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Intra-Annual Non-Uniform Characteristics of Extreme Precipitation Process Events in China

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Abstract: Extreme precipitation process events (EPPEs) with long durations exhibit greater hazard potential and serve as a crucial trigger for basin-wide floods. Studying the intra-annual inhomogeneous characteristics of such EPPEs is of great significance for flood disaster early warning and risk management. Based on daily precipitation data from 610 stations in China during 1960 to 2009, this study introduces two new parameters, namely the concentration degree and the concentration period of EPPEs, to characterize their temporal distribution. Using trend analysis and Morlet wavelet analysis, the study investigates the intra-annual non-uniformity of annual extreme precipitation process events in China. Results indicate that both the concentration degree and concentration period of EPPEs exhibit a spatial pattern of "low-high-low" from southeast to northwest, whereas the spatial distribution of their standard deviations shows an opposite pattern. The area-averaged series of concentration degree and concentration period in the four major regions of China (western, northern, southern, and southwestern regions) demonstrate distinct interannual variations and oscillations. The EPPEs in Northern, Southern, and Southwest China have shown a tendency toward concentration, leading to an increased risk of multiple flood disasters occurring intensively within a certain period of the year. In contrast, those in Western China have exhibited a tendency toward dispersion, with the occurrence time of annual flood disasters tending to be discretized. Except for Southern china, EPPEs in other sub-regions have shown an advancing trend—indicating an elevated flood risk during the post-flood season in Southern China and a heightened flood risk during the pre-flood season in the other regions. A significant negative correlation coefficient is found between the concentration degree of EPPEs and extreme precipitation amount, indicating that a higher concentration of EPPEs corresponds to a smaller extreme precipitation amount, particularly along the coastal areas of south China.

1. Introduction

Extreme climate events are characterized by their abruptness and destructiveness, exerting disastrous impacts on socioeconomic systems, human life, property, and ecosystems, and thus have attracted increasing global attention [1-4]. Among these, extreme precipitation events (EPEs) are often associated with flooding, producing severe effects on both the natural environment and human society. China, located in the East Asian monsoon region and abundant in moisture, is one of the most active regions for EPEs and is significantly affected by them. Previous studies have analyzed changes in China's extreme precipitation mainly from the perspective of extreme daily precipitation. Findings show that extreme precipitation has increased in the western region, the Yangtze River basin, and the southeastern coastal areas, whereas it has significantly decreased in north China and the Sichuan Basin, and the ratio of extreme precipitation amount to total precipitation shows an overall increasing trend across the country [5-7].

Current research on extreme precipitation mainly focuses on extreme daily precipitation, whereas studies on precipitation processes are relatively scarce. Long-duration extreme precipitation process events (EPPEs) have different impacts depending on regional conditions. In humid regions, where soil saturation occurs easily, subsequent rainfall is rapidly converted into surface runoff, intensifying flooding. In ecologically fragile areas, persistent heavy rainfall may trigger debris flows and landslides. Therefore, in addition to extreme daily precipitation, more attention should be devoted to EPPEs. Chen [8] analyzed the regional and persistence characteristics of EPEs in China; Zhao et. al [9] investigated EPEs lasting more than 2 days; Zou et al. [10] defined a scientific threshold for extreme precipitation processes and revealed the linear trends and interannual and multidecadal variations in the frequency of precipitation events over nearly 45 years. However, most of these studies explored long-term trends of EPPEs at annual or seasonal scales or examined the ratio of extreme precipitation amount to total precipitation to describe their spatial distribution. While such methods can represent the climatic state and variations of EPPEs

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to some extent, they cannot characterize the concentration degree and concentration period of EPPEs, nor their temporal evolution—parameters that are crucial for understanding regional flooding (including rainstorm) hazards. Currently, many studies have examined the intra-annual non-uniformity of extreme daily precipitation in China [11-13], but few have focused on that of EPPEs.

Following the method of Zou, this study defines the EPPEs and introduces the indices proposed by Zhang et al. [14]—concentration degree and concentration period—to characterize the intra-annual non-uniformity of EPPEs. A detailed analysis is conducted on the spatial and temporal characteristics of annual EPPE concentration degree and concentration period across China, revealing the intra-annual non-uniform distribution of EPPEs. The findings provide a foundation for further investigation into the mechanisms of flood hazards in China and have implications for short-term climate prediction and disaster prevention and mitigation.

