipitation events and floods, making it one of the reasons for the worsening of natural disasters.

(1) There are significant regional difference in the PCD and PCP in East China, displaying much higher PCD in the northern than in the southern region, while the PCP is about one and a half month earlier in the southern than in the northern region; precipitation concentrates around the middle of May in the southern region while around mid-July in the northern region.

(2) With global warming, there is an increasing trend in annual precipitation in East China, mainly in Jiangxi and Anhui provinces, but there are no significant trends for PCD, and PCP tends to delay mainly in southern Jiangxi and Henan. An increase of droughts and floods may occur in the years of abnormal changes in precipitation, PCD and PCP in eastern China.

(3) It is known from the perspective of long-term changes in East China that the precipitation shares synchronous variations with the PCD and PCP; it is usually the case that the more precipitation, the

stronger the PCD and the later the PCP. Floods in East China are related not only with precipitation, but also closely with spatial and temporal distribution of precipitation. In recent years, there have been abnormal changes in precipitation, PCD and PCP, leading to frequent occurrence of extreme precipitation events and disasters.

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