2. Data and Methods

The dataset used in this study consists of daily precipitation records from 756 meteorological stations across China during 1960–2009, compiled by the National Climate Center. To minimize errors caused by missing data, strict station selection criteria were applied: (1) the record length must be no less than 45 years (in the western region, where stations are fewer and established later, only those with at least 40 years of data were selected); (2) the number of missing days per year must not exceed 30. After filtering, a total of 610 stations were retained.

Definition of EPPEs: For each station, continuous precipitation processes over the 50-year period (1960–2009) were ranked by total precipitation amount from large to small. A continuous precipitation process was identified as an EPPE, when its total precipitation exceeded the 95th percentile (P95) of the corresponding series. Following the definition proposed by Zou et al., a precipitation process at each station is determined based on the continuity of rain days. The period from the start to the interruption of consecutive rain days lasting two or more days is defined as one precipitation process.

Based on Zhang [14], who introduced two parameters characterizing the temporal distribution of precipitation—concentration degree and concentration period, we define the concentration degree and concentration period for EPPEs. Each month's EPPEs within a year are treated as vectors, with 12 months represented on a 360° circular scale. The frequency of precipitation events in each month is taken as the modulus of its vector, and the month index (counted from 0) multiplied by 30° gives the vector direction. The calculation formulas are as follows:

$$\mathrm{ECD}_i = \frac{\sqrt{R_{x\mathrm{i}}^2 + R_{y\mathrm{i}}^2}}{R_i} \quad (1)$$

$$\mathrm{ECP}_i = \tan^{-1}\left(\frac{R_{xi}}{R_{yi}}\right) \quad (2)$$

$$R_{xi} = \sum_{j=1}^{12} r_{ij} \sin\theta_j;\ R_{yi} = \sum_{j=1}^{12} r_{ij} \cos\theta_j \quad (3)$$

where i denotes the year and j the month index; ECD_i and ECP_i represent the concentration degree and concentration period of EPPEs at a given station in year i; θ_j is the vector angle for month j; R_i is the total number of EPPEs at that station in year i; and r_{ij} is the total number of EPPEs in month j of year i.

According to these formulas, ECD reflects the concentration degree of EPPEs across months within the study period. If EPPEs are concentrated in a single month, the modulus of their composite vector equals the total number of EPPEs, giving an ECD value of 1 (the maximum). If EPPEs are evenly distributed among all months, the resultant vector components sum to zero, yielding an ECD of 0 (the minimum). ECP, as the azimuth of the composite vector, indicates the temporal centroid of EPPEs occurrence, revealing the period of the year in which EPPEs are most frequent. Therefore, ECD and ECP together capture the intra-annual non-uniform distribution of EPPEs.

The Thiessen polygon method (TPM) was employed to calculate area-averaged series. The temporal trends were determined through linear regression, and Morlet wavelet analysis [15] was applied to identify periodic variations within the time series.

3. Spatial Distribution Characteristics of the Concentration Degree and Concentration Period of EPPEs

3.1. Mean Spatial Distribution Characteristics of the Concentration Degree and Concentration Period of EPPEs

The long-term mean spatial distribution of the concentration degree and concentration period of EPPEs is shown in Figure 1. As illustrated in Figure 1a, the national concentration degree of EPPEs ranges from 0.74 to 1. In most areas east of 105°E and south of the Qinling Mountains, the concentration degree lies between 0.8 and 0.9. The minimum values appear in southern Hunan and the Yangtze River Delta, ranging from 0.7 to 0.8, indicating that EPPEs in these regions are relatively dispersed. In contrast, north of the Qinling Mountains and west of 105°E, the concentration degree ranges between 0.9 and 1. In the Tarim Basin, the concentration degree reaches as high as 1, suggesting that EPPEs in this area are extremely concentrated and occur only within one or two months. As shown in Figure 1b, the concentration period of EPPEs exhibits a "low-high-low" pattern from southeast to northwest. East of 105°E and south of the Yangtze River, the concentration period ranges between 112° and 180°, corresponding to late April through late June. The lowest values, between 112° and 135°, occur in Jiangxi, Fujian, and northern Guangdong, indicating that EPPEs there mainly occur from late April to early May. In most other areas south of the Yangtze River, the concentration period is less than 165°, corresponding to late June. North of the Yangtze

River, except for the Huang-Huai region, where the concentration period ranges from 190° to 210° (mid-July to early August), most regions exhibit concentration periods between 180° and 190°, meaning EPPEs mainly occur in early July. West of 105°E, the western and eastern parts of Xinjiang, western Gansu, and northwestern Qinghai have concentration periods ranging from 150° to 180°, indicating that EPPEs in these areas primarily occur in June. Most of the remaining regions show concentration periods between 180° and 190°, corresponding to early to mid-July. In Tibet, EPPEs occur relatively later, around late July. In summary, both the concentration degree and concentration period of EPPEs in China exhibit significant spatial heterogeneity, and the temporal occurrence of EPPEs is generally consistent with the migration of the rainband across the country.

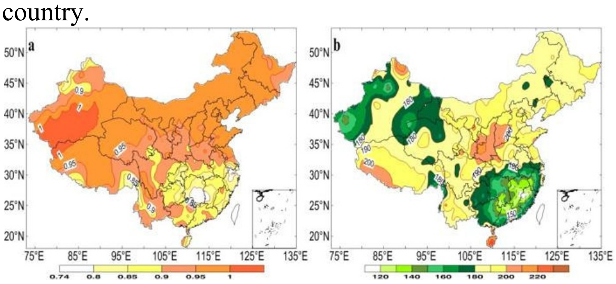

Figure 1. Concentration degree and concentration period of EPPEs.

3.2. Anomalous Spatial Distribution Characteristics of the Annual Concentration Degree and Concentration Period of EPPEs

The spatial distributions of the standard deviations (SDs) of the concentration degree and concentration period of EPPEs are shown in Figure 2. As illustrated in Figure 2a, the SD distribution of concentration degree exhibits an opposite pattern to its mean distribution. Regions with larger concentration degrees show smaller SDs, while regions with smaller concentration degrees experience relatively larger interannual variations in concentration degree. Across China, the SD of the concentration degree of EPPEs ranges from 0 to 0.32, showing a "high-low-high" pattern from southeast to northwest. In northern Xinjiang and areas south of the Yangtze River, the SD exceeds 0.15, and in some localized areas reaches up to 0.32. This indicates that these regions are the most prone to anomalies in the annual concentration degree of extreme precipitation process events, and the Yangtze River Basin is also the area most susceptible to flood disasters. In contrast, the Northeast China Plain, the North China Plain, and the Qinghai-Tibet Plateau exhibit relatively small SDs, below 0.08. The minimum values, below 0.04, appear between the Tarim Basin and the Turpan Basin, indicating that this area has the smallest interannual variation in EPPEs occurrence across China. Figure 2b displays the SD distribution of the concentration period of EPPEs, which resembles that of the concentration degree. The regions with high SD values are mainly located in northwestern China, the Hetao area of the Yellow River, and areas south of the Qinling Mountains in eastern China. In these regions, the SD exceeds 30°, corresponding to a variation of more than one month. In central China, the southeastern coastal region, and western Xinjiang, the SD exceeds 40°, indicating that these are the regions with the largest interannual variations in the concentration period of EPPEs. By contrast, the Northeast China Plain and the Qinghai-Tibet Plateau show relatively small SDs, less than 30°.

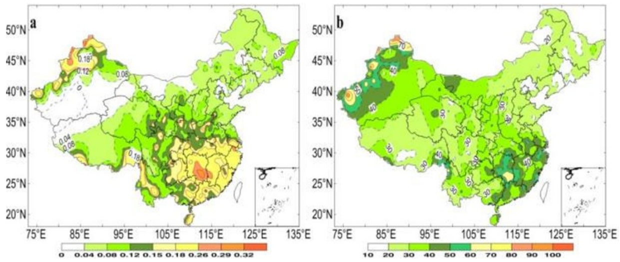

Figure 2. Spatial distribution of the standard deviations of the concentration degree and concentration period of EPPEs.

4. Temporal Variation Characteristics of the Annual Concentration Degree and Concentration Period of EPPEs

4.1. Regional Temporal Evolution of the Annual Concentration Degree and Concentration Period of EPPEs

As discussed above, the spatial heterogeneity of annual EPPEs in China is pronounced. Therefore, the following analysis examines the temporal evolution characteristics by region. According to China's natural regionalization, the country is divided into four regions: the western region, northern region, southern region, and southwestern region. The Qinling-Huaihe line serves as the boundary between the southern and northern regions. Within the southern region, the Yunnan-Guizhou Plateau, the Sichuan Basin, and the southeastern part of the Qinghai-Tibet Plateau are defined as the southwestern region, while the remaining areas constitute the southern region. In the north, areas east of the Hetao region of the Yellow River are categorized as the northern region, and the rest are considered the western region. The regional time series of annual EPPEs were calculated using the TPM.

As shown in Figure 3, the annual concentration degree of EPPEs shows a slightly increasing concentration trend in all regions except the western region, which exhibits a tendency toward dispersion. The concentration period shows a delaying trend only in the southern region, while other regions display advancing trends. In the western region, EPPEs were relatively concentrated during the 1960s, 1980s, and from the late 1980s to the mid-1990s, whereas in other years they were relatively dispersed, particularly in the early and mid-1980s. Over the past 50 years, the western region has shown a slow dispersing trend, with a rate of 0.003 per decade. The concentration period of EPPEs was relatively delayed from the 1960s to the early 1980s, earlier from the mid-1980s to the early 1990s (by about

0.3 months), delayed again during the 1990s and early 21st century, and earlier in other years. Overall, a slow advancing trend has been observed during the past five decades, with a linear rate of change of 1.36° per decade.

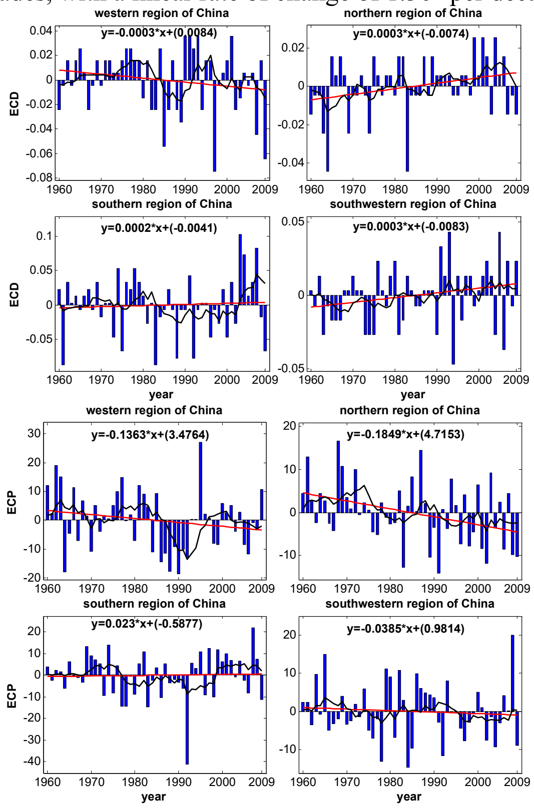

Figure 3. Interannual evolution of the annual concentration degree and concentration period of EPPEs.

In the northern region, the concentration degree of EPPEs underwent a sudden shift in the early 1990s. Before that, the events were generally more dispersed, and after that period, they became more concentrated. The early 1960s were the most dispersed, with 1965 identified as an exceptionally dispersed year, while the late 1990s to mid-2000s were the most concentrated. The concentration period exhibited an opposite trend: it was relatively delayed before the late 1970s, and generally earlier afterward, except for a short delayed phase in the late 1980s. Over the past 50 years, the northern region has shown a concentration trend with a rate of 0.003 per decade, and an advancing trend in concentration time with a rate of 1.85° per decade.

In the southern region, EPPEs show a concentration trend, while the concentration period exhibits a delaying trend. The corresponding rates are 0.002 per decade and 0.23° per decade, respectively. EPPEs were relatively concentrated during the 1960s to early 1980s and the 2000s, particularly during the mid-2000s when the concentration was strongest. In contrast, EPPEs were more dispersed from the mid-1980s to the late 1990s. The concentration period was delayed during the 1960s to mid-1970s and the 2000s, and earlier from the late 1970s to the late 1990s.

In the southwestern region, both the concentration degree and concentration period show consistent trends toward concentration and advancement, with rates of 0.003 per decade and 0.39° per decade, respectively. Before the late 1980s, EPPEs were relatively dispersed, while after that period they became more concentrated. The variation in concentration period is more complex: it was delayed in the 1960s and 1980s but earlier in other years.

4.2. Wavelet Analysis of the Annual Concentration Degree and Concentration Period of EPPEs

To identify the periodic characteristics of the concentration degree and concentration period of EPPEs, continuous Morlet wavelet analyses were performed on the anomaly series of these parameters for each region. The wavelet contour maps are shown in Figure 4. As illustrated, the western region exhibits a distinct periodic oscillation of the concentration degree at a larger scale of 17–20 years, with four alternating cycles of relatively concentrated and dispersed phases over the past five decades. The concentration period shows a clear oscillation at a 27-year scale, experiencing three cycles of delayed and advanced phases.

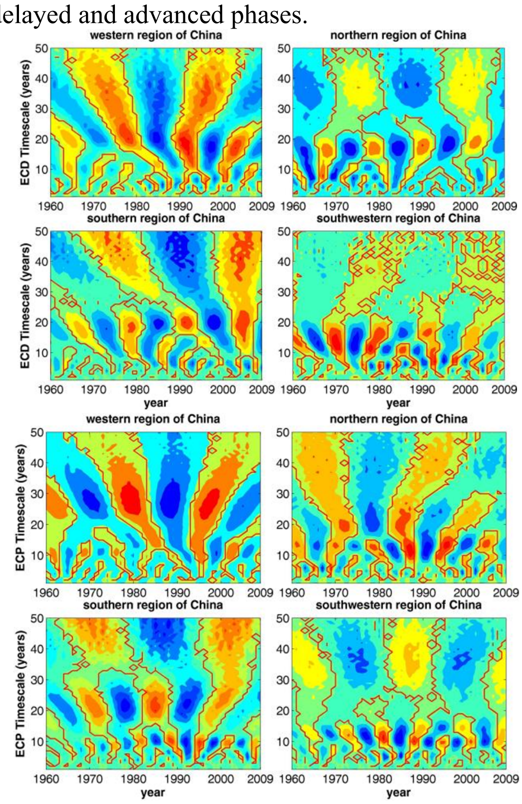

Figure 4. Wavelet contour maps of the annual concentration degree and concentration period of EPPEs.

In the northern region, the concentration degree and concentration period show significant oscillations at scales of 17 years and 11 years, respectively. The concentration degree alternates between five relatively concentrated and four relatively dispersed phases, showing a wavelike pattern of concentrated-dispersed alternation. The concentration period undergoes six alternating cycles of delayed and advanced phases.

In the southern region, the concentration degree and concentration period display primary periods of approximately 18–20 years and 22 years, respectively. The concentration period also exhibits quasi-50-year fluctuations, alternating through a sequence of earlier and later phases. The concentration degree oscillates at an 18-year scale, with four alternating cycles of concentration and dispersion.

In the southwestern region, the concentration degree shows a dominant oscillation period of about 13 years, with six relatively concentrated and six relatively dispersed phases, forming a wavelike pattern of concentration-dispersion alternation. The concentration period exhibits a clear oscillation at a 10-year scale, with seven alternating cycles of early and late phases.

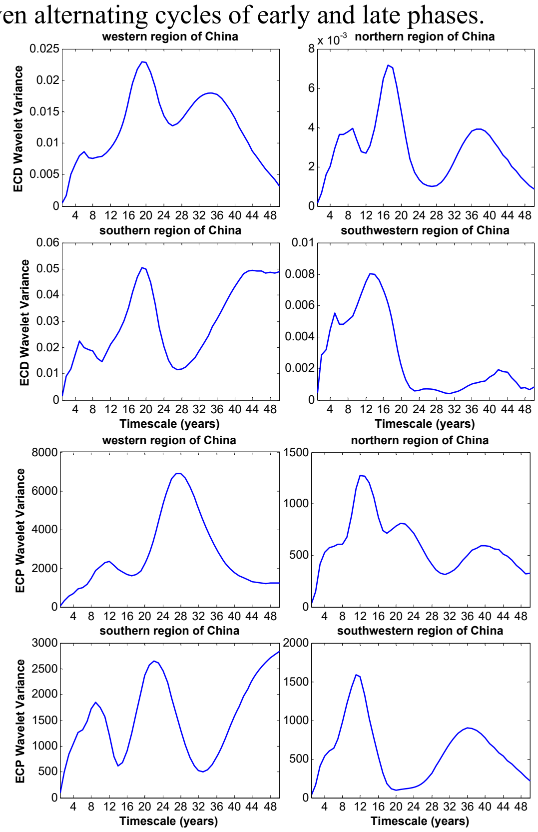

Figure 5. Wavelet variance of the annual concentration degree and concentration period of EPPEs.

The analysis of wavelet coefficients reveals that both the concentration degree and concentration period series contain multiple periodic components. Determining which period serves as the primary period and exerts the dominant influence requires further examination. The wavelet variance and modulus values (complex wavelets) were used to identify the primary and secondary periods and to further elucidate their cyclical variation characteristics. The wavelet variance reflects how the fluctuation energy is distributed across scales, and the scale corresponding to the peak of the wavelet variance curve represents the dominant time scale of the series. As shown in Figure 5, the primary and secondary periods of the concentration degree are 18 years and 34 years in the western region, 17 years and 9 years in the northern region, 19 years and 44 years in the southern region, and 13 years and 5 years in the southwestern region. The corresponding primary and secondary periods of the concentration period are 26 years and 12 years, 11 years and 22 years, 22 years and 11 years, and 10 years and 36 years, respectively.

In summary, over the past approximately 50 years, all regions in China have exhibited pronounced multidecadal (decadal-scale) oscillations in both the concentration degree and concentration period of annual EPPEs.

5. Relationship Between the Concentration Degree and Concentration Period of EPPEs and Extreme Precipitation Amount

The relationships between the concentration degree, concentration period, and extreme precipitation amount of EPPEs are shown in Figure 6. As illustrated, the concentration degree of EPPEs in the western, northern, southern, and southwestern regions exhibits a clear negative correlation with the extreme precipitation amount. The correlation coefficients are −0.53, −0.58, −0.48, and −0.16, respectively. Except for the southwestern region, all correlations pass the 0.01 significance level (the critical values for the 0.05 and 0.01 significance levels are ±0.279 and ±0.361, respectively). The relationship between the concentration period and the extreme precipitation amount varies among regions. Except for the southern region, where a negative correlation is observed, the other three regions show positive correlations. However, these correlations are relatively weak, and only the northern region passes the 0.05 significance test. Therefore, it can be concluded that the extreme precipitation amount in China is mainly influenced by the concentration degree of EPPEs.

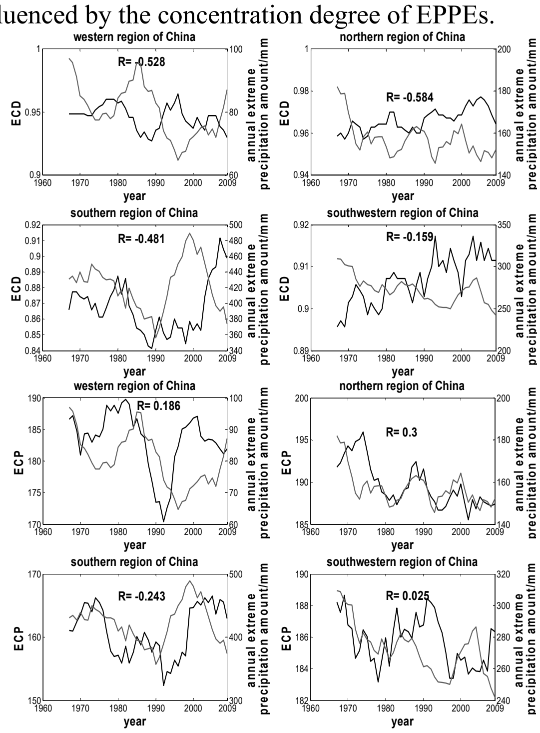

Figure 6. Relationships between the concentration degree, concentration period, and the 7-year moving average of annual extreme precipitation amount (black solid line: concentration degree and period; gray solid line: extreme precipitation amount).

To further explore the relationship between annual extreme precipitation amount and EPPEs concentration characteristics, a composite analysis was performed for anomalous years of the annual EPPEs concentration degree and concentration period. The five years with the largest and smallest concentration degrees and concentration periods were selected as anomalous years. The differences between the composites of high-value years and low-value years are shown in Figure 7. As shown in Figure 7a, most parts of the country exhibit negative differences, with negative centers located mainly in South China and Jiangxi Province, where the difference in extreme precipitation amount exceeds 300 mm. The western region displays smaller negative values. This indicates that when the annual concentration degree of EPPEs is lower, which means the events are more temporally dispersed, the total extreme precipitation amount tends to be higher. In the difference field of the concentration period anomalous years (Figure 7b), most of the southern region shows positive differences. The middle and lower reaches of the Yangtze River Plain exhibit positive differences exceeding 50 mm, with the maximum positive value of 392 mm observed in Jiangxi. However, the southern coastal areas of South China display negative differences exceeding 100 mm in most locations. In the southwestern region, most areas show positive differences, with values exceeding 40 mm in eastern Sichuan, Yunnan, and Guizhou, while negative differences appear mainly in the southeastern Qinghai-Tibet Plateau and western Sichuan. These results indicate that in most parts of the southern and southwestern regions, a larger concentration period (i.e., later occurrence of EPPEs) corresponds to a greater extreme precipitation amount. In the northern region, positive difference areas are mainly distributed in the Hetao region of the Yellow River and the Changbai Mountains in Northeast China, although the magnitude is small, generally less than 50 mm. The rest of northern China exhibits negative differences, suggesting that earlier occurrence of EPPEs corresponds to higher extreme precipitation amounts. In the western region, negative differences are mainly found in Tibet, the Hexi Corridor, and central and northern Xinjiang, while positive differences appear in the remaining areas.

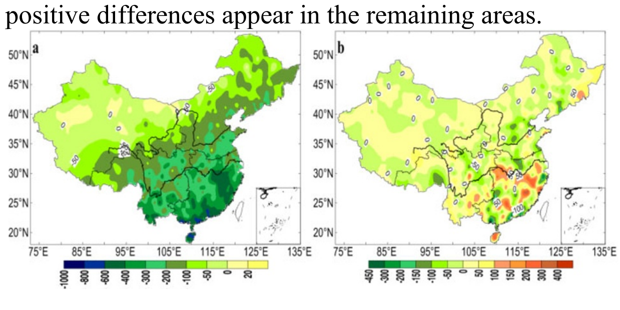

Figure 7. Difference fields of extreme precipitation amount in anomalous years of (a) concentration degree and (b) concentration period of annual EPPEs (unit: mm; high-value years minus low-value years).

6. Conclusions

(1) The concentration degree and concentration period of EPPEs in China show a spatial pattern of “low-high-low” from southeast to northwest. The regions south of the Yangtze River exhibit the lowest concentration degrees and periods, with concentration degrees below 0.9. In contrast, EPPEs in the Huang-Huai-Hai region, Northeast China, and the western region are highly concentrated, with concentration degrees exceeding 0.95. The spatial distribution of the concentration period is consistent with the regional patterns of the rainy season across China.

(2) The spatial distributions of the standard deviations of the concentration degree and concentration period exhibit opposite trends to their mean distributions, showing a “high-low-high” pattern. EPPEs are most prone to anomalies in the southern region and western Xinjiang, while the Northeast and the Qinghai-Tibet Plateau remain relatively stable.

(3) On a regional average basis, The EPPEs in Northern, Southern, and Southwest China have shown a tendency toward concentration, leading to an increased risk of multiple flood disasters occurring intensively within a certain period of the year. In contrast, those in Western China have exhibited a tendency toward dispersion, with the occurrence time of annual flood disasters tending to be discretized. Except for Southern china, EPPEs in other sub-regions have shown an advancing trend—indicating an elevated flood risk during the post-flood season in Southern China and a heightened flood risk during the pre-flood season in the other regions. Over the past 50 years, the concentration degree of EPPEs has displayed a dominant oscillation period of approximately 15 years, while the concentration period has shown an oscillation of about 11 years.

(4) A significant negative correlation exists between the annual extreme precipitation amount and the concentration degree of EPPEs in China. When EPPEs occur more intensively within a shorter time period, the total extreme precipitation amount tends to be smaller; conversely, when EPPEs are more temporally dispersed, the total extreme precipitation amount tends to be larger. This relationship is particularly pronounced in the southern coastal regions of South China.

Funding

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